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Investigation of the Dynamics and Emission Characteristics of X-Pinch Plasmas

A dissertation submitted in partial satisfaction of the  
requirements for the degree Doctor of Philosophy

in

Engineering Sciences (Mechanical Engineering)

by

David Michael Haas

Committee in charge:

Professor Farhat Beg, Chair  
Professor Farrokh Najmabadi  
Professor Tom O'Neil  
Professor Kevin Quest  
Professor George Tynan

2011



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Chair

University of California San Diego

2011

## **Dedication**

To: Naftali Skierso, thank you for all that you taught me. I  
hope I have made you proud.

## Epigraph

*“When we measure something we are forcing an undetermined, undefined world to assume an experimental value. We are not 'measuring' the world, we are creating it.”*

- Niels Bohr

*“All of physics is either impossible or trivial. It is impossible until you understand it, and then it becomes trivial.”*

- Ernest Rutherford

*“A great pleasure in life is doing what people say you cannot do.”*

- Walter Bagehot

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## Publications

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G. W. Collins IV, S. C. Bott, **D. M Haas**, R. E. Madden, K. Gunasekara, J. Kim, M. L. L. Abarr, F. N. Beg, J. P. Chittenden; Effect of the Global to Local Magnetic Field Ratio on the Ablation Modulations of X-pinchs at 80 kA (Submitted: *Physics of Plasmas* 2010)

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## ABSTRACT OF THE DISSERTATION

Investigation of the Dynamics and Emission Characteristics  
of X-Pinch Plasmas

by

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Doctor of Philosophy in Engineering Sciences (Mechanical Engineering)

University of California, San Diego, 2011

Professor Farhat Beg, Chair

A study of x-pinch experiments has been performed on a compact ( $< 1\text{ m}^2$ ) pulse power generator which produced an  $80\text{ kA}$  current with a risetime of  $\sim 40\text{ ns}$ . The first quantitative study of the x-pinch limb ablation has shown a strong correlation with the results from a previously published analytical ablation model. Studies of the coronal plasma velocity and resistivity provided the first approximation of the magnetic Reynolds

number in x-pinch plasmas.  $Re_M$  above one (A1) and below one (W) indicated varying plasma dynamics dominated by convection and diffusion respectively. Variation in the plasma behavior was verified experimentally. Additionally, the effect of a thin high-Z coating on the plasma development was investigated.

Applications of the x-pinch plasma structures were also studied. The evolution of freely propagating supersonic plasma jets was recorded along the axis of the experiment. Mach numbers of  $\sim 6$  and cooling parameters ( $\chi$ ) in the range of  $0.1 - 1$  were found, and the correlation and scaling to large scale astrophysical plasma jets is discussed.

Investigation of the cross point emission recorded the presence of multiple temporally separated x-ray bursts. Here the first peak (occurring around the time of maximum compression) was then utilized in an approach for the non-destructive characterization of inertial confinement fusion capsules, through phase contrast imaging.



# Chapter 1

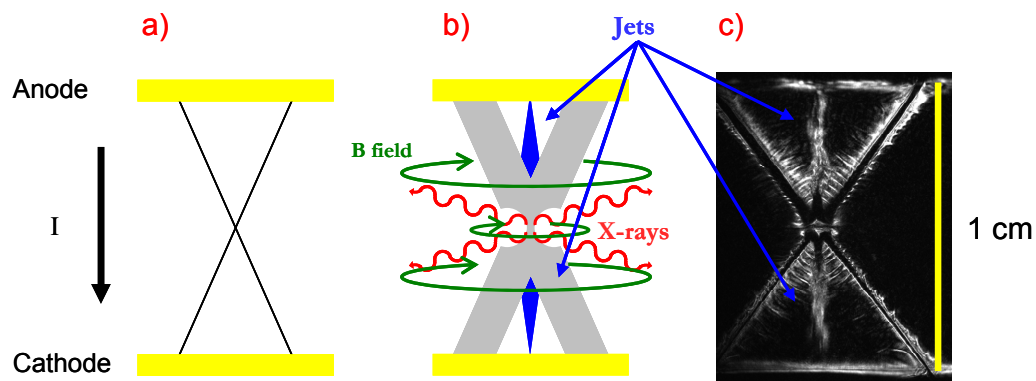
## Introduction

The x-pinch is a specialized configuration of a broader class of pulsed plasma experiments known as z-pinches. In these experiments two or more fine metallic wires (5 - 15  $\mu m$  diameter) make contact at a single point, forming an 'X' between two electrodes [1-11][1-61]. In a two wire configuration, the legs are coplanar; while in a four wire case, the two 'X's' lie in perpendicular planes. Figure 1-1 displays cartoon and dark field schlieren images of a two wire x-pinch, (a) depicts the initial configuration. The application of a current pulse (typically 80-1,000  $kA$  with a rise time of 40-100  $ns$  full-width half-maximum) results in the ablation of the wire surface and the formation of a low density 'coronal' plasma. The wire cores expand on the order of ten times their original diameter due to the plasma's thermal pressure and their continual ablation throughout the current pulse.

Along the limbs of the x-pinch the plasma experiences a local self-induced magnetic field (see Figure 1-1 (i)), which serves to locally confine and pinch the plasma to the individual wire axis. Additionally, as a result of multiple co-directional currents (multiple wires), there is an effective global current centered on the experimental axis

resulting in a global magnetic field. Close to the cross point, the global B-field (ii) is large and serves to accelerate the plasma through the Lorentz force. As a result the plasma moves perpendicularly off the wires, towards the experimental axis as seen in the filamentary structures along the limbs in frame (c). As the plasma stagnates on axis its radial momentum is thermalized while its axial momentum is conserved, resulting in bidirectional jets which propagate towards the electrodes (as indicated in Figure 1-1b/c).

At the cross point of the wires the currents from the individual wires add producing a strong magnetic field which compresses the plasma on the axis, forming a micro z-pinch approximately  $300\ \mu\text{m}$  long (Figure 1-1b). This column then undergoes an unstable axi-symmetric collapse, resulting in the formation of single or multiple compression points. Around the time of peak current these pinch regions are responsible for the soft x-ray ( $1\text{--}12\ \text{keV}$ ) radiation from a small area ( $\sim 1\ \mu\text{m}$ ) near the original cross point of the x-pinch. Following the emission, the plasma column forms multiple gaps isolating regions of plasma while the decaying current maintains a voltage potential along the z axis.



**Figure 1-1** Representations of a 2 wire x-pinch showing the development of the plasma. a) A schematic showing the wire location before the start of the current as well as the magnetic field distribution, b) a schematic of the fully developed x-pinch including magnetic field (green), x-rays (red), and plasma jets (blue). The image presented in (c) shows a schlieren image of a two wire Tungsten X-pinch, 39 ns after the start of the current.

Since their inception, x-pinchs have elicited a great deal of interest due primarily to their use as a backlighter for various applications including biological samples [1-34] [1-35], inertial confinement fusion (ICF) capsules [1-3], and high energy density physics (HEDP) experiments [1-27], [1-31], and [1-83]. The viability of the x-pinch as a ubiquitous diagnostic tool stems from its short duration ( $< 5 \text{ ns}$ ), bright, and high energy ( $> 8 \text{ keV}$ ), radiative characteristics.

Interest in the plasma jets formed on the experimental axis was increased when their applicability to those observed in astrophysics was realized [1-9][1-10]. Previous work has investigated the two possible sources of the axial plasma, and although the contribution of plasma from the legs of the pinch has been compared to hydrodynamic ejection of material from the cross point, the formation mechanism of the jets remains elusive.

The work contained in this thesis advances the body of knowledge associated with the physics of pulse power, wire x-pinch experiments. Experimental and computational results have shown that the ablation and distribution of plasma plays a key role in the development of the wire pinchs. In response, the first research into the x-pinch's non-uniform wire ablation [1-2] and coronal plasma current distribution [1-1] has been performed. The free propagation (above the anode) of an x-pinch plasma jet was investigated for the first time and found to be comparable to those produced in mega-ampere conical wire arrays [1-7]. Finally, the first use of x-pinch radiation to image the low density layers within opaque ICF capsules, was demonstrated [1-4]. While there has been a great deal of progress in the characterization of the plasma properties of the x-

pinch, unanswered questions still remain; these are addressed by prospects for further research.

The results presented in this thesis are from various x-pinch configurations, all of which were driven on a compact pulse power generator which produced an 80 *kA* current, with a rise time of 40 *ns* (FWHM) which followed a  $\sin^{1.2}(t)$  relationship. It has been presented that the current rise-rate in each wire is the principal factor driving the plasma formation and not the maximum current driven in each wire. As a result a selection of the presented results, specifically the wire ablation and the dynamics of the corona plasma, can be applied to other wire configurations, in this way this work is not confined to the x-pinch geometry.

## 1.1 Z-Pinch Physics

Due to the evolutionary nature of the experiment, a comprehensive picture of any element of the developmental sequence necessitates an understanding of the previous stages.

The description of the x-pinch sequence presented below is broken up into sections for clarity. Each should be considered as elements of the overall sequence, influenced by the previous stages.

### 1.1.1 Plasma Equilibrium / Confinement

For a perfectly conducting plasma with a current density  $J$ , it is possible to examine the steady-state equilibrium conditions through a magnetohydrodynamic (MHD) treatment. Considering the equilibrium state (steady state:  $\partial/\partial t = 0$ ) while neglecting

viscosity ( $\nu = 0$ ) and the gravity terms, the MHD equations are simplified to the magnetohydrostatic case [1-63]:

$$\nabla p = J \times B, \quad (1.1)$$

$$\nabla \times B = \mu_0 J, \quad (1.2)$$

$$\nabla \cdot B = 0, \quad (1.3)$$

Here  $B$  is the magnetic field in *Tesla*,  $J$  is the current density in  $\text{Amps m}^{-2}$ , and  $\mu_0$  is the permeability of free space ( $4\pi \times 10^{-7} \text{ NA}^{-2}$ ). The multiplication of equation (1.1) by  $B$  and  $J$  yields:  $J \cdot \nabla p = 0$ , and  $B \cdot \nabla p = 0$  respectively; therefore, the current and magnetic field lines fall on isocontours of pressure, and thus are constrained to be perpendicular to the plasma pressure gradient. This requires that the  $\mathbf{B}$  and  $J$  lines are either closed or extend to infinity. In the z-pinch geometry, closed magnetic field lines ( $B_\theta$ ) surround current lines which extend infinitely along the 'z' axis.

### The Bennett Relation

For a cylindrical current carrying plasma, in which the plasma pressure is in equilibrium with the magnetic pressure, W. H. Bennett [1-62] related the current ( $I$ ) and line density ( $N_{e,i}$ ) to the electron and ion temperatures ( $T_{e,i}$ ) as:

$$8\pi(N_e k_B T_e + N_i k_B T_i) = \mu_0 I^2. \quad (1.4)$$

Above, the line density is expressed as  $N_i = \int_0^R n_i 2\pi r dr$  and the plasma pressure:

$p = \sum_{m=e,i} N_m k_B T_m$ , where  $k_B$  is the Boltzmann constant ( $8.617 \times 10^{-5} \text{ eV/K}$ ) and  $T$  is in

electron volts ( $\text{eV}$ ). Assuming  $N_e = ZN_i$ , ( $Z$  being the average charge state of the atoms) and  $T_e$  approximately equal to  $T_i \approx \langle T \rangle$ , (the mean temperature) equations (1.4) can be

simplified to:

$$8\pi(Z+1)Nk_B\langle T \rangle = \mu_0 I^2. \quad (1.5)$$

The final form of the Bennett relation (1.5) gives the temperature of a pinch plasma in pressure equilibrium and will be referenced in subsequent chapters. Due to the lack of radial dependence, if the temperature of the plasma fluctuates while the current remains constant, the radius of the pinch will adjust to return the temperature to the original value associated with the current. For an ionized tungsten plasma (linear density:  $N_i = 1 \times 10^{19} \text{ m}^{-1}$ ) under an 80 kA current load, the Bennett relation yields a  $(Z+1)T$  of 196 eV.

### **The Pease-Braginskii Current**

R. S. Pease [1-64] and S. I. Braginskii [1-65] independently studied a conducting plasma in equilibrium. Each found that for a steady state plasma, in which the Bennett relation is satisfied, the power deposited by Ohmic heating will be in balance with the power radiated through bremsstrahlung at a unique current known as the Pease-Braginskii current ( $I_{PB}$ ).

Assuming that the temperature and current density are uniform across an optically thin plasma column with radius 'R', the power deposited through Ohmic heating per unit length is:

$$P_{\Omega} = \frac{I^2 \eta_{\perp}}{\pi R^2} \left[ W/m \right]. \quad (1.6)$$

Above, I is the current and  $\eta_{\perp}$  is the Spitzer resistivity perpendicular to a magnetic field:

$\eta_{\perp} = 1.03 \times 10^4 Z \ln \Lambda T_e^{-3/2}$ ,  $T_e$  is in eV, and  $\ln \Lambda$  is the Coulomb logarithm.

Limiting energy loss to bremsstrahlung radiation, for a plasma with an electron density of  $n_e$ , and an average ionization state of  $Z$ , the power radiated per unit length is:

$$P_b = 1.69 \times 10^{-26} Z^3 n_e^2 (T_e)^{1/2} (\pi R^2) \left[ \frac{W}{m} \right]. \quad (1.7)$$

Again  $T_e$  is expressed in  $eV$  and  $R$  is the column radius in *meters*. By equating the power deposited (1.6) with the power radiated (1.7), and using the Bennett relation (1.5) the Pease-Braginskii current is expressed as:

$$I_{PB} = 0.449 (\ln \Lambda)^{1/2} \frac{1+Z}{2Z} [MA]. \quad (1.8)$$

Therefore, in order to overcome the equilibrium state and implode a tungsten wire with a  $\bar{Z}$  of 6, ( $n_e = 2.1 \times 10^{23} \text{ cm}^{-3}$ ) and a conservative  $T_e$  of 10  $eV$ , a  $\ln \Lambda$  of 0.07 is found, resulting in a  $I_{PB} \approx 74 \text{ kA}$ .

In addition to Bremsstrahlung and Ohmic heating, the Pease-Braginskii current is also affected by axial conduction which lowers the plasma's thermal pressure thereby lowering  $I_{PB}$ . Due to the difficulties associated with the estimation and measurement of heat transfer in a compressed plasma it is ignored during the derivation of  $I_{PB}$ .

### **Radiative Collapse**

The energy balance inherent in  $I_{PB}$  is applicable for a steady state plasma, however for a majority of the laboratory experiments the plasma will not be in this state and therefore a better description of the plasma evolution is necessary. If we neglect the presence of instabilities the plasma will undergo an isothermal collapse or expansion according to the Bennett relation (1.5). For a unit length of plasma, it is possible to equate the  $P \cdot dV$  work done on the system, by the current, to the difference of power radiated and absorbed [1-66]:

$$P = \frac{I^2}{2\pi R^2} \frac{d}{dt} (\pi R^2) = P_\Omega - P_B. \quad (1.9)$$

Moving the radial terms to the left side of the equation and substituting in  $I_{PB}$ , J. Shearer found the radial growth rate ( $\gamma_R$ ) to be:

$$\gamma_R \equiv \frac{\dot{R}}{R} = \frac{3}{4} \frac{1}{\tau_r} \left[ \left( \frac{I_{PB}}{I} \right)^2 - 1 \right], \quad (1.10)$$

in which the radiation time constant is defined as:  $\tau_r = 3nkT/P_B = 3/4 (I^2/P_B)$ .

Initially during the pinching process, the current is lower than  $I_{PB}$  and equation (1.8) gives a positive value of the growth rate and the column expands. In this case Ohmic heating dominates, depositing energy in the plasma and raising the thermal pressure. As the current increases and surpasses  $I_{PB}$ , the growth rate  $\gamma_r$  becomes negative indicating a contraction of the plasma. Here, bremsstrahlung effects dominate and the plasma cools reducing the outward pressure. At the same time, the still rising current increases the inward  $J \times B$  force, aiding in the contraction of the plasma. As previously noted, this compression will abide by the Bennett relation, adjusting the column radius (and therefore density) to maintain the temperature. The constriction will continue until the opacity of the plasma becomes important.

The power emitted by Bremsstrahlung radiation is proportional to  $n_e^2$ , as the plasma radius becomes smaller the cooling rate increases, hastening the contraction. This runaway process is therefore referred to as a radiative collapse and will occur when  $I$  exceeds  $I_{PB}$ .



### 1.1.2 Plasma Stability

Research has shown that x-pinchs are highly MHD unstable. To characterize the instability, the plasma is treated as an electrically conducting fluid with zero viscosity using an ideal MHD single fluid model. A small radial perturbation ( $\delta r$ ) is applied to the surface of an initially cylindrical plasma column, changing its distance to the axis. Here  $\delta r$  is a superposition of Fourier components [1-67]-[1-68] and is expressed in cylindrical coordinates as:

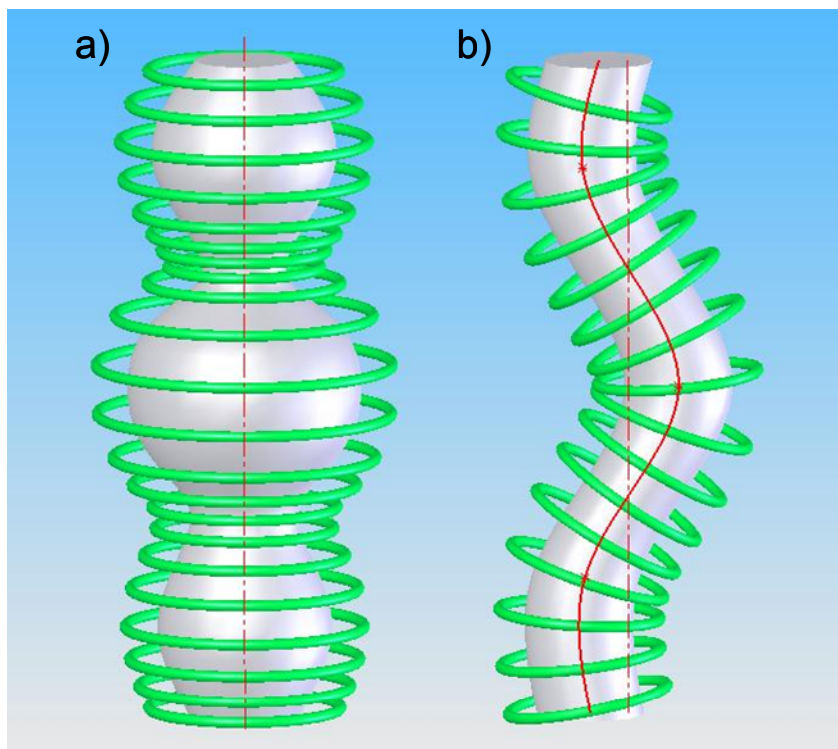
$$\delta r = \xi_0(r) e^{i(m\theta + kz - \omega t)}, \quad (1.11)$$

where  $\xi_0$  is the amplitude of the instability,  $k$  is the axial wave-number, and  $m$  is the azimuthal mode number which determines the  $\theta$  period of the instability. For an axisymmetric radial displacement, independent of the wavelength,  $m = 0$ . Alternatively, in the  $m = 1$  mode, axial symmetry no longer holds and the formation of a helical column occurs. For  $m$  values greater than one the column would appear as a twisted multi-stranded cable, however these modes have not been observed in experiments.

#### Physical Structure of the $m = 0$ and $m = 1$ Instabilities

The  $m = 0$  and  $m = 1$  instabilities are commonly referred to as the *sausage* and *kink* instabilities, respectively. Figure 1-2 illustrates the instabilities' shapes, which display structural similarity to their namesakes. The sausage instability exhibits a quasi-periodic structure, in which the 'necks' have a smaller radius than their neighboring (bulging) regions. In the expanded regions a dispersion of the B-field lines results in low magnetic field strengths which coerces an expansion of the plasma. However, at the small radii the magnetic field is large: ( $B \propto 1/r$ ), creating a high  $P_B$  which serves to

compress the plasma further. As the deformation continues the magnetic pressures of the bulges and necks decrease and increase respectively, and the increasing disparity of  $P_B$  accelerates the deformation. The relative high pressure created at the necks, drives an axial flow away from the compressions and into neighboring regions. As a result, there is no rise in the internal pressure to counteract the increasing magnetic pressure. In this way the difference in magnetic pressure drives the increase in growth rate of the surface perturbation, and the unstable behavior of the plasma.



**Figure 1-2 Depictions of the dominant current-carrying plasma instabilities and the associated self-generated magnetic field lines (green) for the  $m = 0$  'sausage' (a) and  $m = 1$  'kink' (b) MHD instabilities. The original and plasma axes are displayed in red to show the deviation from the equilibrium position.**

In the  $m = 1$  or *kink instability*, the plasma column is deviated from the original axis, resulting in bends or 'kinks' which give this mode its name. A buildup of the magnetic field on the inside (small radii) of the bends creates regions of high magnetic

pressure, while the field dispersion on the outside results in regions of low  $P_B$ . In response the plasma moves from the high to low pressure regions, increasing the amplitude of the perturbations. As the displacement becomes more pronounced the bends become sharper and the pressure difference grows, increasing the rate of deformation.

For the  $m = 0$  case the instability's amplitude will grow as  $e^{\gamma t}$  where the growth rate ( $\gamma$ ) is given in [1-69] and [1-70] as the ratio of the column radius ( $R$ ) to the Alfven velocity  $v_A$ :

$$\gamma = \frac{R}{v_A}. \quad (1.12)$$

Here  $v_A$  is expressed in cgs units as  $\left( v_A = \frac{B}{(4\pi m_i m_i)^{1/2}} \right)$ . The growth rate only need be considered if it is less than the current rise (40 ns), as a longer duration will not develop during the experiment.

For a two wire tungsten x-pinch, around the time of peak current (80 kA) a micro z-pinch is formed with a diameter of 100  $\mu m$  and a magnetic field of  $\sim 320$  Tesla. These parameters yield a  $v_A$  of  $1.52 \times 10^6$  cm/s which gives a gamma of  $3.3$  ns<sup>-1</sup>.

For a current carrying plasma two sets of stability criteria were set forth by Kadomtsev [1-53]. The first regards the stability of a pinch to the  $m = 0$  mode. For a pinch-plasma expanding in to a vacuum, this instability will always be present. The second criterion concerns the column's stability to  $m > 0$  modes. It was concluded that a pinch with a finite current density on the axis will always be subject to the  $m = 1$  mode. Although known to be present, the growth rates for the  $m = 1$  instability are not reported

here, but can be found in reference [1-54].

## 1.2 History of Pinch Plasmas

The x-pinch was preceded by the z-pinch, which came to prominence in the 1950s and consisted of a thin fiber, or metallic, wire fixed between two conducting electrodes. Initial experiments [1-48] [1-49] were conducted using a single wire, and due to the orientation of the wire along the 'z' axis, became known as z-pinches.

The initial design of fast rise pulsed power wire experiments was to compress a plasma to, or above, solid density. Large currents driven through the wires ablated the surface of the fibers/wires and generated azimuthal magnetic fields which compressed the resulting plasma to extremely high densities and temperatures. In the case of deuterium/tritium (DT) fibers, experiments were performed in the hopes of igniting a thermonuclear reaction (for a full description see Bishop 1958 [1-50]). While theoretically feasible, the compression of the plasma fell short of expectations when it was attempted in the laboratory [1-51] [1-52]. The fast rising current did serve to heat the wire, however a uniform compression was prohibited by Raleigh-Taylor and magnetohydrodynamic instabilities, namely the  $m = 0$  and  $m = 1$  modes [1-53] (as described in §1.1.2).

To investigate the behavior of the instabilities, and their role in the release of radiation, subsequent z-pinch experiments were performed by D. Mosher and L. Aranchuk [1-55] [1-56] in the early '70s to mid '80s. Concurrently, other pulsed power work including vacuum spark [1-57][1-58][1-59] and gas puff [1-60] research attempted to compress plasmas through self-generated magnetic fields. In the latter experiments, a

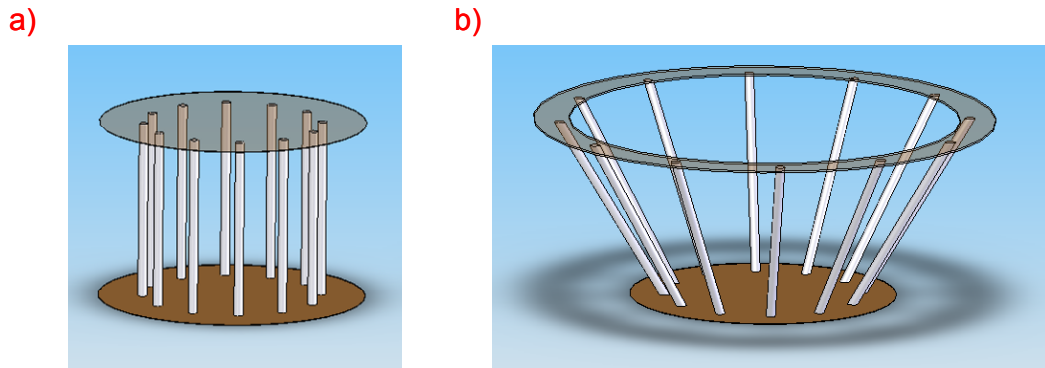
lower initial density and unpredictable electrical breakdown paths resulted in low final densities as well as experimental results that were unreliable and hard to diagnose.

In all of the aforementioned pinch plasma, instabilities resulted in multiple hot spots formed from the non uniform compression of the plasma. These regions were responsible for the release of radiation around the peak current. To overcome the difficulties associated with diagnosing multiple transient hot spots, J. Ulschmid of the Czech Republic proposed crossing two parallel wires between electrodes to scientists at the P. N. Lebedev Institute, Moscow in 1981 [1-11]. In this scheme two wires were fixed between electrodes in the form of an 'X', this was the first known mention of an 'x-pinch' experiment. The modified geometry served to localize the reproducible hot spot to within  $100\ \mu m$  from the initial cross point of the wires, enabling the investigation of repeatable experiments.

### **Wire Arrays**

Another branch of z-pinch research currently being pursued are wire arrays (see references [1-36] to [1-38]). Although not addressed in this thesis, several results are drawn from this subdivision, therefore a brief description is included here for the unfamiliar reader. Cylindrical wire arrays as schematically represented in Figure 1-3a, are constructed from a series of individual vertical wires (4 [1-6] up to 600 [1-7]) arranged to form a cylinder between two electrodes separated by 1-2 *cm*. Due to the larger number of wires, arrays are driven with currents ranging from 0.25 to 28 *MA*, which correspond to currents of  $\geq 30\ kA$  per wire. With current per wire values similar to the experiments described in this thesis, much of the local wire ablation and behavior within a global magnetic field will be applicable. Alternatively, larger coronal dynamics

and resultant structures are dependent on the global magnetic topology and will not be relevant within the x-pinch geometry. A further augmentation are conical arrays [1-7] see Figure 1-3b. While similar to cylindrical arrays, the wires are inclined with respect to the axis, forming the lower part of an inverted cone. These are introduced due to the similarity of the plasma jets formed on their axis to the x-pinch jets discussed in chapter five.



**Figure 1-3** Schematic depictions of 12 wire array configurations: a) a cylindrical wire array and b) a conical wire array. Note: wire diameter not to scale.

### 1.3 X-Pinch Stages

The x-pinch is the evolution of a plasma which can be broken up into five distinct stages of development: wire ablation, coronal development, axial plasma formation/propagation, cross point compression, and emission/radiation. Each process is detailed below in sequence.

#### 1.3.1 Wire Ablation

The first stage of the x-pinch is the ablation of the wires. For all experiments employing metallic wires as the source of the plasma, it is crucial to understand the initial state of the plasma and hence the mechanism by which the plasma was ablated. The

application of a fast-rising, large amplitude current serves to Ohmically heat the thin wires to the point of creating a plasma. Initial work hypothesized that the entire wire became a liquid or vapor early in the current pulse. This was then believed to evolve as a homogeneous plasma column ([1-71] and references therein). These conclusions were refuted by x-ray images of dense wire cores, within a low density coronal plasma [1-28]; in addition, within wire arrays wire cores were identified at their original position for up to 80% of the array implosion time (144-240 ns) [1-32] and [1-33]. These results established the currently accepted model that for the duration of the current pulse, a low-density plasma is continuously ablated from the surface of a cold, dense wire core, thereby sustaining a coronal plasma at the original location of the wire (see Figure 1-4).

As the current rises, the self-generated magnetic field surrounding a current increases as:

$$B(t) = \frac{\mu_0 I(t)}{2\pi r}, \quad (1.13)$$

where  $\mu_0$  is the magnetic permeability ( $4\pi \times 10^{-7} \text{ H/m}$ ),  $r$  is the radius of the current path, and  $I(t)$  is the time dependent current. A consequence of the B field is the magnetic

pressure  $\left[ P_B(t) = \frac{B(t)^2}{2\mu_0} = \frac{\mu_0 I(t)^2}{8\pi^2 r^2} \right]$ , which imparts a force on the plasma. Here the motion

of charge carriers in a magnetic field results in the Lorentz force perpendicular to the current direction and B-field:  $\mathbf{F}_L = \mathbf{J} \times \mathbf{B}$ . In the case of a current carrying wire this force is directed towards the wire axis.

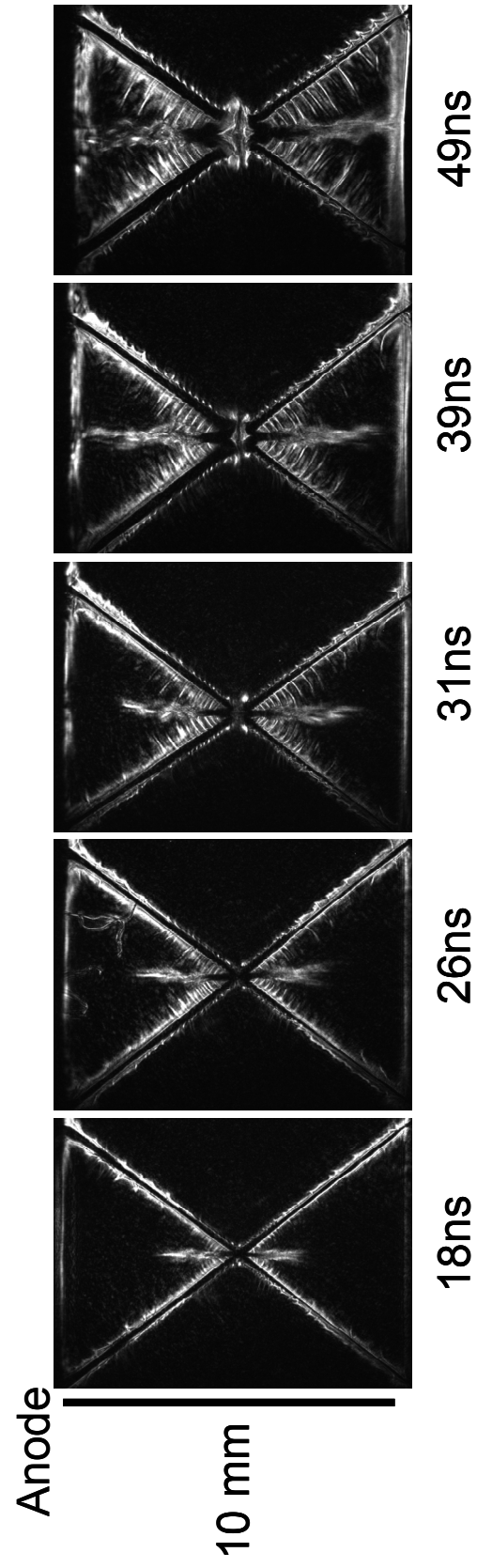
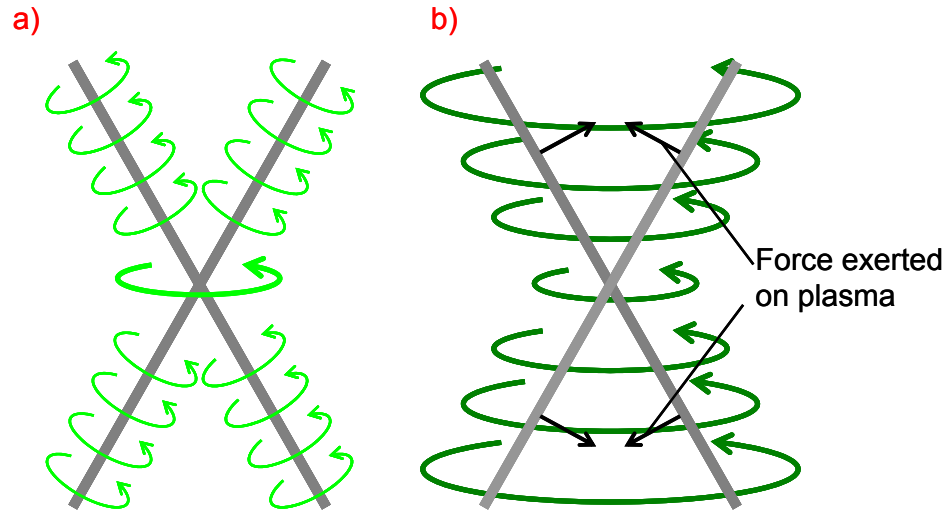


Figure 1-4 Dark field Schlieren evolution sequence of a two wire 7.5  $\mu\text{m}$  diameter Tungsten x- pinch





**Figure 1-5 An x-pinch configuration showing the distribution of the self induced magnetic field for local currents (a), and the global overall current distribution (b). Black arrows in (b) indicate the direction the plasma is driven off the wires by the  $\mathbf{J} \times \mathbf{B}$  force.**

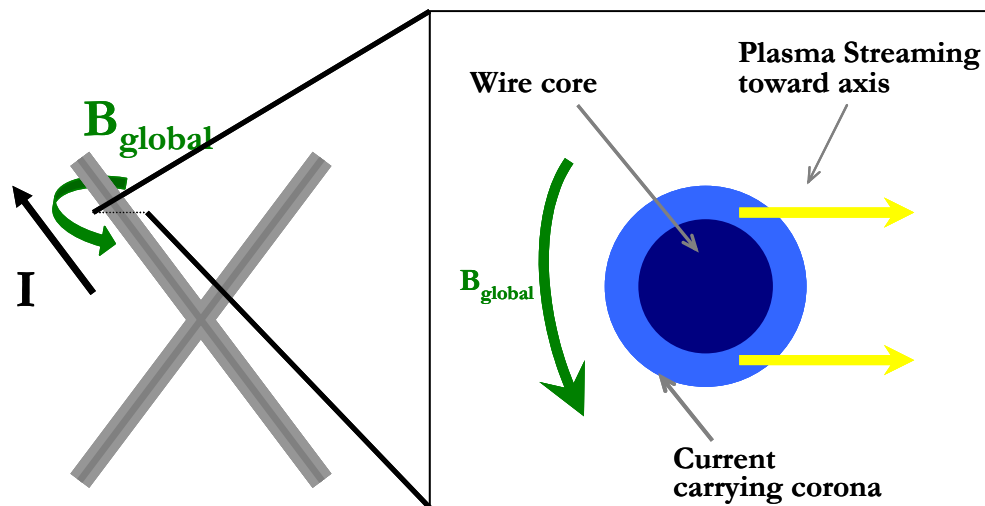
In a two wire x-pinch configuration, each wire is initially displaced from the axis creating two distinct current paths (excluding their cross point). Consequently, in addition to the local field surrounding each wire, the total current erects a global magnetic field around the entire wire arrangement. As a result, both local as well as global magnetic fields are present, as depicted in the cartoons in Figure 1-5a, and b respectively. For the x-pinch the Lorentz force produced from the global field:  $\mathbf{J}_{\text{local}} \times \mathbf{B}_{\text{global}}$ , is directed  $90^\circ$  off the wires, toward the experimental axis, as depicted by the arrows in (b).

Between the wires in Figure 1-5a, the local B-fields oppose each other and therefore their magnitudes detract; however, on the outside of the x-pinch, the direction of the fields coincide and their magnitudes add (see Figure 1-1a). As a result the  $\mathbf{J}_{\text{local}} \times \mathbf{B}_{\text{global}}$  Lorentz force drives the plasma away from its original position surrounding the wires and toward the experiment axis, as depicted in the cross section image in Figure 1-6. Other multi-wire z-pinch arrangements, including parallel wire z-pinches, as well as

cylindrical and conical wire arrays, experience the same amalgamation of local and global fields which contribute to a composite B-field distribution.

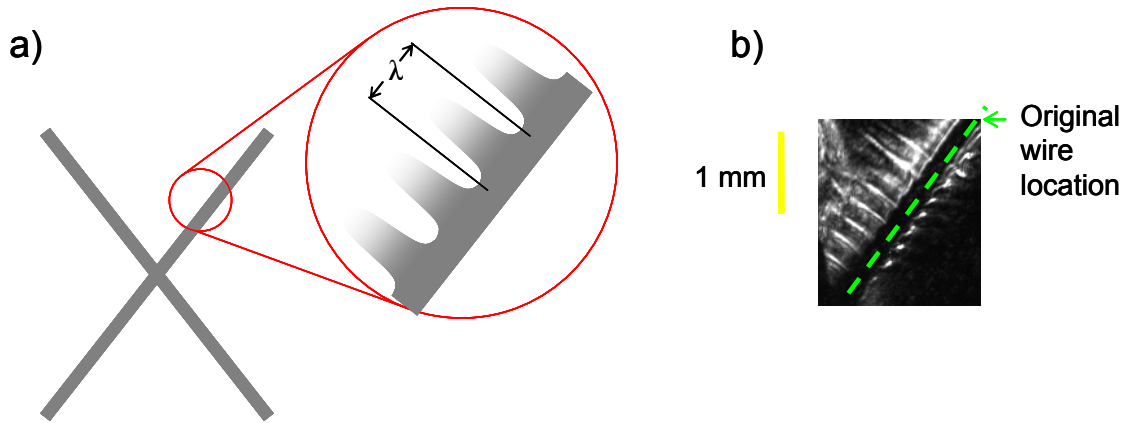
### Ablation Flares

The process of ablating a solid metallic wire into a hot, ionized plasma is currently not well understood. All multi-wire configurations which have a global magnetic field (conical wire arrays [1-36][1-37] and [1-38]) have demonstrated similar non-uniform ablation. Immediately following the ablation, plasma moves off of the wires in an axially periodic structure with a regular wavelength.



**Figure 1-6 Redrawn from reference [1-72]: A schematic representation of the cross section of an x-pinch wire showing the cold wire core surrounded by a current carrying plasma (current is out of the page) under the influence of the global magnetic field**

In x-pinch the initiation of the flares, 18 *ns* after the start of the current, immediately above and below the cross point is documented in the sequence in Figure 1-4. By 49 *ns* their development is visible along the entire length of the limbs. In conjunction with a schematic representation show in Figure 1-7a, an enlarged region of the 39 *ns* image appears in (6b), showing the periodic nature of the ablation.



**Figure 1-7** A detailed view of the ablated plasma from an x-pinch limb. a) a Cartoon showing the locations of flares and (b) an enlarged section of the upper right limb from the 39 ns schlieren image in Figure 1-1b.

In the laboratory individual materials have produced consistent wavelengths regardless of the drive current or experimental configuration, with higher  $Z$  materials exhibiting shorter wavelengths (Al: 0.5 mm, W: 0.25 mm). At present, very little is known concerning the non-uniform nature of the ablating plasma. Although previously recorded in x-pinchs, all of the quantitative data concerning wire ablation has been obtained from multi-wire z-pinchs and wire arrays; the work in this thesis is the first quantitative investigation of the phenomenon in x-pinchs.

### 1.3.2 Coronal Plasma Dynamics

In the limbs of x-pinchs a dense cold wire core is surrounded by a hot, low-density, ‘coronal’ plasma. The lower resistivity of the corona ( $\eta \propto T^{-3/2}$ ), ionization, and lower inductance of a larger diameter conductor,  $L = 2l[\ln(2l/r) - 1]$ , suggest that a majority of the current is carried in the outer plasma. The coupling of the current with the global magnetic field results in an inward  $\mathbf{J} \times \mathbf{B}$  force which accelerates the plasma toward the axis. An investigation of the coronal plasma revealed that the plasma traveled

from the original wire position to the array axis at a constant velocity [1-72]. This implies that the current is not frozen in the plasma, but instead diffuses back to the region surrounding the wire cores, thereby implying a low magnetic Reynolds number for the coronal flow. Additionally, x-ray backlight images (recorded by S. Lebedev *et al* [1-33]) have shown that the high-density wire cores remain stationary throughout the experiment due to a lack of a  $\mathbf{J} \times \mathbf{B}$  force, substantiating the claim that they carry no, or very little, current.

### 1.3.3 Axial Plasma Column

After the plasma has been accelerated away from the wires, it travels to the axis where it stagnates in a plasma column. As can be seen in Figure 1-4, the merged plasma initiates near the cross point of the wires at  $\sim 10$  ns, after the start of the current, and propagates toward the electrodes. The zippering of the plasma along the centerline generates an axial pressure gradient  $\partial P / \partial z$  which drives plasma towards the electrodes.

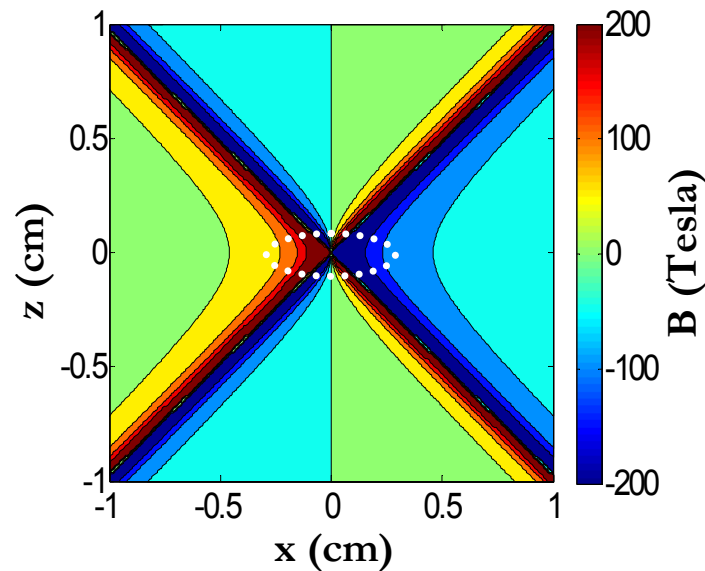
Around 45 ns, after the start of the current, the plasma column is observed to reach from the anode to the cathode at which point it begins to conduct current. This column is made up a low-density, optically thin plasma for which local thermodynamic equilibrium (LTE) tends to overestimate the ionization state of the plasma [1-73] and [1-74]. A discussion of the density conditions for which LTE is valid, as well as, a description of a more applicable Coronal Equilibrium (CE) ionization model [1-74] are presented in chapter five.

The accumulated plasma along the axis of the x-pinch propagates along lines of zero magnetic field. Upon reaching the electrodes, however, it may provide an

alternative path for the current resulting in a self induced magnetic field in and around the plasma jet.

### 1.3.4 Cross point compression and emission

From the geometry of a two wire x-pinch, local B-fields are created around the individual legs of the X, each carrying half of the total drive current. At the cross point of the wires the magnetic field strength is twice that in the limbs; a result of the total current driven through the pinch ( $B \propto I$ ). As a consequence there is a fourfold increase in the magnetic pressure. A static calculation of the B-field strength for an 80 kA current is presented in Figure 1-8.



**Figure 1-8** The calculated B-field strength distribution in a two wire x-pinch from an 80 kA current. The highlighted central region shows a rapid increase in the field strength with decreased radius ( $B \propto 1/r^2$ ).

As previously discussed (§1.3.1), the pressure gradient generated by the superposition of local and global magnetic fields forces the plasma towards the axis as observed in the first three frames of Figure 1-4. An enlarged interferometric sequence of

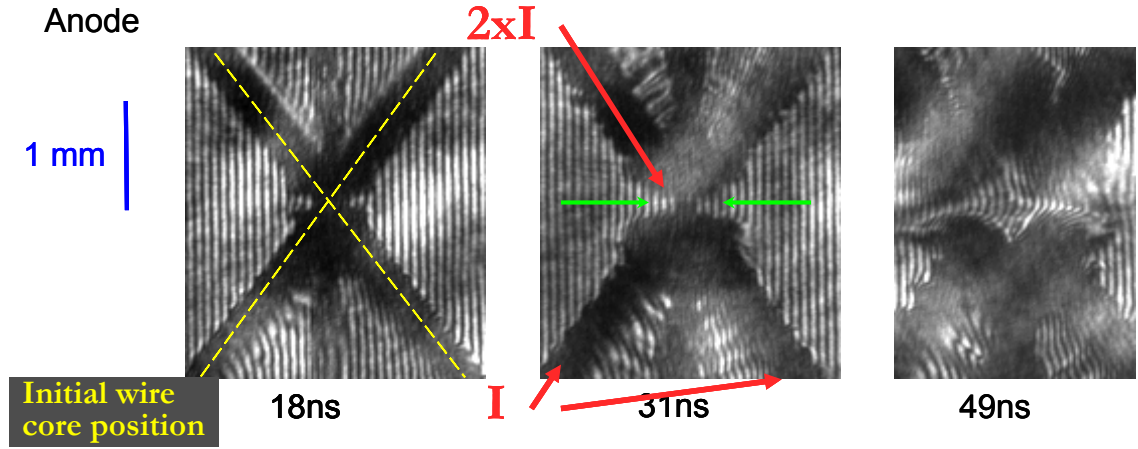
the cross point is displayed in Figure 1-9. Here, in the image recorded at 18 *ns* after the start of the current, the plasma at the cross point has begun migrating toward the axis, as evident by the indentations in the sides of the over-dense plasma. At 31 *ns* (second image) the indentations are more pronounced by the further expansion of the coronal plasma and the continued compression of the plasma column. What results is a 300  $\mu\text{m}$  long, 100  $\mu\text{m}$  diameter column, the small radius of which is achieved through axial mass loss and the radiative cooling of the plasma. The collapse is driven by a decrease in radius, and the continuing increase of the current (risetime  $\sim 40$  *ns*) both of which serve to accelerates the compression (§1.1.1).

This plasma cylinder constrains the current to flow along the axis and then radially at its ends, producing an additional  $\mathbf{j}_r \times \mathbf{B}_\theta$  force which accelerates the plasma toward the electrodes. As time progresses, the axial pressure gradient and the  $\mathbf{j}_r \times \mathbf{B}_\theta$  force drive plasma towards the electrodes elongating the column. Column durations of  $> 5$  *ns* make the instabilities discussed in section 1.1.2 ( $\gamma = 3.3$  *ns*<sup>-1</sup>) significant.

The same development has been recorded for the high density plasma in the vicinity of the cross point, though point projection radiographic imaging in reference [1-76]. As in the optical probing images, compression of the cross-point produces an  $\sim 300$   $\mu\text{m}$  long cylindrical plasma column with a diameter of approximately 100  $\mu\text{m}$ .

As the compression continues the highest rate of mass transport occurs at the location of the strongest axial  $\mathbf{j}_r \times \mathbf{B}_\theta$  force, namely the ends of the column. Here, the plasma is redistributes to the two virtual electrodes at a distance of 150  $\mu\text{m}$  on either side of the cross point. For an ideal system with no instabilities this will result in the lowest density occurring at the ends of the column, pinching the plasma and leaving an isolated

region at the original cross point location. This is exhibited in the simulation results in reference [1-108].



**Figure 1-9** An enlarged sequence of three interferometric images of the cross point from 7.5  $\mu\text{m}$  Tungsten wire X-pinch. The sequence shows the compression of the plasma from the self generated magnetic field.

In laboratory experiments, however, the plasma column is typically referred to as a ‘micro z-pinch,’ and is subject to the  $m = 0$  instability §1.1.1 producing one or more micro-pinches within 150  $\mu\text{m}$  of the cross point. A high rate of radiative cooling prevents the buildup of thermal pressure, allowing the collapse to continue until a small radius is reached. Compression continues until the density has sufficiently increased and the plasma becomes optically thick. At which point the plasma begins to radiate as a blackbody and the Ohmic heating is balanced by the emission. Equating the energy absorption and dissipation rates and incorporating the Bennett equation (1.5) an equilibrium radius was derived by J. Chittenden *et al* [1-108]:

$$r = 2.3 \times 10^{-18} I^{-14/9} \beta^{-4/3} f^{13/9} N^{10/9} \ln \Lambda^{1/3} \quad (m). \quad (1.14)$$

Here,  $I$  is the current drive,  $f$  is derived from the approximation of the ionization ( $Z^* \sim f T_e^{1/2}$ ),  $\beta$  is the ratio of radiation temperature to electron temperature (considering a

blackbody:  $\beta \sim 1$ ),  $N$  is the ion line density ( $\text{m}^{-1}$ ), and  $\ln \Lambda$  is the Coulomb logarithm  $\sim 10$ .

For the short duration of the collapse the current can be approximated as constant, and the plasma at the center of the pinch can be taken to be in pressure and energy balance. As discussed above (1.5), in order for the temperature of the necks to rise while their radii decrease, a reduction in the ion density is required. This density is governed by the axial pressure gradient and the  $\mathbf{J}_r \times \mathbf{B}_\theta$  force. These factors combine to determine the magnitude of the axial mass transport, and consequently the radius of the collapsing plasma.

The collapse of the micro-pinches is halted when their density of the compressed regions drops sufficiently, and the electron drift velocity overtakes the ion sound speed. Here the initiation of micro-instabilities and a plasma resistivity well above the Spitzer value result in a large increase in Ohmic heating. This deposits a large amount of energy in the plasma, culminating with an explosion at the point of compression. Equating the electron drift velocity with the ion sound speed and incorporating the Bennett relation the critical line density was found to be  $N = 1.3 \times 10^{16} A/Z^{*2} (\text{cm}^{-1})$  [1-108]. Assuming an average ionization state of  $Z = 8$  for a tungsten plasma, a lower density limit of  $N = 1.5 \times 10^{16} \text{ cm}^{-1}$  can be found. Plugging the experimental parameters and this density into equation (1.14) gives a final minimum radius of  $0.2 \mu\text{m}$ . It is important to note that in practice the final size of the compressed region will be limited by a lack of azimuthal symmetry, however micron scale emission regions have been inferred from laboratory data, see references [1-112] and [1-113].

The micropinches produce extremely high-energy density plasma [1-78],[1-76], which serve as compact sources of 1-10 keV x-rays, within 2 ns of the maximum



compression. Due to the unstable nature of the pinch, multiple compression regions result in spatially distinct x-ray bursts, having durations of  $\leq 1$  ns, which occur within tens of nanoseconds around the time of peak current. The formation and development of a single plasma column suggests that the subsequent micro-pinches are similar to those observed in single wire z-pinches.

Immediately following the x-ray burst, an axial displacement of the remaining mass occurs. Although not well understood, it is hypothesized that the  $J_r \times B_\theta$  force is responsible for ejecting material from the cross point region [1-108]. Due to the higher magnetic field strength on the axis, the plasma closer to the axis is imparted with a higher velocity resulting in a spherical wave propagating away from the center. This can be seen in the region surrounding the gap in the 49 ns image shown in Figure 1-9. Additional work on the gap evolution on two and four wire x-pinches was performed at UCSD, during the writing of this thesis. This work investigated the expansion rate and density within the gap to further the understanding of the physics associated with the  $J \times B$  forces driving the compression prior to, and during, maximum compression. For a detailed description see the paper published by R. Madden *et al.* [1-111]. It has been suggested [1-76], that the spatial density variations are indicative of shock waves, however this remains conjecture as the necessary properties of the proposed ‘shock’ have not been studied. The final image of Figure 1-9 captures the cross point late in time (49 ns), after the column has disassembled and a gap has formed. Here the variation in plasma velocity is illustrated by the cusps of the evacuated area along the axis.

### **Electron beam**

The gaps in the plasma column, and the residual current drive, establish a voltage

potential across the mini-diode. Consequently, charged particles remaining in the gap will experience a force from the electric field. Due to the low mass of the electrons they experience a large acceleration within the gap, creating a high energy electron beam [1-114]. A release of bremsstrahlung radiation occurs when the free electrons collide with the virtual anode plasma of the micro pinch, leading to emission [1-79] [1-80]. These disruptions are ubiquitous in pulsed power experiments and have also been recorded in cylindrical wire arrays [1-118], gas puffs [1-81], and dense plasma focus (DPF) experiments [1-82].

An initially static electron traversing a gap with an electric potential of  $200\text{ kV}$  (without collisions) will acquire  $200\text{ keV}$  of energy. In reality collisions will remove some of the imparted energy and the observed radiation will be less energetic. Due to the reliance on the gap formation, this emission occurs late in time, when compared with the pinch compression radiation.

## **1.4 Previous work on X-pinch plasma experiments**

While most of chapter one described the evolution of an x-pinch, the primary goal of this section is to familiarize the reader with the previous work relevant to the experiments described in this thesis. As seen in the previous chapter, the ‘x-pinch’ experiment is comprised of several regimes of plasmas. The most extensively researched is the cross point region, which is touted as a small, intense source of x-rays produced during a short duration which has been used widely used to diagnose high density plasmas [1-120]. The motivation for this thesis stems from the fact that the physics

governing both the plasma of this region and the lower density plasma surrounding it are not well understood.

This chapter describes previous work on x-pinch, as well as various wire experiments (including multi-wire cylindrical [1-118], and conical wire arrays [1-7][1-133]) which have expanded the body of knowledge of wire initiated pulse power plasma physics. It should be noted that although work done on z-pinch and wire array experiments used generators capable of producing large currents ( $0.450 - 1 \text{ MA}$ ), only applicable plasma behavior has been reported. Often a higher wire number offsets the increased current, supplying each wire with  $40\text{-}80 \text{ kA}$ , similar to the work presented here. Additionally, much of the fundamental physics has been observed to be generally independent of the current level.

#### **1.4.1 Wire ablation**

In order to describe the rate of mass ablation, a model has been developed by S. Lebedev for discrete wire cores in z-pinch arrays [1-72], and will be described in chapter three. Evidence of non-uniform wire ablation has been seen in wire experiments including x-pinch [1-134] and cylindrical and conical wire arrays [1-72], [1-132] - [1-133] [1-135]. Quantitative work, limited to multi wire z-pinch and wire arrays, has shown that the flare wavelength is governed by the material of the wires, and is independent of the current drive and wire configuration. Results indicated an inverse relationship between the wavelength of the flares and the  $Z$  of the material; tungsten exhibits a  $\lambda$  of  $250 \mu\text{m}$ , Ti a  $\lambda$  of  $400 \mu\text{m}$ , while Al wires have a wavelength of  $500 \mu\text{m}$  [1-33]. Additionally, periodic chemical wire etching, on the order of hundreds of microns,

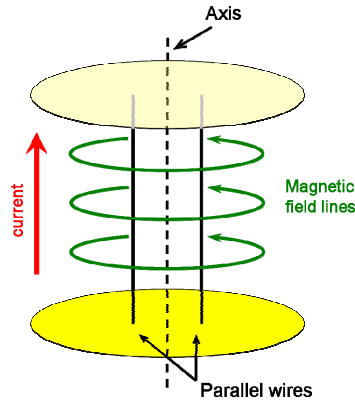
has not affected the wavelength of the ablating plasma [1-102]. As will become evident, the physics governing the behavior of the plasmas in z-pinch and x-pinch experiments remains the same despite the varied geometry, allowing limited results obtained on arrays to be applied to x-pinches.

### **1.4.2 Coronal Plasma**

Previous work has shown that the x-ray yield of an x-pinch can be varied by changing the wire material of the x-pinch. Array experiments have shown that the dynamics of the implosion (i.e. the evolution of the corona) are responsible for the level of compression and the subsequent x-ray emission from the plasma [1-55]-[1-131]. To this end, this section examines previous work relevant to the evolution of the coronal plasma in x-pinches. Due to the limited body of work in this configuration, coronal plasma studies from single and double wire z-pinches have been included.

Experiments performed on single wires [1-88] have discerned a low density (coronal) plasma from the remaining wire core. As the current increased, optical probing captured the coronal plasma imploding axisymmetrically, as an  $m = 0$  instability developed [1-63]. Growth rates were found to be well correlated with those derived from simple MHD models [1-63][1-89]. In conjunction with the instability calculations in reference [1-89], it is possible to say that the majority of the current is carried in the outer 10 percent of the coronal plasma. As a result, the expanded wire core carries none or only a very small fraction of the overall current. This was further verified through x-ray backlighting by D. Kalantar and D. Hammer [1-88] which showed an expansion of the dense core with no signs of instability. This results in a continuous heating of the corona

while energy deposition remains low in the wire core. As expected, rates of expansion for single  $100\ \mu\text{m}$  Al wires demonstrate that the corona expands much faster than the wire core at  $2.4\ \text{cm}/\mu\text{s}$  and  $0.8\ \text{cm}/\mu\text{s}$  respectively (see Figure 5 in reference [1-88]).



**Figure 1-10 Cartoon depicting the setup of a parallel two wire z-pinch experiment**

To investigate the coronal plasma behavior in the presence of an external, axially uniform magnetic field, coupled z-pinch experiments were performed [1-91][1-93]. Here, two individual closely-spaced parallel wires were secured off axis, erecting a global magnetic field which surrounded both wires (see [1-91]). As in the case of the single wires, after the start of the current an ablation of the wire core ensues; however, here the coronal plasma is driven away from the wire core toward the axis by the imposed global B-field. The formation of an axial plasma structure occurs and self-emission from the wires decreased as the radiation from the central column increased [1-91]. Lending weight to the hypothesis that current is redirected through the axial plasma.

Simultaneous backlit ‘side on’ and ‘face on’ images taken by Beg *et al* [1-91] revealed an asymmetry in the expansion of the coronal plasma. They showed the wire radius in the plane of the wires increased at twice the rate as in the orthogonal direction, indicating that there is confinement normal to the plane of the wires. The asymmetric

expansion was seen for Al as well as W, however the aluminum corona expanded at a much faster rate when compared to Tungsten. These results are consistent with the difference in expansion velocities for single wire W and Al z-pinches presented in reference [1-90].

Similar disparities between wire expansion velocities have been seen in higher wire number cylindrical wire experiments. Work by S. Lebedev *et al* [1-72] provided an axial view of the developing wires in the presence of a global magnetic field. Here the plasma was recorded moving at a constant velocity as it traveled from the vicinity of the wires to the axis of the experiment. This suggests that the current remained close to the wire cores and was not frozen into the plasma.

### **Instabilities**

The dominant instability mode along ablated wires is the  $m = 0$  mode. For the case of multiple wires in a global magnetic field, the instability is correlated -- in that, the amplitude of the perturbations as well as the axial positioning are the same in closely spaced wires [1-91] and [1-92].

For closely spaced parallel wires a central plasma column is formed between the wires comprised of hot coronal plasma. Late in time the column connects the electrodes providing a conducting path for the current. As a result the column is subject to the  $m = 0$  and 1 instability modes as seen in Figure 6 of reference [1-91], which displays schlieren images of two parallel  $7.5\ \mu\text{m}$  W wires with an initial separation of  $1.5\ \text{mm}$ . Deviations associated with the  $m = 1$  mode are confined to the plane of the wires resulting in an 'S' shape rather than a helix. The amplitude of the instability was observed to increase with time, while the wavelength remained constant throughout the experiment [1-91].

Geometries with an initially larger wire separation were seen to follow a similar sequence of events, however, occurring over a longer timescale.

### **X-pinch Instabilities**

The expansion of wires in an x-pinch is similar to those described above. The formation of a low density coronal plasma for both pinching and non-pinching x-pinches can be seen in reference [1-84]. As in single wire experiments, uniform expansion of the limb wire cores has been recorded through x-ray backlighting. Additionally, the wire cores expand significantly slower than the low density coronal plasma surrounding them.

X-pinch radiographic images have shown sharp boundaries between the dense core and the opaque coronal plasma. These results are consistent with those from exploding wire (single and parallel) experiments performed in references [1-119] and [1-126]. Additionally, the expansion velocity of the core plasma is constant and only depends on the wire material [1-76], demonstrating that energy deposition into the core occurs early, and ceases when the current transitions to the coronal plasma.

### **1.4.3 Axial Plasma Jets**

This section reviews previous work done to characterize the parameters and plasma sources associated with the plasma jets formed on the pinch axis. Although research of the jets formed from conical wire arrays has been done (see [1-86] - [1-87], [1-7], and references therein) this overview will only concern itself with experimentally produced x-pinch plasma jets. As an extension of this work, a comprehensive overview detailing the non-dimensional parameters necessary for scaling of laboratory to

astrophysical jets has been performed by D. D. Ryutov [1-10] an overview of which is presented in chapter five.

Observations of the plasma formation on the axis, immediately above and below the crosspoint, were recorded using laser backlighting as well as soft x-ray pinhole imaging [1-94][1-95]. Axial velocities for the plasma column, in two and four wire x-pinch [1-97] [1-98], correspond well with the velocities and aspect ratios found by I. Mitchell in x-pinch performed on the Generador de Potencia Pulsada (Gepopu: 100 *kA* in 130 *ns*) reference [1-99]. The axial plasma velocity of x-pinch which did not exhibit constriction at the cross point [1-99], was in agreement with the averages from standard experiments that underwent compression at the cross point.

Simultaneous side on and front images [1-99] showed that neither the plasma column nor the x-pinch wires have a diameter significantly larger in the plane of the wires when compared with the orthogonal direction. This contradicts the results presented above for the parallel wire z-pinch loads, but validates the assumption of cylindrical symmetry for the x-pinch plasma limbs.

Early work utilized an asymmetric arrangement termed a ‘K’ pinch to study the propagation direction of the jet [1-100]. Here the plasma column was found to bisect the angle formed by the wires, and it was therefore concluded that the plasma on the axis is not formed from material evacuated from the cross point but rather by the ablated plasma from the wire cores accelerated by the global  $\mathbf{J} \times \mathbf{B}$  force. These results were supported by interferograms taken of non-pinch wire loads which displayed a plasma column despite the absence of a constriction [1-97]. Additional experiments investigating the



results of varying degrees of asymmetry were performed in reference [1-103]. It was also found that an increase in the asymmetry resulted in more divergent plasma columns.

Analysis of the density measurements in reference [1-96] demonstrated that an accumulation of plasma on the axis, exclusively from the wires, would result in a jet velocity much higher than measured in experiments; this implied that the plasma column was not exclusively composed of coronal plasma ablated from the wires. Further analysis of density profiles [1-99] lent credence to the notion of two sources of plasma.

As the column extends away from the cross-point it expands radially. Assuming propagation into a vacuum, this will occur at a speed close to the sound speed of the plasma and at a divergence angle of  $5^\circ$ . However, experiments have shown columns with divergence angles of 1 to 2 degrees in a majority of cases [1-99]. In response, one proposal asserts that the column's divergence is explained by an increase in width due to an accumulation of plasma (from the limbs) on the outer edge [1-99]. However, the disparity between the axial velocities of the coronal plasma and the axial plasma column velocity is still unexplained. In response, detailed MHD models [1-87] and 3D simulations [1-101] have been used to study the confinement mechanisms of the narrow plasma jets created in conical wire arrays. Results showed that the observed spreading angle can be achieved through a combination of the azimuthal magnetic field confinement and the supersonic radial flux of plasma from the wires. In the latter mechanism, the kinetic energy of the incident plasma is thermalized upon reaching the axis, while its momentum serves to radially confine the plasma. It should be noted that in wire arrays, the increased symmetry (6 up to 32 fold) may attribute more confinement effectiveness from the radially incident plasma than would be seen in the case of an x-

pinch. At the time of the writing of this thesis, only four papers have been published discussing simulations of the generation and propagation of the axial jets [1-100] [1-104] [1-108] [1-109]. This limited collection demonstrates the need for more information characterizing this plasma.

For Au x-pinch electron densities of values  $\geq 6 \times 10^{18} \text{ cm}^{-3}$  have been measured for the axial jets [1-105][1-116];, however, similar radiographic analysis could not be performed on data images from Al x-pinch due to aluminum's low atomic number ( $Z = 13$ ), which resulted in a low density axial column completely transparent to probe x-rays. Alternatively Al jet densities as high as  $1.4 \times 10^{19} \text{ cm}^{-3}$  were found using laser interferometric techniques [1-99].

### **X-Pinch Jet Simulations**

Initial detailed two-dimensional MHD numerical simulations have been performed to model the plasma dynamics of an x-pinch [1-104] subject to a high voltage, short risetime current pulse. While neglecting radiative cooling, a high density plasma formed at the cross point of the wires due to the radial collapse of the plasma. In contrast, incorporating radiation effects showed the formation of two separate, dense plasma regions: one near the original cross point and the other migrating away from the center of the pinch along the axis (the model assumed mirrored symmetry across the cross point). In this model a low density cavity forms between the central plasma and the column extending toward the electrodes, leaving a region of plasma at the original cross point of the wires. These results more accurately represent what is seen in experiments; a pinching off of the plasma above the cross point and an axial flow toward the electrodes.

Radiative high-resolution two and three-dimensional resistive MHD modeling in reference [1-108] by J. Chittenden *et al* produced a supersonic jet along the axis as a result of continual wire ablation coupled with the Lorentz force from the current.

#### **1.4.4 Hot spot formation / radiation**

The cross point is the source of the highest intensity radiation from the x-pinch and varies dramatically based on the initial parameters of the experiment. Radiation properties such as intensity, energy, and timing have been optimized to provide a reproducible radiation source. Additional research has temporally correlated the breakup of the plasma with the emission of radiation. The implementation of this short duration x-ray source as a diagnostic tool (see section 1.2) has lead to the massive undertaking to diagnose the high density cross point region. The focus of this section is to review the large body of work that relates the physical properties of the cross point to the radiation emitted.

#### **Micro Z-pinch formation, implosion and radiation**

At the cross point of the wires the plasma radius decreases uniformly, until a 200-300  $\mu m$  long, 100  $\mu m$  diameter z-pinch is formed between two virtual plasma electrodes [1-76]. The formation of the ‘micro z-pinch’ plasma develops in much the same manner as a single wire z-pinch [1-55] and [1-130].

Initial studies of the x-pinch plasma demonstrated that emission was predominately from the cross point region [1-77], while more recent work has determined that the micropinches produce extremely high-energy density plasmas which serve as the compact sources of x-rays [1-78] and [1-76]. Approximately 2 *ns* before the x-ray

burst(s), the presence of the sausage instability is evident along the micro z-pinch and the development of one or more 6-10  $\mu m$  diameter neck(s) are seen [1-76].

For various materials (W, Nb, Pd) and varying Mo wire diameters the timing of the x-rays varies, however the plasma dynamics associated with the emission remains the same. The ion density of these high compression spots has been estimated to be as high as  $10^{24} \text{ cm}^{-3}$  from calibrated radiographic images [1-76] [1-126], while reasonable assumptions of plasma parameters can be drawn from MHD simulations performed in reference [1-127].

Although direct plasma measurements have only been made just before emission ( $\sim 2 \text{ ns}$ ), filtered pinhole images have established the size of bright spots at  $\leq 6 \mu m$  [1-96], [1-78], while backlighting studies [1-117] and [1-76] have achieved wave-optics-limited spatial resolutions of 1-3  $\mu m$  implying a sub-micron source size. Direct size measurements of the emitting plasma are not feasible at this time.

Novel diagnostics have been able to locate the point source of x-ray emission with an accuracy of a few microns and have shown the position of the micro-pinches to be well correlated with the locations of the x-ray bursts [1-76].

Various wire materials have produced multiple points of compression during a single experiment. As a result, ‘radiating regions’ may include several points of emission along the length of the micro z-pinch with separations of 100-200  $\mu m$ . Work in references [1-96], [1-120] and [1-12] recorded the emitting region to be approximately 0.5 mm in height, centered around the cross point.

These hotspots have exhibited electron temperatures in excess of 1 keV [1-117], while time resolved x-ray emission has been able to identify Mo x-ray pulse durations as

short at 250  $ps$  (FWHM) [1-76]. Work on Ti x-pinchs by S. A. Pikuz *et al* was able to identify electron densities up to  $3 \times 10^{23} \text{ cm}^{-3}$  and temperatures of 2.5  $keV$  for hot spots with durations as short as 50  $ps$  [1-75]. Data from x-pinchs of several different wire materials [1-117] showed a strong dependence of the burst duration on the wire material, and only a weak dependence on the wire diameter and current level. Additionally, the emission timing was found to rely on the current amplitude and wire configuration; emission from large diameter wires occurred later when compared with the radiation from thinner wires [1-96]. D. H. Kalantar *et al* [1-84] noted that, for a given configuration, the timing of the first x-ray burst with respect to the current was reproducible, however subsequent emissions appeared to be temporally random.

Time resolved x-ray signal measurements from reference [1-76] have shown that when multiple x-ray bursts are observed, the first produces twice the intensity of subsequent emissions. It was also found that Al, while requiring less current to ‘pinch’, had a higher likelihood of producing multiple emission spots when compared with Mo x-pinchs indicating that the atomic number of a material may effect the radiative collapse and/or radiation.

Initial two dimensional radiative MHD simulations of a Mo x-pinch cross point plasma [1-122] and [1-123], accurately modeled the radial compression and the development of instabilities recorded in the laboratory. Results reproduced source sizes of a few microns and x-ray intensities as high as  $10^{17} \text{ W/cm}^2$  [1-121]. The use of an initially uniform plasma column and a two dimensional treatment imposed an axial symmetry and eliminated the development of instability modes in which  $m > 0$ .

Recent two and three dimensional, resistive MHD simulations, using the GORGON code (as described in reference [1-106] and [1-107]) have added a greater levels of detail are consequently have been able to reproduce the full plasma evolution from the wire ablation through the formation of the micro z-pinch [1-108] and [1-115]. The formation of the hot spots was triggered by the  $m = 0$  instability.

Additional work modeling the explosion of the hot spots and the breakup of the micro z-pinch can be found in references [1-124] and [1-125]. Although the same structures are reproduced in the numerical model, an adequate explanation of their formation is still being sought after.

### **Emission Spectroscopy**

Both time integrated and time resolved measurements have been performed on the cross point of x-pinches.

From a single Nb x-pinch, time integrated spectroscopic images presented in [1-117] recorded two distinct spectra from closely separated sources. The first showed higher emission intensity and the analysis of these spectra implied an electron temperature from 800-1000  $eV$ . These results correlate well with spectra from various wire material x-pinches which display He-like lines implying electron temperatures in the range of 500 – 1300  $eV$  [1-76].

The relative intensities of the line, and continuum radiation are linked to the plasma density [1-117]. Shots demonstrating a high level of continuum radiation with broad line-radiation are indicative of a higher density at the emission points. However, x-pinches with lower continuum radiation and narrower, higher intensity line-radiation

produced low contrast blurry backlight images, which are associated with large sources or low levels of plasma compression.

X-pinch continuum radiation has been measured extending well into the 6-10 *keV* range for various wire materials [1-76]. While the intensity of this radiation is highly dependent on the ‘quality’ of the pinch, it is only slightly dependent on wire material, increasing as the atomic number (*Z*) of the material is increased.

At the time of this thesis the mechanisms responsible for the emission of radiation from the compressed plasma are not well understood. One theory postulates that the release of large amounts of radiation enables a radiative collapse (see references [1-128][1-129]), leading to an implosion of the plasma on axis. The conjecture consists of a magnetically driven compression (see [1-128][1-129]) which results in extreme temperatures and densities, responsible for the subsequent emission of 1-7 *keV* radiation.

The fitting of modeled spectral data to the experimental results from titanium [1-136] and aluminum [1-136] [1-137] utilized the K-shell line emission to identify ion densities of  $10^{19} - 10^{24} \text{ cm}^{-3}$  having plasma temperatures of 1 *keV*. Higher energies of emitted radiation (3-7 *keV*) were recorded by D. H. Kalantar and D. A. Hammer [1-120].

L-shell emission was recorded from Mo X-pinchs performed on the ZEBRA generator at the University of Nevada Reno. Through the incorporation of a non-Maxwellian hot electron fraction from 3-7%, time resolved spectroscopic modeling revealed electron densities ranging from  $10^{19} - 2 \times 10^{21} \text{ cm}^{-3}$  and temperatures from 850 - 1100 *eV* [1-138]. The analysis of secondary (later) x-ray emission by S. B. Hansen *et al* [1-139] found similar results, however later emission emanated from 17-20  $\mu\text{m}$  diameter sources, twice the size of the initial 10  $\mu\text{m}$  emitting plasma. For the primary x-ray

emission the fraction of hot electrons necessary to model the recorded emission was observed to increase with the current [1-138], supporting the fact that the hot electrons are responsible for carrying the current after the formation of the gap.

The spatial variation of emission was also investigated in reference [1-137]; line emission was observed along the axis in the direction of the anode and suppressed closer to the cathode, supporting the presence of a unidirectional electron beam.

X-pinchs have been studied on pulsers capable of producing varying currents from 450 *kA* in 100 *ns* on the XP facility [1-96], to 5 *MA* in  $\sim 150$  *ns* on the Blackjack 5 generator [1-85]. It is important to note that currents less than 100 *kA* are sufficient to achieve pinching with emission in the *keV* range. Below Table 1-1 summarizes the properties of the various plasma regions of the x-pinch with results gathered from references [1-35] and [1-79].

**Table 1-1 Summary of X-pinch plasma properties**

| Region         | Size ( $\mu m$ ) | Duration<br>( <i>ns</i> ) | Density<br>( $cm^{-3}$ ) | Temperature<br>( <i>keV</i> ) | Emission<br>( <i>keV</i> ) |
|----------------|------------------|---------------------------|--------------------------|-------------------------------|----------------------------|
| Wire cores     | 20-100           | 100                       | $10^{23}$                | 0.001                         | --                         |
| Coronal plasma | 100-5,000        | 100                       | $10^{17} - 10^{19}$      | 0.01-0.1                      | 0.01-1                     |
| Jets           | 1000-5,000       | 30                        | $10^{18} - 10^{20}$      | 0.05-0.3                      | 0.01-1                     |
| Hot spot       | 1 - 100          | 0.05 - 5                  | $> 10^{23}$              | 0.8-8 up to 15                | 1-10                       |
| Electron beam  | 300-2,000        | 2 - 10                    | $10^{10} - 10^{14}$      | $> 5$ up to 60                | 10-100                     |

## 1.5 Applications of the X-pinch

A great deal of the research performed on x-pinch experiments has stemmed from the multitude of applications utilizing the small, bright, soft x-ray emission of the central region [1-11] [1-12]. Prominent early work, investigating the cross point emission, consisted of microlithography and x-ray microscopy [1-13]. Currently employed x-ray sources are subject to low x-ray fluxes which necessitate long exposure times for the high



resolution reproduction of microlithography masks, or x-ray microscopy studies of biological samples. Extended sampling time leads to degraded biological samples [1-14], the breakdown of the x-ray sensitive resistance, and a reduction in the reliability of lithographic reproductions [1-15]. The use of high intensity synchrotron x-ray facilities is hampered by their prohibited costs and lack of accessibility. As a result, viable sources are limited to Laser Produced Plasmas (LPP) [1-22] and pulsed, discharged produced plasmas (DPP). An assessment of gas puff pinches has been performed [1-16]-[1-22], but the x-pinch's reproducible, high energy x-ray source has proven an ideal candidate for sub-micron x-ray lithography and microscopy studies [1-23] and [1-24].

Work within the last ten years has refined the output of the x-pinch for use as an x-ray backlighting diagnostic tool and has included the suppression of multiple emissions, the regulation of x-ray timing, and tailoring of the radiation wavelength through the selection of wire material. The x-pinch has enabled the research of stationary objects [1-25], as well as dynamic high-density plasmas such as those found at the cross point of x-pinches [1-26] [1-27], in single wire z-pinches [1-28] [1-29], and wire array experiments [1-30]-[1-33]. Extending previous work on microscopy, B. M. Song *et al.* were able to extend the application of the x-pinch to point projection radiography of low contrast biological samples through phase contrast imaging [1-34] [1-35].

The reproducible keV wavelength radiation from the cross point has also been used as an intense source of high energy x-rays for calibration of x-ray film [1-39] and [1-40].

Additionally, the high spectral intensity ( $10^5 - 10^6 \text{ W/\AA sr}$ ) of z-pinch hot spots [1-41] supports the use of the x-pinch's reproducible x-ray source for the pumping of

short wavelength (XUV) lasers [1-42], [1-43] in place of the traditional higher cost and less efficient pump systems [1-44]-[1-47]. The proposal to use the plasma emerging from the hot spots as the active short wavelength lasing medium has also been suggested [1-43].

A primary result emerging from the study of axial plasma that forms in x-pinch is the similarity they bear with astrophysical plasma jets [1-8]. The generation of small scale laboratory plasma jets, with parameters which scale to those in astrophysical phenomenon [1-9][1-10] provide a scheme to study radiation and momentum transfer, as well as other similar plasma properties of large scale events.

## **1.6 Objectives and Outline of the dissertation**

The x-pinch is an interesting source of high energy density physics; however, its contributions to a variety of physics research demonstrate the importance of understanding and utilizing the various plasma regimes to their full potential.

The majority of the past x-pinch research has been concerned with the hot, dense, emitting plasma created at the cross point of the wires. The work presented investigates the creation and dynamics of the coronal plasma, as well as its role in the development of the x-pinch plasma jets. Additional research examining further possible applications of the cross point emission as a diagnostic tool conclude the dissertation.

Chapter one presents an introduction of the x-pinch to the unfamiliar reader. A brief description of the experiment's geometry is included, followed by an overview of past and current applications of the x-pinch, and the use of cross point radiation primarily as a diagnostic tool. A complete description of the x-pinch sequence and the associated

physics follow. The chapter concludes with the body of work previously performed on pinch experiments since their inception in the early '60s. From this overview it is clear that although extensive effort has been devoted to characterization of the emission, a void exists in the literature regarding the plasma dynamics which generate the radiation.

Chapter two details the experimental setup used to create and study the plasma during the experiments. Research was performed using a compact ( $< 1\text{ m}^2$ ) 80 kA pulser with a risetime of  $\sim 40\text{ ns}$  (10-90%). A detailed description of the pulse generation and pulse forming line, as well as a discussion of the optical and x-ray diagnostics are included.

As in wire experiments, in order to study the plasma dynamics in x-pinchs it is imperative to understand the generation of the plasma. A study of the ablation and flare structure of plasma adjacent to the wire limbs through laser backlit schlieren and interferometric imaging is presented in chapter three. Density contrast measurements showed that the flares are distinct plasma structures, while their reproducible periodic structure eliminates the possibility of them being a random occurrence. Analysis done along the streams has shown good agreement with the standard rocket model (described in this chapter), thereby providing a good indication of the mass ablation rate for the wires in the experiment. Although previously examined in wire arrays this is the first quantitative investigation in x-pinch experiments.

In chapter four, the coronal plasma dynamics studied through a combination of laser backlighting and time resolved, self-emission x-ray images, are presented. Results showed a faster uniform expansion of the x-pinch limbs for Al wires when compared with those of higher  $Z$  materials. In low  $Z$  materials, current remained frozen in the

corona and thereby migrated to the axis. Conversely, in high atomic number materials the current diffused through the corona, remaining in the vicinity of the wire cores for a majority of the x-pinch sequence. Current switched to the axis after the current peak at approximately 43 ns. Additionally, the impact of radiation on the plasma behavior was highlighted through the first comparison of coated and uncoated x-pinch wires.

Although performed on x-pinchs, results from chapters three and four are applicable to the plasma formed in various wire array experiments (cylindrical, conical, planar, arrays etc.), and contribute to the fundamental understanding of the coronal plasma in complex wire arrangements.

Chapter five consists of a description of the plasma jets formed on the experimental axis. From recent work on conical wire arrays at Imperial College in London [1-7] and the scaling relations developed by Ryutov *et al* in [1-9] [1-10], a connection between the jets created in wire experiments and those formed from astrophysical events can be made. In order to apply the results from one system to another, non-dimensional parameters must be investigated; therefore chapter five begins with an overview of the scaling of x-pinch features to astrophysical plasma jets. The observed plasma flow necessitates a fluid description, and therefore a section within the chapter is devoted to the criteria essential for a hydrodynamic treatment of the plasma. This is the first investigation of whether astrophysical jets can be studied on small scale current generators.

As presented above, due to its small source size and  $h\nu \sim keV$  radiation, the cross point emission has been used to study biological samples and high-density plasmas. As an extension, a study of the hard x-ray emission ( $> 6 keV$ ) and its feasibility as a

diagnostic tool for Inertial Confinement Fusion (ICF) shells is discussed in chapter six. Although already addressed as a conventional backlighting tool, this chapter assesses the x-pinch's ability to diagnose low-density/low contrast media within opaque casings.

Chapter seven concludes the dissertation with a summary of the work presented, and statements on how this thesis has furthered the knowledge of the x-pinch, and related wire z-pinch fields. Additional recommendations for future research are also discussed.

X-pinch experiments encompass plasmas with temporal and spatial scales ranging from the picosecond, sub-micron cross point, to jets exhibiting  $> 40$  ns durations and lengths in excess of 5 mm. In order to analyze and correlate x-pinch dynamics, novel hardware modifications and the use of simultaneous imaging techniques were employed. The work presented in this dissertation has extended the analysis of flair ablation to the x-pinch geometry and made significant strides in the understanding of the current distribution, a largely unsolved issue in pinch experiments, through the correlation of the plasma density with x-ray emission.

The similarities in behavior of the x-pinch coronal plasma to that of multi-wire z-pinches (in both experiments and simulations) demonstrate that the physics governing the core and coronal plasma is similar; therefore results can be applied despite the varying configurations. Advancements were made utilizing the x-ray emission for diagnosing micron scale impurities in low density foams contained inside opaque shell layers. However, a deep understanding of the emission will yield a more substantial knowledge of the hot spots and also aids in the understanding of the radiative collapse which occurs in the plasma. And finally, results demonstrating that astrophysically relevant jets can be produced in x-pinches were obtained. In light of the results presented, extreme

temperatures and densities in very close proximity within the x-pinch are responsible for the questions which remain regarding the exact nature of the wire ablation, current path, and variations of the size and timing of the x-ray emission. It is these ambiguities which demonstrate the need for further research, a selection of which are presented at the end of this document.

From previous work and the description of the results from varying configurations it is clear that a portion of the physics associated with plasma phenomenon occurring in x-pinch have been studied in alternate contexts. In light of this, the results presented here are novel and worthy of consideration as they extend existing x-pinch studies down to the 80 *kA* current level and include the first studies of various wire generated plasma physics in an x-pinch configuration.

## Chapter 2

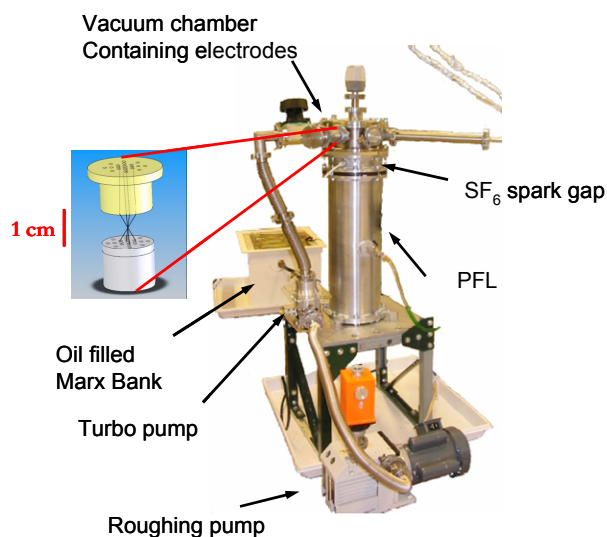
# Apparatus and Diagnostics

In this chapter a detailed description of the compact pulse power generator, used to drive a large current through x-pinch experiments, is relayed. An explanation of voltage and current diagnostics used to verify the operation of the pulser follows. The remainder of the chapter is devoted to the diagnostics used to investigate the dynamics and emission characteristics of the plasma.

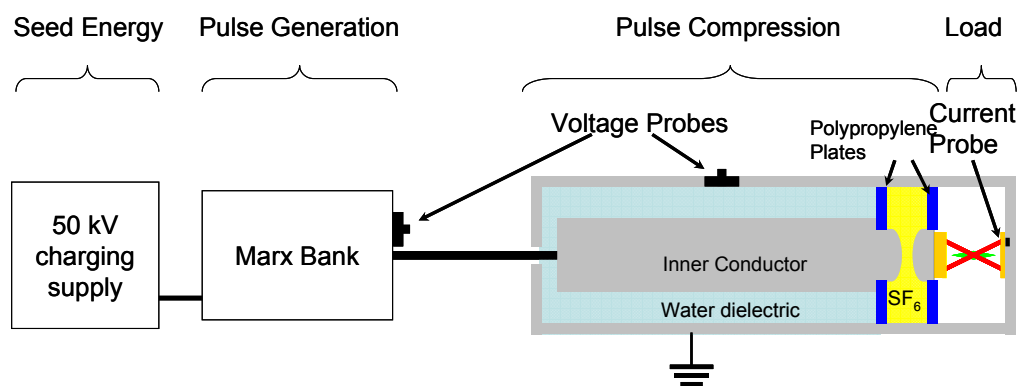
### 2.1 The compact X-pinch generator

Various parameters must be considered when utilizing a pulse power device; these are driven by the conditions necessary to maintain confinement of a plasma generated during the experiment. In order to balance the thermal pressure generated in a high-density pinch plasma, undergoing Ohmic heating, a high current rise rate,  $dI/dt, > 10^{12} A/s$  is necessary to surpass the growth of instabilities, as discussed in [2-1]. The device should also have a high impedance relative to that of the load, thus ensuring the drive current is not affected by the pinch dynamics.

These requirements were met through the use of a conventional compact pulse power device. The device consists of five stages: a Marx bank, transmission line, pulse forming line (PFL), spark gap switch, and the load and is capable of delivering a current pulse of 80kA with a rise time of 40 ns (10-90%). A picture as well as a schematic of the stages can be seen below in Figure 2-1 and Figure 2-2 respectively.



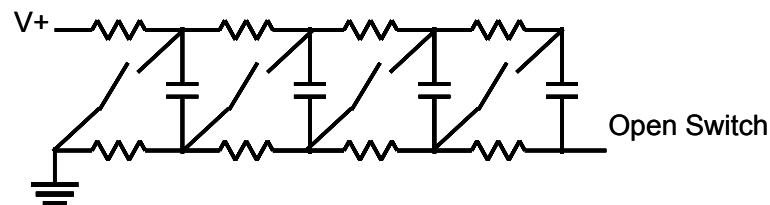
**Figure 2-1 Photograph of compact x-pinch pulser, including Marx bank, transfer cable, pulse forming line (PFL), vacuum chamber, and vacuum pumping system**



**Figure 2-2 Schematic representation of the electrical system involved in pulse compression. Generation of a 500ns pulse (1) from a Marx bank, followed by the compression of the pulse through a PFL to an 80ns pulse (2).**



The first stage is a Marx bank [2-2] housed in a reservoir of Shell Diala AX electrical insulating oil to prevent flashovers from the high charging voltages. This stage is made up of four  $0.22 \mu F$  capacitors, each rated at  $50 kV$ , which are connected by four air-filled spark gap switches. By controlling the pressure in the gaps, while maintaining a fixed electrode separation, it is possible to adjust the breakdown voltage of the switches and therefore the charge voltage of the bank. In the Marx bank, resistors were used to charge the capacitors in parallel (see Figure 2-3a) by a  $50 kV$  Glassman Series FX voltage supply. When fully charged the Marx bank holds  $1,100 \text{ Joules}$  of stored energy. The bank is then triggered by a Maxwell Trigger Generator which supplies a pulse with a peak voltage of  $5 kV$ .



**Figure 2-3 Electrical circuit diagram for Marx bank in a charging circuit configuration, capacitors connected in parallel**

Only the first switch of the Marx bank is triggered externally, this leads to a drop in the voltage across the first capacitor, which increases the voltage across the remaining switches leading to a sequence of self triggering. The switches are critically arranged, and fixed in place by clear acrylic, enabling the radiation from one spark gap to ionize the air in the following gap, minimizing the jitter inherent in self breaking switches. Through this process the capacitors are connected in a series configuration, and the final switch (after the fourth capacitor) delivers the Marx bank energy to the coaxial transmission line.

The voltage from the Marx bank  $V_{MB}$  is transmitted to a pulse forming line (PFL)

by a high voltage cable. The incorporation of this UR-74 coaxial transmission line allows the Marx bank to be connected in a variety of arrangements, adding flexibility to the design of future work.

The transmission line is attached to a water-filled pulse forming line (PFL). The inner and outer conductors, seen in Figure 2-2 in grey, together serve as a 0.9 m long capacitor while de-ionized water serves as the dielectric due to its high voltage hold-off strength on short time scales ( $< ms$ ). In a coaxial line with an inner radius of ' $a$ ' and an outer radius of ' $b$ ' the impedance (in Ohms) is given by:

$$Z = \frac{377}{2\pi\epsilon_r^{1/2}} \ln\left(\frac{b}{a}\right), \quad (2.1)$$

where  $\epsilon_r$  is the relative dielectric constant of the insulator (for water  $\epsilon_r = 78.38$ ). Taking the speed of light in water as  $c_w = c/\sqrt{\epsilon_r} \cong c/9$  the single transit time  $\tau$  is:  $\tau = d/c_w$ .

Therefore the risetime of the PFL corresponds to double the single transit time.

For the PFL discussed here the inner and outer conductors have radii of  $a = 7.5$  cm and  $b = 9.5$  cm respectively with an overall length of  $d = 90$  cm. The water used between the conductors is de-ionized with a resistivity above  $10^5 \Omega m$  while the central conductor is supported by polypropylene plates, both factors mitigating the chance of flashover within the pulse forming line. From the above formulas we obtain a  $Z$  of 1.6 Ohms and a risetime of 52 ns (single transit time of  $\tau = 26$  ns), using these values to find a capacitance  $C_{PFL} = \tau/Z$  we get  $C_{PFL} = 26ns/1.6\Omega = 16.25nF$ .

In order to achieve an effective voltage transfer and mitigate energy losses the capacitance of the pulse forming line  $C_{PFL}$  must be lower than that of the Marx bank  $C_{MB}$ . From the parameters above we find  $C_{MB} = 55$  nF and the condition is satisfied.

The voltage from the Marx bank  $V_{MB}$  can be used to find the peak voltage into the PFL:

$$V_{PFL} = \frac{2C_{MB} \cdot V_{MB}}{C_{PFL} + C_{MB}}. \quad (2.2)$$

A charge voltage of  $50 \text{ kV}$ , yields a Marx bank voltage of  $V_{MB} = 200 \text{ kV}$  which results in a  $V_{PFL}$  of  $307 \text{ kV}$ , an increase of 53%, which is known as the *ring-up effect* [2-3].

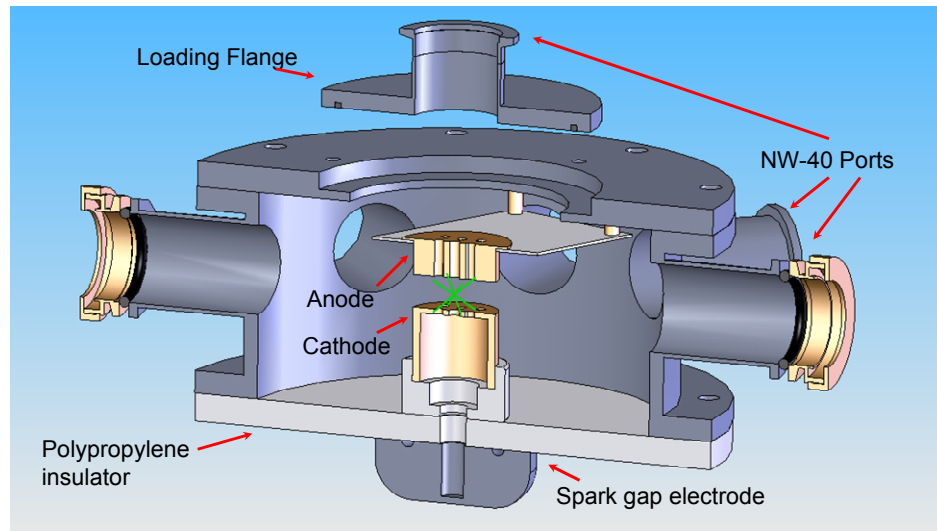
The PFL terminates in a self-breaking, sulfur hexafluoride ( $\text{SF}_6$ ) filled gas switch. Varying the gas pressure alters the breakdown voltage of the switch, thereby controlling when the energy from the PFL is transferred and therefore the maximum current delivered to the load. A  $13 \text{ mm}$  thick polypropylene plate is used as the interface between the de-ionized water and the  $\text{SF}_6$  spark gap.

The spark gap is connected through another  $13 \text{ mm}$  polypropylene plate, to the lower electrode which secures the bottom of the load wires. In this case, the insulating plate serves as the interface between the pressurized  $\text{SF}_6$  compartment and the vacuum chamber as well as electrically isolating the conductors from the ground plane. From the charging circuit the electrode connected to the spark gap is identified at the cathode and will appear at the bottom of all x-pinch images shown in this thesis; while the electrode connected to ground is the anode and will appear at the top of the x-pinch images.

To perform the experiment the Marx bank was charged to  $\sim 50 \text{ kV}$  which delivered an  $80 \text{ kA}$  current pulse to the load with a rise time of  $40 \text{ ns}$  (10-90%). This was achieved through the following sequence: charging supply  $\rightarrow$  Marx bank  $\rightarrow$  transmission line  $\rightarrow$  pulse forming line  $\rightarrow$  self-breaking switch  $\rightarrow$  load. The entire sequence takes approximately  $600 \text{ ns}$  to complete.

## 2.2 Load Chamber

The electrodes were positioned at the center of a cylindrical chamber with a diameter and height of 19.0 and 9.5 *cm* respectively. The chamber was fitted with eight radial NW-40 vacuum ports placed symmetrically about the center of the chamber. The centers of the ports were approximately 6cm from the bottom of the chamber. An additional NW-40 port was placed directly above the load for diagnostic access. Furthermore, a 13 *cm* diameter flange was incorporated in the chamber top which allowed for easy access while reloading of the experiment see Figure 2-4.



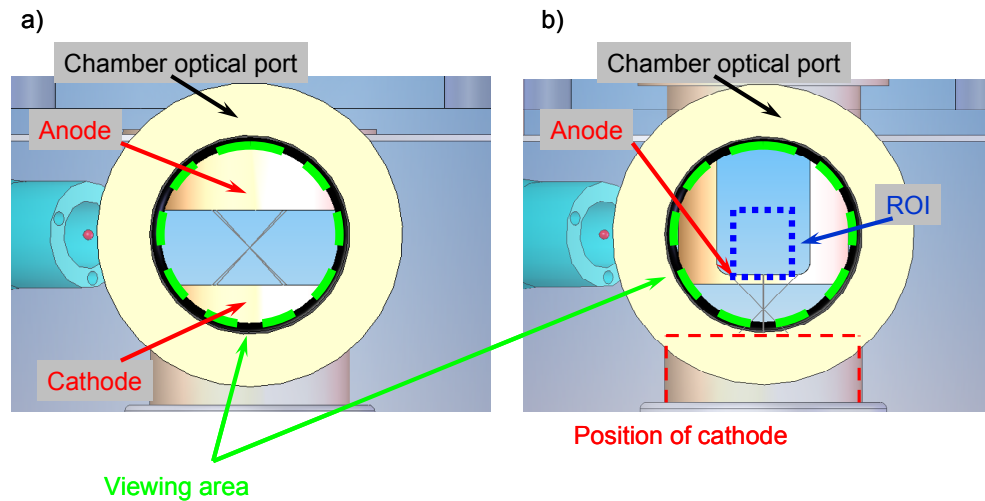
**Figure 2-4** Cross sectional view of a 3D model showing the vacuum chamber, load hardware, x-pinch, and diagnostic access points

## 2.3 Wire Load and Load Hardware

Two electrode configurations were used to provide diagnostic access to different regions of the load. The first x-pinch arrangement shown in Figure 2-5a provided diagnostic access to the wires between the anode (top) and cathode (bottom). The second

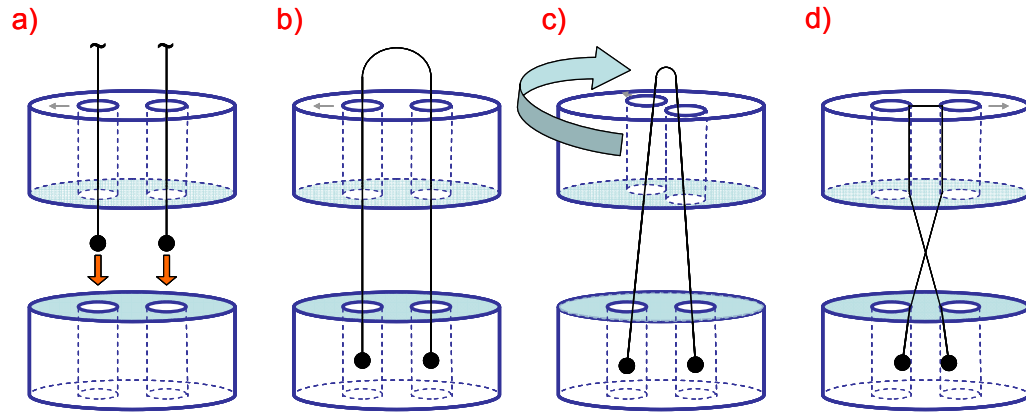
setup, Figure 2-5b ‘jet configuration,’ moved the electrodes down, eliminating the view of the cathode while providing visibility above the anode.

To load wires in an x-pinch configuration the top electrode was removed and a wire with lead weights attached to the ends was fed through two opposing holes (Figure 2-6a); the length of wire was sufficient that the wire ends extended beyond the bottom electrode.



**Figure 2-5 Electrode arrangement as seen through the optical port on the vacuum chamber. a) Shows the setup used to look at the x-pinch dynamics, while b) shows the configuration used for the study of plasma jets above the anode.**

In experiments requiring a four wire x-pinch, an additional wire was inserted in the same manner, in this case from above the wires were perpendicular to one another (Figure 2-6b). The electrode was carefully lowered into the chamber so the wires would penetrate corresponding holes in the lower electrode. At this point the wires hung parallel between the electrodes (7c). Finally, the top electrode was rotated just over  $180^\circ$  so that the wires would touch at a single cross point (7d).



**Figure 2-6 Schematic sequence showing the loading of wires into the electrodes and the construction of an x-pinch**

An alternate anode was used to load the wires in the jet configuration. In this case the electrode had a large opening which allowed the jet formed at the axis to propagate unobstructed away from the cross point. In this case four individual wires were used to construct the pinch thereby eliminating any wires on the axis. Again the wires were hung in parallel and the anode lower into the chamber, once the wires were in the corresponding holes in the cathode the anode was rotated just over  $180^\circ$  to form a single cross point. For this configuration the heights of the electrodes were altered to lower the load in reference to the viewing ports while keeping the anode/cathode gap constant at 1 *cm*. This allowed for greater diagnostic access above the anode.

Once the load was in-place, the chamber was evacuated to a pressure of  $\sim 10^{-4}$  *mbar*, this pressure was verified before performing all experiments.

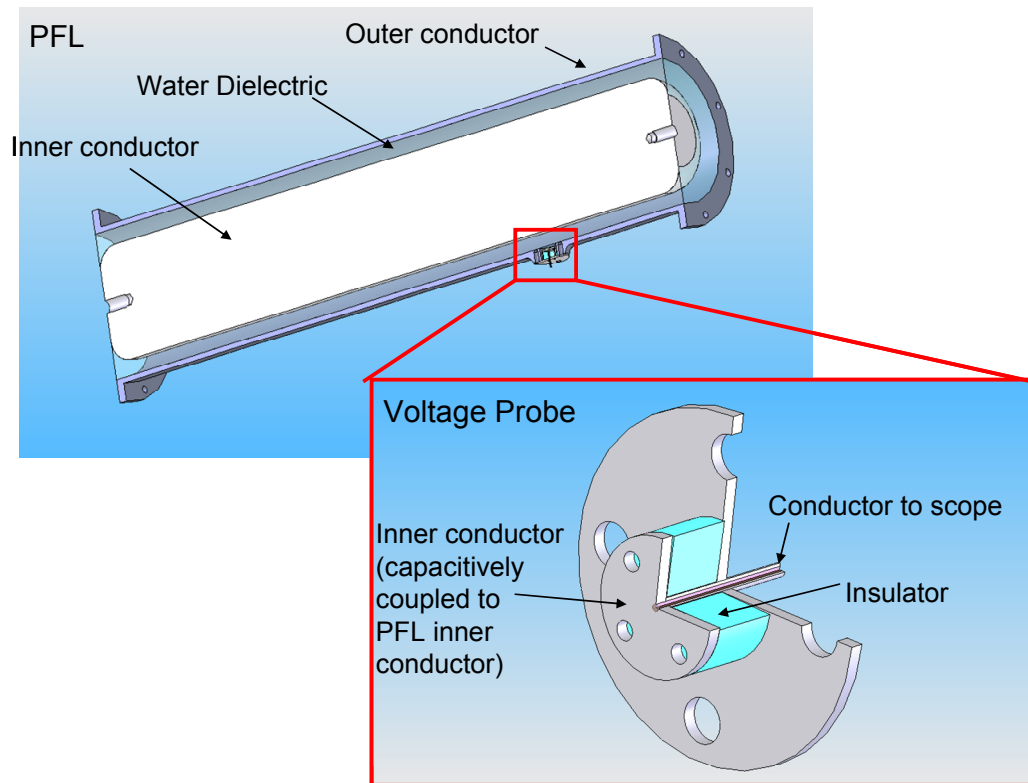
## 2.4 Voltage and Current Monitoring

The generator described above is capable of delivering a peak current of 80 *kA* pulse, with a rise time of 40 *ns* (10-90%). Due to the high voltages and currents involved, malfunction or breakdown at various stages in the generator was possible. In

order to verify the generator was performing properly, and to aid in determining where a failure had occurred, voltage and current monitors were used. The monitors consisted of a capacitively coupled probe for monitoring the voltage in the PFL and a Rogowski coil to capture the current signal within the vacuum chamber.

#### 2.4.1 PFL Voltage Monitor

To monitor the voltage in the pulse forming line a capacitive coupled probe was mounted to the outer conductor of the compression stage [2-5]. The probe is made up of an isolated conducting plate in the outer conductor see Figure 2-7.



**Figure 2-7 Pulse forming line voltage monitor**

The probe is capacitive coupled to the inner conductor of the PFL [2-4][2-6] with a self capacitance of  $C_{\text{probe}}$ . Assuming  $Q$  is the charge on the capacitor the voltage probe

will produce a current (in amps) which corresponds to:

$$I_{probe} = \frac{dQ}{dt} = C_{probe} \frac{dV_{PFL}}{dt} \quad (2.3)$$

Assuming the voltage probe can be treated as a parallel plate capacitor due to its relative small size:

$$C_{probe} = \frac{A\epsilon_0\epsilon_{PFL}}{d}, \quad (2.4)$$

where A is the area of the capacitor ( $m^2$ ),  $\epsilon_{PFL}$  represents the relative permeability of the dielectric of the PFL (de-ionized water), and d represents the distance between the plates (m). The output of the probe was converted from  $dI/dt$  to a voltage signal through the use of a signal integrator before being recorded on the oscilloscope. Compensating for the integrator ( $\tau$ ) and the resistance of the terminator ( $R_{scope}$ ) in the scope, the voltage recorded by the scope will be a function of the PFL voltage:

$$V_{scope} = \frac{C_{probe}R_{scope}V_{PFL}}{\tau} \quad (2.5)$$

Using a probe with an area of  $A = 3.1 \pm 0.1 \text{ mm}$ , a plate separation of  $20 \pm 1 \text{ mm}$ , and recalling  $\epsilon_0$  for de-ionized water is 81, the probe capacitance from equation (2.4) is:  $C_{probe} = 1.1 \pm 0.1 \text{ pF}$ . Rearranging equation (2.5), while substituting an internal scope resistance of  $R_{scope} = 50 \text{ } (\Omega)$ , an integrator value of  $\tau = (4.4 \pm 0.3) \times 10^{-5} \text{ s}$ , and the previously found  $C_{probe}$ , the PFL voltage can be found as follows:

$$V_{PFL} = (7.7 \pm 0.6) \times 10^4 V_{scope} \quad (2.6)$$

A voltage trace from a typical shot can be seen below in Figure 2-8.



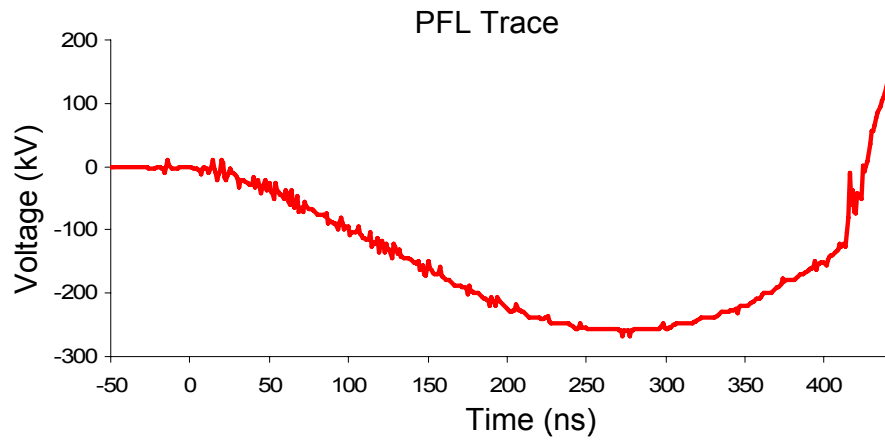


Figure 2-8 Pulse Forming Line voltage as recorded from PFL voltage probe

### 2.4.2 Load Current Monitor (Rogowski coil)

The current monitoring was performed using a Rogowski coil placed around one of four return posts close to the load, which ensured the recorded signal was the current transmitted through the load.

A Rogowski coil is made up of an annular conductive ring placed around a current conductor [2-6] [2-7] see Figure 2-9. As a current is driven through the central

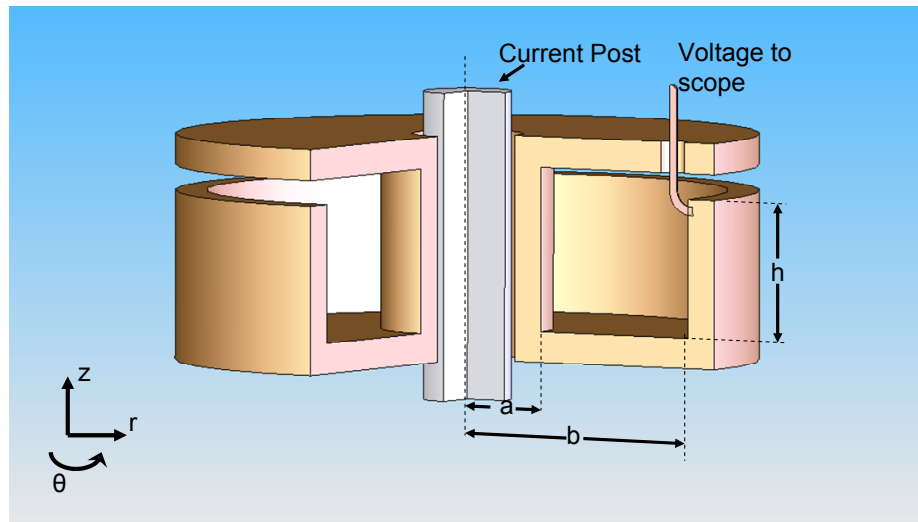


Figure 2-9 Schematic of Rogowski coil cross section surrounding a current post

post, a rising magnetic field is induced in the theta  $\theta$  direction surrounding the post. If a conductive loop is placed in the magnetic field perpendicular to the field lines the varying B-field will generate a current around the loop. This current can be picked up as a voltage across the loop. The response of the probe can be determined from Faraday's law of induction which states the voltage induced across a surface (V) is equal to the rate of change of the magnetic flux:

$$V_{Rogowski} = -\frac{d}{dt} \Phi_M . \quad (2.7)$$

In the above equation  $\Phi_M$  is the magnetic flux and can be expressed as:

$$\Phi_M = \oint_S B \cdot dS = \frac{\mu_0 I_{post}}{2\pi} \oint_S \frac{dzdr}{r}, \quad (2.8)$$

where B was substituted as  $\mu_0 I / 2\pi r$ . Substituting phi from equation (2.8) and inserting the dimensions from Figure 2-9 we arrive at the following expression for the voltage in the loop:

$$V_{Rogowski} = -\frac{d}{dt} \oint_S \frac{\mu_0 I_{post}}{2\pi r} dzdr = -\frac{d}{dt} \int_a^b \frac{\mu_0 I_{post} h}{2\pi r} dr . \quad (2.9)$$

In the above expression the integral along the z-axis can be replaced by h since the magnetic field does not vary in that direction.

The subsequent integration of equation (2.9) followed by extraction of the time invariant parameters from the derivative yields:

$$V_{Rogowski} = \frac{h\mu_0}{2\pi} \ln \frac{b}{a} \frac{dI_{post}}{dt} . \quad (2.10)$$

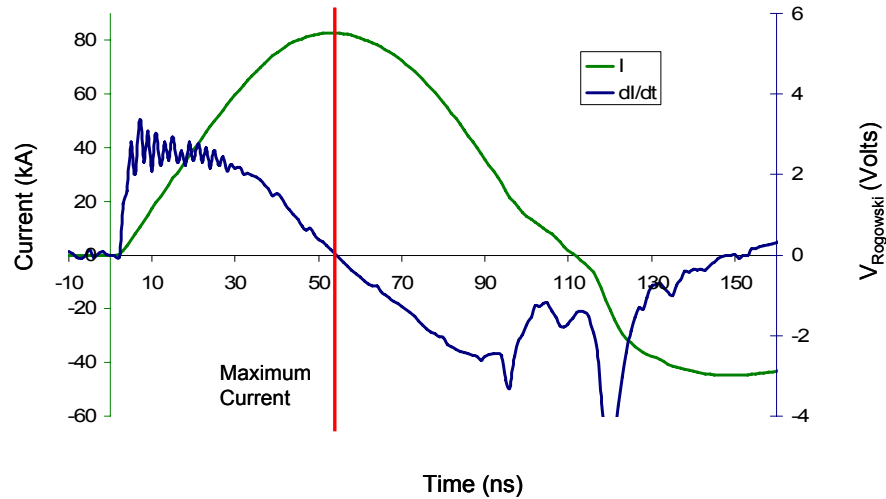
From equation (2.10) we see that the voltage induced in the Rogowski coil is a product of a constant, the physical parameters of the coil, and the rate of change of current through the post. Substituting the Rogowski coil dimensions:  $a = 5.0 \pm 0.1 \text{ mm}$ ,  $b = 15.0 \pm 0.1 \text{ mm}$ , and  $h = 8.0 \pm 0.1 \text{ mm}$ , propagating the errors incurred from machining, and multiplying the above expression by a factor  $f$  to account for the attenuator placed on the scope the Rogowski coil voltage (in volts) will be:

$$V_{Rogowski} = (1.76 \pm 0.06) \times 10^{-9} f \frac{dI_{post}}{dt} . \quad (2.11)$$

The Rogowski coil is placed around one of the four return posts which hold the anode in place, consequently a factor of four is needed to convert from the post current to the total experimental current  $I_{total} = 4I_{post}$ . Therefore applying this multiplier to equation (2.11), and solving for  $dI_{total}/dt$  while using a 10 dB attenuator gives:

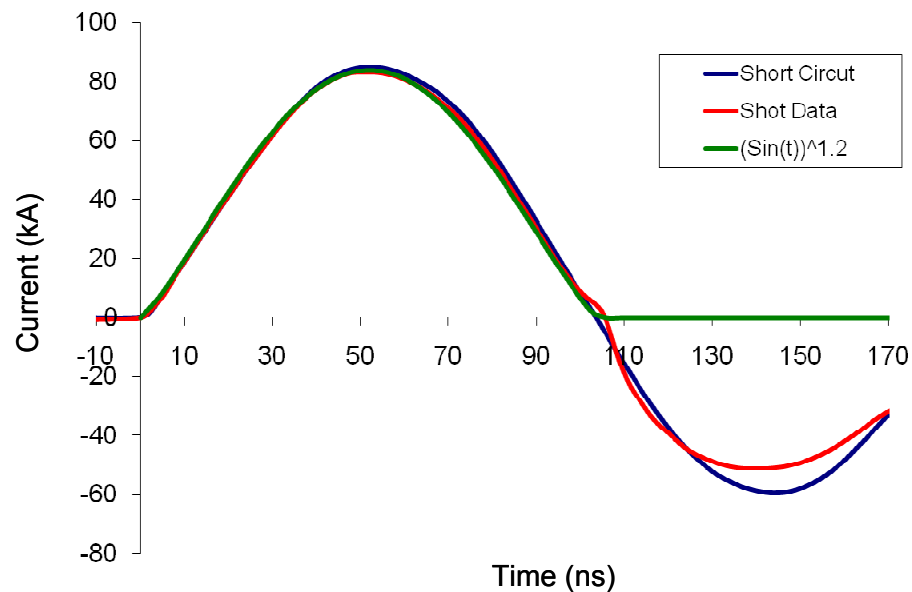
$$\frac{dI_{total}}{dt} = (2.13 \pm 0.07) \times 10^8 V_{Rogowski} . \quad (2.12)$$

For the experiments performed in this thesis the voltage from the Rogowski coil was recorded on a 1 gigahertz scope which gave a time resolution of 1 ns. After the experiment,  $dI/dt$  was calculated and a numerical integration was performed to determine the driving current for the experiment. Figure 2-10 below displays the  $dI/dt$  signal as well as the integrated current for a typical shot.



**Figure 2-10  $dI/dt$  (green, left axis) and current (blue, right axis) curves for a typical x-pinch load**

Displayed in Figure 2-11 are the current traces from a typical short circuit as well as an x-pinch load. In order to perform analytical work later in this thesis, an approximation to the current trace is needed, and corresponds to a sine to the 1.2 fit as plotted in the figure.



**Figure 2-11 Current traces showing the close correlation between a short circuit and load current. Also pictured is the analytical curve used for calculation.**

## 2.5 Overview of Diagnostics

Typically, in order to adequately characterize a plasma, parameters including electron and ion densities, the ionization state, and the ion and electron temperatures are required. Further information concerning the expansion velocity and the development of instabilities may also be of interest.

To monitor the evolution of the load during the experiment a variety of diagnostics were mounted through eight side-on (radially aligned) ports in the vacuum chamber. For this work select parameters of the plasma were investigated using x-ray self emission, and pulsed laser backlighting. Additionally, time integrated self emission images were used to characterize the plasma and are discussed in a later chapter.

### 2.5.1 Optical Probing

In order to gain information concerning the refractive index and hence the electron density of a plasma, an Nd-YAG (Neodymium-doped Yttrium Aluminum Garnet) laser was used to backlight the experiment.

Light can only pass through a plasma if the frequency of the plasma  $\omega_p$  is lower than that of the probe beam  $\omega_{\text{light}}$ . To determine the maximum density which can be probed, known as the critical density  $n_c$ , the frequency of the light is set equal to the plasma frequency:

$$\omega_{\text{light}} = \omega_p = \sqrt{\frac{4\pi n_c e^2}{m_e}}, \quad (2.13)$$

where  $e$  and  $m_e$  are the charge and mass of an electron. Solving for  $n_c$  and substituting  $\omega_{\text{light}} = c/\lambda$ , (where  $\lambda$  is the wavelength of the light) we see that the critical density scales

with the wavelength of probe light ( $\lambda$ ) as:

$$n_c = \frac{m_e}{4\pi e^2} (\omega_{light})^2 = \frac{m_e c^2}{4\pi e^2} (\lambda)^{-2}, \quad (2.14)$$

therefore light with a shorter wavelength (higher frequency) will have a higher critical density and therefore be able to probe higher density plasmas. Substituting for the constants, a compact form of equation (2.14) follows:

$$n_c = 10^{21} \lambda^{-2} cm^{-3}, \quad (2.15)$$

where  $\lambda$  is in microns.

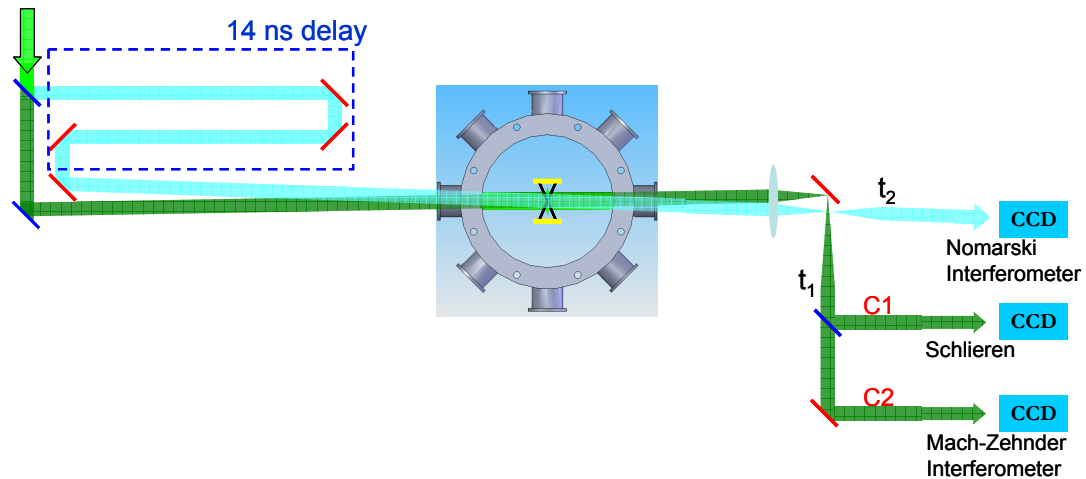
The Nd-YAG laser emits light in the near infra-red ( $\lambda=1064$  nm) which then traverses a KDP harmonic generating crystal. This doubles the frequency of the light resulting in a  $\lambda$  of 532nm (green). Substituting this wavelength into equation (2.15) yields a critical density  $n_c = 4 \times 10^{21}$  electrons per cubic centimeter.

Once at 532 nm the 3 mm beam was expanded through a diverging telescope to a diameter of 40 mm to encompass the entire experiment.

In order to gather time dependent data from one experiment two images were recorded at successive times see Figure 2-12. This allowed tracking of the position of the plasma at two times and hence velocity measurements. To achieve this, before reaching the vacuum chamber the probe beam was split in two, one beam propagated through a delay line, resulting in a fourteen nanosecond delay relative to the other beam, as depicted in the figure below. The beams were then realigned and traversed identical paths through the experiment. The two beams retained a slight difference in angle ( $< 3^\circ$ ) enabling them to be separated near their focal points after exiting the chamber.

Often it is useful to retrieve two images at the same probe time. Upon exiting the

chamber two configurations are possible for each probe beam, single image recording or splitting of the beam for simultaneous image capturing. As in the  $t_1$  configuration, upon exiting the chamber the beam is split by a 50/50 beam splitter (blue) into two identical imaging channels. These beams are designated as channel one and two (C1 and C2) and are used for different types of imaging – dark field schlieren, shadowgraphy, and interferometry – which are explained below. The simultaneous image recording allowed for comparisons between low density and higher density plasmas during a single probe time of the experiment.



**Figure 2-12** Diagram of the optical setup used to diagnose the experiments. The dashed blue box indicates the time delay used to separate the 2 pulses before they propagate through the chamber. After the chamber  $t_1$  results in a Nomarski image while  $t_2$  is used to form a Schlieren as well as an interferometric image through a Mach-Zehnder interferometer.

The images from each channel are recorded on 5 x 7 mm, 16 bit CCD chips housed in respective SBIG ST-402ME cameras. The cameras are connected to computer-based image recording software which integrates a  $\sim 2$  second exposure (longer than the experiment). Temporal resolution is obtained through the short duration of the laser pulse. In order to mitigate self-emission, narrow band ( $\delta\lambda \sim 2$  nm) laser light filters were

mounted directly in front of the CCD chip on the cameras. For each image, prior to the experiment, a ‘background’ shot was taken, after the experiment was loaded and the optics aligned. This provided a reference for comparison with the ‘shot’ image, recorded during the experiment, and enabled the immediate dismissal of aberrations from the optics system rather than the experiment.

Taking into account the resolution of the CCD chips used and the magnification of the optics system, the images recorded had a resolution of  $\sim 20 \mu m$  dependant on the setup. The duration of the laser pulse, and hence the temporal resolution of the optical probing was  $5 ns$ .

In order to monitor the timing of the probe beam a sample of the beam was taken near the chamber. The light was captured by a diode sensitive to optical light and the signal recorded on a  $1 GHz$  oscilloscope.

### **2.5.1.1 Schlieren imaging**

There are two types of schlieren – light and dark field imaging. The experiments reported relied exclusively on dark field schlieren, therefore only this technique will be discussed here.

Dark field Schlieren imaging is an optical technique commonly used to image low density plasmas in various experiments. A collimated probe beam is propagated through a target area and then a focusing lens. The light is focused at the focal distance of the lens and an image of the target area is made at the image plane as shown in Figure 2-13a. Placing a schlieren stop at the focal spot of the lens will block all the light from propagating, leaving the image plane dark (assuming a perfect lens and a target area free



of any refractive medium) Figure 2-13b.

In the case of a refractive medium, e.g. a plasma in the target area, with a refractive index gradient perpendicular to the propagation direction of the probe beam, the light from the probe beam will be refracted and deviate parallel to the density gradient [2-8] (as in Figure 2-13c). If we assume the probe beam is propagating in the z direction (perpendicular to the image plane) and the y-axis is vertically aligned, the deflection in the vertical direction ( $\theta_y$ ) is proportional to the gradient of the refractive index in the y direction at that point.

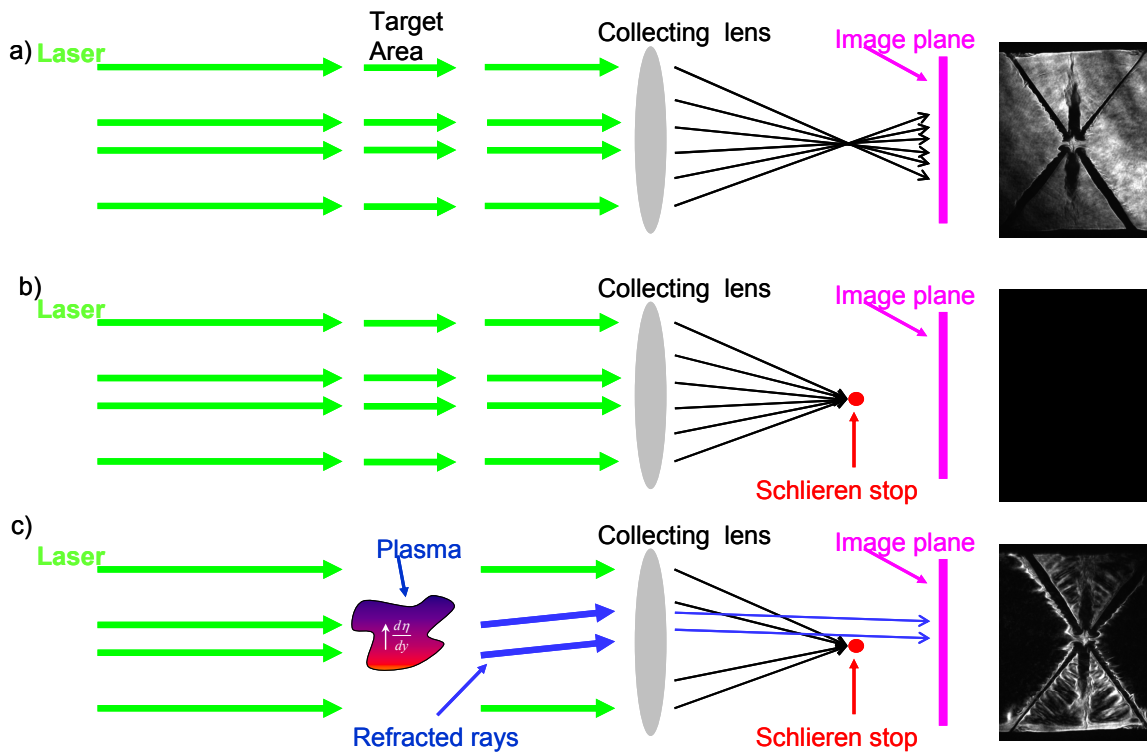


Figure 2-13 Sequence of images showing the propagation of light rays through a system and the resulting images recorded at the image plane. a) Light is focused by a lens and after crossing through the focal point propagates to the image plane. b) The focused light is stopped by a schlieren stop and leaves the image plane dark. c) Light refracted by the system is focused to a different focal distance (circumventing the stop) and propagates to the image plane forming an image.

This can be expressed as:

$$\theta_y = \frac{d}{dy} \int \eta(y, z) dl, \quad (2.16)$$

where  $\eta(y, z)$  is the refractive index and the integral is taken over the path length ( $dl$ ) of the light through the medium. The refractive index of the plasma is given by:

$$\eta = \sqrt{1 - \frac{n_e}{n_c}}, \quad (2.17)$$

where  $n_e$  is the electron density and  $n_c$  is the critical density defined in equation (2.14). If the electron density is much lower than the critical density, the refractive index can be expressed as  $\eta \approx 1 - n_e/2n_c$ , leading the angle of refraction to be:

$$\theta_y \approx \int \frac{d}{dz} \frac{n_e}{2n_c} dl = \frac{1}{8 \times 10^{21}} \int \frac{dn_e}{dy} dl. \quad (2.18)$$

It is clear from the above relation that the angle of refraction is a direct result of the electron density gradient in the plasma.

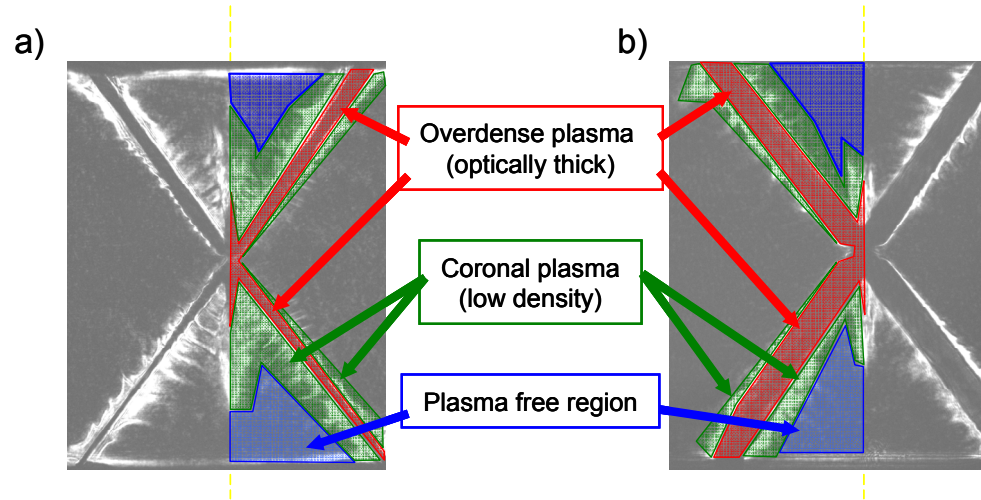
In the case where a circular schlieren stop is placed at the focal point of the lens, light from the probe beam that is not sufficiently refracted is blocked and therefore does not propagate to the image plane. In this dark field schlieren technique the radius of the stop sets the critical density; the plasma must be above this value in order to be imaged.

The incorporation of the electron density and the geometry of the system give rise to the detection limits of the system. The upper detection limit corresponds to the light that is propagated through the system, i.e. light that is collected by the first lens outside the chamber and not lost to the surroundings (see Figure 2-13). In the case of the lower

limit, in order for light to propagate to the image plane, it must be refracted sufficiently to circumvent the stop.

For a plasma with a parabolic density profile, Schmidt and Ruckle [2-8] related the detectable electron density,  $n_e$  to the maximum angular deflection  $a_{\max}$  by  $a_{\max} = C_1 n_e / n_c$ , where  $n_c$  is the critical density and  $C_1$  is a constant whose value is 1. In this case the distance to the first optic and its diameter constrain the highest density plasma recorded.

Conversely, the minimum density which can be recorded is constrained by the size of the schlieren stop  $d_s$ , and the focal length ( $f$ ) of the focusing optic. Together these parameters define the minimum schlieren angle  $a_{\min}$  as  $a_{\min} = d_s / 2f$ .



**Figure 2-14 Backlit schlieren frames with overlay regions indicating various plasma regimes: blue (plasma free), green (low density), and red (high density). The image in (a) captured a two wire 10  $\mu\text{m}$  diameter Fe pinch at 30 ns after the start of the current, and the image in (b) is from a two wire 15  $\mu\text{m}$  Al wire x-pinch taken 24 ns after the start of the current.**

As a result of the density limits, images with three distinct regions are produced, as displayed in Figure 2-14. Regions with a very low density, or void of plasma, are

recorded as black and are outlined in blue. Similarly, plasma exceeding the diagnostic density limit will also produce dark regions and are highlighted in red. In contrast, the regions encompassing the coronal plasma and the associated gradients will diffract light to a lesser extent and thereby be recorded in the images as outlined in green in the figure above. These regions appear both inside and outside the wire's original position due to the surface ablation as described in the previous chapter. The plasma jets on the axis are also examples of plasma within the schlieren diagnostic range, and therefore are captured in these images.

Evaluating the above equation with the properties of the system:  $\lambda = 532 \text{ nm}$ , and a  $40\text{mm}$  diameter focusing optic placed  $15.75 \text{ cm}$  from the pinch, yields a maximum angular deflection of  $a_{\text{max}} = 0.13 \text{ radians}$ . This corresponds to an upper detection limit of  $4.5 \times 10^{20} \text{ cm}^{-3}$ . The use of a  $635 \mu\text{m}$  schlieren stop, in conjunction with a lens having a focal length of  $150 \text{ mm}$  yields an  $a_{\text{min}} = 0.002 \text{ radians}$ , resulting in a lower density limit of  $7.5 \times 10^{18} \text{ cm}^{-3}$ .

### 2.5.1.2 Shadowgraphy

Shadowgraphy, another plasma diagnostic employed in these experiments, also relies on density gradients to refract light from the incoming parallel probe beam. Shadowgraphy is similar to schlieren imaging in that light is deflected by  $\theta_y$  equation (2.18) according to the density gradient, however in this diagnostic there is no stop to block light from making its way to the image plane. In shadowgraphy, light that propagates through regions with large density gradients is diverted significantly, leaving that portion of the image dark. The refracted radiation goes on to brighten undisturbed

areas of the image, or in the case of very high density gradients, the light will be lost from the system.

In the Schlieren technique the intensity variations were due to the first spatial derivative of the refractive index and in this case they arise from the second derivative. The intensity incident on the CCD (image plane) compared to the intensity of an undisturbed beam will be:

$$\frac{\delta I}{I} = L \left( \frac{d^2}{dx^2} + \frac{d^2}{dy^2} \right) \int \eta dl, \quad (2.19)$$

where x and y are the coordinates orthogonal to the propagation direction of the beam, and L is the distance between the object and the image plane [2-9].

The dependence of schlieren and shadowgraphy on the first and second spatial derivative of electron density makes de-convolution of quantitative electron densities very difficult. Consequently, in this thesis no quantitative electron density values were obtained from these images. Instead, they were used in a qualitative manner to indicate the presence of large density gradients, enabling size measurements, as well as tracking the evolution of structures present in the plasma.

### **2.5.1.3 Interferometry**

Interferometric techniques were applied in order to gain quantitative information regarding the electron density of the plasma. Here a light source is split into two identical collimated beams. The first propagates undisturbed, while the other passes through the plasma region of interest, inducing a phase shift relative to the reference beam. The recombination of the two beams at a detector reveals the relative phase shift

yielding information about the medium traversed (phase shift is dependent on the linear density of the plasma as presented below). Various requirements have led to the development of many types of interferometers, however a description of only the techniques used to gather data for this thesis are presented below; namely the Nomarski and Mach-Zehnder interferometers.

The first distinction of an interferometer is the method by which two beams are obtained from a single source. Both techniques are described by amplitude division, where a partition of the amplitude over the same section of the wavefront is used, thereby eliminating the spatial coherence limitation of the laser source. As a result, this method can be used to probe large objects [2-11].

During an experiment the probe beam traverses a plasma with regions of high electron density. These areas will have a lower index of refraction,  $\eta \approx 1 - n_e/2n_c$ , resulting in a phase shift  $\phi$ , relative to the undisturbed reference beam, and proportional to the electron density of the plasma. Upon recombination the relative difference in phase leads to a shift of the interference fringes. This fringe shift corresponds to the line integral of the refractive index taken along the path through the plasma  $\int n_e dl$ . If the profile is known it is possible to unfold the integral, for the case of a flat density profile it becomes:  $n_e \cdot l$ , where  $l$  is the path length through the plasma. In most experimental circumstances this is an unrealistic assumption and the density profile can only be recovered through an Abel Inversion [2-13].

Recalling that for a plasma, where the electron density is much lower than the critical density, the refractive index is proportional to the electron density. The fringe

shift ( $f$ ) can be related to the line integral of electron density ( $n_e \text{ cm}^{-3}$ ) as:

$$f = 4.48 \times 10^{-12} \lambda \int n_e dl, \quad (2.20)$$

where the wavelength ( $\lambda$ ) is expressed in meters, and the integral is taken over the path the probe beam takes in the plasma. Considering a probe beam traveling a distance  $l$  through the plasma, the line density can be expressed as:

$$\int n_e (\text{cm}^{-3}) dl = 4.2 \times 10^{17} f \quad (2.21)$$

For equation (2.21) to be true,  $n_e$  must be constant through the plasma. If this is not the case then  $n_e$  may be taken as the average electron density along the probe beam path.

The resolution of an interferometry system depends on many factors including optic and beam quality. To eliminate aberrations from the optics and ensure the fringe shift is generated exclusively by an electron density in the plasma, before each experiment a ‘background’ shot is recorded in order to mark the original location of the fringes.

While performing conventional analysis (i.e. following fringes across an image), the minimum detectable electron density corresponds to a  $1/4$  fringe shift.

Through the use of a computer based interferometric analysis program it is possible to measure smaller fringe shifts and hence lower densities. The program performs a Fast Fourier Transform (FFT) on the interferogram, isolates the carrier frequencies, and then generates a smooth phase plot by performing a reverse FFT, also known as phase unwrapping. The same sequence is adapted to the background image, after which the phase plots are subtracted to acquire the relative phase shift.

As with the aforementioned imaging techniques the upper density limit was imposed by the refraction of light out of the systems or the reflection of light from over dense plasma. In both cases high density areas will appear as dark regions on the interferogram images.

Incorporating the parameters of the system  $\lambda=532 \text{ nm}$  equation (2.21) simplifies to:

$$n_e l (\text{cm}^{-2}) = 4.2 \times 10^{17} f. \quad (2.22)$$

When inserting the conventional quarter fringe shift into the above equation a minimum areal density of  $1 \times 10^{17} \text{ cm}^{-2}$  is possible. However the interferometry data appearing in this thesis was analyzed using the software package IDEA [2-10]. Through this method the minimum detectable fringe shift was refined from the observable (quarter of a fringe) to the resolution of an image. The width of the fringes set a detectable shift limit of  $f \approx 0.1$ , from equation (2.22) the minimum detectable areal density is  $n_e l = 4 \times 10^{16} \text{ cm}^{-2}$ .

Through the use of the interferogram analysis program IDEA it was possible to generate a continuous areal density plot which provided a more complete picture when compared with measuring densities at discrete location. As shown in equation (2.22) the multiplication of a constant converts the 2D phase plot (generated in IDEA) into a continuous areal density plot.

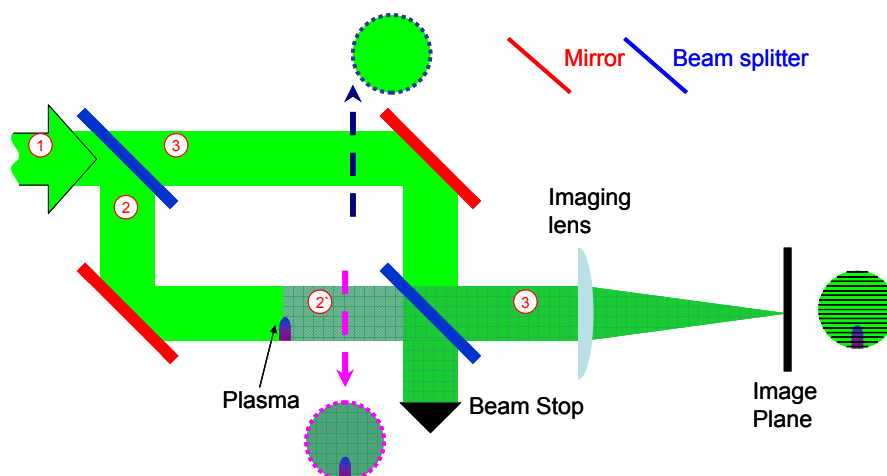
Due to physical constraints surrounding the chamber, two types of interferometers were employed to diagnose the plasma. They were a Mach-Zehnder and a Nomarski interferometer.



## Mach-Zehnder Interferometer

As depicted in Figure 2-15, the physical separation of the probe and reference beams allows the probing of a variety of objects. After the probe beam (2) has traversed the experiment (2'), a beam splitter is used to recombine the two beams onto a detector (3). The beams are overlapped allowing them to interfere with each other. Their relative phase difference results in a pattern consisting of light (constructive interference) and dark (destructive interference) fringes. Finally the plasma is imaged onto a detector, in this case a CCD camera.

The benefit of using a Mach-Zehnder interferometer is that the reference beam is ensured to remain undisturbed. Additionally, the fringe separation and orientation do not depend on the magnification, leaving the sensitivity and of the system independent of the experimental setup.



**Figure 2-15 Representation of a Mach Zehnder Interferometer setup.** The initial laser beam (1) is split into a reference and a probe beam (2,3) after traversing the experiment they are rejoin to produce interference fringes.

## Nomarski Interferometer

Figure 2-16 shows a schematic of the Nomarski interferometry setup for this

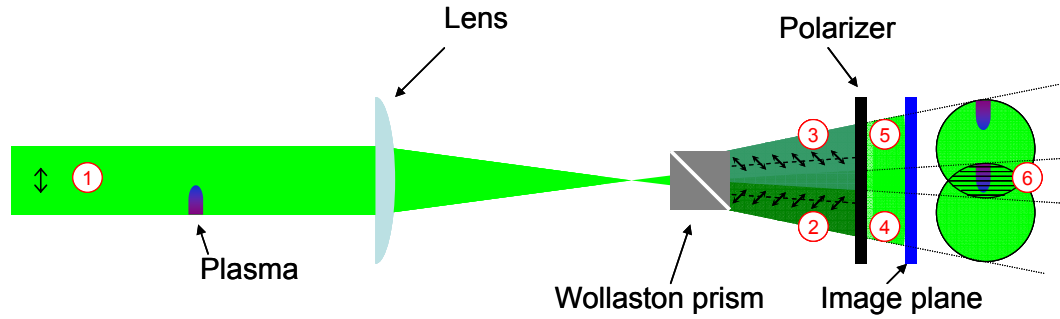
experiment. Here, a single probe beam traverses the target area of the experiment. Here a portion of the beam travels through the plasma while the remainder of the beam is undisturbed. Assuming the probe beam is vertically polarized (1), and after going through the chamber the beam is focused by a lens and then diverges with spherical wave-fronts. At this point a Wollaston prism (45° to vertical) splits the beam into two equal intensity components having orthogonal polarizations [+45 (2) and -45 (3)] with an angular separation of 7° (set by the prism). Each contains the full image, including both the undisturbed region and the imaged plasma. The polarizations of the two beams are realigned (4,5) by a polarizer, whose polarization is set parallel or perpendicular to the original beam's orientation (1).

The two beams are imaged on a plane with a region of overlap (6), the realignment of the polarizations allowed the beams to interfere with one another and form a fringe pattern in this area. As part of the probe beam passes through the plasma it acquires a phase shift relative to the undisturbed portion of the beam. When this region is overlapped with the undisturbed part of the beam a measurable fringe shift is recorded. Because both beams traverse the same path through the experiment the undisturbed wave-fronts remain matched, resulting in a high contrast fringe pattern.

The fringe separation ( $\delta$ ) is related to the spacing between the imaging lens and the Wollaston prism (a), and the distance between the prism and the detector plane (b) as:

$$\delta = \frac{\lambda b}{\epsilon a}, \quad (2.23)$$

where  $\lambda$  is the probe beam wavelength and  $\epsilon$  is the angle of the orthogonally polarized beams coming from the prism. Thus the fringe separation can be changed by altering the



**Figure 2-16 Nomarski interferometric imaging setup using a single propagating beam.**

lens-to-prism distance while the fringe orientation can be varied by a rotation of the polarizing elements. The implementation of a Nomarski interferometers stems from its relative ease of alignment and lack of stability problems. It is important to ensure the object to be imaged remains small with respect to the probe beam.

The maximum detectable electron density is constrained by the critical density of the plasma. However, as with all imaging, when the density is within a few orders of magnitude of  $n_c$ , refraction and opacity effects can limit this range even further.

The following table summarizes the density ranges that each optical probing technique is appropriate for:

**Table 2-1 Density ranges for various optical probing techniques**

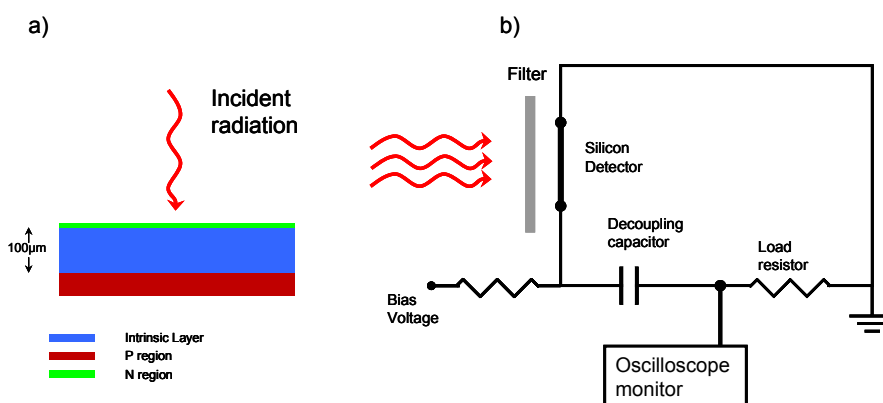
|                             | Minimum Density                      | Maximum Density                      |
|-----------------------------|--------------------------------------|--------------------------------------|
| Schlieren Imaging           | $4.5 \times 10^{18} \text{ cm}^{-3}$ | $7.5 \times 10^{20} \text{ cm}^{-3}$ |
| Shadowgraphy                | $\sim 10^{18} \text{ cm}^{-3}$       | NA                                   |
| Mach-Zehnder Interferometry | $4 \times 10^{16} \text{ cm}^{-2}$   | $4.5 \times 10^{18} \text{ cm}^{-3}$ |
| Nomarski Interferometry     | $4 \times 10^{16} \text{ cm}^{-2}$   | $4.5 \times 10^{18} \text{ cm}^{-3}$ |

### 2.5.2 X-Ray Diodes (XRD)

Experiments in this thesis utilized an array of seven silicone positive-intrinsic-negative (PIN) diodes were fielded, each covered by a different filter material (see

section 2.5.3). The diodes fast response and their sensitivity to x-rays from 1-20 *keV*, [2-11] along with a specifically chosen set of filters, enables a time resolved estimate of the energy emitted by the plasma in various spectral energy ranges [2-14].

An illustration of the diodes can be seen in Figure 2-17a along with the bias circuit diagram in Figure 2-17b. The diode is made up of a silicon intrinsic (I) semiconductor between a p-type (P) and an n-type (N) semiconductor regions. A reverse bias is imposed on the diode which causes the intrinsic layer to act as an insulator, stopping current while setting up an electric field across the I layer. As photons are absorbed by the silicon they liberate charge carriers which are accelerated by the

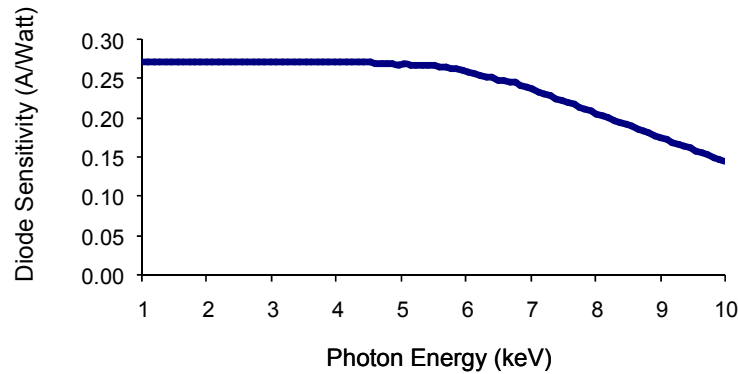


**Figure 2-17 a) a schematic of the silicon diode from XRD showing the 100µm thick silicon layer and the location of the P and N type regions. b) An electrical diagram showing how the bias voltage is applied across the diode and where the oscilloscope monitors the voltage signal.**

electric field, producing a current which is recorded. This gives a time resolved x-ray emission.

The IRD AXUV series diodes fielded on these experiments had a 1  $mm^2$  active surface area which covered a 100 µm Si layer. This thick Si layer allowed for a greater percentage of x-ray photons to be absorbed, and therefore a higher sensitivity for the diode. During each experiment the diodes were reverse-biased to 40 volts.

A curve of the diode sensitivity can be seen below in Figure 2-18, the diodes are sensitive from 1-10 *keV*, with a lower response at higher energies.



**Figure 2-18** The sensitivity curve for the 100 $\mu$ m thick silicon diodes over the photon energy range of 1-10 *keV*

The current from the diodes is passed through a resistor and the voltage across that element is monitored by a Tektronix TLS 216 logic scope. The recombination time and hence the temporal response of the diodes is  $\ll 1$  ns while the oscilloscope has a sampling rate of 1 GHz which will limit the time resolution of the diodes to 1 ns.

A set of seven diodes were used in conjunction with specifically chosen filters (see section 2.5.3) to gain information about the time resolved spectral emission of the plasma.

### 2.5.3 Filter Sets

The use of filter sets in conjunction with PIN diodes, time integrated images, and XUV cameras can provide spectral resolution to these diagnostics supplying information concerning the emission characteristics of the central plasma. The various filters were constructed of thin metal foils and specifically chosen plastics, placed between the plasma and the detector.

By varying the material and thickness of the filters it is possible to match the transmission characteristics of the filters over one spectral range while mismatching them in another. By subtracting the signal obtained through one filter from that obtained from the second, a band pass system is created. The resulting signal corresponds to a narrower spectral region than either of the filters can produce individually.

The foils were constructed from elements with close atomic numbers ( $Z$ ). The foil thickness and the addition of plastics was adjusted to match the transmission curves over the entire energy range (1-10  $keV$ ) excluding the region between their L or K shell absorption edges. The discrepancy of these L or K shell absorption energies defines the energy band pass of the Ross filter pair.

Matching of transmission curves (outside the band pass) ensures that the spectra through the foils will be identical for the energies lying outside the target energy window, and therefore any difference in the detected signals will be proportional to the total X-ray power delivered between the two absorption edges. Therefore the subtraction of two signals is directly related to the X-rays incident within the Ross filter energy band.

The transmission profiles of the filters used for the PCDs, as described in section 2.5.2, can be seen in Figure 2-18. By subtracting the transmission of the 10  $\mu m$  Iron filter from that of the 7.5  $\mu m$  Nickel, a band-pass window from 7.1 to 8.3  $keV$  is found. This spectral range includes copper's 8.1  $keV$  line-radiation, therefore a high yield in this energy range indicates that the plasma is hot enough to remove electrons from the Cu  $k_\alpha$  electrons (note: copper is present in all experiments as the largest constituent material of the brass electrodes).

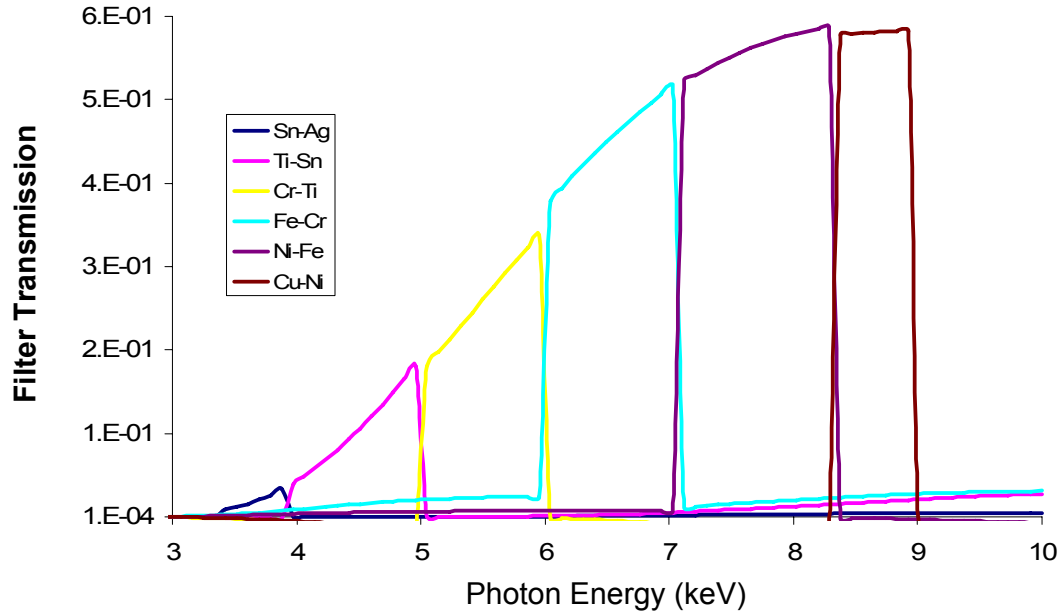


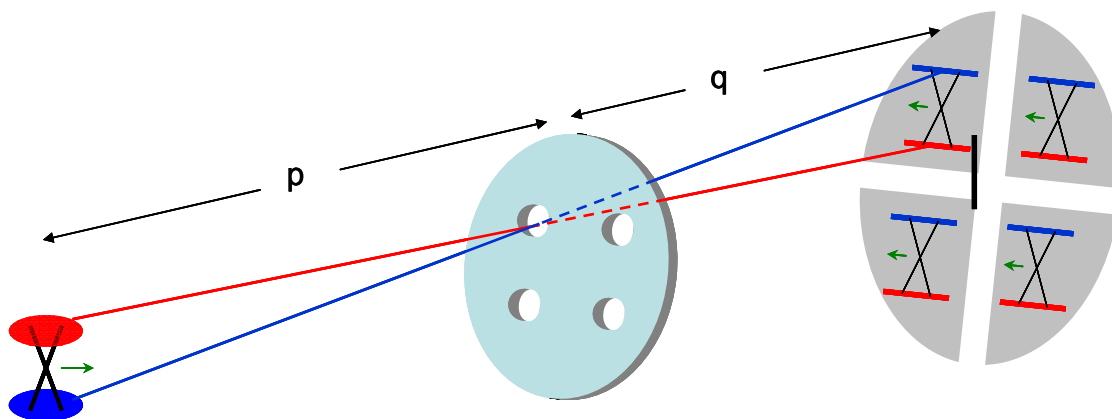
Figure 2-19 Difference of filter transmission curves from 1-10 keV

This technique can be used to isolate line radiation, yielding information about the temperature of the observed plasma.

#### 2.5.4 Extreme Ultraviolet Pinhole Imaging (XUV pinhole imaging)

To capture time-resolved images, a four frame, time gated, Micro Channel Plate (MCP) camera was used in conjunction with a simple pinhole camera setup (see Figure 2-20). Each pinhole projected a full image of the experiment onto one of the four independently triggered quadrants on the camera. A schematic breakdown of each of the frames is explained below and can be seen in Figure 2-21a.

XUV light emitted from the plasma encounters the thin gold cathode on the front of the camera (1). Within the cathode the x-rays free electrons which travel to the back of the cathode. For the majority of the experiment the cathode has a floating voltage so the electrons remain on the electrode. A voltage pulse, which triggers the camera, places a voltage on the gold sheet creating an electric field between the cathode and

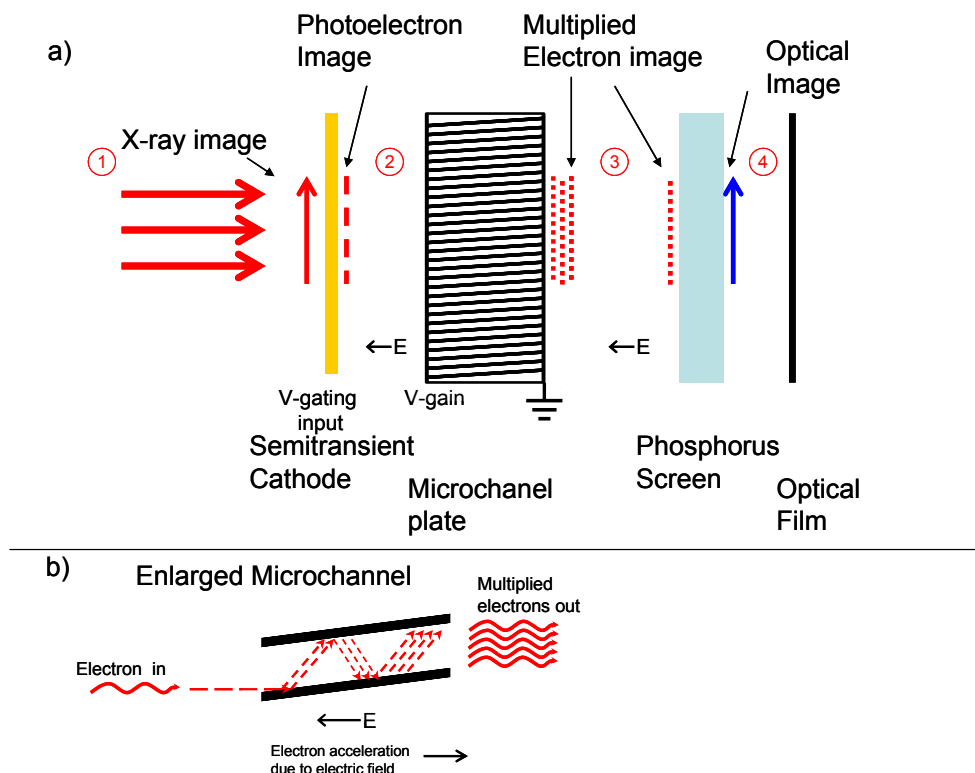


**Figure 2-20 Cartoon showing the projection of images through a pinhole camera setup onto the four distinct quadrants of an MCP camera**

microchannel plate (2). This serves to accelerate electrons from the cathode into the micrometer size channels which make up the microchannel plate. The channels are inclined relative to the camera to provoke a collision of the electron and the channel wall, freeing more electrons. A static gain voltage exists in the direction of the channel, and as electrons are freed they are accelerated down the channel by the imposed electric field (Figure 2-21b). With this increase in energy the electrons are able to free more electrons upon their next collision, leading to an amplification of the signal. Once they reach the end of the channel a static electric field accelerates them toward a phosphorus screen (3) which converts the electrons to optical radiation upon impact. Visible light from the screen illuminates Kodak T-Max 400 optical film (4) which is used to record the time resolved image.

The three subsequent frames are recorded in the same manner, and all four images are recorded and later developed simultaneously on a single piece of film. The frames are divided by 2 mm regions which are insensitive to XUV radiation and therefore serve to separate the images.





**Figure 2-21 Schematic of microchannel plate: a) detailed cartoon of the image path through an MCP camera. b) A single microchannel (enlarged) showing the path and multiplication of an electron while it is accelerated by the imposed electric field.**

The active areas are energized by a high voltage power supply capable of producing 6 *kV* pulses lasting 5 *ns*. The supply produces four simultaneous high voltage pulses which are staggered in time by various length cables which connect the high voltage supply to the MCP camera. While the sensitivity of the camera scales as  $V^x$  (with  $x$  between 5 and 10), setting a high voltage also increases background noise on the images; therefore typical voltages were in range from 4.8 to 5.4 *kV* and were dependent on the intensity of radiation expected. The duration (Full Width, Half Maximum) of the voltage pulse is directly responsible for the length of time the frame is 'open,' hence the integration time of the image is 5 *ns*. While a longer interframe time is possible and would allow observation of entire experiment, a shorter interframe time enables a more

detailed study of the plasma evolution. A set of four cables, each with a different length, was used to connect the supply to the camera; the dissimilar length wires were used to set the interframe time to 9 ns.

The level of detail is controlled by the geometry of the system. The set of four pinholes was positioned a distance ‘p’ from the plasma. While the distance from the pinhole array to the gold cathode is labeled as ‘q’ resulting in a magnification of  $m = q/p$ . The distances chosen (and hence the magnification) allowed an image of the entire x-pinch in each frame.

The components used in the system will also govern the ultimate resolution of the system, in this case the MCP detector resolution, geometric effects limiting “pinhole resolution” and the diffraction limit.

The limit set by the MCP camera is governed by the size of the microchannels, in this case  $\sigma_{\text{det}}$  leading to a detector resolution of:

$$\Delta x_{\text{det}} = \frac{p\sigma_{\text{det}}}{q}. \quad (2.24)$$

The two remaining limits deal with the entirety of the system. Taking d as the pinhole diameter, and  $\lambda$  as the wavelength being imaged, from the geometry of the system the smallest object that can be resolved through a pinhole is [2-16]:

$$\Delta x_{\text{geo}} = d \left( 1 + \frac{p}{q} \right). \quad (2.25)$$

Diffraction effects will become important [2-15] for objects at the diffraction limit which is dependent on wavelength as:

$$\Delta x_{diff} = 1.22 \frac{\lambda p}{d}. \quad (2.26)$$

For the setup described above, the pinholes were placed 28 *cm* from the x-pinch (p), while the camera was positioned 20 *cm* from the pinhole array (q), and the diameter of the pinholes (*d*) was 100 or 200  $\mu m$ . This produced a magnification of  $\sim 0.7$  and a geometry-limited pinhole resolution of  $\Delta x_{geo} = 480 \mu m$  for the 200  $\mu m$  pinholes. Finally, substituting the above values into equation (2.26) can express the diffraction limit in terms of the wavelength (in microns) as  $\Delta x_{diff}(\mu m) = 34.16(\lambda/d)$  if *d* is in *cm*. As long as the diffraction limit is lower than the geometrical limit, the system is not further inhibited. However, when  $\Delta x_{diff} > \Delta x_{geo}$ , (ie.  $1708\lambda > 480\mu m$ ) the system's limiting factor will be its geometrical constraint. A table highlighting the limits of the pinholes used is displayed below. Diffraction effects become important when the wavelength  $\lambda > 281 \text{ nm}$  ( $h\nu < 4.42 \text{ eV}$ ). Since the camera is sensitive to energies of 4 *eV* and above, the diffraction limited case will not be important. Therefore the geometry and wavelength filters will be the premier constraints on the system.

**Table 2-2 Geometrical and diffraction limits for various size XUV pinholes**

| <b>Pinhole Size (<math>\mu m</math>)</b> | <b>Geometrical Limit (<math>\mu m</math>)</b> | <b>Photon Energy Cutoff (eV)</b> |
|------------------------------------------|-----------------------------------------------|----------------------------------|
| 12.5                                     | 30                                            | 1131                             |
| 25                                       | 60                                            | 283                              |
| 50                                       | 120                                           | 73                               |
| 100                                      | 240                                           | 18                               |
| 200                                      | 480                                           | 4                                |

More information can be gained by adding filters to the system to restrict the radiation incident on the camera. As an example a 4  $\mu m$  thick Mylar filter was frequently placed in front of the pinholes to cutoff low energy x-rays while protecting the camera from debris.

The sensitivity of the MCP camera is flat from 10 up to 80  $eV$ , and begins to decline for higher energies at a rate that is determined by the thickness of the gold coating. Eventually, the cameras response reaches a small but finite value, allowing the device to record radiation up to energies of 2.5  $keV$ . Additionally, across the recording frame, the voltage and consequently the gain vary; therefore a quantitative comparison of the x-ray emission from the MCP is complex and was not attempted.

The timing of the MCP was monitored through a resistive divider which sent a sample of each of the high voltage pulses (for each frame) to the scope. The timing of these pulses was compared with the current trace after allowances for variable cable lengths had been made.

Timing for this diagnostic as well as all others mentioned above will be with respect to the start of the current through the load.

# Chapter 3

## Plasma Ablation

The initial phase of an x-pinch wire experiment is the ablation of the wires creating a plasma which surrounds the remaining wire cores. This process is responsible for the subsequent coronal dynamics during the remainder of the experiment (chapter four). As will be seen, the corona is directly responsible for the current distribution (chapter four) as well as the formation of the axial plasma column late in time, as presented in chapter five.

The process of wire ablation is paramount in all wire z-pinch experiments and is not limited to the x-pinch configuration reported here. In cylindrical z-pinch arrays, wire ablation has been linked to the formation and dynamics of the axial plasma column [3-1], as well as the final x-ray emission [3-2]. Although present in planar, cylindrical, and conical z-pinch arrays, the study of wire ablation is difficult due to the complex geometry and high number of wires (up to 600) which limits the diagnostic access to individual wires. The work presented in this chapter comprises the first qualitative density study of wire ablation in an x-pinch for a variety of materials.

This chapter includes an overview of wire ablation in multi-wire pulse power

experiments, as well as a description of the ‘rocket model’ [3-2], a theoretical model developed to depicts ablation in cylindrical wire arrays. Through a quantitative density analysis of the streams, the first comparison of x-pinch ablation with the rocket model was performed; the highly correlated results demonstrated that wire ablation is consistent across experimental geometries. The chapter concludes with an investigation into the formation mechanism of the ablation streams. Rather than a uniform ablation off the wire, an  $m = 0$  instability would produce regions of high and low density; in response, a study of the density contrast of the streams with their surroundings was performed.

This initial ablation is responsible for the mass distribution during the remainder of the experiment. As a result, classifying the plasma formation is paramount to understanding the physics of x-pinches and other pulse power wire experiments.

### **3.1 Introduction to Wire Ablation**

Due to the uniform cross section of the wires of a multi-wire pinch, as the current is applied, Ohmic heating and the applied electric field are consistent along their length. Additionally the geometry of various systems creates a uniform or a gradually changing  $B_{\text{global}}$  field between the electrodes. As a consequence a uniform ablated-plasma would be expected to move away from the wires. To model the ablation, S. Lebedev *et al* developed what is commonly referred to as the ‘rocket model’ RM to asses the amount of mass that has left the region surrounding the wire core and the mass distribution within wire arrays.

### 3.1.1 Rocket Model

Previous work (§1.4.1) has shown that late in the current pulse, the wire cores are present at their original location despite having been seen to stream plasma towards the axis of the experiment [3-6]. In 2001, S. Lebedev *et al* presented a model to describe the ablation rate of the wires in pulse power experiments, specifically cylindrical wire arrays. Through this description, a radial representation of the mass can be found which is a good approximation of the ablation phase recorded in experiments [3-2] and [3-6].

In figure 1-6 a cold dense core, carrying little or no current, is surrounded by a hot coronal plasma theorized to carry a majority of the current [3-3]. For the duration of the experiment the core is heated by radiation transport from the corona, which in turn is heated through resistive heating from the current [3-4] [3-5]. The path of the current remains conjecture as it can not be experimentally measured at this time.

Due to the complex nature of the problem a number of simplifications/assumptions are made in order to model the plasma. The heating and the ablation are constrained to be uniform along the length of the wires. While the wire cores carry little or no current and remain stationary throughout the experiment, the coronal plasma carries a majority of the current and is responsible for the radiative heating of the wire cores. These simplifications limit the applicability of the RM to experiments as it does not allow for the three-dimensional axial variations observed. Finally, the magnetic Reynolds number of the corona is assumed to be low ( $Re_M \ll 1$ ). Therefore after the plasma is accelerated away from the wires (by the  $J \times B$  force) the plasma moves towards the axis with no current and therefore free from any forces. This has been verified though the end on laser probing of cylindrical arrays: once the plasma leaves the wires it

moved towards the axis at a constant velocity [3-6]. For the model presented here, the velocity is taken to be constant in time which is supported by experimental results [3-10].

For stationary wire cores the flow of plasma, and hence the ablation can be modeled by a momentum balance, where the change in the plasma's momentum is equated with the force exerted on it by the magnetic field [3-6]:

$$V_{abl} \frac{dm}{dt} = -\frac{\mu_o I(t)^2}{4\pi R_0}. \quad (3.1)$$

Above,  $dm/dt$  is the rate of mass ablation from the wires,  $V_{abl}$  is the ablation velocity,  $R_0$  is the original radial position of the wires (relative to the global axis), and  $I(t)$  is the current profile used to drive the experiment. For the experiments described in the work presented  $I(t)$  is proportional to  $\sin^{1.2}(t)$  see chapter two. For a constant ablation velocity the integration of equation (3.1) yields the total mass ablated from the wire up to a given time  $(t)$ :

$$\delta m(t) = \frac{\mu_o}{4\pi V_{abl} R_0} \int_0^t I(t)^2 dt. \quad (3.2)$$

Therefore, taking into account the time it takes for plasma to travel from the wires to a radial position at time  $t$ , the density distribution as a function of radius is:

$$\rho(r, t) = \frac{\mu_o}{8\pi^2 R_0 r V_{abl}^2} \left[ I \left( t - \frac{R_0 - r}{V_{abl}} \right) \right]^2. \quad (3.3)$$

Observations by S. V. Lebedev *et al* recorded end on interferometric images of array experiments which show the coronal plasma moving away from the wires, with a constant velocity of  $1.5 \times 10^7$  (cm/s) [3-6]. This velocity has been confirmed for various wire materials on MAGPIE [3-7], as well as matching well with simulations [3-8].



Accordingly, this well documented velocity is universally used as the constant plasma ablation velocity, and will be applied in the analysis below.

This eloquently simple rocket model was initially derived for wire arrays and has been extensively verified through the experimental [3-6] [3-9] and 2D MHD simulation results [3-10] [3-11]. However, in experiments in which global as well as local magnetic fields are present, the plasma moves perpendicularly off the wires in periodic ‘ablation streams’ rather than a continuous front [3-2] and it is the goal of this chapter to shed some light on these observed streams.

### 3.1.2 Ablation Streams

The high sensitivity of Schlieren imaging establishes it as an effective diagnostic tool, useful in the identification and tracking of low density structures. Figure 3-1 shows dark field schlieren images of three x-pinchs from various wire materials: aluminum, iron, and tungsten at approximately the same time after the start of the current. In the Fe and W images (b,c) there are clear periodic dark and light regions which are visible 2-3 *mm* above/below the cross point, and repeat down the legs of the x-pinch. These correspond to streams of dense plasma moving, perpendicular off the wires, toward the axis of the pinch. Further inspection shows these structures are not apparent in the Al image (a) presumably due to the fact the stream densities are below the detection threshold of the diagnostic ( $7 \times 10^{18} \text{ cm}^{-3}$ ).

These ubiquitous structures have been observed in multi-wire experiments having local as well as global magnetic fields, including z-pinchs, cylindrical wire arrays, and radial wire arrays (see chapter one and references therein). Experiments have produced

streams with consistent wavelengths, dependent on the wire material used [3-7]; however the generation mechanisms of this ‘fundamental’ mode are still unknown. Theories include: a non-uniform initial plasma ablation, and the growth of magnetohydrodynamic instabilities once the plasma has formed around the wire cores. The former has been investigated through the physical modification of the wire diameter [3-14] and found not to affect the resulting plasma streams. In the latter, the development of a modified MHD ‘sausage’ instability is theorized to be responsible for the axially varying ablation [3-17]. However, contrary to the standard behavior of the  $m = 0$  mode, the streams maintain their initial wavelength throughout the ablation, rather than evolving to longer wavelengths with higher amplitudes.

Another instability postulated to effect the ablation is the electrothermal instability where spatial temperature variations are responsible for generation of the plasma streams [3-15]. Here heat transfer is achieved by hot electrons whose temperature can be written as  $T_{hot\_e}$ . These nearly collisionless particles set up an electric field which drives a return current of cold electrons away the wire core with a temperature of  $T_{cold\_e}$ . Taking into account both electron currents  $I_{hot}$  (hot) and  $I_{cold}$  (cold) the total heat flux was found by M. Haines [3-15] to be:

$$q = \frac{5}{2} \left( \frac{k_b}{e} \right) I_{cold} (T_{hot\_e} - T_{cold\_e}), \quad (3.4)$$

where  $k_b$  is the Boltzmann constant and  $e$  is the charge on an electron. The electrical conductivity of the plasma ‘ $\sigma$ ’ is proportional to  $T_e^{3/2}$ , therefore a spatial variation in the cold electron temperature distribution will lead the cold electron current to increase at locations of higher temperature. As a result, this increase in current

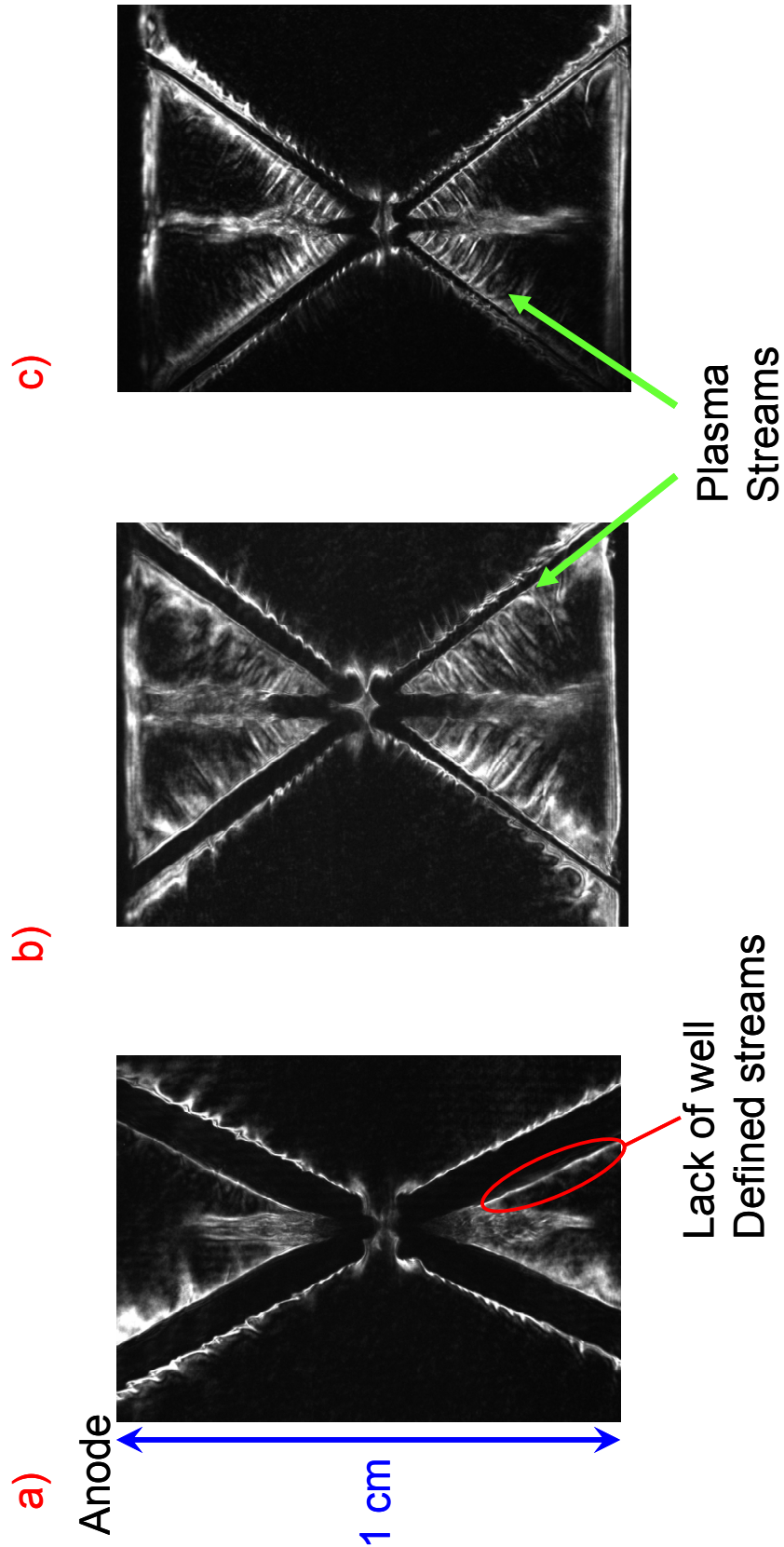


Figure 3-1 Schlieren images of 2 wire x-pinchs showing ablation streams normal to the wire cores. The x-pinch compositions and times were: a) 15  $\mu\text{m}$  Aluminum at 38ns, b) 10  $\mu\text{m}$  Iron at 42 ns, and c) 7.5  $\mu\text{m}$  tungsten at 39ns.

enhances the Ohmic heating, increasing the temperature variations driving the instability.

In order to adequately represent these structures in resistive MHD codes, random temperature or density perturbations are introduced to seed the streams and mimic the results obtained in experiments. Simulation work by J. Chittenden *et al* [3-12] and [3-13] captured the evolution of a random temperature perturbation to the common periodic structure observed in experiments. This work supports a dependence on the magnetic topology of the system and a lack of correlation with the initial plasma formation.

The presence of ablation streams does not affect the results generated from the ablation model. The RM gives an axially integrated radial representation of the mass within an experiment. Therefore measurements of the mass contained in the corona between the wires and the axis, as well as, the mass accumulated on axis are represented accurately.

The work performed here is the first application of the Rocket Model to the plasma ablation in x-pinches. As will be confirmed in the remainder of this chapter and the next, a majority of the plasma dynamics observed in wire arrays is directly applicable to x-pinches.

### **3.2 Experimental Setup**

For the experiments discussed in this chapter the x-pinches were constructed with  $7.5\ \mu\text{m}$  tungsten wires attached between two electrodes with a fixed separation of  $1\ \text{cm}$ . X-pinches were limited to two wires to allow the diagnostics to be set normal to the plane of the wires. This guaranteed the optical probe beam would only pass through the plasma from a single wire, ensuring that all measurements are the result of a single ablation

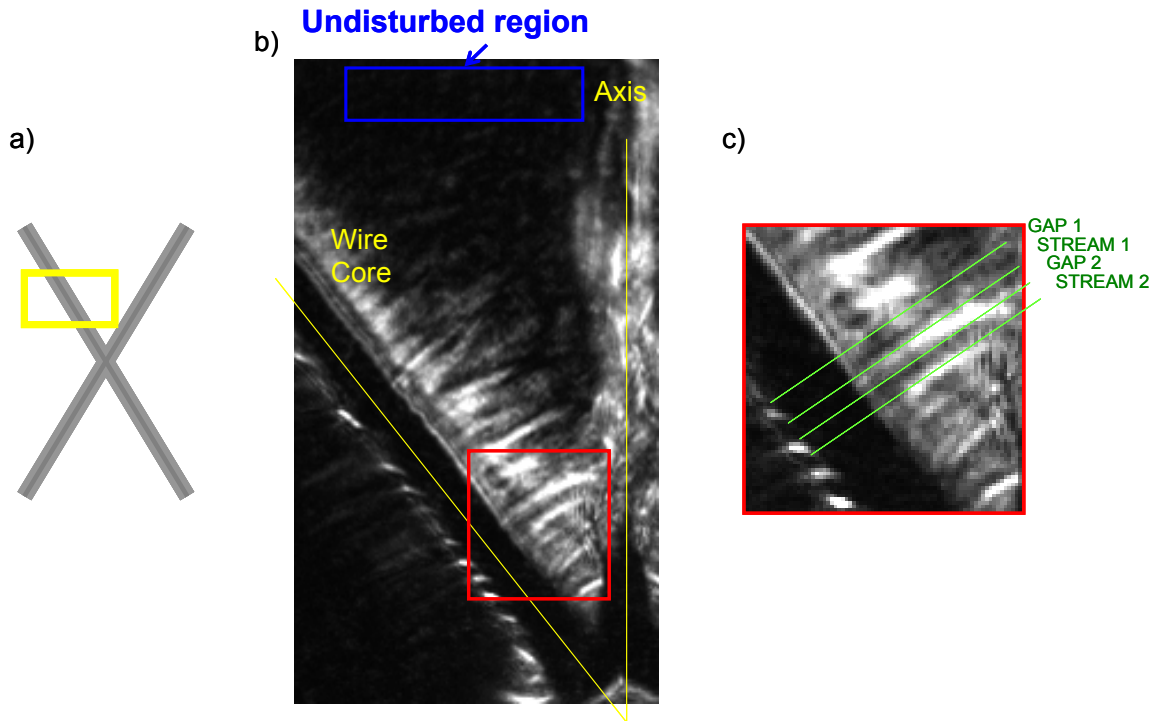
‘stream’ or ‘gap’. The wire diameter and material were chosen to match machine parameters, and previous work has shown reproducible results from this configuration. The experiments were simultaneously imaged with high resolution ( $< 20 \mu m$ ) dark field Schlieren and Nomarski interferometry techniques which allowed for high magnification and analysis of the regions of interest. As described in Section 2.5.1.1 Schlieren images allow a clear identification of plasma structures formed by the x-pinch, while interferometric images enabled quantitative electron density values to be recorded. The lower detection limit of the interferometer was set at approximately a  $\frac{1}{4}$  of a fringe shift corresponding to an  $n_e dl \approx 1 \times 10^{17} cm^{-2}$ , and the maximum limit is set by the refraction of the laser light outside the collecting lens. In this system the maximum density corresponds to an  $n_e dl \approx 1 \times 10^{19} cm^{-2}$  see §2.5.1.1.

### 3.3 Tungsten X-pinch Ablation Streams

Below Figure 3-2b shows a magnified schlieren image of the upper left arm of a tungsten x-pinch the location of which is schematically represented in (a). Here ablation structures perpendicular to the wires are evident, these correspond to the bright regions composed of high electron densities and will be designated as ‘streams’ from this point forward. The dark areas are regions generated by low electron densities and will be designated as ‘gaps’. In order to accurately determine the locations of the streams, a further enlargement close to the cross point is displayed in (c). Overlaid on the image are four green lines indicating the locations of the streams and gaps.

At the top of the schlieren image is a region designated as the ‘undisturbed region’. The lack of exposure in this portion of the image corresponds to an absence of

plasma, and hence will provide a reference region with zero electron density (see below).



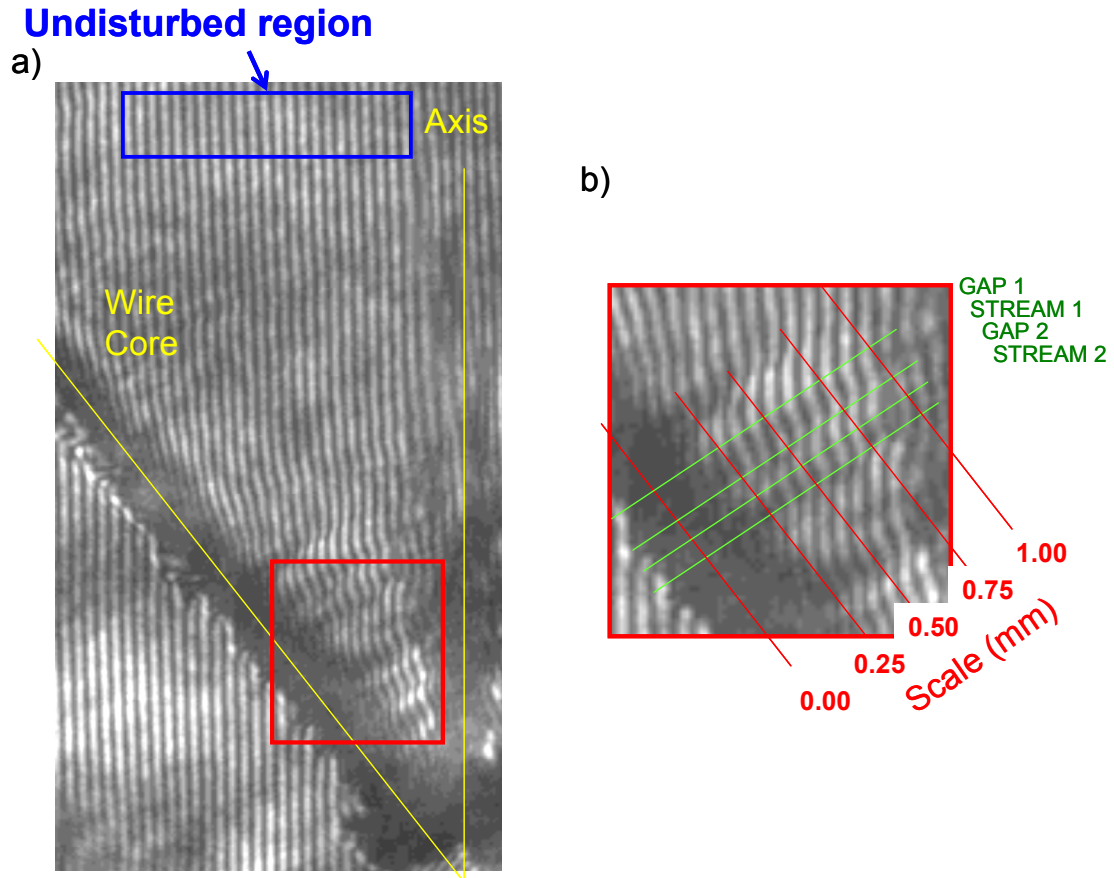
**Figure 3-2** Sections of a schlieren image of a two wire,  $7.5\ \mu\text{m}$  x-pinch taken at  $39\ \text{ns}$ . a) A schematic showing the section of the x-pinch shown in (b). b) An enlarged view of the upper left leg of an x-pinch displaying the plasma ablating from the wire. c) A further enlargement of the region immediately surrounding the wire core identifying the plasma streams and gaps

Figure 3-3 displays the simultaneously interferometric image of the location seen in Figure 3-2. The undisturbed region is comprised of fringes which exhibit no measurable shift when compared with the background image taken before the shot. They thereby provide a reference region where the electron density can be taken to be zero.

A further magnified view of the interferogram is shown in Figure 3-3b for the purpose of identifying the position of the plasma streams. In this case the gaps are identified by regions of local maximum fringe shift while the streams are represented by minimal local fringe shift.

The fringe shifts were recorded at four positions radially outward from the wire

core, along the ablation structures. The measurements were taken at 0.25, 0.50, 0.75, and 1.00 millimeters, and are indicated by the red lines in Figure 3-3b.

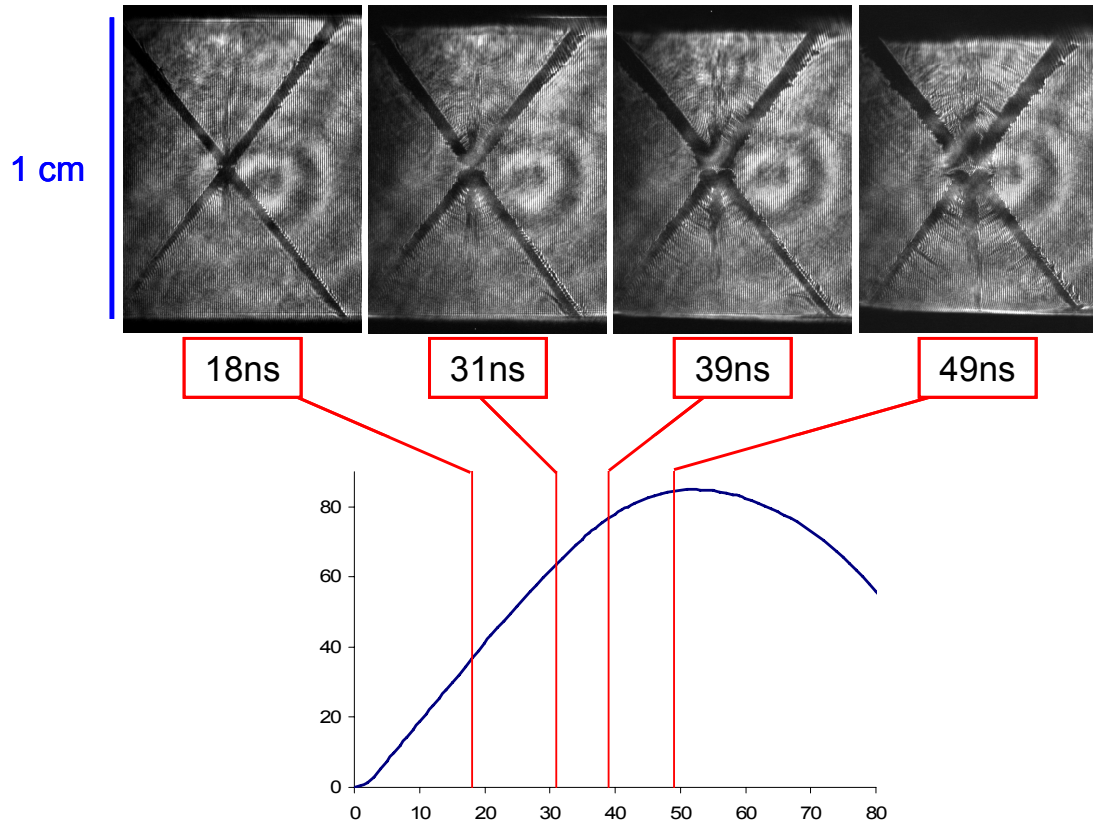


**Figure 3-3** Interferometric image of a W x-pinch at 39 ns (Figure 3-2). a) A magnified view of the upper left leg. b) Further magnification marking the gap/stream locations.

These fringe-shift measurements were repeated for a series of interferometric images captured at various times during the rise of the drive current which can be seen below in Figure 3-4. The position of the streams was highly reproducible; in the below sequence the position of the streams varied by less than the period of the ablation flares ( $\sim 140 \mu\text{m}$ ).

In order to correlate the position of the gaps and streams, in each image of the above sequence the location of stream 2 was chosen as close as possible to its original

position in the 39 *ns* image. The resulting positions of stream one and gaps 1,2 were taken immediately adjacent to Stream 2, in the direction propagating away from the cross point.



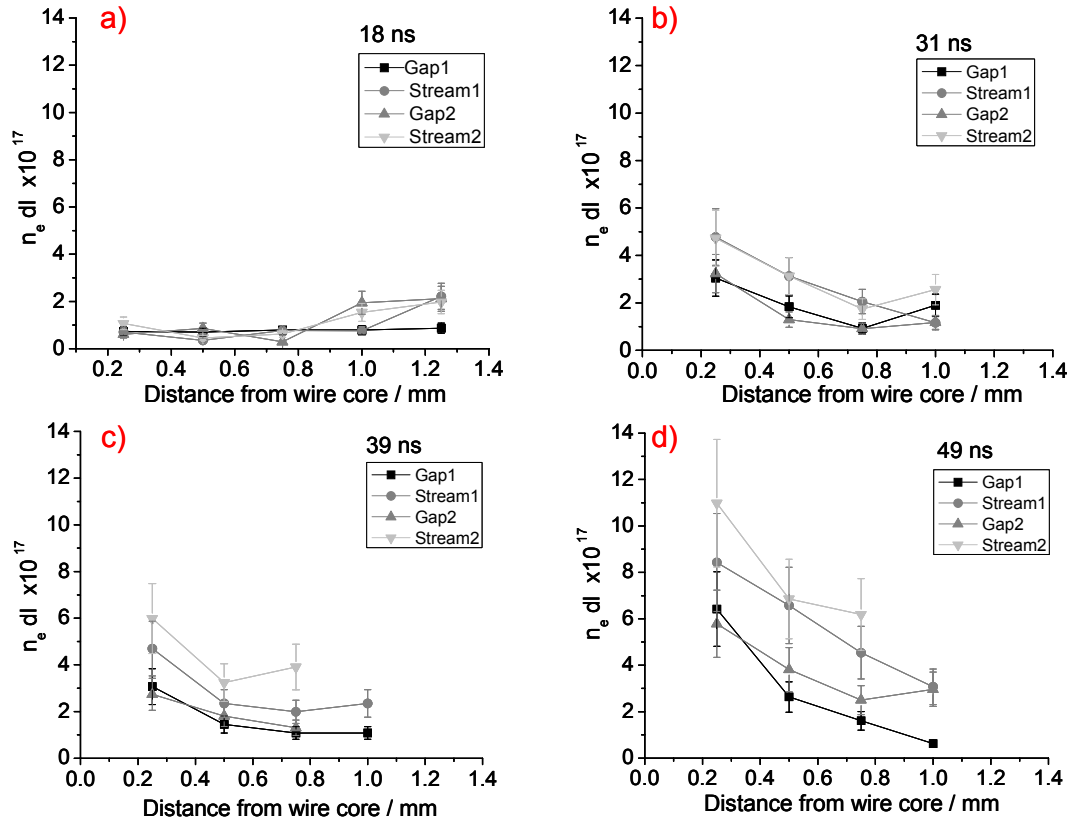
**Figure 3-4** A series of four interferometric images, from 18 to 49 *ns* after the start of the current rise from sequential shots.

From section 2.5.1 the fringe shift,  $f$ , is related to the electron density,  $n_e$ , by:

$$\int n_e (cm^{-3}) dl = 4.2 \times 10^{17} f. \quad (3.5)$$

The fringe shift values were converted to areal electron density. The results are plotted below in Figure 3-5 as a function of radial distance from wire core, along each of the line outs drawn above in Figure 3-3.





**Figure 3-5** Plots of areal electron density taken at four locations along the stream and gap positions from 18 ns to 49 ns

Early measurements taken 18 ns after the start of the current are close to the sensitivity limit of the interferometer and show little density variation in the radial or axial directions. For 31 ns, Figure 3-5b shows an increase in electron density close to the wire core. Here, density measurements taken at the stream positions are noticeably higher than those taken at the gaps. As time progresses a substantial increase in the density of stream 2 is observed beginning at 31 ns (see graphs 'b-d'). The measurements taken from the final two frames show that stream 2 (closer to the axis) show a higher density than those from stream 1 (further away from the global axis1). From the final frame shown (49 ns) the density of stream 2 has reached  $1.1 \times 10^{18} \text{ cm}^{-3}$  as a distance of

0.25 *mm* from the wire core. Also evident is that through 39 *ns* the gap densities remain similar to each other while lower than that of the stream; it is not until late in time (39-49 *ns*) that their densities rise.

### 3.3.1 Rocket Model Comparison

It is useful to compare the density profiles of the ablation streams from the wires with the modeled mass distribution (equation (3.3)) predicted by the Rocket Model. To accomplish this, a conversion from electron density to mass density requires an average ionization state be assumed for the plasma. Additionally, to convert from areal density to volumetric density the streams were assumed to be cylinders, therefore their thickness into the page was taken to be the same as their width.

As noted earlier various experimental parameters are required to generate a mass distribution curve. The value of  $R_0$  (distance to the global axis) is taken as the average distance of the stream positions relative to the x-pinch axis. In this set of experiments this value was fixed at 1 *mm*, while the ablation velocity ( $v_{abl}$ ) was fixed at  $1.5 \times 10^7$  *cm/s* as discussed above.

For the rocket model, an estimate of  $Z = 10$  was used for the ionization state of the plasma. When combined with the density measured this value corresponds to an electron temperature of approximately 15 *eV* which does not contradict the filtered XUV images of the flares. For all curves generated, the ionization value was kept constant, as the velocity and hence the temperature is assumed to be uniform for the duration of the experiment.

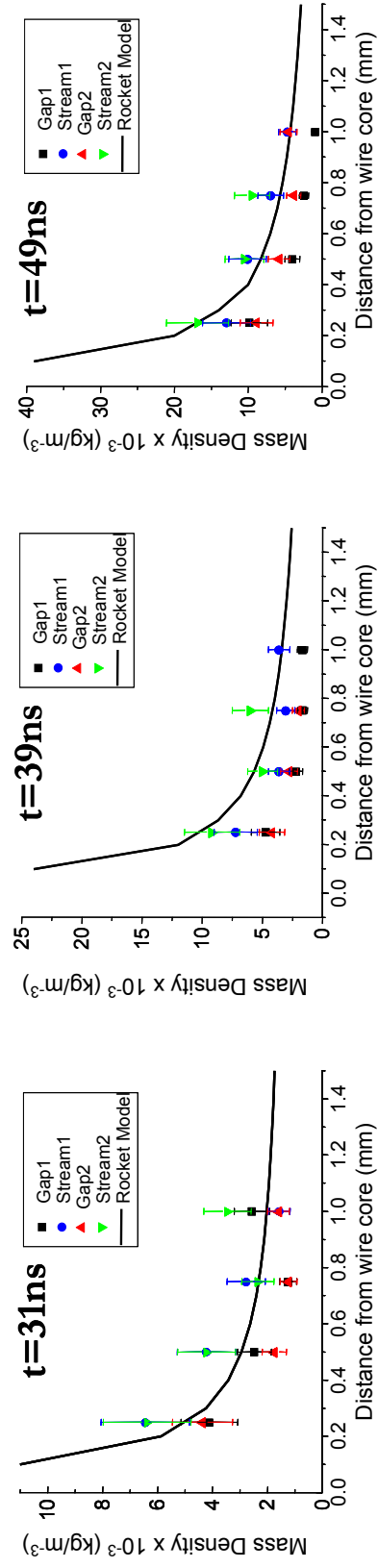
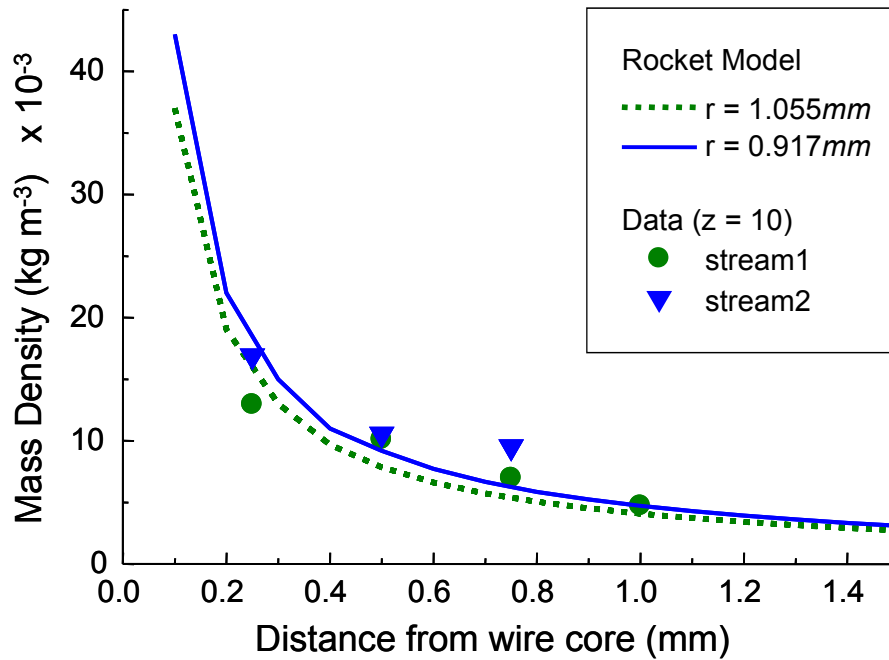


Figure 3-6 Plots comparing experimental density results with the theoretical curve generated by the Rocket Model assuming  $Z=10$  for a) 31 ns b) 39 ns and c) 49 ns.

A comparison of the experimental data with the values predicted by the rocket model (Figure 3-6) indicates that they are in good agreement for a given ionization state. In all cases the stream density lies close to, or above the predicted values; while the gap densities all lie below the model. This demonstrates that the rocket model is able to effectively generate the density curves observed in experiments, providing a good estimate for the average mass ablation rate in these x-pinch experiments.



**Figure 3-7 Comparison of the measured, and expected (rocket model) mass density profiles of the two stream positions at 49 ns ( $V_{abl} = 1.5 \times 10^7$  cm/s)**

As can be seen in Figure 3-6, the two stream positions yield different densities, a result of the variation of their positions relative to the global axis. The exact location of the streams was used to generate two curves from the rocket model, which are contrasted with experimental data ( $t = 49$  ns) in Figure 3-7. As can be seen below, using a smaller radius (0.92 mm) produces a higher density curve which results from a larger magnetic field. From the plotted rocket model results it is evident that a small difference is

expected from the two positions and is represented in the observations. This result verifies that the momentum balance assumed in the Rocket model is applicable in these experiments regardless of the varying  $J \times B_{\text{global}}$  force present in an x-pinch. This work comprises the first comparison of the rocket model theory to the ablation observed in x-pinch. Assuming a realistic ionization state of the plasma ( $Z = 10$ ), a reasonably accurate mass distribution profile was generated.

In addition to characterizing the density profile of the ablated plasma it is useful to investigate the mechanism responsible for the generation of the filamentary structures.

### 3.3.2 Density Contrast

The density contrast between the streams and gaps may provide information regarding the possible mechanism responsible for the formation of the non-uniform ablation. In addition to the density profiles along the streams, the presented data also contains information regarding the density contrast between the gaps and streams.

From the above data the electron density ration ( $n_{e,\text{stream}} / n_{e,\text{gap}}$ ) can be determined. Assuming a fixed ionization state ( $Z$ ), electron density can be converted to a mass density ‘ $\rho$ ’ ratio ( $\rho_{\text{stream}} / \rho_{\text{gap}}$ ). This ratio is plotted against time and position in Figure 3-8a and b respectively. In the first plot the ratios  $\rho_{\text{Stream1}}/\rho_{\text{Gap2}}$  and  $\rho_{\text{Stream2}}/\rho_{\text{Gap2}}$  are plotted for comparison; the values were taken at 0.5 mm from the wire core, and can be seen to increase with time.

From the rocket model description, the mass ablation rate changes with position from the global axis. Averaging the two ratios plotted in the figure (at each time) yields a value representing experiments where the stream and gap positions are the same distance

from the axis, for example in cylindrical wire arrays. The averages (not shown) were calculated and were fit with a linear function shown in Figure 3-8a in addition to the individual density ratios.

It is also informative to look at the density ratio as a function of distance. Figure 3-8b shows the time averaged density ratios plotted against distance from the wire core. The density contrast is seen to rise slightly with increased distance from the wire core, going from  $\sim 1.5$  at  $0.25\text{ mm}$  to  $\sim 2.3$  at  $0.75\text{ mm}$ . The error bars are a result of the averaging of density ratios from shots at different times. Here the density contrast ratio is relatively constant through both time, and distance from the wire core.

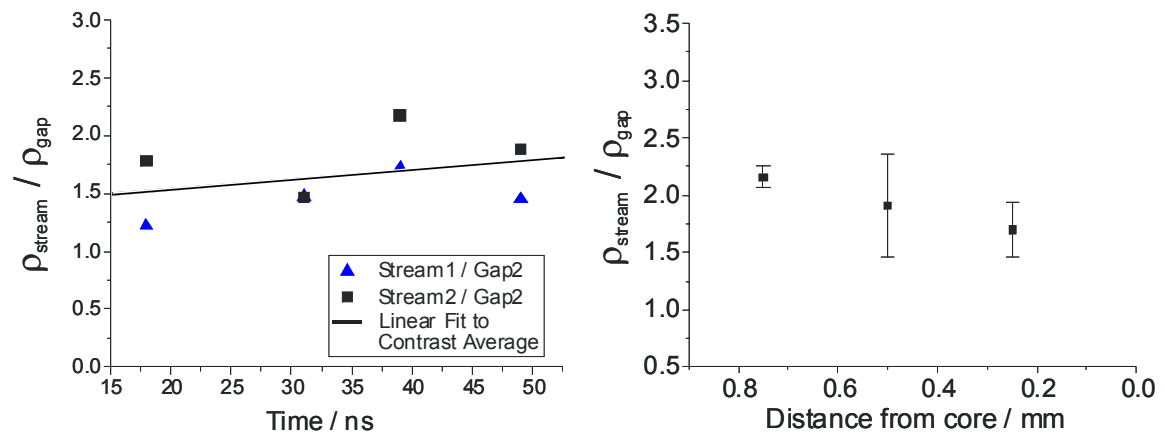


Figure 3-8 Stream to gap density ratio a) varying in time ( $0.5\text{ mm}$  from the wire core) and b) as a function of distance (time averaged)

### 3.4 Summary

The work presented in this chapter marks the first investigation of the non-uniform coronal plasma present in x-pinch. The presence of periodic density structures are similar to those routinely observed in cylindrical and conical wire array experiments. This led to the first application of the Rocket model (previously developed for wire

arrays) to the plasma ablation observed in x-pinches. The good agreement between the theory and the experimental results reinforces the hypothesis that the ablation of the wires is dominated by the current rise rate in each wire and the presence of a local and global magnetic fields rather than the maximum current achieved during the experiment.

## Chapter 4

# Coronal Plasma Dynamics

Following the initial ablation of the wires, the dynamics of the coronal plasma may play a role in determining the radiation (chapter six) and axial structure formation (chapter five) of x-pinch experiments. As a result, a comprehensive understanding of the dynamics is important. For the majority of the pinch sequence, the corona provides a path, in addition to the wire cores, for the current to travel along. If the magnetic field is ‘frozen-in’ the low density plasma has the potential to redistribute the current, including the resulting Lorentz forces, from their initial position along the x-pinch limbs. This mobility results in drastically varying plasma characteristics which stem from the resistivity ( $\eta$ ) of the wire material used to form the x-pinch and the resulting plasma.

Previous work has investigated the pinch sequence using x-ray backlighters [4-1] [4-3] and optical probing techniques [4-12][4-13] and [4-19]. High energy photons ( $h\nu > 1 \text{ keV}$ ) typically used in x-ray backlighting are not absorbed and therefore have not provided good contrast for the low density coronal plasma. Alternatively, laser probing techniques can be used to detect electron densities from  $10^{18} - 10^{19} \text{ cm}^{-3}$ , but are limited by the high densities found in x-pinch plasmas. As a result, the location, migration, and



current carrying parameters of the corona, have received relatively little experimental study. However recently an examination of the low density plasma has been performed with 3D resistive MHD codes [4-1]. In this chapter the coronal plasma development, as well as, the subsequent dynamics are investigated.

Various wire materials were studied using simultaneous optical backlighting and emission diagnostics to infer density and current distributions during the experiments. X-pinchs constructed from pure wire materials allowed the development of a baseline of behavior for materials with various atomic numbers. The latter portion of this chapter describes work investigating the effects of a thin high-Z coating on the dynamic development of x-pinch plasma structures. Molybdenum wires, both bare and with a thin coating of gold, were investigated to determine the effect of a small amount of a high Z material during the initial wire ablation on the x-pinch behavior. In particular, the formation and evolution of the low density coronal plasma ( $< 10^{18} \text{ cm}^{-3}$ ) and its effect on the subsequent pinch dynamics was studied.

## **4.1 Introduction to the coronal plasma**

As a high-amplitude current is driven through fine metallic wires, Ohmic heating and ablation (chapter three) result in the formation of a low-density plasma around the wires. In a pinch experiment this corona is made up of high temperature plasma that has a lower resistivity when compared to that of the remaining wire cores. This establishes a favorable path for the current during a majority of the pinch sequence. Forces due to the global magnetic field lead to a migration of the corona from the wire's initial position toward the global axis. As in the previous chapter, the assumption of a low magnetic

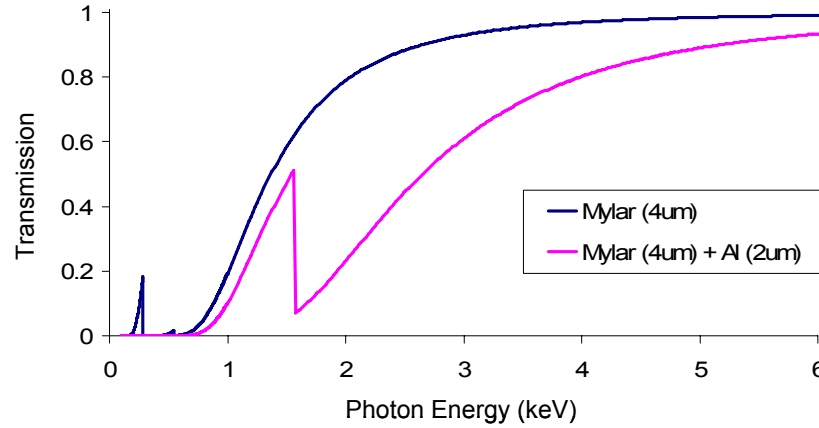
Reynolds number results in an acceleration close to the wire core and a constant velocity to the axis. Alternatively if the  $Re_M$  is greater than one, the B-field will be frozen into the plasma and the plasma's displacement may alter the current path during an experiment. A great deal of the dynamics of the x-pinch sequence result from the distribution of Lorentz forces which drive the plasma; therefore the location of the corona, and resultant the current, is of great importance in the understanding of the plasma dynamics.

## 4.2 Experimental Setup

For the purposes of examining the effects of the wire material on the coronal plasma and the subsequent dynamics pinches consisting of two  $7.5\ \mu m$  Tungsten wires,  $10\ \mu m$  Iron, and  $15\ \mu m$  Aluminum were studied. Additionally, results from  $13\ \mu m$  bare molybdenum (Mo) wires were compared with gold coated molybdenum wires [Mo(Au)] where the gold coating was 3–5% by weight, resulting in an average Au thickness of  $0.09\ \mu m$ . In all the x-pinch experiments, the gap between the anode and cathode was fixed at  $10\ mm$ .

To record the dynamics of the low density coronal plasma, a four frame extreme ultraviolet (XUV) MCP pinhole camera was utilized (as discussed in chapter two). All four frames had two pinholes, both with a magnification of 0.7. Each set contained a “primary”  $200\ \mu m$  pinhole covered by a  $4\ \mu m$  Mylar filter allowing visible and XUV light through, unless otherwise stated. The “secondary” component of each set consisted of a  $400\ \mu m$  pinhole filtered with  $4\ \mu m$  of Mylar plus  $2\ \mu m$  of Aluminum. The additional filter prevented emission below  $h\nu = 1\ keV$  from reaching the MCP camera, while the

larger diameter served to increase the photon flux. The transmissions of the filters are displayed below in Figure 4-1. The variation in filters on each channel provided simultaneous emission imaging in two different energy ranges.



**Figure 4-1 MCP Filter Transmissions**

In the data presented below, each shot yielded three XUV frames with an inter-frame time of 9 ns. Each frame contains two images with the image from the harder filter appearing on the left. Note that the larger pinholes ( $h\nu > 1 \text{ keV}$ ) only show pinhole limited images, indicating that the source was smaller than the pinhole.

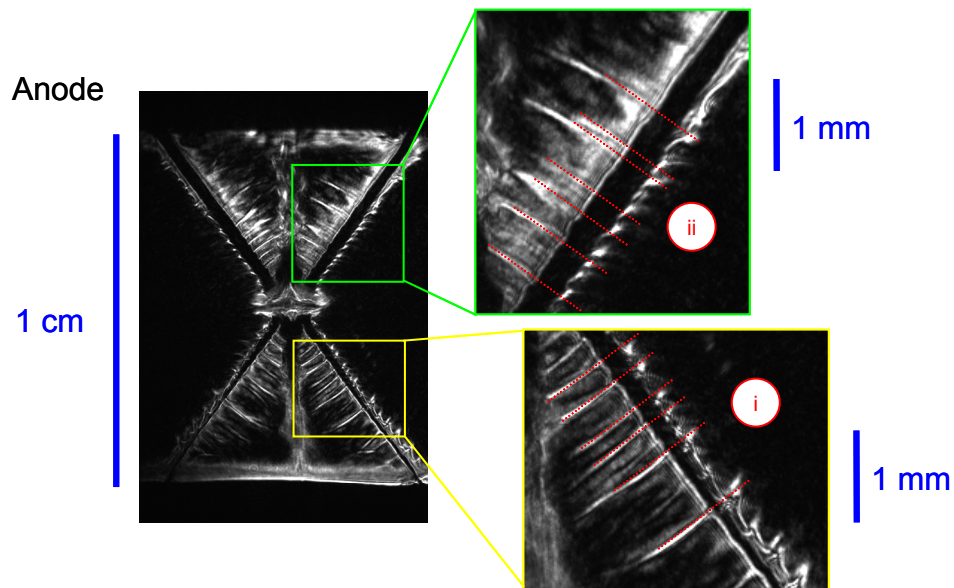
Imaging was achieved through dark field Schlieren and Shadowgraphy (see section 2.5.1) and all timings for the optical and MCP images are given with respect to the start of the current pulse.

### 4.3 Optical Probing of X-pinch Corona

In order to show the details of the expanding coronal plasma, enlargements of the individual wires of a tungsten x-pinch are shown in Figure 4-2. In these frames, plasma is seen streaming off the inside of the wire (the side closest to the pinch axis) toward the global axis, while the plasma on the outside of the x-pinch (away from the global axis)

remains confined to the wire. Here the global magnetic field drives the plasma off the wires toward the global pinch axis (through the  $\mathbf{J} \times \mathbf{B}$  force), while the local B-field confines the plasma around the wire core. For a detailed discussion of the periodic wire ablation, and work performed, see chapter three.

Immediately surrounding the wire the local B-field dominates and will establish axial symmetry around the individual wires. This results in corresponding plasma structures on the ‘inside’ and ‘outside’ of the wires as highlighted with dashed lines and labeled i and ii in Figure 4-2.



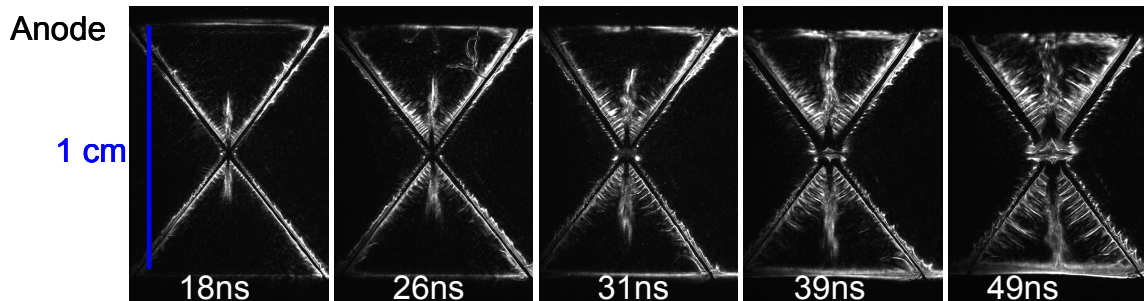
**Figure 4-2 Enlarged schlieren image of individual wires from a 2 7.5  $\mu\text{m}$  Tungsten wire x-pinch at 49 ns after the start of the current pulse**

Also present in Figure 4-2 is a distinct disparity in the width of the individual wires. In order to investigate this further, Schlieren imaging was used to monitor the coronal plasma development of an x-pinch, and a sequence recording the evolution of two 7.5  $\mu\text{m}$  tungsten wire x-pinch is shown in Figure 4-3. As the experiment progresses, the width of the over-dense region increases non-uniformly, with the plasma close to the

anode expanding faster than that close to the cathode.

Bright regions surrounding the overdense wire core, are the result of plasma gradients and this will henceforth be referred to as the coronal plasma. As time progresses, this region expands normal to the surface of the wire. Under the influence of the global B-field the ablated material forms filaments as it streams from the inside of the wires (the side closer to the axis of the pinch); for a complete discussion refer to chapter three. These filaments are evident for the duration of the sequence in Figure 4-3. In response to the non uniform expansion, the width of the corona was taken as the average length of several filaments.

Similar to the over-dense plasma, the corona can also be seen to expand at a greater rate closer to the anode and slower along side the cathode.



**Figure 4-3 Schlieren images of 7.5  $\mu\text{m}$  2 wire tungsten x-pinch**

An examination of a similar series of schlieren images taken of Iron wires Figure 4-4 shows a similar expansion of the wires, where the radial expansion adjacent to the anode is greater than that by the cathode. Other evolutionary resemblances include the formation of ablation streams along the wires and the development of an axial plasma column.

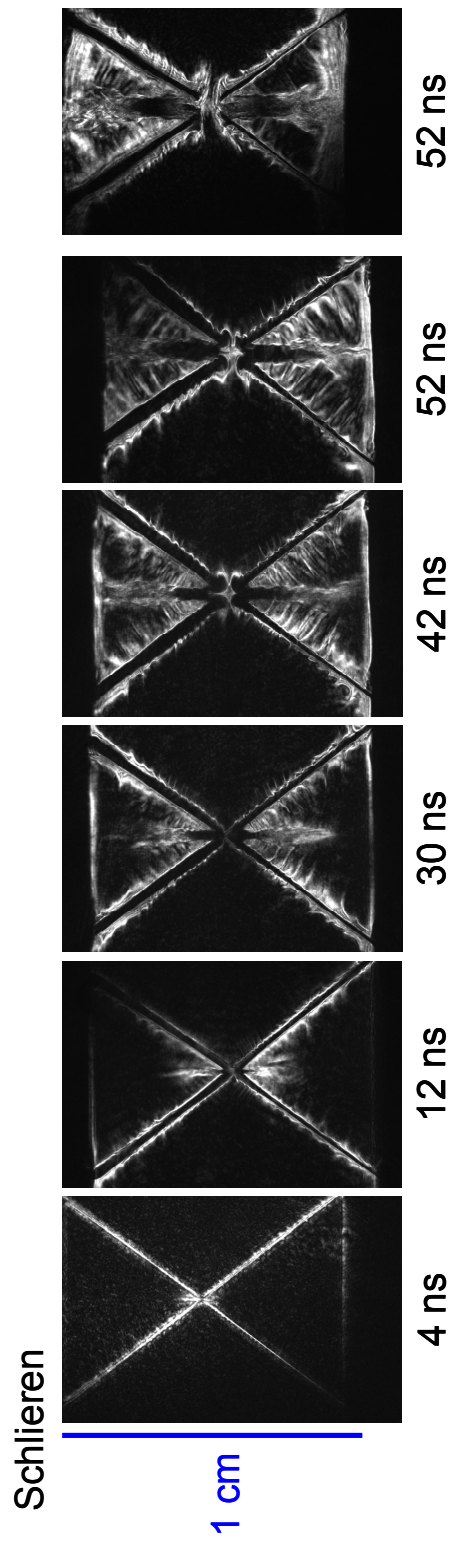


Figure 4-4 Schlieren sequence of 10  $\mu\text{m}$  Iron X-pinch

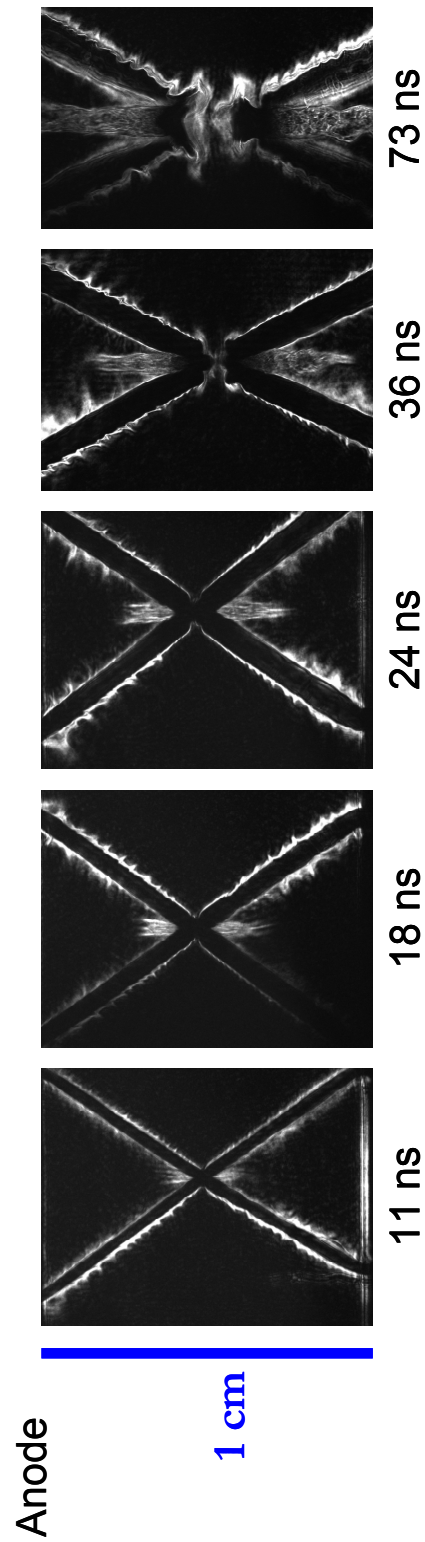
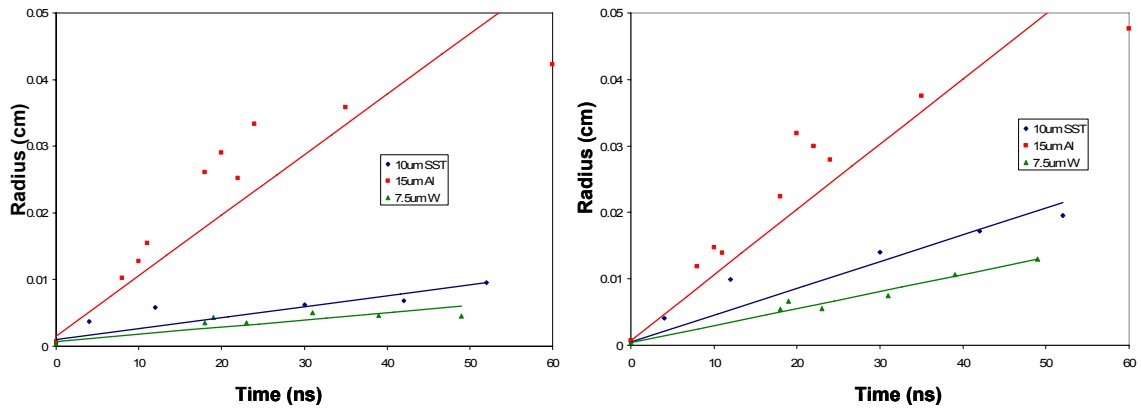


Figure 4-5 Schlieren sequence of 15  $\mu\text{m}$  Aluminum X-pinch

Figure 4-5 shows a sequence from x-pinch experiments constructed of two  $15\ \mu\text{m}$  aluminum wires. In contrast to the previous wires, the width of the plasma along the legs appears uniform along their length, and the rate of expansion is much greater than that observed in the tungsten and iron sequences.

For the three aforementioned materials, the width of the optically thick plasma was measured at the anode as well as the cathode for a series of successive experiments. The average radius (avg. of left and right legs) of the regions was plotted against the timing of each shot and can be seen below in Figure 4-6. A linear trend was applied to determine an expansion velocity of the over-dense plasma for the various wire materials.



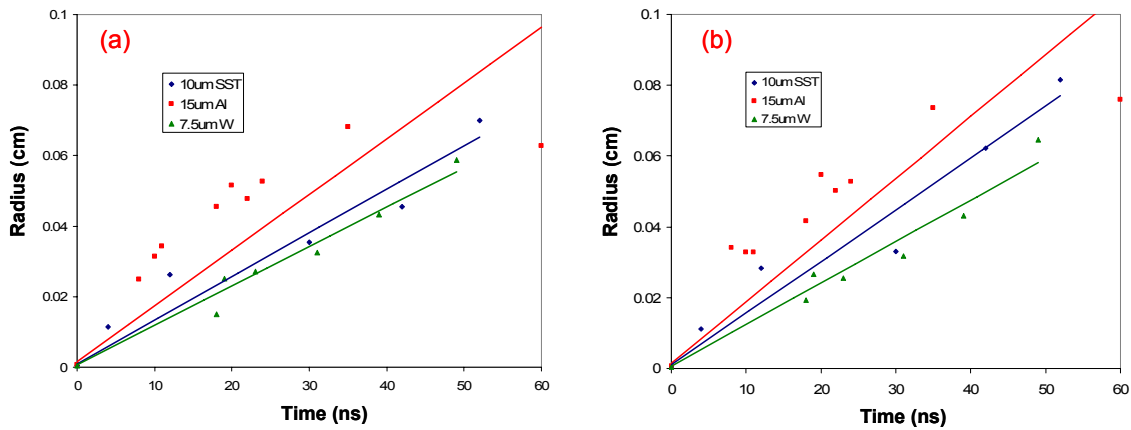
**Figure 4-6** Graphs displaying the radius of the overdense plasma as a function of time. (a) The radius of the wire adjacent to the cathode, and (b) the radius of the plasma close to the anode.

In (a) of Figure 4-6 above, the plasma velocity of the two higher  $Z$  materials, Tungsten and Iron, are relatively similar at  $1 \times 10^5$  and  $2 \times 10^5\ \text{cm/s}$  respectively. Above, Aluminum exhibits a higher expansion velocity of  $9 \times 10^5\ \text{cm/s}$ .

From an initial visual examination of an individual frame in Figure 4-3, and 4-4 it is clear that the wires adjacent to the anode expand at a faster rate when compared to the plasma near the cathode. This is confirmed by the data in Figure 4-6b which yields  $3 \times$

$10^5$  and  $4 \times 10^5$  cm/s for W and Fe, respectively. As in the data taken adjacent to the cathode, the Aluminum wires display a significantly higher velocity than the other materials at  $10 \times 10^5$  cm/s. For Aluminum, the difference in velocities between the electrodes is  $\sim 10\%$ , while for the other wire materials the difference is 50 to 66 percent, verifying a more uniform expansion along the Al wires. A discussion addressing the poor fit of the trend line to the Al wire expansion data is presented below in section: 4.7.1.

The same images were analyzed with respect to the optically thin coronal plasma surrounding the wires. In the schlieren images this region is identified as the white region surrounding the overdense (dark/black) plasma region. For images exhibiting the density perturbation structures discussed in chapter three, the coronal radius was taken at the limit of the regions of high density (or the limit of the bright regions). Again, the measurements taken at the anode were distinguished from those taken at the cathode; for comparison both can be seen below in Figure 4-7.



**Figure 4-7** Graphs of the radius of the coronal plasma as a function of time for (a) the plasma close to the cathode and (b) the plasma adjacent to the anode.

Similarly to the previous case of the overdense plasma, at the cathode we find the



velocities (Figure 4-7a) of the higher Z materials W ( $Z = 74$ ) and Fe ( $Z = 26$ ) grouped closely together at  $1.1 \times 10^6$  and  $1.2 \times 10^6$  cm/s, respectively. As before Al ( $Z = 13$ ), has a more distinct velocity of  $1.6 \times 10^6$  cm/s when compared with other materials. An analysis for the plasma adjacent to the anode yields the data in Figure 4-7b. Here the following velocities were obtained: W:  $1.2 \times 10^6$ , Fe:  $1.5 \times 10^6$ , and Al:  $1.7 \times 10^6$  cm/s. As before, the velocities of all of the materials are higher at the anode than at the cathode. The percentage increase for the low density Al coronal plasma was relatively low at 6% when compared with 8% for tungsten and 20% for Iron. A listing of the expansion velocities for the various wire materials is summarized below in Table 4-1.

**Table 4-1 Summary of the velocities of expanding coronal plasma surrounding the x-pinch wire legs**

|          | Cathode overdense plasma (cm/s) | Anode overdense plasma (cm/s) | Cathode coronal plasma (cm/s) | Anode coronal plasma (cm/s) |
|----------|---------------------------------|-------------------------------|-------------------------------|-----------------------------|
| Tungsten | $1.0 \times 10^5$               | $3.0 \times 10^5$             | $11 \times 10^5$              | $12 \times 10^5$            |
| Iron     | $2.0 \times 10^5$               | $4.0 \times 10^5$             | $12 \times 10^5$              | $15 \times 10^5$            |
| Aluminum | $9.0 \times 10^5$               | $10.0 \times 10^5$            | $16 \times 10^5$              | $17 \times 10^5$            |

Due to a high contrast ratio with the background density it is appropriate to assume the expansion of the x-pinch legs will be dominated by the sound speed of the wire material, as a result a lower estimate of the plasma temperature is possible. Equating of the coronal expansion velocity with the sounds speed  $c_s$ :

$$c_s = 9.79 \times 10^5 \left( \frac{\gamma Z T_e}{\mu} \right)^{1/2} \text{ cm/s}, \quad (4.1)$$

it is possible to estimate the product  $ZT$ . Setting  $\gamma$  (the adiabatic index) to  $5/3$ , averaging the final two columns in Table 4-1 for each material, and using the appropriate  $\mu$  (ion

mass / proton mass:  $m_i/m_p$ ) for each material yielded the values displayed in Table 4-2.

Due to the low density of the coronal plasma, the ionization states were determined using the coronal equilibrium (CE) model which is detailed in chapter five. In this model the ionization energy of the most prevalent  $Z$  state ( $I_z$ ) is related to the temperature by:  $I_z = (2.5) * T_e$ .

**Table 4-2 A listing of the ionization states and temperatures ranges for the material expansion velocities found in Table 4-1.**

| Material | ZT (eV) | Assumed Ionization State 'Z' | Temperature Range (eV) |
|----------|---------|------------------------------|------------------------|
| Tungsten | 152     | 5-6                          | 25-30                  |
| Iron     | 64      | 3-4                          | 16-21                  |
| Aluminum | 46      | 3                            | 15                     |

The higher wire expansion velocity of the aluminum wires, over those of tungsten and iron, may be attributed to a difference in material properties for the various materials. For simplicity, a uniform expansion of the wires across the electrode gap will be assumed below; accordingly, the averages of the anode and cathode expansion rates are displayed in the first column of Table 4-3.

Currently, it is impossible to determine the effect of the  $\mathbf{J} \times \mathbf{B}$  force on the coronal plasma due to a lack of a detailed B-field distribution within the x-pinch. In response, despite the strong evidence in variation of the current path for low and high  $Z$  materials presented above, here it will be assumed that all magnetic field topologies have the same effect for all the wire materials.

From self emission imaging presented above, and previous work [4-16], the temperature of the coronal plasma may be taken to be  $\sim 15$  eV. In conjunction with their

respective ionization energies, the theoretical sound speeds for various materials were found and appear in the table below.

Neglecting the magnetic fields, the theoretical sound speed values exhibit a similar trend to the experimental expansion data, indicating that the expansion is dominated by the sound speed of the materials. As a result of the good agreement, it is appropriate to conclude that the wire expansion is dominated by the sound speed of the materials.

**Table 4-3 Average (anode/cathode) experimental expansion velocities and theoretical sound speeds for various x-pinch wire materials.**

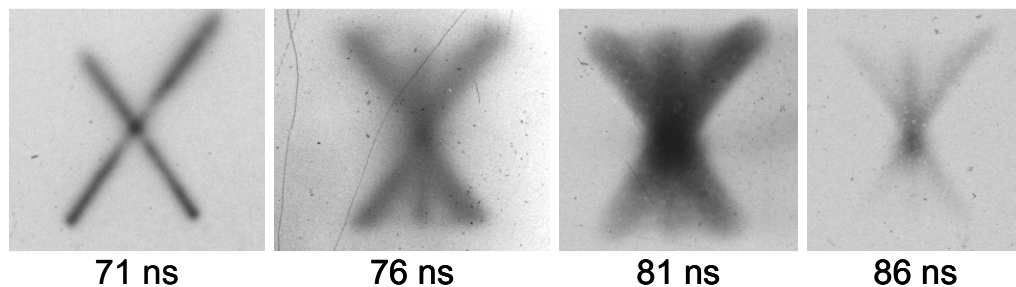
|                                  | Under dense plasma (corona) | Theory @ 15 eV     |
|----------------------------------|-----------------------------|--------------------|
| Al expansion vel ( <i>cm/s</i> ) | $16.5 \times 10^5$          | $16.3 \times 10^5$ |
| Fe expansion vel ( <i>cm/s</i> ) | $13.5 \times 10^5$          | $14.6 \times 10^5$ |
| W expansion vel ( <i>cm/s</i> )  | $11.5 \times 10^5$          | $8.84 \times 10^5$ |

An alternative explanation for the variation in expansion rates of the wires may be the relative temperatures of the coronal plasmas. The dominant emission mechanism is Bremsstrahlung radiation, which goes as  $(P_b \propto Z^3 n_e^2)$ . Therefore, lower atomic number materials will radiate less efficiently, retaining a greater amount of their internal energy. Aluminum's relatively low atomic number ( $Z_{13} = 13$  vs.  $Z_W = 74$ ) causes it to radiate less efficiently retaining more of the imparted energy from Ohmic heating. This results in a higher residual amount of thermal energy and thus a higher temperature. In accordance with (4.1) this results in a higher sound speed and may explain the faster expansion velocity. In contrast, the higher atomic numbers of the W and Fe allow them to radiate more efficiently leaving less kinetic energy available to expand the plasma.

Both methods described above are supported by the data presented in the graphs in (Figure 4-7) and numerically in Table 4-1. In order to verify the first method, an accurate measurement of the current and B-field distributions within the coronal plasma should be attained. Validation of the second hypothesis would be accomplished by a measurement of the total radiation emitted by the corona. Both topics should be the topic of future work to definitively understand the coronal expansion.

#### 4.4 Self emission X-pinch imaging

From the above sequences, beginning at 12 *ns* in Iron, and 18 *ns* in W and Al, (Figure 4-3, 4-4, and 4-5 respectively) a plasma structure can be seen forming along the mid-plane of the x-pinch. In time this structure propagates toward the electrodes and may be a direct result of the coronal plasma coming off the wires. Details of the axial plasma column are further covered in chapter five. However, the schlieren images do not capture the transport of the plasma from the wire limbs to the mid-plane of the pinch. To explore this, under the assumption that the plasma is below the optical detection threshold, a series of XUV images were recorded and are displayed below.



**Figure 4-8** A self emission image sequence from a two  $7.5\ \mu\text{m}$  tungsten wire x-pinch. Throughout the pinch sequence emission can be seen along the wires for the full 1 *cm* length of the x-pinch.

Figure 4-8 shows a series of time-gated self emission images of a two wire tungsten x-

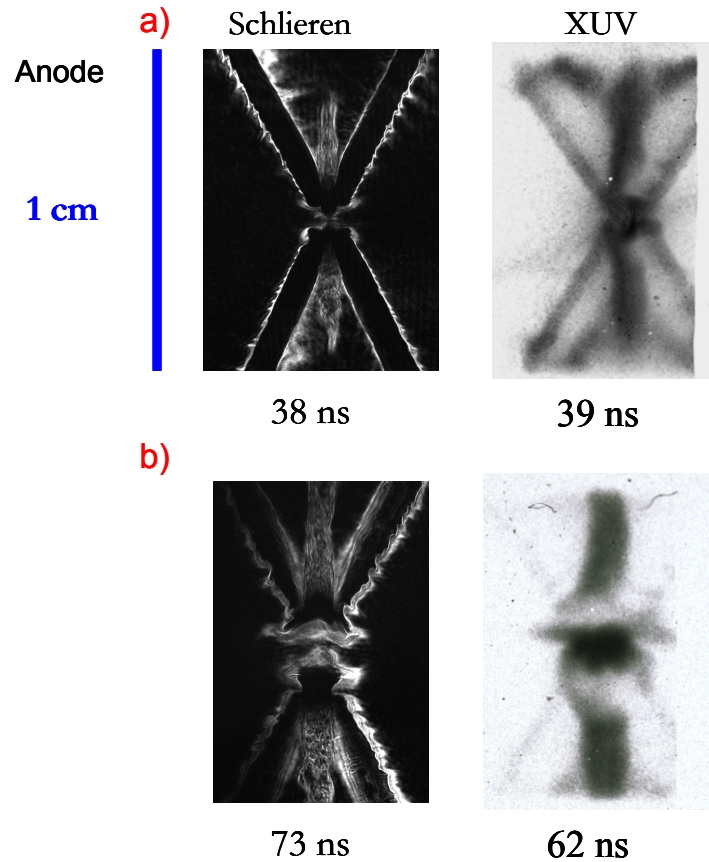
pinch. The non-consistent level of exposure and resolution of the film of successive frames is due to the use of various pinhole diameters. Despite the resolution being significantly lower than that exhibited in the previous optical probing images, throughout the sequence emission is observed from the vicinity of the original wire cores. Late in time ( $\sim 76$  ns) emission can also be seen along the centerline of the pinch. These results correlate well with the location of the axial plasma previously seen in the optical probing sequence in Figure 4-3.

As discussed in chapter three, the lack of visible flare structure in the Al Schlieren frames (Figure 4-5) implies a low density outside the range of the diagnostic. In response simultaneous self emission images was recorded to capture hot (emitting) plasma, which may be below the optical detection threshold. XUV images are presented alongside schlieren images at similar times in Figure 4-9 to emphasize the difference in density ranges of the diagnostics.

In the 39 ns XUV frame, a plasma moving off of the wires and toward the axis is visible. In contrast the optical probing image captured a gap between the legs and central plasma structure. This indicates that the plasma migrating away from the wires in the XUV images has a low density. Additionally in this image the coronal plasma as well as the wire cores appear dark, which is indicative of continuous heating and therefore the current present in both.

Figure 4-9b displays a similar comparison of two Al images later in time. In both images the central column is evident connecting the electrodes; however, while the schlieren image shows the dense wire cores, the XUV image does not. Additionally, in the MCP image the central column is highly emitting, indicating it continues to be heated

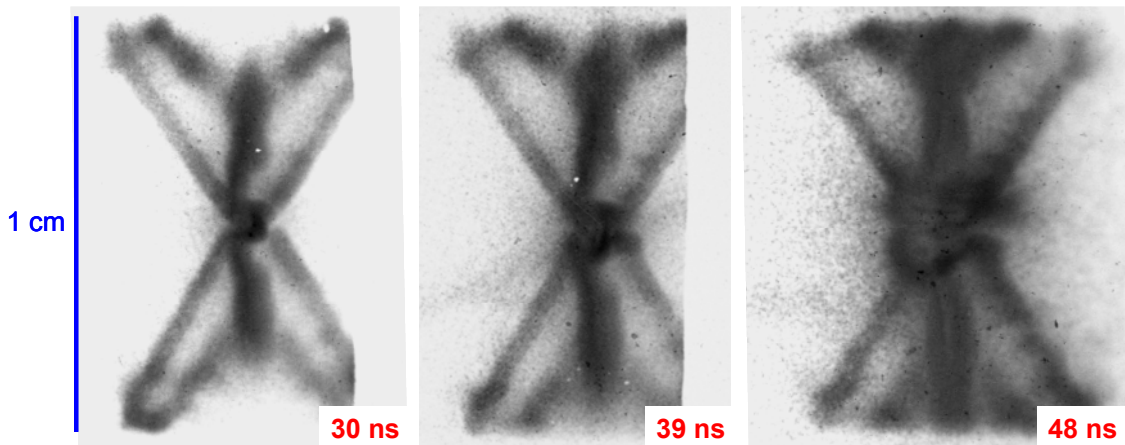
while the legs are no longer producing XUV radiation.



**Figure 4-9** Nearly simultaneous Schlieren and XUV images from two wire  $15\ \mu\text{m}$  Al x-pinchs, highlighting the differences in various temperature and density ranges

In this experiment the primary method available to heat the plasma is Ohmic heating from the current. Thus, late in time the images indicate that the current has been drawn away from the legs of the pinch to the central column. The lack of emission from the wire cores (in the XUV image) indicates they have cooled and are no longer carrying a significant current; while their presence in the schlieren images demonstrates that the wire cores remain dense. A lower temperature raises the plasma resistivity of the limbs allowing for a higher degree of current diffusion. The data produced around  $38\ \text{ns}$  indicates that the current did not immediately switch to the axis but was instead

convected with the coronal plasma as it migrated from the legs to the central column.



**Figure 4-10** A series of XUV images from a two wire Al x-pinch. All three frames came from a single shot with the timing from left to right being 30, 39, and 48 ns.

To investigate the migration further, lineouts were taken from two successive self emission images from a two wire Al x-pinch (frames at 30 and 39 ns, presented in Figure 4-10). Processing of the distance between the wire core and the migrating plasma, along with the interframe time, yielded a plasma velocity of  $3.67 \pm 0.7 \times 10^4$  m/s. Additional velocity measurements from the 39 and 48 ns frames was impeded by the stagnation of the plasma on the axis.

#### 4.5 Molybdenum X-pinch

In order to further investigate the role of resistivity on the dynamics of the coronal plasma surrounding the wires, two additional sets of experiments were conducted. Both were performed using 13  $\mu\text{m}$  Molybdenum wires. In the first series, bare Mo wires were used to establish a standard behavior for the material. In the second set, a thin layer of a high Z material (gold) was coated on the wires. The thin coating was used to alter the composition of the initial coronal plasma while leaving the bulk wire material the same.

As a result, experiments recorded the varying behavior of different coronal materials.

#### 4.5.1 Bare Molybdenum X-pinchs

A Schlieren series of 13  $\mu\text{m}$  molybdenum x-pinchs is shown below in Figure 4-11. An examination of the legs of the x-pinch reveals the expansion of the wires to be relatively uniform above and below the cross-point, similar to that previously observed in low-Z (aluminum) x-pinchs. The sequence also captures the coronal plasma merging on the axis to form a plasma structure above and below the cross point, which propagates toward the electrodes, similar to the axial column observed in other wire materials. The propagation velocity was found to slightly decrease as the column lengthens, and is presumably due to the stagnation of the flow at the electrode which is investigated in chapter five.

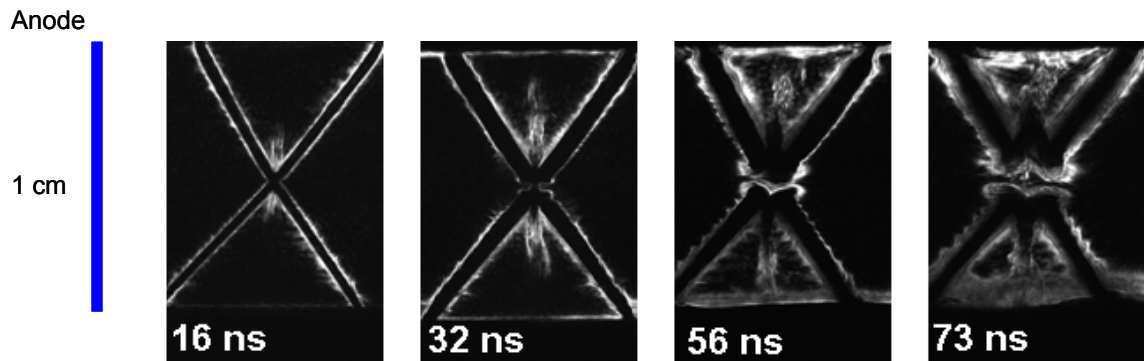
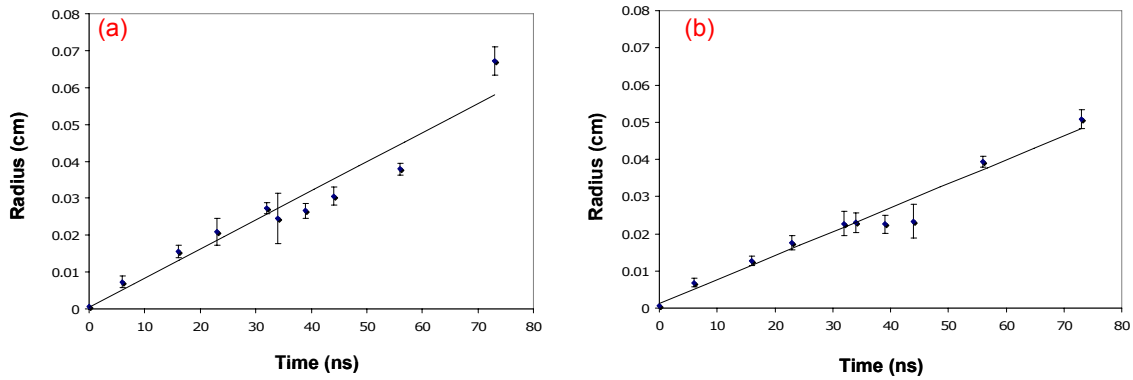


Figure 4-11 Schlieren series of bare 13  $\mu\text{m}$  Mo two wire x-pinchs

Similar to the analysis performed above in §4.3, the widths of the over-dense plasma surrounding the legs of the bare molybdenum x-pinchs yielded the graphs in Figure 4-12. As in aluminum (see above), the cathode and anode wires expand at

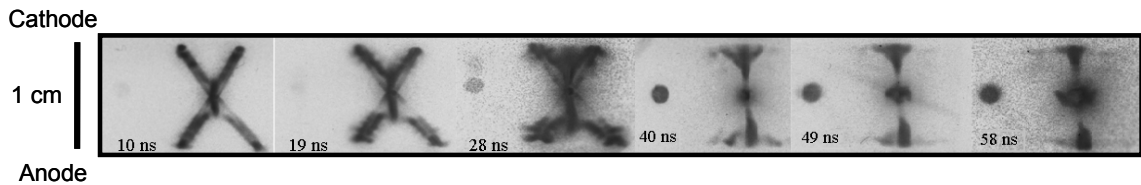


approximately the same rate, with the anode slightly faster, at  $6.0 \times 10^5$  and  $8.0 \times 10^5$  cm/s respectively.



**Figure 4-12** Graphs showing widths of the over-dense plasma surrounding the legs of Mo wires for (a) the cathode side and (b) the anode side.

To observe the evolution of the low density plasma, gated self-emission images were recorded and are presented in Figure 4-13. The sequence is made up of frames from two shots (10-28 ns shot 1 and 40-58 ns shot 2), each yielding three frames. Each frame contains two images resulting from two distinct pinholes having different filters (see §4.2). The ‘primary’ set of x-ray pinhole images (right side of each frame:  $> 4$  eV) are dominated by strong emission from the coronal plasma surrounding the wire limbs. The ‘secondary’ images appear on the left of each frame ( $> 1$  keV), and record a time sequence of hard x-ray emission from the experiment.



**Figure 4-13** Series of MCP images of a 13 μm bare Mo two wire x-pinch

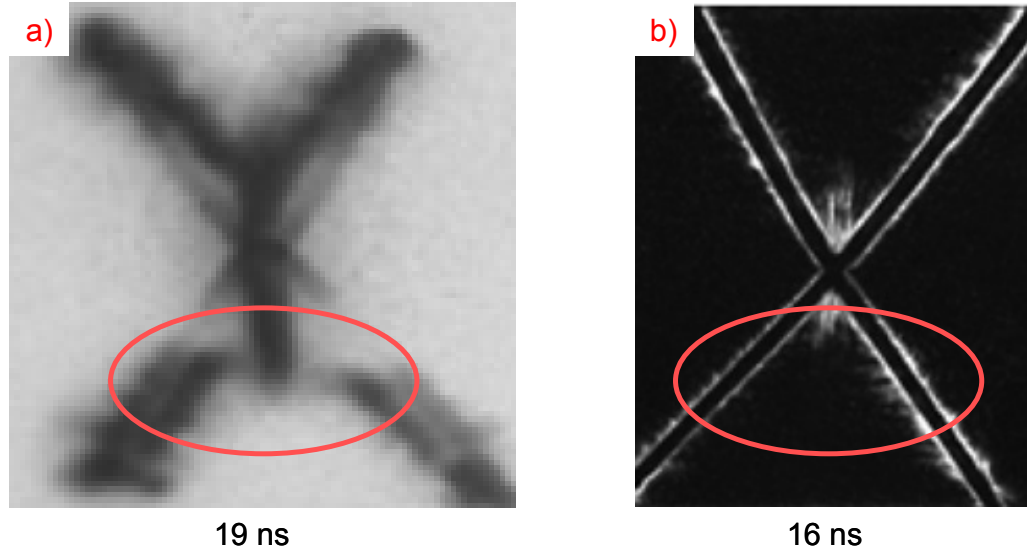
XUV imaging captured the intense radiation from the ablated plasma which can

be seen moving away from the wires. A comparison with Schlieren images (Figure 4-11) taken at comparable times, shows that the corona plasma in the MCP frames is not evident in the laser probing images; indicating that its density is below the detection threshold of the Schlieren system ( $n_e < 7.5 \times 10^{18} \text{ cm}^{-3}$ ). In contrast, the emission from the wire cores is relatively low (indicating that they have cooled below the XUV detector threshold of  $\sim 4 \text{ eV}$ ) even though they maintain a high density as evident by their presence in the optical probing images thorough 73 ns after the start of the current. Also recorded by the primary pinholes is the formation of an axial z-pinch column, which connected the electrodes approximately 40 ns after the start of the current. Plasma formation along the axis was present as early as 19 ns into the experiment.

A side by side comparison, Figure 4-14, highlights the difference in the initial formation of this axial structure. In the 19 ns XUV image the coronal plasma has begun moving away from the wires merging above and below the cross point (Figure 4-14a), while the corresponding Schlieren image does not show any of the low density features extending radially inwards from the wire position (Figure 4-14b). The MCP images captured the plasma migrating off the legs and merging on the axis (in a zipper fashion) to form the column; however in later optical probing images the plasma on the axis is distinct from the wires on either side (Figure 4-14 and 4-14a).

In time, a column on both sides of the cross-point is evident in the Schlieren images. However, along the axis further from the cross point, their density drops below the sensitivity of the detector; and their length does not coincide with that observed in XUV images at comparable times (see Figure 4-15a). Examining the XUV image at 28 ns, the plasma column has reached the anode, however this is not reflected in the 32 ns

Schlieren image.

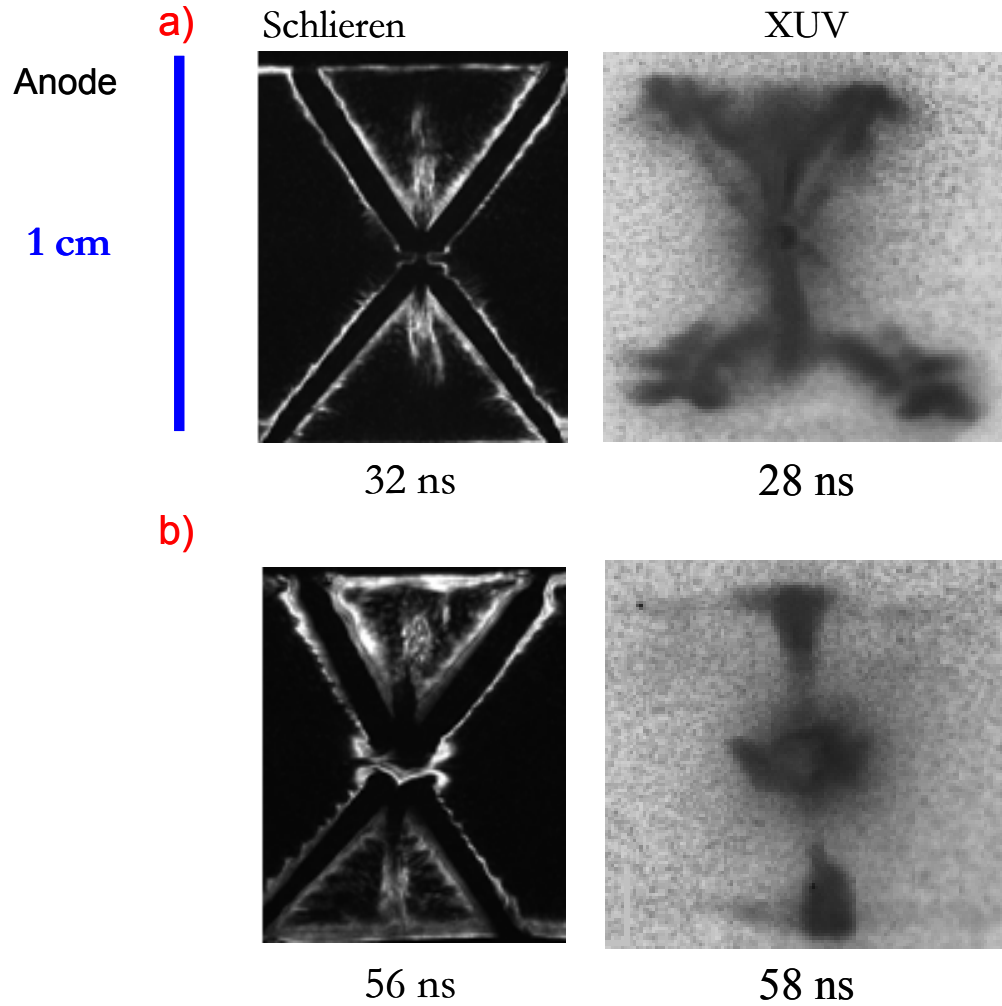


**Figure 4-14 Comparison of a) XUV and b) Schlieren image of the low density plasma surrounding the wires in a two  $13\ \mu\text{m}$  Mo wire x-pinch**

Progressing through the Schlieren sequence, the jet structures reach the electrodes after peak current ( $50\ \text{ns}$ ) in the  $56\ \text{ns}$  image (Figure 4-15b). Late in time the z-pinch column captured by optical probing is consistent with the  $58\ \text{ns}$  XUV framing image.

The XUV image later in time ( $58\ \text{ns}$ ) shows non-uniform emission along the length of the column; the hardest emission being from the original wire cross point, followed by the regions adjacent to the electrodes. At this time there is negligible emission from the expanded wire cores, regardless of the fact that concurrent Schlieren images show the wire cores are still present and have expanded to a diameter of  $\sim 800\ \mu\text{m}$ .

From the work presented in chapter six and previous work utilizing time resolved x-ray emission ([4-5] and [4-6]), it is known that a hard x-ray spot is formed at the cross point of the wires immediately prior to the current maximum. The emission recorded through the secondary set of pinholes in Figure 4-13 confirms the emission of the greatest flux of hard x-rays ( $> 1\ \text{keV}$ ) around the time of peak current ( $\sim 50\ \text{ns}$ ).



**Figure 4-15 Side by side comparison of the axial plasma column in expanded XUV and optical probing images for bare Mo x-pinch. Images in (a) were taken before current maximum (~40ns) while those appearing in (b) were recorded well after current maximum**

The lack of ‘legs’ in the secondary images indicates only weak radiation ( $< 1 \text{ keV}$ ) from the wire cores and surrounding corona. Additionally, the pinhole limited images demonstrates that the source is smaller than the aperture, confirming that the emission results from a small source in the vicinity of the cross point of the wires. The  $> 1 \text{ keV}$  x-ray burst begins before the current maximum and lasts for approximately  $15 \text{ ns}$ . A more detailed description of the x-ray source and yield is discussed in the chapter regarding emission from the cross point (chapter six).

#### 4.5.2 Au coated Molybdenum x-pinches

In order to isolate the effects resistivity and radiation have on the dynamics of the coronal plasma while maintaining the properties of the wires, it is necessary to retain the bulk wire material. To accomplish this, a thin layer of gold was placed on 13  $\mu\text{m}$  Molybdenum wires. In doing so, it was possible to examine whether the dynamics of the coronal plasma are governed by the radiation of the corona or of the bulk material properties of the wires. The Au coating represented a small material fraction (3-5% by weight) corresponding to a  $\sim 0.01 \mu\text{m}$  thick layer on 13  $\mu\text{m}$  diameter wires.

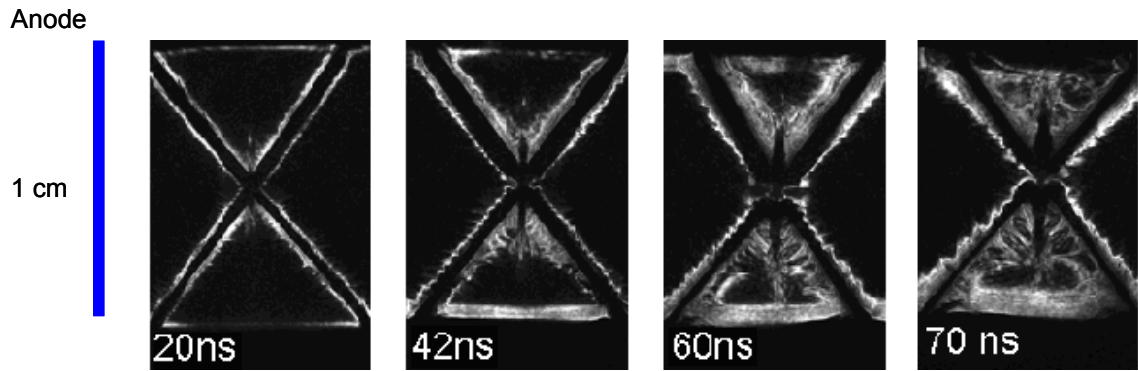


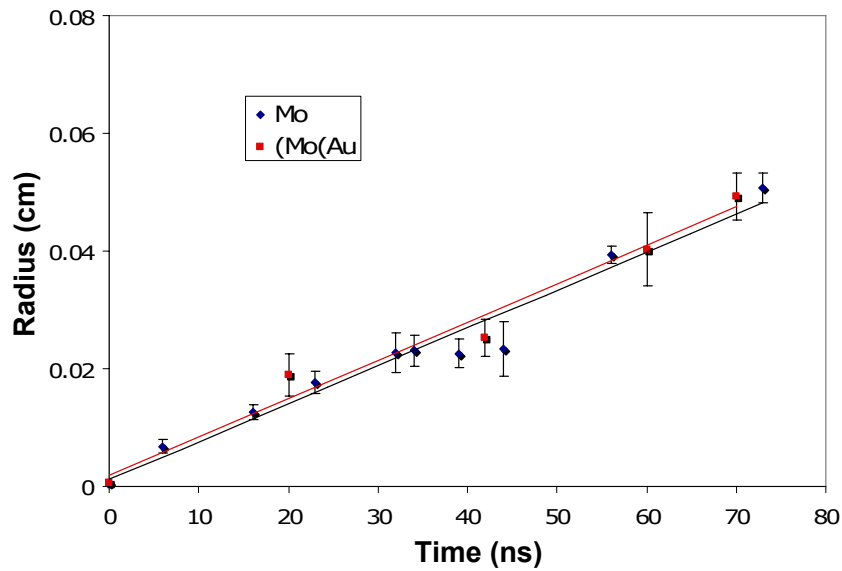
Figure 4-16 Schlieren sequence of two 13  $\mu\text{m}$  wire Au coated Mo x-pinches

Figure 4-16 shows a series of Schlieren images for gold coated molybdenum [Mo(Au)] wire x-pinches. Examining the plasma along the wires of the pinch, only the legs adjacent to the cathode show distinct plasma streams extending perpendicular from the wires and toward the axis of the pinch. Particularly pronounced in the 60  $\text{ns}$  frame, these finger-like features were not captured in the bare Mo x-pinches. These filaments are similar to those observed in Fe and W x-pinches, investigated in chapter three.

Measurements of the radii of the cathode over-dense plasma surrounding the legs of the x-pinch are plotted in Figure 4-17. Corresponding results from the bare Mo wires

have been included for comparison.

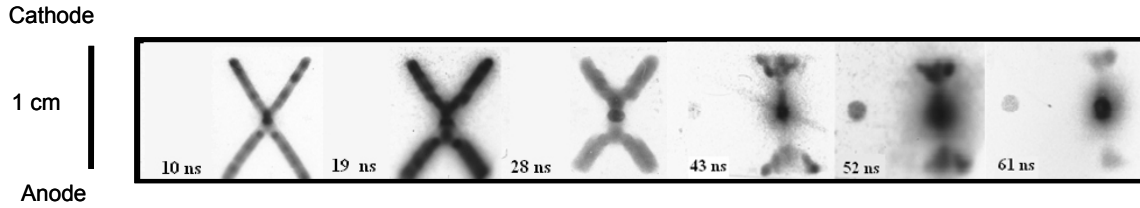
Taking the slope of the linear fit in Figure 4-17a yields the expansion velocities of the overdense plasma near the cathode of  $6 \times 10^5 \text{ cm/s}$  for both the bare and Au coated wires. This reinforces that the material will expand at the sound speed of the bulk wire material.



**Figure 4-17** Measurements of the plasma surroundings the legs of a Molybdenum x-pinch for the overdense plasma region

As in the bare Mo wires, a plasma structure is formed on the axis approximately 20 ns after the start of the current. This plasma advances away from the cross point, but is delayed when compared to the similar formation in the bare wires. Contact with both electrodes is not recorded by optical probing until  $\sim 70 \text{ ns}$  into the sequence. Additionally, these jets are well collimated, presumably due to an increase in radiative cooling, provided by the high Z material.

In order to record the low density plasma, Figure 4-18 shows an XUV series of Au coated Mo wire images. As in the previous section ‘primary’ ( $4 \mu\text{m}$  Mylar filter) as

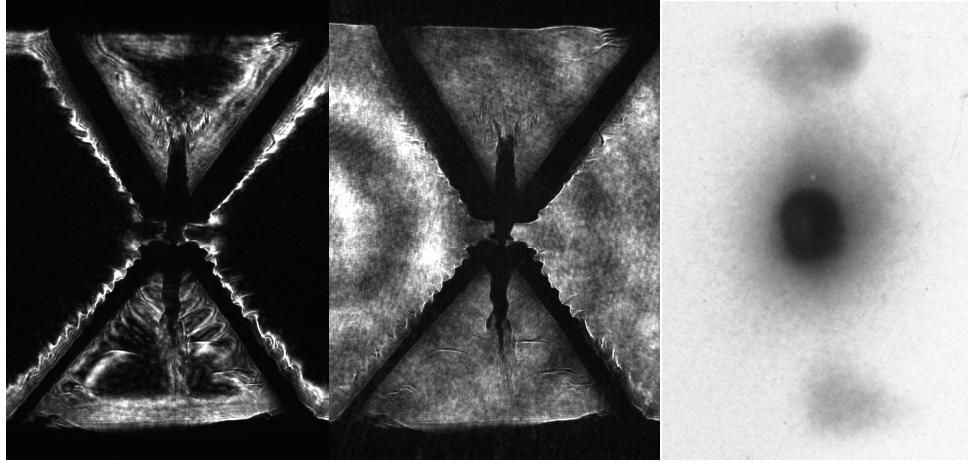


**Figure 4-18 XUV series from two Au coated 13  $\mu\text{m}$  Mo wire x-pinch**

well as ‘secondary’ (4  $\mu\text{m}$  Mylar + 2  $\mu\text{m}$  Al filter) pinhole images were recorded. Initially the coronal plasma on either side of the wires uniformly expands. As time progressed evidence of an  $m = 0$  instability developed along the legs of the x-pinch in the form of small dark spots on the film, indicative of emitting compression points. Late in time ( $\sim 43 \text{ ns}$ ) the emission from the legs has ceased and the central hot spot appears at the original cross point of the wires. By this point an axial plasma column has begun to form, however its progression towards the electrodes is delayed compared to the column produced in bare wires. Well after the current maximum, the structure and evolution of the coronal plasma are similar to those recorded in the XUV images of the bare Mo wires and these results are consistent with those gathered from optical probing. It is worthwhile to reiterate that the altered plasma and delayed spatial evolution are the result of a very thin coating of high  $Z$  material.

Above Figure 4-19 shows simultaneous Schlieren (a), shadow (b), and XUV (c) images of a gold coated molybdenum x-pinch approximately 60  $\text{ns}$  after the start of the current. This comparison highlights the variation in the diagnostic density ranges; the Schlieren image clearly shows the structure of the low density coronal plasma, not evident in the shadowgram (b). Similarly, the XUV image recorded the low density ( $<10^{18} \text{ cm}^{-3}$ ) hot plasma, extending from the anode to the cathode while the two optically

backlit frames show voids along the centerline of the x-pinch adjacent to the electrodes.



**Figure 4-19** Simultaneous (a) Schlieren, (b) shadowgraphy and (c) gated XUV images of a 2-wire Au coated  $13\ \mu\text{m}$  Mo x-pinch. All the images were taken during the same shot  $60\ \text{ns}$  after the start of the current.

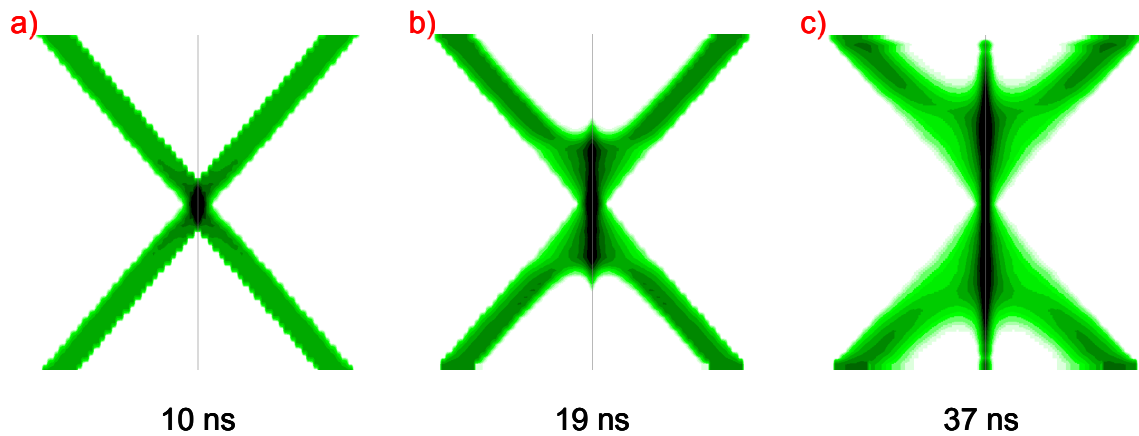
Additionally, the figure in (c) shows strong emission from the hot spot well after the current maximum, indicating heating after the peak compression and gap formation.

## 4.6 Simulations

The coronal dynamics of the x-pinch were simulated using a 2D MHD code [4-14], which modeled the plasma dynamics in the radial and axial directions. The evolution of magnetic fields, Joule heating and plasma energy radiation loss were taken into account. The physics of the formation of the coronal plasma due to the ablation of initially cold wires is very complex, and depends on the material properties (including resistivity, heat capacity, phase transitions, etc); as a consequence, it is not well understood at the present time (see [4-15]-[4-18] and the references therein). An experimental based fit, supported by theoretical models [4-15],[4-16], suggests that the mass production rate of cold plasma by wire ablation can be fitted with the expression:  $GI^p$ , where  $G$  is a numerical factor reflecting the material properties and found



empirically,  $I$  is the current through the wire, and  $p$  is an adjustable parameter which is close to 2. In the model, the formation of the coronal plasma (due to wire ablation) was modeled using this analytical formula, in which the time dependent current profile  $I(t)$  was taken from the experiment. Additionally, due to complexity nonlinear effects, inclusion of MHD instabilities and the radiative collapse of the cross-point were not incorporated and may serve as the subject of future work.

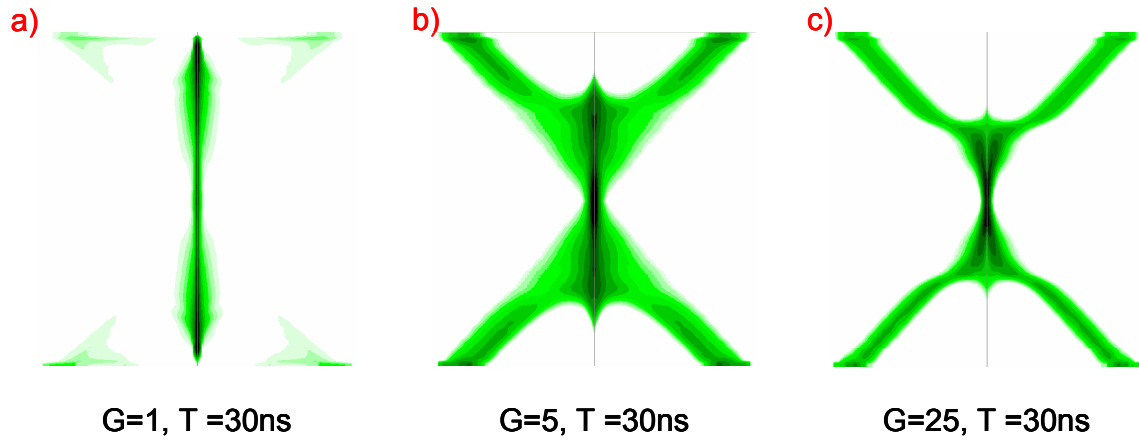


**Figure 4-20 Two dimensional simulation images displaying various times for a constant  $G$**

Above, Figure 4-20 shows a set of plasma density profiles from the 2-D MHD simulation at various times after the start of the current for a fixed  $G$ . Similar to the experimental data, plasma originating at the wires is driven off and compressed on the central axis. The radius of the plasma varies along the wire length meaning that the plasma density, in the wire vicinity, becomes lower near the cross point. The density in the central column increases with time and finally a z-pinch column is formed between the electrodes, similar to that observed in the framing images.

Figure 4-21 is comprised of simulation results for various  $G$  factors to indicate the sensitivity of the plasma evolution to the parameter. A clear difference in the coronal

plasma formation and dynamics can be seen for low versus high G factors. As the value of G is increased it corresponds to a decrease in the ablation rate.



**Figure 4-21** Two dimensional simulation images displaying the same time capture (30 ns) for values of G varying from 1 to 25

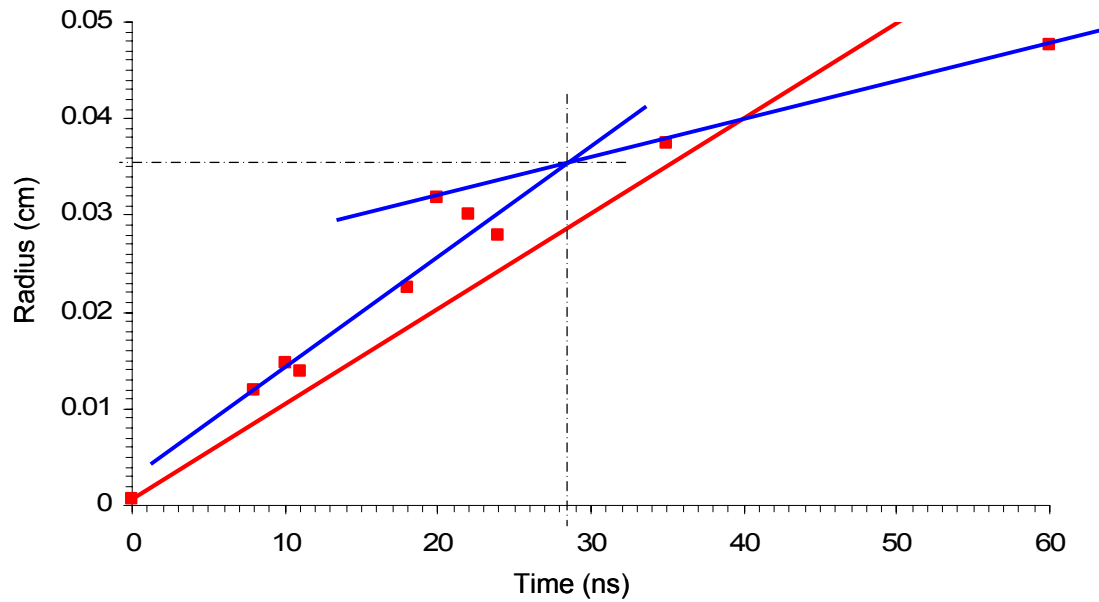
The rocket equates the momentum of the plasma coming off the wires with the force exerted by the magnetic field. For various materials, differences in ion masses may correspond to an inverse compensation of the ablation velocity to maintain the momentum coming off the wires.

## 4.7 Discussion

This section discusses the above obtained results from the optical probing and self emission imaging of various wire materials; most importantly the conclusions drawn from the simultaneous use of these diagnostics will be presented. Optical probing recorded wire diameter expansion rates as high as  $1.7 \times 10^6 \text{ cm/s}$ , while time resolved XUV imaging captured variations in the behavior of coronal plasma for different wire materials. A study of the results identified the locations of various density plasmas, and identified regions continuously heated during the experiment.

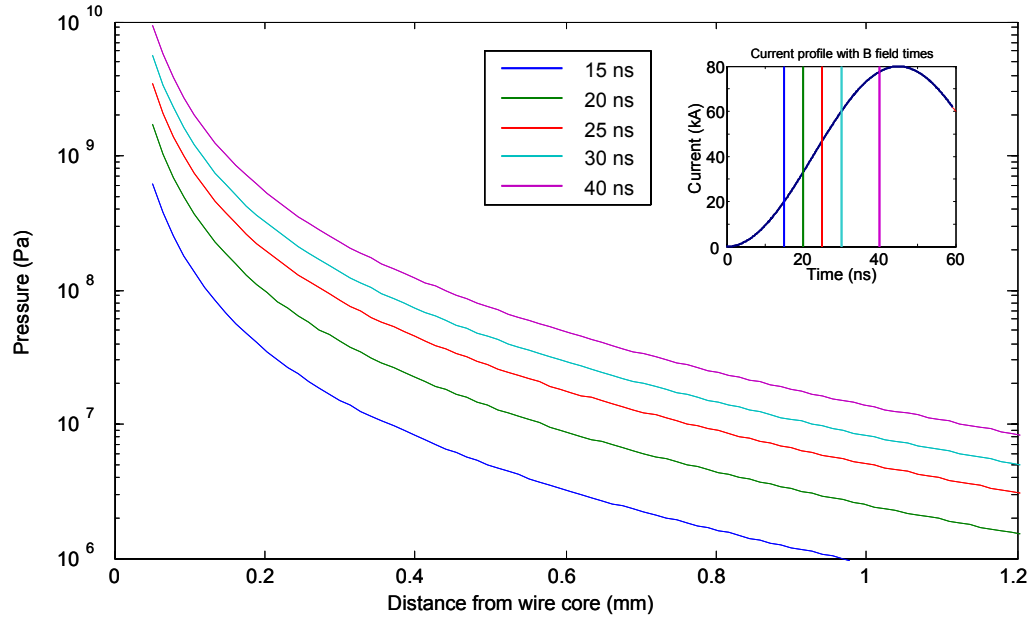
### 4.7.1 Thermal vs. Magnetic Pressure

A more detailed inspection of the Al expansion data presented in Figure 4-6 reveals a change in slope of the data, as depicted in Figure 4-22 by the overlaid blue lines. Their intersection identifies a change in the dynamics at approximately 28 ns and at a distance of 355  $\mu\text{m}$  from the wire core.



**Figure 4-22** Wire core data for two 13  $\mu\text{m}$  Al wire x-pinchs. The red line shows the overall trend of the data and the two blue lines show a fall-over in expansion rate after  $\sim 28$  ns.

Following Ohmic heating, the thermal pressure of the plasma is responsible for the expansion of the wire cores. Previous experiments [4-20] suggested that the wire cores remain at a low temperature ( $\sim 5$  eV) for the duration of the experiment. As the current rises, the magnetic pressure increases as a result of the increased B-field, which serves to confine the plasmas around the wire cores. A static calculation of the magnetic pressure, for various times, appears in Figure 4-23.

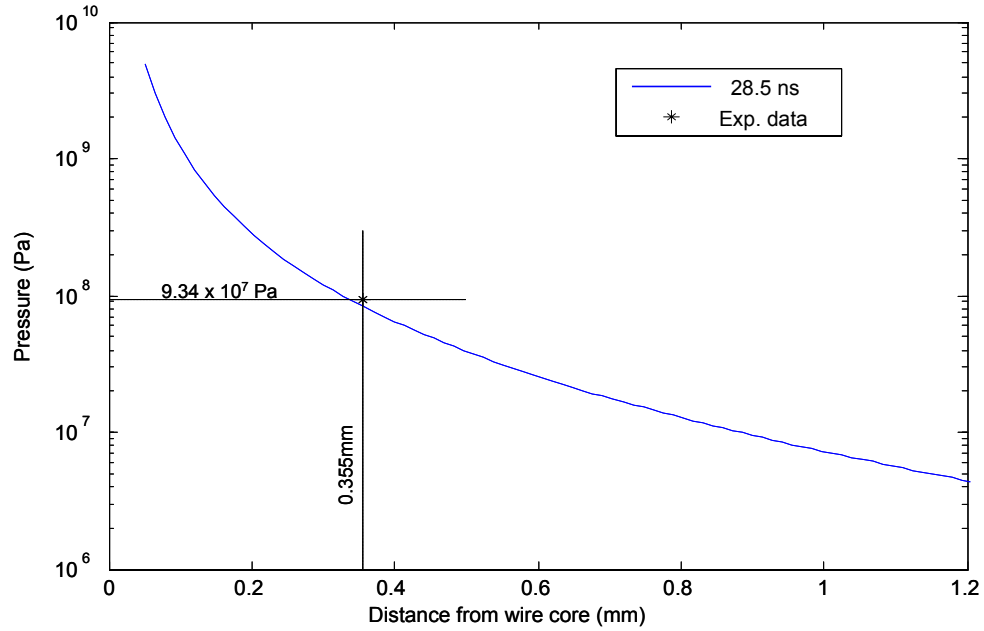


**Figure 4-23 Magnetic pressure profiles for various times 4.2 mm from the cross point (60% up a wire limb). The subplot is a representation of the current profile and the times of the pressure profiles.**

Using typical properties of the wire cores, the thermal pressure can be calculated from:  $P = N_i k_B T_e (Z + 1)$ . Where  $N_i$  is taken in  $m^{-3}$ ,  $k_B$  is in  $(J/K)$ ,  $T_e$  is in *Kelvin*, and pressure is in *Pa*. For the wire core of a two wire aluminum x-pinch it is appropriate to assign an ionization state ( $Z$ ) of 6,  $T_e \sim 5 \text{ eV}$  and a  $n_e \sim 1 \times 10^{20} \text{ cm}^{-3}$ , which result in a thermal pressure  $P_{th}$  of  $9.34 \times 10^7 \text{ Pa}$ .

From the time associated with the rollover of the wire expansion velocity in Figure 4-22 (28.5 ns) a magnetic profile curve was generated and appears in Figure 4-24. Also included, is a point marking the thermal pressure calculated from the experiment

From the graph above, the magnetic pressure at a distance of 355  $\mu m$  from the wire core is  $8.29 \times 10^7 \text{ Pa}$ , which is in good agreement with the thermal pressure found above.



**Figure 4-24** Calculated magnetic pressure at 28.5 ns after the start of the current. The (\*) indicates the thermal pressure calculated for a distance of 355  $\mu\text{m}$  from the wire core.

This suggests that the wires cores expand freely until the pressure from the magnetic field is approximately equal to the thermal pressure at which point the core plasma is constrained by the  $P_B$ , resulting in a slower expansion rate. This is similar to the process observed in three-dimensional MHD modeling by J. Chittenden *et al.* in reference [4-8].

#### 4.7.2 Coronal Emission

During the experiment, the current is responsible for heating the plasma through Ohmic heating, while the hot plasma's primary mechanism of energy loss is emission. In this way, plasma emission can be used to identify the location of the current in an x-pinch. Simultaneous optical probing identifies regions of high and low density which correlate to high and low emission respectively.

In optical probing images, the presence of the wires and their coronas indicated densities above  $10^{18} \text{ cm}^{-3}$ , while the lack of the migrating plasma resulted from the a low

plasma density. With the radiation rate proportional to  $n_{ion}^2$ , the higher density of the wire cores facilitated their emission (cooling) while the low density of the central column allowed it to retain energy. As a result the axial plasma was observed emitting well after the peak of the current.

In W and Fe emission from the axial plasma, demonstrated that current was present after 76 ns, and heating occurred in the axial plasma column as well as the wire corona).

Similar self emission observations were made in reference [4-11] and the work here complements that study by obtaining similar results for thinner Al wires (13  $\mu m$  here vs. 125  $\mu m$  in the referenced work). Additionally, this work extends the previous study through the comparison of XUV frames with simultaneous optical probing to gain information regarding the density of hot (emitting) and cold plasma.

### **Resistivity**

The current and resulting magnetic field distribution is governed by the resistivity of the plasma which is examined here. After the creation of a plasma on the surface of the wires, the magnetic field evolution will be governed by the induction equation, which gives the temporal evolution of the magnetic field as a function of current convection and diffusion:

$$\frac{dB}{dt} = \nabla \times (V \times B) + \frac{\eta}{\mu_0} \nabla^2 B. \quad (4.2)$$

Above  $\eta$  represents the resistivity of the plasma and  $\mu_0$  the permeability of free space ( $4\pi \times 10^{-7} T \cdot m / A$ ). For a plasma in which the speed can be taken as  $V_0$  and length scale is  $l_0$ ,

the convective term will be  $\nabla \times (V \times B) \approx V_0 B / l_0$ , and the diffusive term becomes

$\eta \nabla^2 B = \eta B^2 / \mu_0 l_0^2$ . Taking the ratio of the convective to the diffusive term yields the

magnetic Reynolds number:

$$\frac{V_0 B}{l_0} \frac{l_0^2}{\eta B^2} = \frac{\mu_0 V_0 l_0}{\eta} = \text{Re}_M. \quad (4.3)$$

For a plasma with a high magnetic Reynolds number (low  $\eta$ ), current convection will dominate. Correspondingly, a plasma with a high resistivity yields a low  $\text{Re}_M$  and is indicative of a plasma in which current is able to diffuse. The resistibility of a plasma is related to the ionization and temperature by L. Spitzer [4-9] as:

$$\eta = 1.03 \times 10^{-4} \frac{Z \ln \Lambda}{T_e^{3/2}} [\Omega \cdot m], \quad (4.4)$$

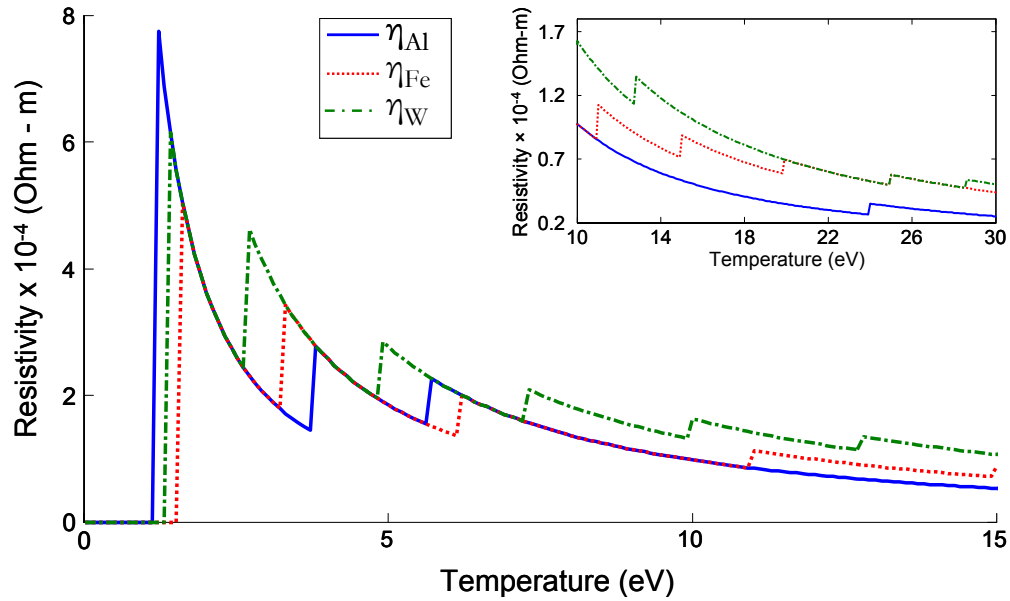
where  $Z$  is the ionization state,  $T_e$  the electron temperature in  $eV$ , and  $\ln \Lambda$  is the coulomb logarithm which can be taken as 10.

From the temperature dependence in equation (4.4) the hot corona, surrounding the cold wire core, provides a path of least resistance for the current to travel in. As the experiment continues the current heats the corona further decreasing  $\eta$ .

In higher  $Z$  materials, additional ionization states allow the resistivity to remain higher as the temperature is increased as indicated in Figure 4-25

For a corona temperature of  $\sim 10 \text{ eV}$  [4-2], a tungsten plasma will have a  $Z$  of 5 and a resulting  $\eta$  of around  $0.98 \times 10^{-4} \Omega \cdot m$ , while an aluminum plasma will have only entered its 3<sup>rd</sup> ionization state and will have an eta of  $1.63 \times 10^{-4} \Omega \cdot m$ . This variation in resistivity supports the notion that different plasmas, at the same temperature, will behave

differently; with one dominated by convection (low  $Z$ ) and another (higher  $Z$ ) by diffusion.



**Figure 4-25 Discrete ionization level resistivity curves for various wire materials as a function of temperature. The subplot extends the temperature range up to 30  $eV$ . The CE model was used to determine ionization energy.**

From the difference in behavior of the Fe and Al wire experiments, the resistivity profiles in Figure 4-25 place a lower limit on the temperature at  $\sim 11$   $eV$ . Up to this point the resistivity profiles overlap significantly and thus do not correlate with the difference in coronal behavior.

### Molybdenum wires

Experiments using two wire x-pinchs constructed from bare and gold-coated molybdenum were performed to examine the effect of varying atomic number on the behavior of the coronal plasma. Similar to the low- $Z$  aluminum, XUV images of bare molybdenum wires recorded the expansion of the coronal from the original wire position and its migration to the central axis by the global  $\mathbf{J} \times \mathbf{B}$  force. Less than sixteen



nanoseconds into the experiment, an initiation of the plasma column occurred and it was observed traveling towards the electrodes at  $\sim 7 \times 10^6 \text{ cm/s}$ , with the plasma on the anode side exhibiting a slightly higher velocity than the cathode. Late in time the axial plasma exhibits emission along its entire length.

The non-uniform emission from the plasma surrounding the molybdenum wires, and later along the axis, may result from the magnetohydrodynamic ( $m = 0$ ) instability, a consequence of current flow in the low density plasma (see chapter one). This provides further support that the magnetic field is convected by the plasma. With the radiation rate proportional to the square of the ion density, the corona acted as a poor radiator, remaining hot and emitting well after the dense wire cores had cooled.

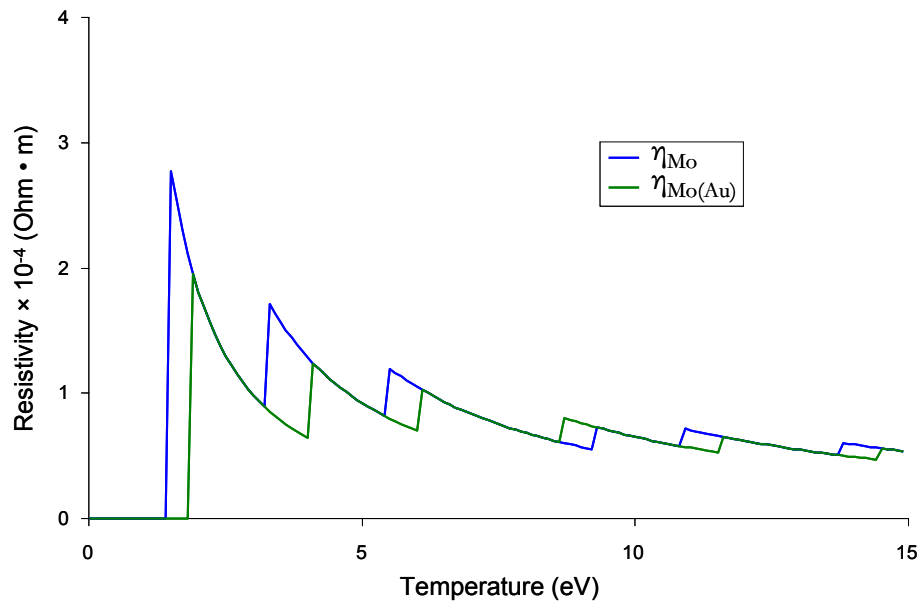
As in the Al experiments, the current was supported by a low density plasma, ( $n_e < 5.5 \times 10^{18} \text{ cm}^{-3}$ ) evident by the inability to observe the axial current path in comparable Schlieren imaging. After the formation of the corona, the expanded wire cores remained at their initial positions and showed little emission. In conjunction with radiation from the central column, this suggested that the current had fully transferred from the limbs to the central plasma column once it had fully formed ( $\sim 40 \text{ ns}$ ).

### **Gold coated Mo wires**

In x-pinch experiments constructed from molybdenum wires coated with a thin layer of gold, optical probing demonstrated that the expansion of the wire corona was dissimilar to the uniform bare Mo wire expansion and closely resembled the W and Fe wire experiments.

In initial XUV images, the corona expands in a similar manner to the bare wire case. However, soon after initiation hot spots are formed along the legs resembling the structures produced from the  $m = 0$  instability, routinely observed in single and multi-

wire experiments. In contrast, these spots were not observed in the uncoated molybdenum x-pinch. The soft x-ray images revealed emission from the coronal plasma surrounding the wires for a majority of the experiment. The inclusion of a thin gold coating may have increased the resistivity of the plasma enabling diffusion which allowed the current to remain localized around the wires and prevented it from traveling to the axis with the corona. This behavior was previously seen in high Z wires including W and Fe and contrasted observations from bare Mo. To investigate the claim the resistivity values for Mo and Au were plotted and appear in Figure 4-26.



**Figure 4-26 Discrete ionization-level resistivity curves for Mo and gold coated Mo wires as a function of temperature. The CE model was used to determine ionization energies**

In the above graph the only temperature for which the resistivity of gold is greater than that of Mo is from 8.7 – 9.2 eV. Although this explains the observations seen in the experiments where Mo wires are dominated by convection and the gold coated wires are dominated by convection it is a very narrow temperature window. However, the curves presented are generated from the discrete ionization levels of the materials. The use of

continuous ionization functions would generate a larger temperature range. Therefore, for the temperature range around 10 eV the results obtained with bare and Au coated Mo lend credence to the argument that the current distribution in the various wire materials is governed by the resistivity.

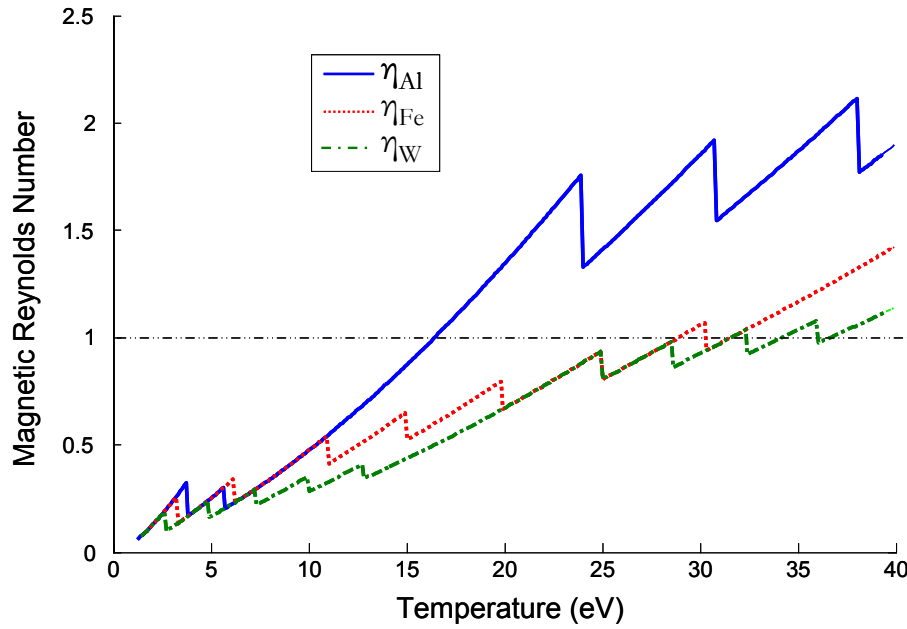
However it is clear that this argument is made with assumptions including the resistivity is governed by the Spitzer model and that a difference in density will not have a large effect  $\eta_{\perp} \propto \ln\left(\frac{1}{\sqrt{n}}\right)$  (a  $\Delta n_e$  of  $1.5 \times 10^{18} \text{ cm}^{-3}$  corresponds to a  $\Delta(\ln \Lambda)$  of -0.28). The above data demonstrates the same trend for high and low Z materials seen in the previous sections but demonstrates the limitations of experiments. Due to the complex nature of the wires and the fields present, this work would benefit greatly from 3D MHD simulations which will be discussed at the end of this thesis in future work.

### **Magnetic Reynolds number**

To determine the magnetic Reynolds number, in all materials the coronal plasma was assumed to have a velocity of  $3.67 \pm 0.7 \times 10^4 \text{ m/s}$  (determined from the Al XUV images), and a length scale of 1 mm was used. The magnetic Reynolds numbers for plasmas from various materials were found from equation (4.3) and are plotted in Figure 4-27. The critical magnetic Reynolds number is one and is indicated in the plot. Flows having a  $Re_m \gg 1$  are driven by convection and those with a  $Re_m \ll 1$  are driven by diffusion.

The MCP images from aluminum x-pinchs exhibited a ‘zippering’ of plasma along the axis, away from the cross-point. The emission from the low-density plasma demonstrated a continual heating as it altered the current path from the vicinity of the

wires to the axis.



**Figure 4-27 Graph of magnetic Reynolds number for various materials.**

In this way, the corona convected the B-field as it traveled to the axis forming the central plasma column. A lack of late-time (emission ( $> 60 \text{ ns}$  :  $h\nu > 4 \text{ eV}$ ) from the wire cores, and surrounding coronal plasma, indicated they had cooled. Alternatively, in high  $Z$  materials, self emission images recorded x-rays from the corona surrounding the wire cores for a majority of the experiment. In this case, as the plasma was driven toward the axis, the current remained near the wire cores because the magnetic field was able to diffuse back to the vicinity of the wires.

In order for the Al magnetic Reynolds numbers to match the experimental results in which the plasma is dominated by convection ( $Re_m > 1$ ) a temperature  $> 15 \text{ eV}$  is dictated by the plot in Figure 4-27. Alternatively, in W and Fe, experiments demonstrated magnetic diffusion plays a dominant role ( $Re_m < 1$ ). These results are consistent for temperatures below  $30 \text{ eV}$ . In both cases the temperatures are well within

the accepted range for the coronal plasma as given by simulations [4-21], [4-22] and experimental results.

As the temperature increases we see that these profiles remain below unity up to  $\sim 30 \text{ eV}$  at which point the  $Re_m$  is no longer associated with a diffusive plasma. However, this temperature is above those reported in previous research and it is unclear that the corona will reach this temperature during the experiment. Additionally, high cooling rates in tungsten and iron may lower their plasma temperature further exaggerating the difference in behavior with aluminum. In x-pinch experiments this work represents the first estimation of the magnetic Reynolds number within the coronal plasma.

## 4.8 Summary

Data was analyzed to characterize and examine the dynamics of the coronal plasma ablated along the limbs of an x-pinch. The corona as well as the overdense plasma followed a trend in which the expansion of the wire material was governed by the sound speed. In the case of the overdense plasma, aluminum exhibited velocities of  $\sim 9 \times 10^5 \text{ cm/s}$  which was well above those seen for W and Fe of  $\sim 2$  and  $\sim 3 \times 10^5 \text{ cm/s}$ . A comparison of the expansion rates for various materials with the theoretical  $c_s$  values at  $15 \text{ eV}$  (reasonable for the corona) indicated that the plasma expansion is primarily driven by the sound speed of the wires. A more detailed inspection of the Al wire expansion data highlighted a transition, around  $30 \text{ ns}$ , to a slower expansion rate. The kinetic pressure ( $P = 9.3 \times 10^7 \text{ Pa}$ ) agreed well with the magnetic pressure ( $8.3 \times 10^7 \text{ Pa}$ ) calculated for the location indicating that a balance of the pressures was responsible for a confinement of the plasma around the x-pinch limbs.

Self emission imaging allowed the probing of the low density plasmas. In high  $Z$  materials (W) the current remained in the vicinity of the wire core for a majority of the experiment; only late in time did the current transition to the axis. In contrast XUV imaging of low  $Z$  materials (Al) captured an emitting plasma between the wires and the axis indicating that the current was frozen in the plasma and as a result swept to the axis by the global B-field. Results from bare molybdenum wires paralleled those from aluminum, while images from Moly wires coated with a thin layer of gold demonstrated behavior similar to the high  $Z$  material wires.

The variation in behavior of the plasma was explained through an analysis of the variation in magnetic Reynolds numbers of the wire materials. The magnetic Reynolds number indicates whether the current is frozen in the plasma or has the ability to diffuse. For diffusive high  $Z$  materials (W and Fe),  $Re_m < 1$  were found for plasmas below 32 eV. For high  $Z$  materials (W and Fe) the diffusive nature recorded in experiments was implied by  $Re_m < 1$  for plasmas below  $\sim 30$  eV. Alternatively, convection dominated aluminum plasmas (low  $Z$ ) were found to have magnetic Reynolds numbers  $> 1$  for plasmas above 15 eV. High  $Z$  radiative effects may exacerbate the results giving an artificially small temperature range. It is important to note that the temperature estimates are well within the range previously established for the coronal plasma.

The work presented here represents the first simultaneous use of complimentary diagnostics, sensitive to various densities and temperatures, to investigate the location of the current in x-pinch experiments. Additionally, it serves as the first estimation of the magnetic Reynolds number in x-pinch experiments.

# Chapter 5

## Plasma Jets

In astrophysics, plasma outflows with significantly varying parameters have been observed emanating from various astrophysical objects. Previous research has established active galactic nuclei (AGN) as the source of well-collimated, highly relativistic jets [5-13] [5-14], while Planetary nebulae (PN) produce poorly collimated flows at non-relativistic velocities [5-18], [5-9], and [5-19]. Additionally, young stellar objects (YSO), also known as protostars, exhibit bipolar jets in what is thought to be a mechanism to shed angular momentum from accretion disks [5-15]. In addition to the divergence in flow characteristics, the scale lengths of these plasmas vary widely. As an example, reference [5-17] provides an estimate of parameters for Herbig-Haro (HH) jets which are highly collimated and emerge from newly formed stars in bipolar pairs, [5-15].

However dissimilar, the jet parameters can be related to various scales (including those produced in the laboratory) by the non-dimensional scaling discussed below. The characterization of these jets facilitates the understanding of their propagation behavior. Additionally, they can provide information regarding the objects from which they originate.

Although there are numerous astrophysical systems available for study, the application of only a limited number of diagnostics is feasible. In these systems, results are commonly inferred from image sequences much shorter than the characteristic evolution time of the system, and the ability to alter aspects of the system is not available. This creates a fundamental need for studies which can be performed and repeated in a controlled manner.

In response, work studying the evolution of millimeter scale plasma jets in the laboratory has been instituted. The purpose is to establish relationships between the evolution of these jets and those seen in astrophysics. In contrast to the large scales, laboratory scales allow the varying of experimental parameters and initial conditions. More importantly, the capability to monitor and repeat the entire sub-microsecond sequences has proven incredibly useful. These experiments provide the test beds against which theories and large scale experiments can be compared and evaluated.

The current and following sections are not a full review of the jets observed in astrophysical systems, but are meant to serve as an overview of the important parameters required for the scaling of plasma jets as their physical parameters span many orders of magnitude.

The chapter opens with a description of the plasma jets seen in astrophysical specifically Young Stellar Objects (YSOs). This is followed by sections describing the hydrodynamic and magneto-hydrodynamic scaling of these jets as well as the non-dimensional parameters appropriate for their characterization, such as the Mach number ( $M$ ) and cooling parameter ( $\chi$ ). Due to the jet's low density, a discussion of Local Thermodynamic Equilibrium vs. Coronal Equilibrium as the appropriate ionization model



has been included.

The introduction is followed by a general description of the plasma jets formed along the axis of an x-pinch experiment and includes a discussion of the effective convergence limit of the plasma from the pinch limbs. The greater radius of the wires at the extremes of the x-pinch limbs may result in this region contributing minimally to the axial plasma resulting in a lower effective convergent flow limit. In response, the limb's contribution was investigated experimentally, and the self propagation length of the jets adjusted accordingly. This is followed by a characterization of the jets produced by an 80 *kA* x-pinch. The parameters studied included density, propagation velocity, and sound speed. The chapter concludes with a comparison of the parameters observed in x-pinch jets, and those observed in astrophysics, in order to assess their scalability and the applicability of experimental results to astrophysical systems.

## 5.1 The Scaling of Laboratory Plasma Jets

Astrophysical systems have scale lengths ranging from the sub-parsec (seen in YSO's [5-15]) to those of galaxies (active galactic nuclei) [5-13]. Observations of HH jets [5-16] have established length scales ranging from  $10^{11}$  -  $10^{18}$  *cm*, opening angles of  $\sim 5^\circ$ , velocities on the order of  $10^7$  *cm/s*, and electron densities in the range of  $10^{4-6}$  *cm*<sup>-3</sup>. Additionally, low temperatures around  $\sim 1$  *eV*, magnetic fields of  $\sim 5 \times 10^{-7}$  *T*, and low pressures in the range of  $\sim 1 \times 10^{-7}$  *Pa* were calculated. These extreme values, and evolution times of hundreds or thousands of years make comprehensive studies difficult, and simulations very labor intensive.

To work around the discrepancy between astrophysics and the laboratory it is

necessary to scale the spatial and temporal evolution, while ensuring that the initial conditions and basic physics remain unaffected. The applicability of scaling between the two systems was investigated by Ryutov *et al.* in 1999 and 2001, and included similarity conditions for two cases: those which can be described using pure hydrodynamics [5-4] and those requiring a full ideal-MHD description [5-5] and [5-6].

### 5.1.1 Hydrodynamic Scaling

The plasma can be considered a fluid under certain conditions. The first is that the mean free path is shorter than the system's scale length. Second, dissipation is negligible, which occurs when the Peclet number is large. Third, viscous effects are also negligible, as characterized by a large Reynolds number. Under these considerations a polytropic gas serves as a good approximation (reference [5-23]). In this case the Euler equations are:

$$\begin{aligned}\rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) &= -\nabla p, \\ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\ \frac{\partial p}{\partial t} - \gamma \frac{p}{\rho} \frac{\partial \rho}{\partial t} + \mathbf{v} \cdot \nabla p - \gamma \frac{p}{\rho} \mathbf{v} \cdot \nabla \rho &= 0.\end{aligned}\tag{5.1}$$

Above,  $\rho$  is the density,  $\mathbf{v}$  is the fluid velocity, and  $\gamma$  represents the adiabatic index. For a polytropic gas  $p \propto \rho^\gamma$  where the adiabatic index ( $\gamma$ ) is taken as 5/3 for a monatomic gas with 3 degrees of freedom.

In order for the above conservation equations to remain invariant between two systems the following transformations are applied for position  $\mathbf{r}$ , density  $\rho$ , and pressure  $p$ :

$$r_1 = ar_2; \quad \rho_1 = b\rho_2; \quad p_1 = cp_2. \quad (5.2)$$

Here  $a$ ,  $b$ , and  $c$  representing positive scaling factors. The relations in equation (5.2) represent the scaling between the laboratory and the astrophysical plasmas, and are referred to as the ‘Euler similarity’. Once found, the scaling factors can be used to relate the temporal evolution  $t$  and velocity  $v$  of the two systems by:

$$t_1 = a\sqrt{\frac{b}{c}}t_2 \quad v_1 = \sqrt{\frac{c}{b}}v_2. \quad (5.3)$$

Under these transformations it is possible to consider a closed hydrodynamic system (denoted ‘ $n$ ’) in which the initial conditions are given by the product of dimensionless scaled position functions:  $(F(\frac{r}{h}), G(\frac{r}{h}), \text{ and } H(\frac{r}{h}))$  with the scaling factors  $(\tilde{v}_n, \tilde{\rho}_n, \tilde{p}_n, \text{ and } \tilde{h}_n)$  as:

$$v_n|_{t=0} = \tilde{v}_n F(r/h), \quad \rho_n|_{t=0} = \tilde{\rho}_n G(r/h), \quad p_n|_{t=0} = \tilde{p}_n H(r/h). \quad (5.4)$$

For two geometrically similar systems in which the scaling factors are allowed to vary and the position functions (F, G, and H) are applicable, the systems will evolve in the same manner, provided they have the same Euler number (Eu). The Euler number has been defined in reference [5-4] as:

$$Eu = \tilde{v} \sqrt{\frac{\tilde{\rho}}{p}}. \quad (5.5)$$

From the discussion by D. D. Ryutov *et al.*, the Euler number is similar to the Mach number  $(M = v/c_s)$ . In the case of supersonic or strongly driven systems the characteristic velocity is taken as that of the flow, as a result the Mach number is equivalent to the Euler number.

Provided the above requirements are met, the two systems will develop with the characteristic timescales ( $\tau_n$ ) related in the following manner:

$$\tau_2 = \tau_1 \frac{h_2}{h_1} \sqrt{\frac{\tilde{p}_1/\tilde{\rho}_1}{\tilde{p}_2/\tilde{\rho}_2}}. \quad (5.6)$$

For ‘strongly driven’ flows [i.e. where the velocities driven by the source ( $v_d$ ), considerably exceed the initial sound speed] the characteristic timescale can be simplified to:

$$\tau = \frac{h}{v_d}. \quad (5.7)$$

The treatment described above is valid for two systems which are fully described by hydrodynamics. However, if the transport of radiation has a substantial effect on either system, (as in those of astrophysics: ref. [5-9]) it is necessary to scale the equations which describe radiation hydrodynamics, see references [5-21] and [5-22]. Since the full scaling is quite involved and the full application to astrophysics is not necessary for the work performed here, it is left to the interested reader to pursue the complete scaling.

The discussed hydrodynamic flow relationships are only valid in the complete absence of magnetic fields. Realistically, the scaling laws will still apply in the presence of small B-fields which are present in experiments but do not affect the dynamics of the system. For cases in which the magnetic forces are comparable to the inertial forces, a more complete ‘magneto’ hydrodynamic (MHD) set of equations is required.

### 5.1.2 Magnetohydrodynamic (MHD) Scaling

For a system with a considerable magnetic field, apparent when  $\beta$  is small (Beta is

the ratio of the plasma pressure to the magnetic pressure:  $\beta = \frac{(Z+1)nkT}{B^2/2\mu_0}$ , the ideal MHD equations are written as:

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\ \rho \left( \frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) &= -\nabla p - \frac{1}{4\pi} \mathbf{B} \times \nabla \times \mathbf{B}, \\ \frac{\partial \mathbf{B}}{\partial t} &= \nabla \times \mathbf{v} \times \mathbf{B}.\end{aligned}\tag{5.8}$$

As before, a polytropic gas is assumed, however the transforms from equation (5.2) are amended to include the magnetic field:  $B_1 = \sqrt{c} B_2$ , while the initial conditions are established as in the hydrodynamic case.

For the MHD description to be valid, in addition to the criteria imposed in the purely hydrodynamic case (negligible dissipation and viscosity) Ohmic dissipation is required to remain small.

## 5.2 Plasma Jet Characterization

Plasma structures similar to those observed in x-pinches have been recorded and studied in conical wire arrays experiments (see [5-1] and references therein). The behavior of these plasmas resembled that of YSOs, as a result the relationships to scale laboratory results to astrophysical scales was developed. Scaling and the required validity criteria necessary for comparison, are presented here.

It is also necessary that both systems have the same physical characteristics and can be described by the same dimensionless parameters. The first three are related to the global properties of the systems. Blondin, Fryxell, and Konigl (1983) found that an axisymmetric, adiabatic flow, propagating into a homogeneous medium can be fully

described by the Mach number ( $M = v_j/c$ ) and the density contrast ( $\eta = \rho_j/\rho_a$ ) (the ratio of jet to ambient-medium density) [5-9].

For most cases of astrophysical jets, radiation plays a predominant role in their development and therefore the adiabatic assumption does not hold. Normally, the full set of radiation-hydrodynamic equations is required; however, in the case of an optically thin plasma, losses can be accounted for by a radiation loss term characterized by the dimensionless cooling parameter ' $\chi$ ,' the ratio of the jet cooling distance  $d_{cool}$  to the jet radius  $r_j$  [5-9]. The cooling distance is defined as the product of the characteristic velocity with the cooling time, and the cooling time is the temporal period in which the jet has radiated a selected fraction of its internal energy. Including  $\chi$ , the global dynamics of a plasma jet, of any scale, may be described by the dimensionless parameters:

$$\text{Mach number } M = \frac{v_j}{c_s}, \quad (5.9)$$

$$\text{Density contrast } \eta = \frac{\rho_j}{\rho_{ambient}}, \quad (5.10)$$

$$\text{Cooling parameter } \chi = \frac{d_{cool}}{r_j} = \frac{\varepsilon_T}{P_R \tau_H}. \quad (5.11)$$

In equation (5.11)  $\varepsilon_T$  is the thermal energy density,  $P_R$  is the power radiated per unit volume, and  $\tau_H$  is a characteristic hydrodynamic jet time evolution [5-10]. As in most cases, the scale length of the plasma jet was taken as the radius of the jet  $r_j$ .

The additional three parameters, which assess the validity of a hydrodynamic description of the jets, investigate the local properties of the plasma. For the jet to be collisional, the plasma mean free path is required to be less than the radius of the jet. Their ratio: the localization parameter [5-2], is written as:

$$\delta_{\perp} = \frac{\lambda_{mfp\perp}}{r_{jet}} \cong \frac{m_{ion}^2 v_{therm}^4}{8\pi Z^4 e^4 n_{ion} \ln \Lambda \sqrt{\pi/2}} \frac{1}{r_{jet}} \ll 1 \quad (5.12)$$

Here  $\lambda_{mfp\perp}$  corresponds to the particle mean free path perpendicular to the propagation direction of the jet (i.e. radial). The remaining parameters communicate the extent of the dissipative processes affecting the flow; the Reynolds number:  $Re = r_j v_j / \nu$  assess the viscous effects, while the Peclet number:  $Pe = r_j v_j / \nu_h$  tracks the heat conduction. The  $Pe$  number may also be expressed as the ratio of heat convection to heat conduction, and  $\nu_h$  represents the thermal diffusivity of the plasma. Together with equations (5.9) - (5.11) the following parameters fully characterize the plasma for the purpose of scaling between two systems:

$$\text{Localization parameter } \delta_{\perp} = \frac{\lambda_{mfp\perp}}{r_{jet}}, \quad (5.13)$$

$$\text{Reynolds number } Re = \frac{r_j v_j}{\nu}, \quad (5.14)$$

$$\text{Peclet number } Pe = \frac{r_j v_j}{\nu_h}. \quad (5.15)$$

Therefore, two systems observing the aforementioned hydrodynamic criteria and which exhibit similar non-dimensional parameter values will evolve similarly.

In HH objects, velocities over  $2 \times 10^7 \text{ cm/s}$  and temperatures around  $5,000 \text{ K}$  have been recorded, producing flows with Mach numbers  $> 10$  [5-2]. Various other astrophysical jets' values have been found with Mach numbers exceed 20 and density contrast ratios range from of 0.01 to  $> 100$  [5-9].

Observed results have found jet length to width ratios of 100:1 and many have

attributed the high levels of collimation to radiative cooling [5-9]. In these structures cooling lengths have been observed to be  $5 \times 10^{14} \text{ cm}$ , in combination with the above aspect ratio, this yields a cooling parameter close to unity.

In the case of Herbig-Haro jets, Reynolds numbers range from  $6 \times 10^8 - 2.6 \times 10^{10}$  with Peclet numbers as high as  $1.5 \times 10^{12}$ . While these values cover a wide range, it is worthwhile to note that they are all above critical transition values associated with the onset of instabilities ( $\text{Re} > 10^6$ ,  $\text{Pe} > 1$ ). A summary of these jet values can be found in at the end of the chapter in Table 5-4. From these values it is clear that the properties of naturally occurring plasma jets span many orders of magnitude making the accurate recreation of them in the laboratory difficult.

Due to the low density of the plasma that makes up the jets, Local Thermodynamic Equilibrium (LTE) may not be appropriate. In response, a review of LTE and the Coronal Equilibrium (CE) models (developed for low density plasmas) are discussed below.

### 5.2.1 Local Thermodynamic Equilibrium (LTE)

In order to classify a plasma as being in LTE, the mean free path (mfp) of the photons produced in the plasma must be longer than the relative temperature gradients,  $\lambda_{\text{mfp}}$  must be on the order of  $\frac{T}{|\nabla T|}$  as noted by *Zeldovitch and Raizer* [5-12]. Due to this, photons escape the plasma or are reabsorbed in regions whose temperatures and densities different from the region in which they originated. Therefore, photons will not be in thermal equilibrium with the electrons and ions of the plasma. Additionally, the mfp of the electrons and ions are required to be much smaller than the scale length of the plasma.



This ensures they are absorbed before exiting the plasma. In an example aluminum plasma with a temperature between 10-1000  $eV$ , the mfp of photons will be  $\geq 300$  times the collision length of electrons [5-11]. An additional requirement for a plasma to be in local thermodynamic equilibrium is that the rates for electron impact ionization are equated with those of reverse three body recombination (collisional processes dominate radiative processes) which can only be accommodated in relatively high density plasmas. For a 300  $eV$  Al plasma this occurs above  $10^{23} \text{ cm}^{-3}$ .

To solve for the charge state distribution, two requirements are added to the set of equations generated from the Saha equation which representing all ionization states. The first requires that the sum of all the partial densities must equal the total ion density, and the second ensures charge neutrality.

In an LTE plasma, the electrons and ions are governed by a Maxwellian-Boltzmann velocity distribution – particles are primarily ionized thorough photoionization, while three-body recombination is prevalent. However, the low density observed in the jet plasmas allows for a majority of the radiation to escape and results in a low frequency of three body collision. In response, a corona equilibrium (CE) model [5-11] is presented below for consideration. In that model, a lower plasma density allows for the release of a greater amount of radiation.

### **5.2.2 Coronal Equilibrium (CE)**

In the CE model, due to the low density of the plasma, the rate of spontaneous electron decay is very large compared to the collisional electron excitation rate. Therefore it is valid to assume that an excited electron will decay by spontaneous

emission to the ground state before being further excited to a higher energy level, and most ions are in their ground state. Due to the optically thin properties of the plasma, photoionization, photoexcitation, and three-body recombination are infrequent; instead the plasma is dominated by electron impact ionization (designated:  $I$ ) and two-body (radiative  $R^{(r)}$  + dielectric  $R^{(d)}$ ) recombination  $R^{(r+d)}$ .

By equating the ionization with the recombination rates, while maintaining charge neutrality, the charge state distribution was found by D. Salzmänn [5-11]. Here the distribution does not depend on the electron or ion density, therefore the ion distribution is independent of density.

High atomic number materials allow for a larger number of ionization states, as a result it becomes increasingly difficult to solve the ion distribution. In response a common approximation for CE is given in reference [5-11] as:

$$\frac{E_{\zeta}}{T} \cong 2 - 5. \quad (5.16)$$

Where  $T$  is the temperature of the plasma and  $E_{\zeta}$  is the ionization energy of the highest populated ionization state. Here, the most populated charge state ( $\zeta \approx \bar{Z}$ ) will be the one where the ionization energy ( $E_{\zeta}$ ) is 2-5 times the temperature of the plasma.

### 5.2.3 Equilibrium Model Comparison

The primary mechanism by which local thermodynamic equilibrium differs from coronal equilibrium is the manner used to describe the equilibrium ionization rates. In the former (LTE), a steady state occurs when the ionization rate is compensated by collisional recombination; here the energy of the plasma is conserved, as photons are

unable to escape the plasma due to high density. In the latter (CE), collisional ionization is balanced by radiative recombination which dissipates energy when the photons escape the optically thin plasma.

Preliminary analysis of interferometric images established the areal electron density of tungsten jets at approximately  $10^{17} \text{ cm}^{-2}$ . Simultaneously self emission imaging, through various filters (see chapter four), found a reasonable estimate of the temperature for the tungsten x-pinch to be around  $10 \text{ eV}$ . In this case the CE model predicts an average ionization of  $\bar{Z} = 2 - 5$ , while the LTE model gives a  $\bar{Z}$  of 12. Similarly, for a  $50 \text{ eV}$  W plasma jet (conical array jet [5-1]) the  $\bar{Z}$  values are 6-12 and 27 from CE and LTE, respectively. From previous work [5-2] temperature and ionization state predictions are well correlated with those derived from CE while those from LTE over predict the average ionization state.

In order to highlight the differences between the LTE and CE models a summary comparison appears in Table 5-1 as gathered from [5-11]. Additionally, an approximation of the ionization states of a tungsten plasma are shown for comparison. In the corona equilibrium model a lack of three body recombination does not recapture the photons during recombination events which results in a slow cooling of the plasma. In conjunction with a heating source (Ohmic heating), the CE model is able to describe a steady-state plasma, but not an equilibrium one.

As demonstrated in chapter four the internal energy of the plasma has a substantial effect on its behavior, which in turn effects the subsequent jet formation. Additionally the study of gold coatings established radiation as the main factor regulating the energy present in the corona. As a consequence, the low density of the axial jets

necessitate a CE treatment to accurately model the radiation processes occurring as the jets propagate away from the cross point.

**Table 5-1 Local thermodynamic equilibrium vs. Corona equilibrium**

|                                                                                    | LTE (High Density)                                                                                                                                                                                                                              | CE (Optically thin)                                                                                                                                                                                                                                  |
|------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Applicable Density                                                                 | For a $T=300\text{ eV}$ Al plasma<br>$N_e \geq 6 \times 10^{24}\text{ cm}^{-3}$                                                                                                                                                                 | $n_i \leq 1 \times 10^{18}\text{ cm}^{-3}$                                                                                                                                                                                                           |
| Description                                                                        | Electrons & ions in equilibrium<br>Photons not in equilibrium with plasma particles<br><br>Electron impact ionization = three body recombination<br><br>Rate of energy-conserving processes >> rate of energy dissipating (radiative) processes | Electrons & ions in equilibrium<br>Photons escape plasma<br><br>Spontaneous decay >> collisional ionization => most ions remain in their ground state<br><br>Rate of energy-conserving processes << rate of energy dissipating (radiative) processes |
| Ionization mechanisms                                                              | Electron impact Ionization<br>Auto ionization<br>Photoionization                                                                                                                                                                                | Electron Impact ionization<br>Auto ionization                                                                                                                                                                                                        |
| Recombination mechanisms                                                           | Radiative-Dielectric recombination<br>Three body recombination                                                                                                                                                                                  | Radiative-Dielectric recombination                                                                                                                                                                                                                   |
| For a W plasma:<br>$T_e = 20\text{ eV}$<br>$n_e = 1 \times 10^{17}\text{ cm}^{-3}$ | $Z = 12$                                                                                                                                                                                                                                        | $Z = 4 - 6$                                                                                                                                                                                                                                          |
| For a W plasma:<br>$T_e = 50\text{ eV}$<br>$n_e = 1 \times 10^{17}\text{ cm}^{-3}$ | $Z = 27$                                                                                                                                                                                                                                        | $Z = 6 - 12$                                                                                                                                                                                                                                         |

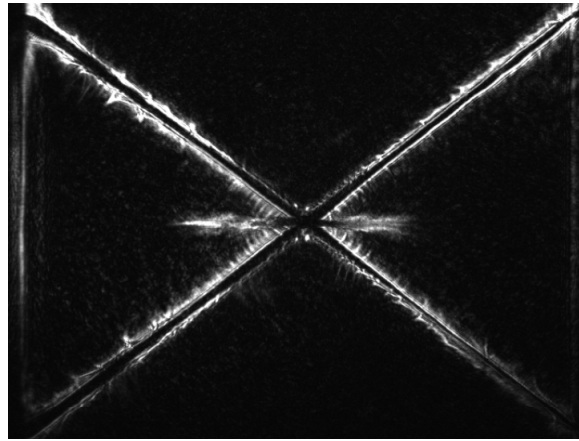
### 5.3 Introduction to the X-Pinch Axial Plasma Columns

As seen in chapters one and four, shortly after the start of the current, plasma is observed accumulating on the axis of the x-pinch. This structure initially appears immediately above and below the cross point and propagates along the axis toward the electrodes as captured in Figure 5-1.

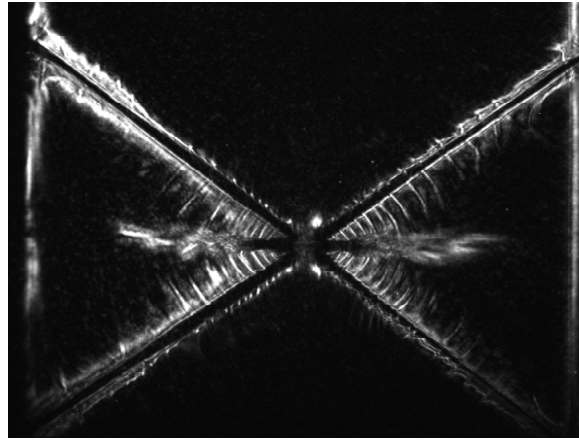
Anode

1 cm

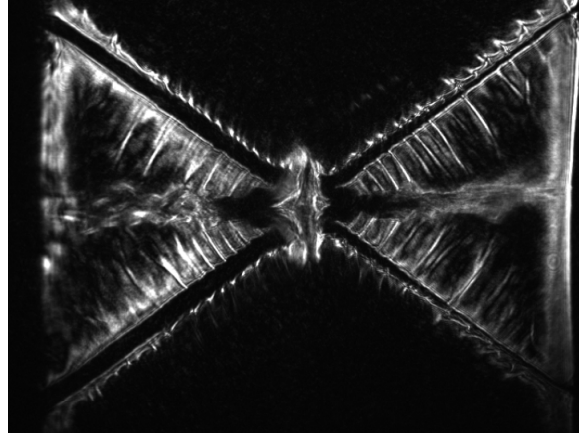
Cathode



18ns



31ns



49ns

Figure S-1 Abridged dark field schlieren sequence showing the development of the plasma jet along the axis for a two 7.5  $\mu\text{m}$  Tungsten wire X-pinch (full sequence shown in chapter one figure 1-4)

Low levels of symmetry, in two and four wire x-pinch, led to jets that deviated from the axis by up to  $5^\circ$ . Between 35-55 *ns* after the onset of the current, plasma on the axis contacts both electrodes, providing an alternative current path thereby enabling the development of instabilities in the plasma column. Alternatively, for geometries in which the electrode does not obstruct the axis, a ‘jet-like’ plasma is observed propagating into vacuum, well beyond the anode-cathode gap, as shown in the following sections. Jet experiments on conical wire arrays ([5-1] and [5-2]) have recorded unobstructed jets with lengths of many jet radii beyond anode plane.

Figure 5-1 shows a sequence of dark field Schlieren images capturing the dynamics of the low-density plasma present in a two  $7.5\ \mu\text{m}$  wire W x-pinch. As early as 10 *ns* (not shown), plasma has gathered adjacent to the original cross point of the wires, and by 18 *ns* the plasma column has extended  $\sim 2.5\ \text{mm}$  in the direction of the electrodes. The 18 and 31 *ns* images recorded a collimated plasma column propagating toward the electrodes as it bisects the expanded wire cores. The image captured at 49 *ns* recorded the plasma column contacting the electrodes. Also present are the plasma streams (discussed in chapter three) extending from the wires to the axis. The same evolution and plasma dynamics, on the axis, have been observed for x-pinchs constructed from Al, Mo, Mo (Au coated), and Iron wires, the results of which are presented below.

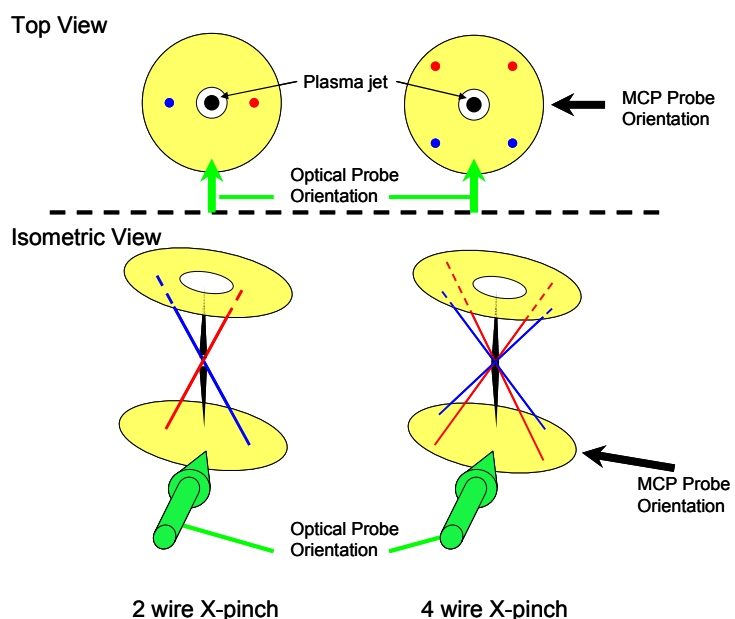
## 5.4 Experimental Setup

For the experiments reported in this chapter, wires were mounted between electrodes which had a fixed separation of 1 *cm*. X-pinchs were constructed from two wires, allowing greater accessibility, and four wires which increased the symmetry of the

system. Two-wire pinches were mounted so that the plane of the wires was orthogonal to the probe laser beam, ensuring that measurements on axis were not influenced by the plasma surrounding the wire cores. For experiments involving four wires, the plane of each 'x' was at a 45° angle to the probe beam as well as the MCP camera leveraging the maximum unobstructed view possible (see Figure 5-2. In this arrangement the optical probe beam was orthogonal to the view of the MCP camera). Imaging of four wire pinches was primarily performed above the anode. The wire materials used and their associated diameters are summarized in the following table:

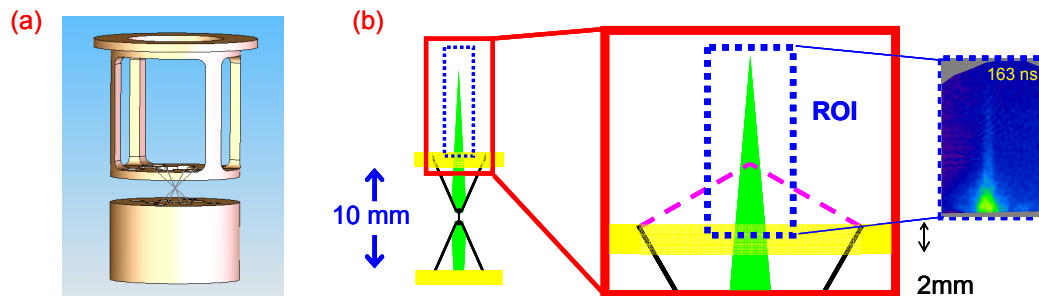
**Table 5-2 Summary of wire material configurations used in axial plasma jet experiments**

| Wire Material | Wire thickness ( $\mu\text{m}$ ) | Number of wires |
|---------------|----------------------------------|-----------------|
| Tungsten (W)  | 7.5                              | 2               |
| Tungsten (W)  | 5                                | 4               |
| Aluminum (Al) | 15                               | 2               |
| Iron (Fe)     | 10                               | 2               |



**Figure 5-2 Schematic showing diagnostic orientation relative to wire position for a two and four wire x-pinch**

Initial studies of the jet evolution from the cross point of the wires to the upper electrodes were done with a conventional (solid brass) anode and cathode. However, to allow the jets to propagate above the anode plane, a modified upper electrode was implemented. This upper electrode had a central aperture allowing the plasma to propagate above the anode plane. A schematic of the electrode is shown in Figure 5-3a while the position of the jet studied, is depicted in Figure 5-3b. As a point of reference, when viewed from the side the altered anode is 2 *mm* thick and therefore its ‘top’ is positioned 7 *mm* above the cross point of the x-pinch. Horizontal view ports were cut through the anode allowing diagnostic access in two perpendicular directions. The labeled ‘region of interest’, ROI (outlined in dashed blue), highlights the region captured in the optical probing images, and an image acquired 163 *ns* after the start of the current is linked to the ROI as a reference for the reader. Note: only the top of the 2 *mm* thick anode may appear in some images and was used as a vertical reference for the location of the jet.

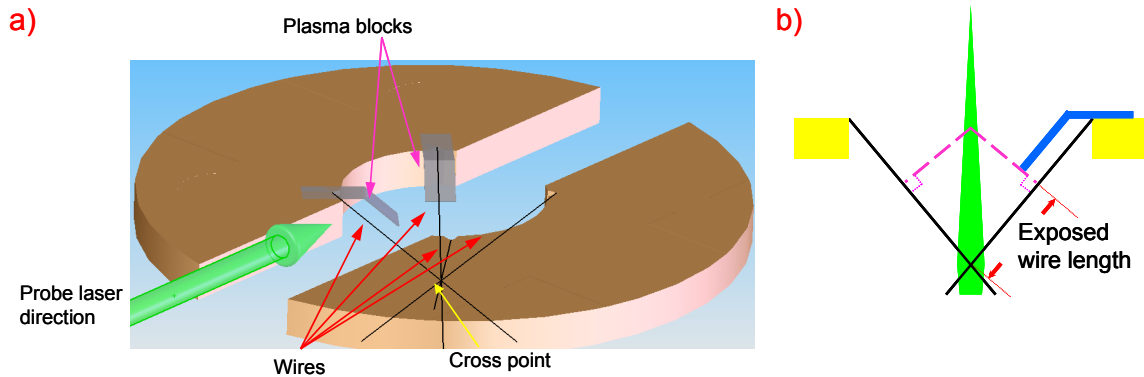


**Figure 5-3** Images of the electrode setup used to study jet propagation beyond the anode in x-pinchs: a) A schematic (CAD) model of the electrodes, b) an illustration of the x-pinch and the electrodes, the region of interest ROI (above the anode) is outlined in blue. Also shown is an enlarged view of the section immediately above the anode outlining the plasma flow convergence region (dashed pink). The image linked to the ROI is an experimental areal density plot generated from an interferogram of a plasma jet taken at 163 *ns* after the start of the current.

The ablation of the plasma normal to the wire surface and the angle the wires



make with the axis produce a plasma flow which converges above the anode plane (note that the electrical contact point of the wires is at the top of the anode). The vertical extent of this convergence region is 6 mm above the top of the anode, as indicated in Figure 5-3b by the dashed pink lines; any jets propagating above this point are unconfined in the radial direction by the flow of plasma, and can be considered ‘freely propagating’.



**Figure 5-4 Illustrations of the upper electrode (anode) including the plasma blocks discussed in the text. The image in (a) is an isometric view of a three dimensional model of the top electrode showing two of the four wires blocked by the 100  $\mu\text{m}$  thick polypropylene shield. B) displays a cross-section of an x-pinch showing two opposing wires and the block (blue) placed on one wire. The dashed (pink) line shows the modified convergence region. Additionally, the exposed wire length is measured from the cross point, along the wire, as indicted.**

It is hypothesized that far from the cross point, the local B-field dominates over the global magnetic field and confines the coronal plasma around the wire cores. Additionally, a smaller global magnetic field ( $B \propto 1/r$ ) and increased time of flight, delay the plasma from reaching the axis. To investigate this, 300  $\mu\text{m}$  thick polypropylene shields were installed on two of the four wires on the anode, preventing plasma from the upper portion of the limbs from reaching the axis (see Figure 5-4a. In each set of experiments identical blocks were placed on adjacent wires, both were on the right side of the laser probing images, so their effect could be distinguished from the unblocked wires. In the first set of shielded experiments the shields left 4.2 mm (60%) of the wires

exposed, as measured along the wire from the cross point. In the second set of shielded experiments the blocks left 2.8 *mm* (40%) of wires exposed. As a result the new respective merger points were 6.4 *mm* and 4.3 *mm* above the cross point as depicted in Figure 5-4b. After each shot the shields were inspected to verify they had not moved or completely ablated during the experiment.

An additional modification of the anode removed material along the path of the probe laser allowing an unobstructed view of the jet from the cross point up beyond the plane of the anode as depicted in Figure 5-4.

#### 5.4.1 Imaging

Initial observations of the jets were captured using dark field Schlieren imaging to follow the evolution of the plasma on the axis. This method utilized low density gradients to image the plasma and had a lower detection limit of  $n_e \, dl \approx 10^{19} \, \text{cm}^{-2}$ , as described in chapter two.

In order to quantitatively monitor the electron density in the plasma, two sequential interferometric images, separated by 14 *ns*, were captured during each experiment. Their paths through the experiment were identical to within 3°. Upon exiting the chamber, the beams were split and propagated through a Nomarski and Mach-Zender interferometer independently (different interferometers were instituted due to equipment limitations). Images were recorded on 16 bit CCD cameras and had a spatial resolution of  $\sim 13 \, \mu\text{m}$ . The detection limit of the interferometers yielded a minimum  $n_e \cdot dl$  (areal density) of approximately  $1 \times 10^{17} \, \text{cm}^{-2}$ .

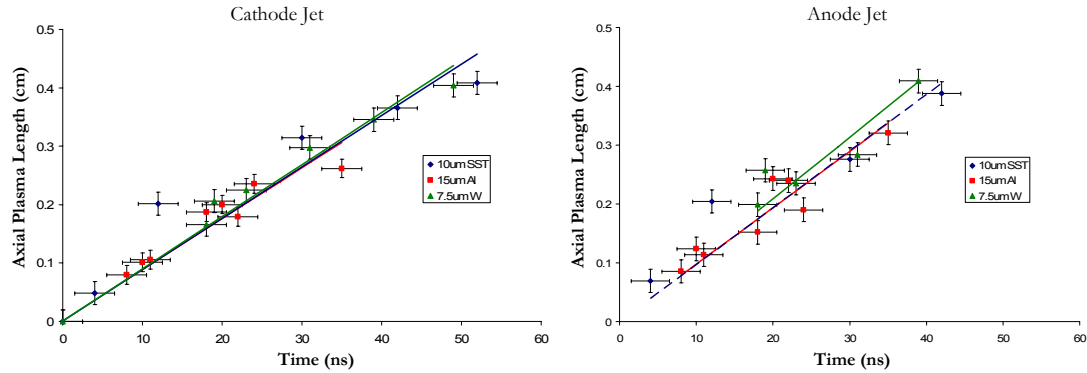
## 5.5 Plasma Column Characterization

A study of the axial plasma jet was able to provide information regarding the formation and evolution mechanisms active in the low density coronal plasma. This section investigates the propagation velocity, jet density profile, and source of the plasma which formed the jets.

### 5.5.1 Axial Plasma Propagation Velocity between Electrodes

Sequences of images from optically backlight x-pinches were recorded and are presented in previous chapters. These image sequences facilitated the tracking of the plasma as it propagated along the pinch axis. By recording the distance from the original cross point to the tip of the plasma jet, qualitative information about the propagation velocity was attained. This was performed for several wire materials, whose sequences can be seen in chapters one through four. The results are presented below in Figure 5-5 plotted as a function of time. Linear fits have been applied to the data to determine the average axial propagation velocity. The vertical error bars on the data are a consequence in the uncertainty determining the exact jet tip location, and represent the averaging of several measurements. The horizontal error bars are set by the 5 ns duration of the laser pulse.

The plot exhibits the similarity between the axial plasma velocities for various wire materials which corresponding to  $8.9 \pm 0.6$ ,  $8.8 \pm 0.2$ , and  $8.7 \pm 0.5 \times 10^6$  cm/s for W, Fe, and Al respectively. The same procedure was performed for the axial plasma appearing on the anode side of the cross point and yielded  $10.4 \pm 1.3 \times 10^6$  cm/s for tungsten,  $9.6 \pm 1.2 \times 10^6$  cm/s for Iron, and  $9.6 \pm 0.8 \times 10^6$  cm/s for Aluminum.



**Figure 5-5** Graphs of the anode and cathode axial plasma positions, as a function of time, for various wire materials X-pinchs. Linear trends for the data are show in respective colors. The data presented applies to the axial plasma between the electrodes.

Although the anode velocities were higher than those of the cathode, in both cases the trend of higher Z materials exhibiting higher velocities held, with W having the highest velocity in both cases. A summary of the averaged anode-cathode jet velocities appear in Table 5-3.

The average cathode jet velocity is in good agreement with previous axial plasma velocities of  $8 \times 10^6$  cm/s for two 10  $\mu$ m Al wires observed by Ian Mitchell [5-3] using a 100 kA current pulse (risetime 130 ns).

**Table 5-3** Summary of jet propagation velocities between the electrodes for various wire materials.

|                                              | W             | Fe            | Al             |
|----------------------------------------------|---------------|---------------|----------------|
| Average Jet velocity<br>$\times 10^6$ (cm/s) | $9.6 \pm 0.5$ | $9.2 \pm 0.7$ | $9.15 \pm 0.7$ |

### 5.5.2 Upper Limb Contribution to Axial Plasma Jets

It is postulated that the upper portions of the x-pinch limbs do not supply a significant quantity of plasma to the axis. As the jet propagates away from the cross point the x-pinch, geometry dictates that the distance from the limbs also increases. As a result the time of flight to the axis is increase and contributions may be mitigated.

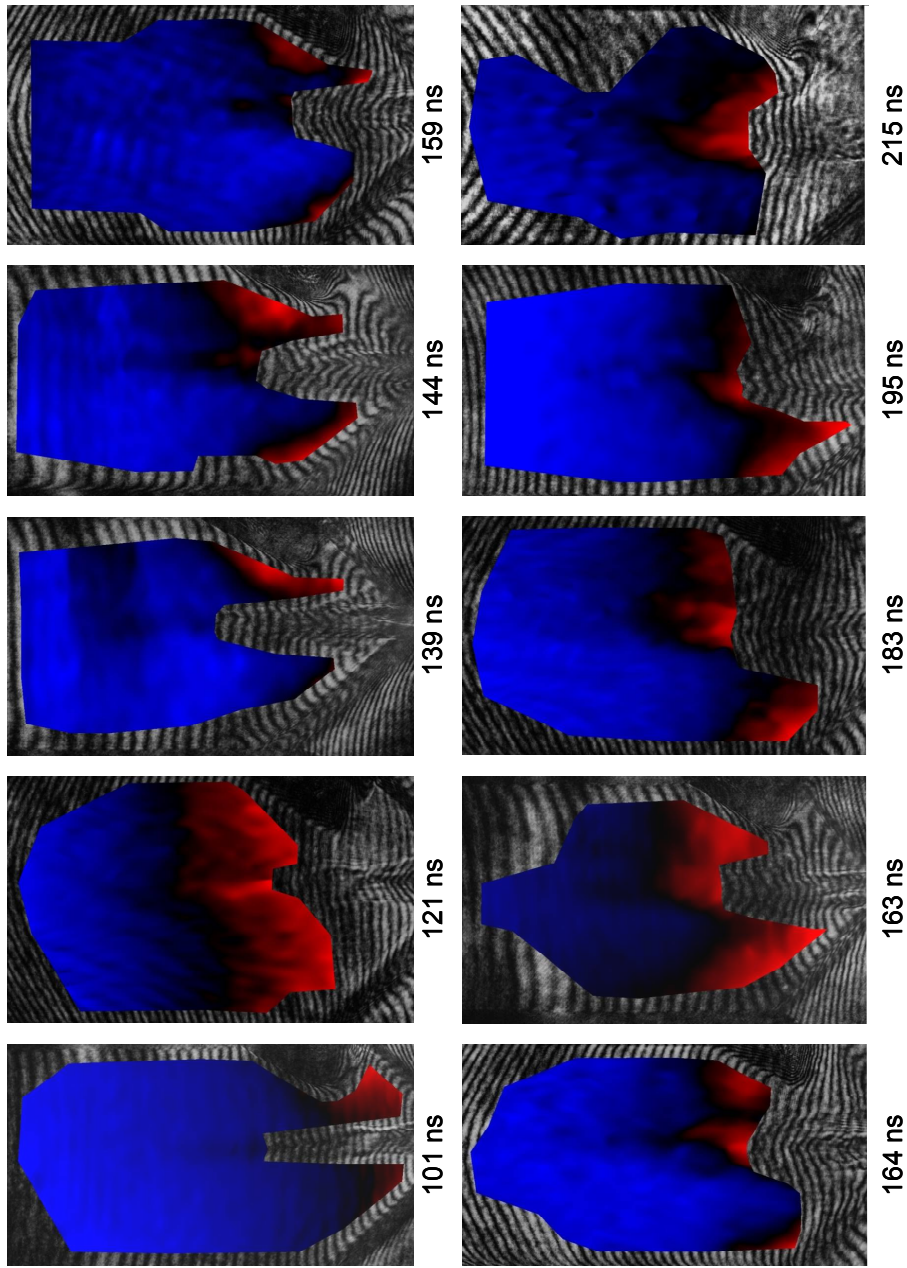
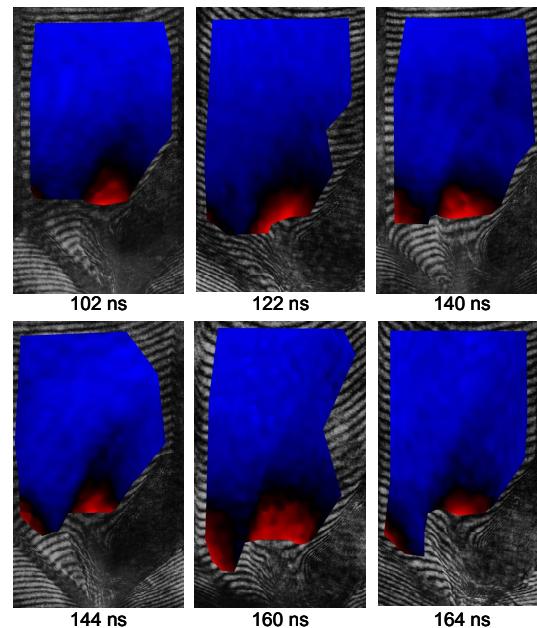


Figure 5-6 Above anode jet sequence for a four wire  $7.5\text{ }\mu\text{m}$  tungsten x-pinch in which the top portion of two of the four wires is blocked by a  $300\text{ }\mu\text{m}$  thick  $2.8\text{ mm}$  long polyethylene block (short block).

This hypothesis was tested in a four wire pinch in which two identical shields were placed on neighboring wires, while the remaining two wires were left unobstructed. The resulting jet images were examined and compared to non shielded four wire x-pinch.

Figures 5-6 and 5-7 display interferometric time sequences of the above anode jet for a four  $7.5\ \mu\text{m}$  wire x-pinch generated with short and long blocks respectively. At the center of each image an areal density map was overlaid on the fringe patterns to more easily visualize the plasma jet. The individually tailored shapes of the density maps resulted from the purposeful exclusion of low contrast fringes and other regions difficult to process. This primarily included the area surrounding the plasma block and the base of the jets. The jets generated with the short-blocks ( $2.8\ \text{mm} \sim 40\%$  of wire) were captured above the anode at  $\sim 101\ \text{ns}$  after the start of the current and remained beyond  $200\ \text{ns}$ . Throughout the sequence, the plasma propagates close to the axis.



**Figure 5-7** An interferometric time sequence of a four wire  $7.5\ \mu\text{m}$  tungsten x-pinch in which the top portions of two of the four wires are blocked by a  $300\ \mu\text{m}$  thick  $4.2\ \text{mm}$  long polyethylene block (long block).. The images are overlaid with their generated areal density maps, highlighting the location of the high density plasma jet.

Similar to the previous case, in the long block sequence in Figure 5-7, jets were observed propagating above the anode at  $\sim 102$  ns. However, in contrast to the previous sequences, the jets are observed to have a strong deviating to the right. This final case implemented a long shield (4.2 mm) which blocked  $\sim 60\%$  of the wire length. Although the shields were  $300\text{ }\mu\text{m}$  thick, in the images they appear solid due to their orientation to the probe beam.

### Comparison

To assess the propagation of the jet for the various configurations, three temporally comparable images of the four-wire unblocked (a), short block (b), and long block (c) tungsten x-pinch are presented in Figure 5-8. To illustrate the position of the plasma jet, a series of horizontal lineouts were taken at one millimeter axial increments and are plotted alongside each image.

Increases in the density on the sides of the profiles are a result of emission and/or edge effects from the anode. Also evident is an increase in the density on the right side of the shielded profiles which corresponds to a surface ablation of the plastic shields under exposure to XUV radiation from the wires. For the short and long blocks this plasma is distinct from the jets and does not affect their trajectories.

In the first two cases, distinct peaks in the density profiles (highlighted by red dots) appear near the axis ( $\pm 0.15$  mm) for the entire length of the jet. In the long block presented in (c), the lineout closest to the cross point, the peak of the density profile coincides with the axis of the experiments. However as the distance from the cross point increases, the peak of the profile migrates to the right as marked by the series of red dots marking the jet location in the profile.

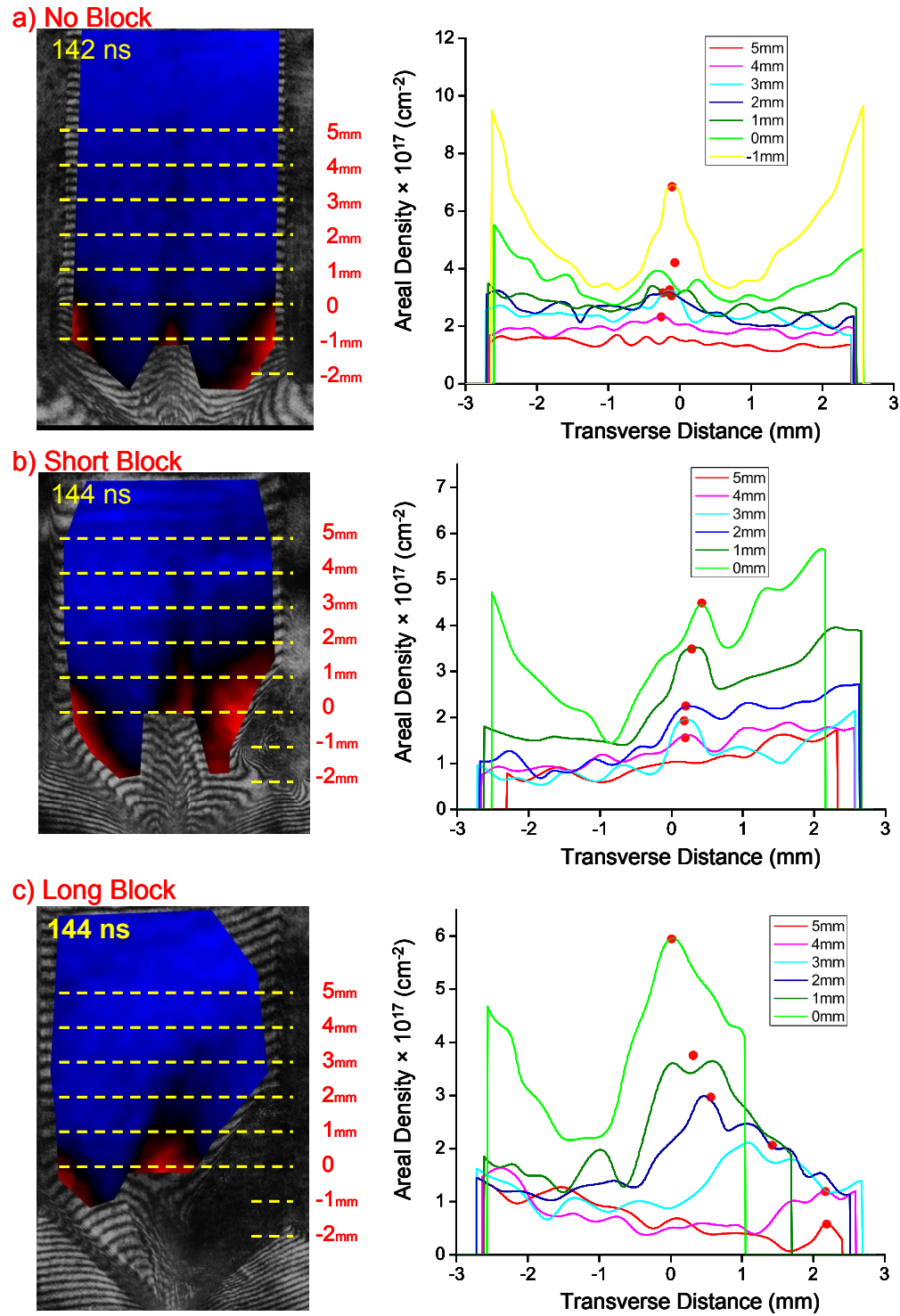
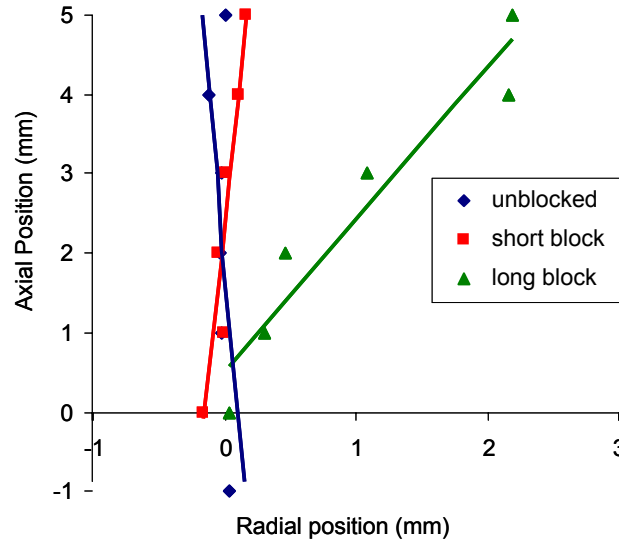


Figure 5-8 Composite, above anode, interferometric and areal density images from four  $7.5 \mu\text{m}$  thick tungsten wire x-pinch. The image in (a) was produced with four unblocked wires, the image in (b) with the right two wires having 'short' blocks, and (c) with the right two wires having long blocks (see text). Each image is accompanied by a plot of the lineouts designated in the areal density image.



In the density plots a transparent red dot highlights the location of the center of the jet on each lineout.



**Figure 5-9** Plot of the radial jet position as a function of axial height for the unblocked, short, and long block cases. Data was gathered from the profiles displayed in Figure 5-8.

In order to obtain a clear picture of the jet location, the peaks of the profiles were plotted against their axial height in Figure 5-9. Linear fits highlight the angle of the jets which are  $-3^\circ$  and  $3.7^\circ$  for the unblocked and ‘short block’ cases respectively. Both of these values are typical of what is observed in experimentally produced plasma jets.

The unblocked and short block cases are distinct from the ‘long block’ case whose jet propagates to the right at an angle of  $28^\circ$ . As a result it is possible to infer that the bottom and middle portions ( $\sim 60\%$ ) of the wire limbs have a large contribution to the axial plasma while the impact of the upper portions is negligible.

As a follow-up a possible plasma sources are presented in the discussion section below.

## Discussion

For portions of the wires farther than 3 mm from the cross point, the large ratio of local to global magnetic field strength is believed to constrain the plasma to the vicinity

of the wires. In response thin non-conducting shields were fixed along two neighboring x-pinch wires preventing plasma from reaching the experimental axis.

From the above results, the short blocks obstructed plasma from the upper 2.8 *mm* ( $\sim 40\%$  of the leg length) of the wires and did not significant effect on the propagation of the jets when compared to unblocked experiments. In both cases, the jets appear to have a slight ( $\sim 3^\circ$ ) deviation from the axis. This is likely a result of the low symmetry of the flow reaching the axis, a consequence of the low wire number in these experiments, and is often evident (see Figure 5-11). Due to similarities with the control case, the short blocks can be ruled out as a source of the deviation. Alternatively, when two longer shields were attached (covering  $\sim 60\%$  of the leg length) a significant change in the propagation of the axial plasma jet resulted. In these experiments the jet deviated towards the blocked wires due to a lack of opposing momentum.

A clear difference in the contribution of the lower and upper portions of the x-pinch limbs was observed. The inconsequential contributions from the upper 2.8 *mm* of the limbs prompted a reassessment of the convergence regions from the wire limbs. Retaining the assumption that the wire ablation occurs normal to the surface of the wires, the modified convergence region now ends  $\sim 6.5$  *mm* above the x-pinch cross point. This is 6.5 *mm* lower than the initial maximum geometric limit.

In conjunction with the above jet propagation length and radius from Figure 5-11, the jets were recorded up to 19 jet radii above the plasma convergence region.

## 5.6 Jet propagation above the anode

Optical probing approximately 50 *ns* after the start of the current recorded the plasma column colliding with the electrodes. To circumvent this, a modified anode (unobstructed on the axis: described in §5.4) was instituted to eliminate stagnation, allow propagation above the anode, and provided diagnostic access to the plasma. Above-anode optical probing sequences are displayed below in Figure 5-10. The Schlieren images (a) provided a clear indication of the position and structures present in the jets, while the interferometric images (b), yielded quantitative areal density information. Each pair of images (stacked) was acquired from a single shot demonstrating the utility of simultaneous diagnostic imaging;

Results from the above-anode W pinches captured a plasma approximately 80 *ns* after the start of the current. The plasma remains collimated through ~150 *ns*, and is not present after 200 *ns*. A precursory analysis of the fringe shift identifies an areal electron density in the plasma jet of  $\sim 10^{17} \text{ cm}^{-3}$  close to the electrode. An in-depth investigation of the density profiles of the jets follows.

### 5.6.1 Density Imaging

Interferometer images were processed using the software package IDEA [5-7]. Through the analysis described fully in chapter one, the relative fringe shift  $f$  is related to the areal electron density ( $n_e dl$ ) as:  $\int n_e (cm^{-3}) dl = 4.2 \times 10^{17} f$ . A sequence of areal electron density maps, generated from interferometric images, is displayed in Figure 5-11.

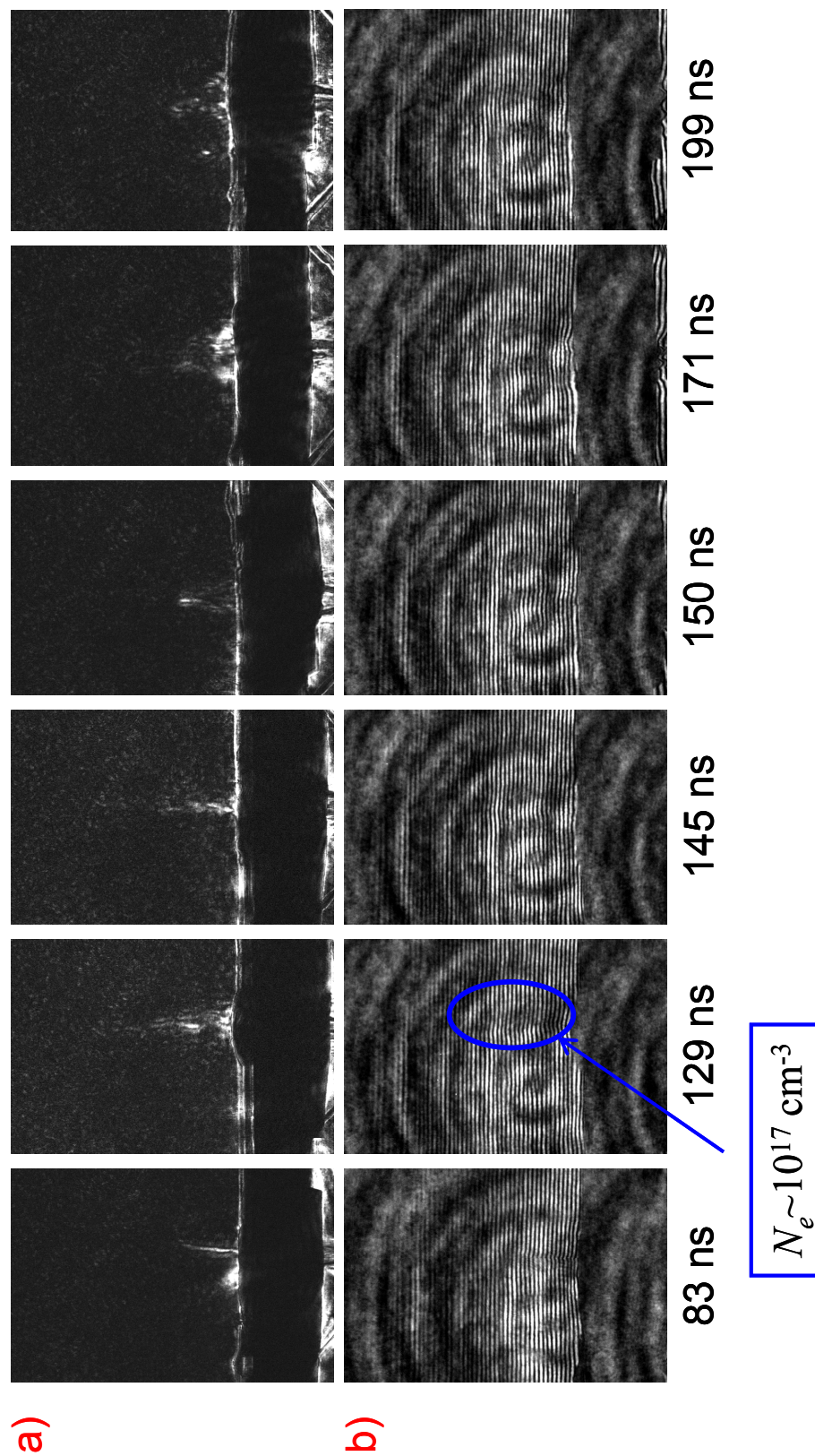


Figure 5-10 Backlight sequences showing the propagation of the plasma from a 7.5  $\mu\text{m}$  x-pinch above the anode. Series are a) dark field schlieren and b) interferometric imaging techniques.

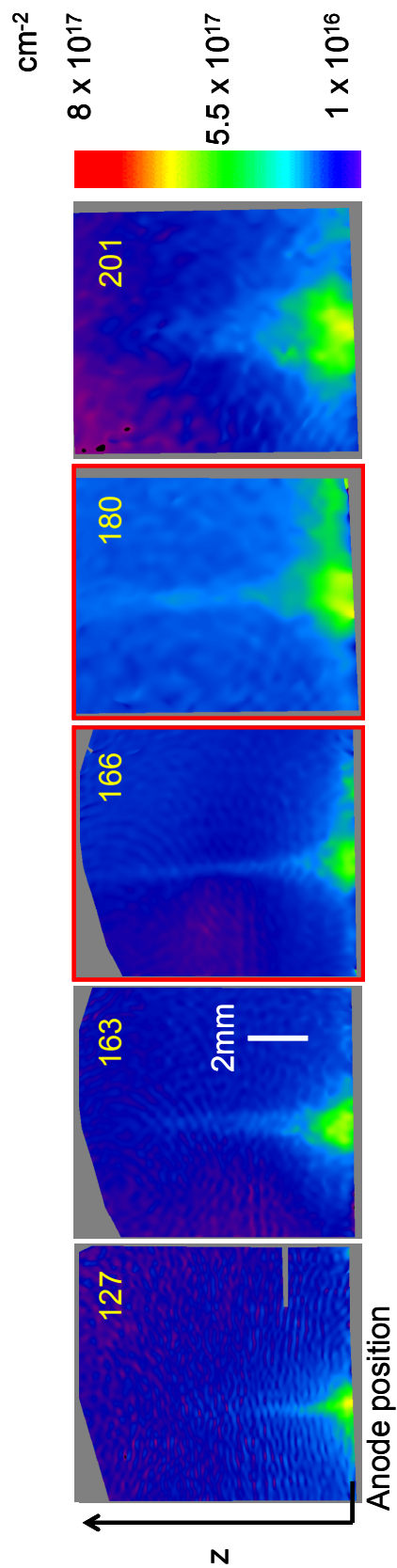


Figure 5-11 A series of areal density images showing the evolution of the plasma jet above the plane of the anode. Top edge of the electrode shown (bottom of the images) corresponds to 7mm above the cross point of the wires. The numbers appearing in the top right corner of each image indicate the time (in ns) of each shot. Note: The position of these images is indicated by the blue dashed line in Figure 5-3b.

This sequence of images exhibits densities of  $\sim 10^{17} \text{ cm}^{-2}$  at the bottom of the jet (top of the electrode), which increases with time, while  $n_{e,dl}$  values of  $1 - 2 \times 10^{17} \text{ cm}^{-2}$  distinguish the tip of the plasma jet from the background density. As time progressed, the extension of the jets along the axis was recorded 9 mm above the anode plane (16 mm above the cross point).

For a majority of its length, the jet demonstrates a significant contrast with the background density. Far above the anode, however, the density at the tip of the jet provides only a low level contrast. Therefore, a systematic method for determining the end of the jet was implemented. A quantitative density profile was taken along the centerline of the jet, and plotted as a function of distance from the top of the anode Figure 5-12a. An average of the background density for each image was taken and plotted along with the density profile, appearing in the plot as a horizontal line. The lengths of the jets were determined as the point at which jet density profile crossed the background threshold. This methodology was applied to a series of images, two of which can be seen in Figure 5-12b.

Both images in this figure were taken during the same shot. The location of the lineouts are marked in gray in the images on the right side of Figure 5-12, while their corresponding density profiles are plotted in Figure 5-12a. In the image recorded at 163 ns, the density profile clearly crosses the background threshold and gives a jet length of  $8.10 \pm 0.05 \text{ mm}$ . However, for the image taken at 177 ns the jet extends beyond the diagnostic viewing area. In cases such as this a linear extrapolation of the density profile was used to determine the length of the jet (indicated by a dashed line in the plot). Typical densities profiles along the axis of the jets resembled  $1/r$  curves.

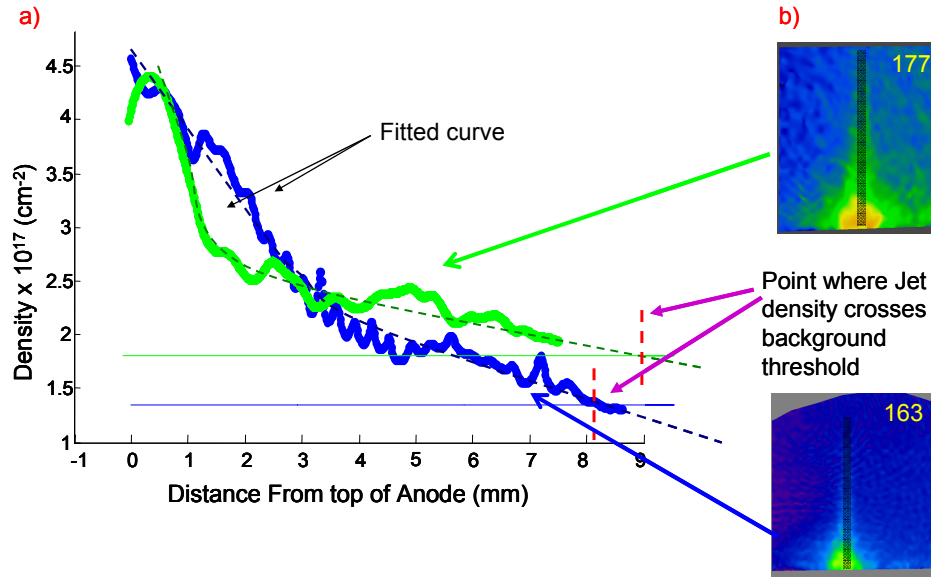


Figure 5-12 (B) shows two areal density plots captured from the same shot. The locations of the lineouts are indicated by transparent vertical grey lines in the figures. (a) The graph displays the respective density profiles as well as the average background density for each of the images. Linear extrapolations for the profiles are represented by dashed lines in respective colors. Vertical dashed lines mark the location of the end of the jet, while highlighting the increase in jet length and density in the later image.

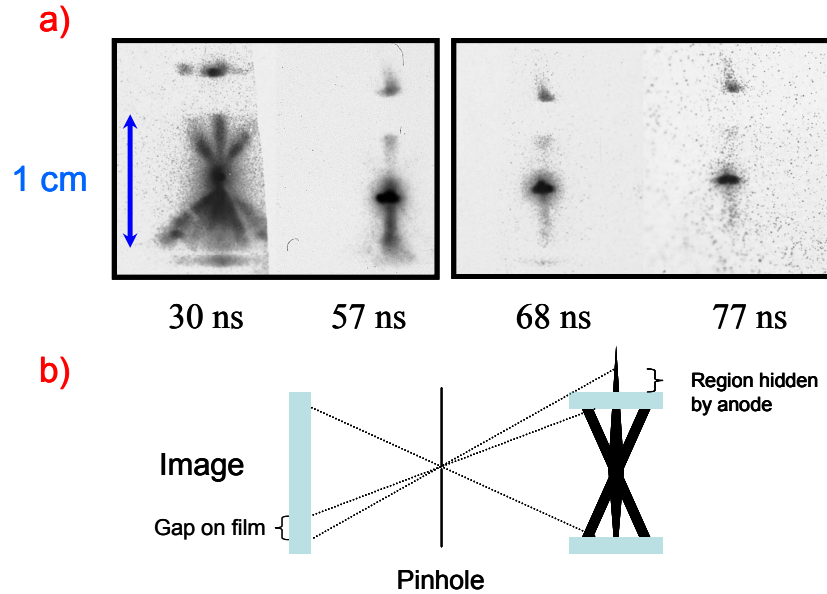
Therefore by using a linear fit the density profile will intersect the background density sooner than a  $1/r$  extrapolation. In this way a linear fit provides a minimum jet length and hence a lower limit on the jet velocity inferred from these measurements. Consequently, between 163 and 177 ns, the jet propagated a distance of (at least)  $0.8 \pm 0.1$  mm. These measurements were performed for a series of jet shots the results of which are discussed below.

As the jet propagates away from the cross point, radiative cooling and expansion in the lateral direction are responsible for cooling the plasma. Consequently the emitting jet length is expected to be shorter than the jet observed in optical probing.

### 5.6.2 Jet Radiation

In order to estimate the cooling parameter ( $\chi$ ) a measurements of the jet's cooling

length were necessary. Self-emission images of an axially unobstructed x-pinch (hole on axis), show the presence of a radiating axial plasma between the electrodes as well as above the anode, Figure 5-13a.



**Figure 5-13** a) A sequence of gated XUV images from  $7.5\ \mu\text{m}$  four wire tungsten x-pinchs, showing the emission from the jet along the axis. The schematic presented in (b) depicts the setup and highlights the region blocked by the anode.

In the above XUV images the radiating plasma extends  $\sim 11\ \text{mm}$  above the cross point of the wires, and is present well after the current maximum. Note: The  $2\ \text{mm}$  gap expected from the anode plate appears to be  $2.5\text{--}3\ \text{mm}$  in height due to the geometry of the system as shown schematically in Figure 5-13b.

## 5.7 Analysis and Discussion

The observed results clearly demonstrate the presence of an axial plasma which extends well beyond the plane of the anode. More importantly, the plasma extends beyond the region of convergence formed by the wires and therefore represents a *freely propagating* plasma jet. In order to relate this plasma jet to those seen in other systems,



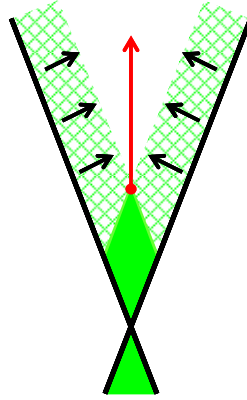
parameters including the velocity, aspect ratio, and the Mach number of the jet must be characterized. In addition, the values responsible for the scaling of the systems, such as the cooling parameter and contrast ratio, must be calculate.

### 5.7.1 Source of the Plasma

As discussed in the introduction to this chapter, plasma forming on the axis is not exclusively from material ejected from the cross point or streaming from the wires. Therefore, to further characterize the jets it is useful to investigate the main mechanism driving plasma along the axis.

To investigate the propagation velocity of the central column, a ‘zippering’ of plasma from the wires was considered. This simple method neglects any axial pressure gradients which may serve to increase the propagation velocity of the jet; this analysis was performed to investigate if the wire ablation dominates the axial velocity propagation. Here, the plasma is considered to be driven by the imparted axial velocity as it is driven off perpendicularly to the wires. After traveling to the axis the plasma from one wire collides with plasma from the opposing wire. The location where the two fronts meet will be referred to as the merging point and is depicted with a red dot in Figure 5-14. As the experiment continues plasma is continuously ablated and driven to the axis, driving the merging point towards the electrodes.

In the zipper configuration, using the established wire ablation velocity of  $1.5 \times 10^7 \text{ cm/s}$  (see chapter one), and a wire opening angle of  $88^\circ$  (adapted from experiments), a merge point velocity of  $2.2 \times 10^7 \text{ cm/s}$  was calculated.

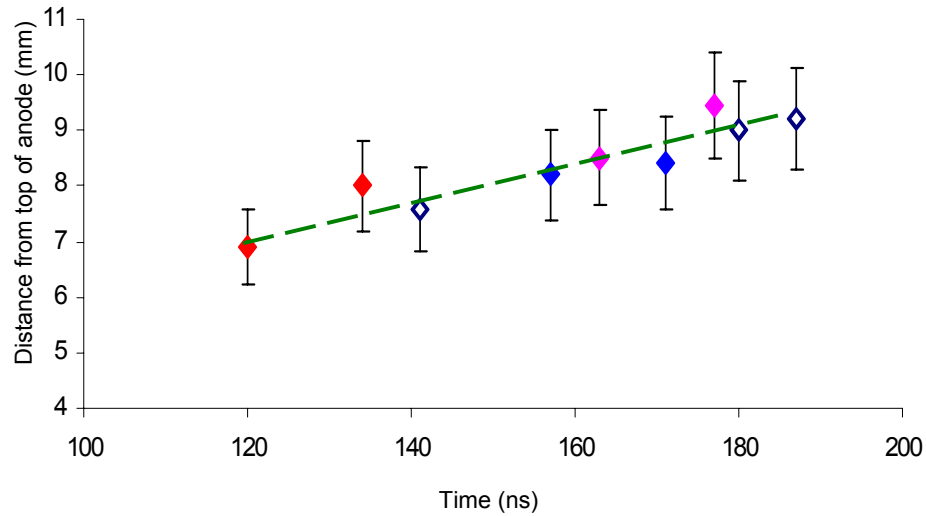


**Figure 5-14** An illustration of the 'zippering effect' of the plasma fronts (patterned green) from the individual wires (black). Shown in red is the merging point moving away from the cross point as the experiment proceeds. The solid green region indicates the overlap of the two fronts, the proposed axial jet.

This value is significantly higher than the average jet velocity found in optical probing of  $8.8 \times 10^6 \text{ cm/s}$ ; however, it is within a factor of two of the average Al jet velocity of  $1.1 \times 10^7 \text{ cm/s}$  determined from an XUV series of images recorded in Figure 4-10. This indicates that the formation of the central column is dominated by plasma streaming from the limbs, and that the standard ablation velocity accurately predicts the rate at which the Al plasma streams to the axis. Additionally, the results indicate that the merge point is formed from low density plasma  $n_e < 10^{18} \text{ cm}^{-3}$  (transparent to the laser beam). At the time of the writing of this thesis high resolution XUV image sequences of other wire materials were not available for comparison.

### 5.7.2 Freely Propagating Jet Velocity

All jet lengths presented here were acquired  $> 6 \text{ mm}$  from the top of the anode; i.e. beyond the initial geometric convergence limit discussed at the beginning of this chapter ensuring that they were freely propagating. Measurements of above anode jet lengths from a series of experiments and were plotted in Figure 5-15 as a function of time.

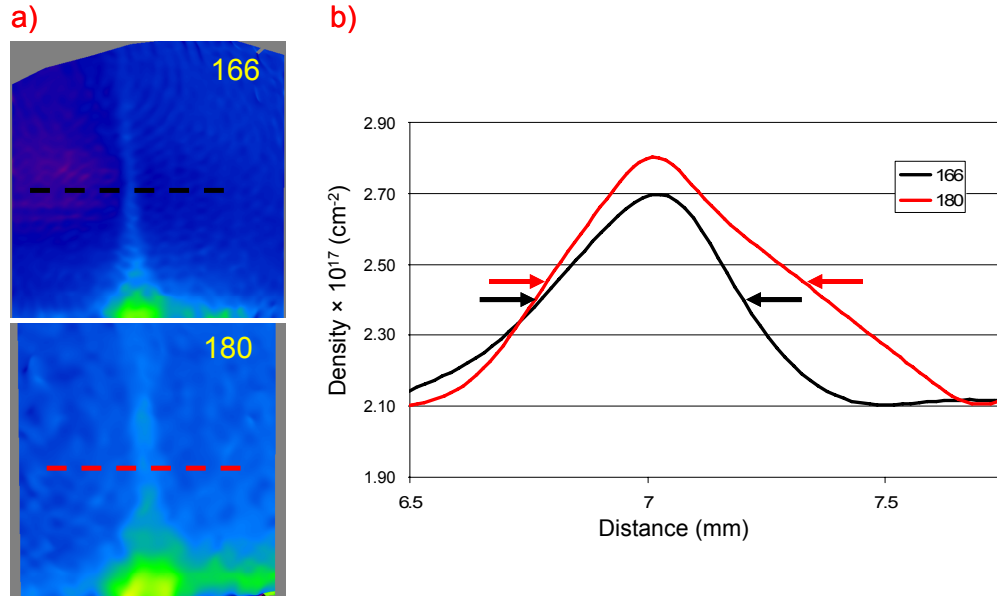


**Figure 5-15** Plot of jet length as a function of time for plasma above the anode. Like marker pairs represent images from the same shot, while hollow dark blue points are uncorrelated (taken from individual experiments). The dashed line designates a linear fit to the data.

The data pairs appearing in the same colors were recorded from single shots while the three hollow points in dark blue are from separate individual shots. The grouping of data by shot shows that the individual jet velocities display similar trends as the overall data set, therefore shot to shot reproducibility is good. The errors associated with these values result from the limits with which the interferometric measurements can be performed. The high resolution of the images and the FFT analysis generated an experimental error of  $\sim 10\%$ . Additionally, a linear fit of the data was included (displayed in green) and gave an average jet velocity of  $3.3 \pm 0.6 \times 10^6 \text{ cm/s}$ .

### 5.7.3 Sound speed of the Jet Plasma

Beyond the convergent flow region, the jets are unconfined in the lateral direction and will expand into the surrounding vacuum at the sound speed ( $c_s$ ) of the plasma. Figure 5-16a shows two images captured during the same shot. In each, density profiles were taken across the jet and the results are plotted in Figure 5-16b.



**Figure 5-16 (A): Density plots from the same shot separated by 14 ns. Horizontal dashed lines indicate the location of the radial lineouts taken across the jets. (b) The graph displays the central (jet) portion of the density profile lineouts as a function of horizontal distance. The colored sets of arrows designate the FWHM height for the respective profiles.**

In the later image the profile is taken farther from the top of the anode to account for the propagation of the jet during the interim of the images. The distance was determined from the axial velocity found in the previous section and the 14 ns temporal separation of the frames. From the FWHM of the jet diameters, an increase from 0.32 mm to 0.4 mm was found. Gathering results from multiple shots, an average sound speed of  $c_s = 5.5 \pm 2.6 \times 10^5 \text{ cm/s}$  was obtained.

To verify the above  $c_s$  value, calculations of the temperature and ionization state of the plasma were compared with the values expected for the experiment. Rearranging the sound speed equation gives:

$$Z T_e [eV] = \left( \frac{c_s [cm/s]}{9.79 \times 10^5} \right)^2 \frac{m_{ion}}{\gamma} \quad (5.17)$$

For tungsten ( $m_{\text{ion}} = 184$ ), and a  $\gamma$  of 5/3, a  $ZT_e$  value of 35  $eV$  was found. Using the coronal equilibrium ionization model [5-8] in which the ionization energy is 2 - 5 times the temperature: (see §5.2.2) and assuming a  $Z$  of  $\sim 5$  (reasonable for the corona), gives an electron temperature of  $7 \pm 1.6$   $eV$ . This value is consistent with the approximate temperature range inferred from the presence of jets in gated self-emission imaging ( $h\nu > 4.4$   $eV$ : §5.6.1).

Coupling the sound speed with the plasma's axial velocity, a Mach number of  $6 \pm 3$  was found for the jets. Admittedly, the errors on this measurement are considerable; despite this, even in the extremes, the observed jets are supersonic.

A comparison of the length of the jets observed in XUV and optical imaging found lengths of  $\sim 4$   $mm$  above the anode in the former compared to lengths of up to 9  $mm$  above the anode in the latter. These results demonstrate that there is substantial radiative cooling along the length of the jet.

#### 5.7.4 Jet Radiation

The presence of the jet in self emission images beyond the period of the current demonstrates that the plasma on the axis maintains a temperature greater than 4  $eV$ . As there is no heating mechanism this late in the experiment, this suggests that the plasma behaved as a poor radiator and retained its internal energy. Because the radiation rate is proportional to the square of the ion density, the slow energy radiation further supports the low density of the plasma jet discussed earlier.

#### 5.7.5 Astrophysical Scaling

As discussed at the opening of the chapter, the jets produced in x-pinch

experiments may be of interest for laboratory astrophysics. To determine their applicability, several factors must be considered. A fluid description should be appropriate for the plasma, and restrictions on the Reynolds and Peclet numbers ensure that the energy flow is dominated by heat convection, while dissipative effects such as viscosity and thermal conductivity are negligible [5-4]. Using the thermal velocity  $5.5 \times 10^5 \text{ cm/s}$  and a density of  $2 \times 10^{18} \text{ cm}^{-3}$  [5-4], a localization parameter of  $\delta_{\perp} < 10^{-2}$  was calculated (see equation (5.12)) . Substituting the values associated with the jets, both the Reynolds and Peclet numbers are  $> 10$ .

In addition to these limits, the three dimensionless parameters associated with radiative jets, the Mach number  $M_a$ , cooling parameter  $\chi$  (ratio of cooling length to jet radius), and density contrast ratio  $\eta$  (ratio of jet density to background density), need to be quantified. For the jets discussed above:  $M_a \sim 6$ , and from self-emission imaging we estimate cooling lengths of 0.5- 5 mm for jets with a radii of  $\sim 0.5 \text{ mm}$ , yielding a  $\chi$  in the range of 1 - 10. The jets created in the described x-pinch experiments propagating into vacuum, and therefore  $\eta$  is always much greater than 1.

Table 5-4 relates common values for the aforementioned astrophysical systems as well as those observed in the laboratory. As can be seen in the first section, the general flow parameters highlight the vast differences in scale of these two systems. The second section reveals the validity of a fluid description for both the astrophysical and laboratory systems. Although it is not required that the parameters appearing in the third section match, they must fall within the limits facilitating a fluid description of the plasma (i.e.  $\delta_{\perp} \ll 1$ ,  $Re \gg 1$ , and  $Pe \gg 1$ ). Inconsistent localization, Reynolds, and Peclet numbers

in the two systems will limit the size of the spatial scales for which the similarity criteria may be applied.

**Table 5-4 Summary of the common scaling parameters for plasma jets in astrophysics as well as the laboratory settings**

| Parameter                                   | Astrophysical system         | Laboratory                          |
|---------------------------------------------|------------------------------|-------------------------------------|
| Velocity (v)                                | $2 \times 10^7$ cm/s         | $3.3 \pm 0.6 \times 10^6$ cm/s      |
| Radius (r <sub>j</sub> )                    | $\sim 10^{13}$ cm            | 0.05 cm                             |
| Length                                      | $3 \times 10^{15-18}$ cm     | 0.95 cm                             |
| Density                                     | $\sim 10^2$ cm <sup>-3</sup> | $2 \times 10^{20}$ cm <sup>-3</sup> |
| Length to width ratio                       | $\geq 100:1$                 | $\sim 20$                           |
| Cooling length                              | $5 \times 10^{14}$ cm        | 0.05- 0.5 cm                        |
| Temperature                                 | $10^4$ K $\sim 1$ eV         | $\sim 10$ eV                        |
|                                             |                              |                                     |
| Mach (M)                                    | $> 10$                       | $\sim 6$                            |
| Density contrast ( $\eta$ )                 | 1-2                          | $\gg 1$                             |
| Cooling parameter ( $\chi$ )                | $\leq 1$                     | 0.1 - 1                             |
|                                             |                              |                                     |
| Localization parameter ( $\delta_{\perp}$ ) | $\ll 10^{-6}$                | $\sim 2.4 \times 10^{-3}$           |
| Reynolds number (Re)                        | $> 10^8$                     | $> 10$                              |
| Peclet number (Pe)                          | $10^7$                       | 1.8                                 |

As described above, the validity of the hydrodynamic description holds while  $\delta_{\perp}$  is much less than one and a Peclet number greater than one. However, the value of Pe is not very high, and as a result heat conduction may effect the plasma at scales smaller then  $0.7r_j$  according to Ryutov *et al.* [5-4]. In a similar fashion viscous effects become important for structures smaller then  $0.1r_j$ .

For the transforms given in equation (5.2) it is possible to find the scaling factors a, b, and c between the two systems. From the values contained in Table 5-4 *a* corresponds to  $2 \times 10^{16}$ , *b* to  $1 \times 10^{-18}$ , and *c* to  $1.4 \times 10^{-20}$ . From these parameters we can find the scaling factors for the time and velocity presented in equation (5.3):

$$t_{astro} = 1.7 \times 10^{17} t_{lab} \quad v_{astro} = 1.2 \times 10^{-1} v_{lab} . \quad (5.18)$$

As a result 100 years in the astrophysical systems correlates to 19 *ns* in the laboratory.

## 5.8 Summary

The results presented in this chapter are the first quantitative investigation of the plasma jets produced on compact ( $< 1 \text{ m}^2$ ) laboratory experiments and their scalability to the large scale plasma jets ubiquitous in astrophysics. This work also represents the first quantitative study of the formation and propagation of axial plasma jets in x-pinchs, with velocities between the electrodes of  $\sim 9 \times 10^6 \text{ cm/s}$  (optical) for various wire materials and  $1.1 \times 10^7 \text{ cm/s}$  (XUV) for aluminum. Propagation velocities from self emission imaging correlated well with axial zipper velocity estimates using the standard ablation velocity for wire array plasmas.

Once formed, the jets were observed propagating up to 16 *mm* from the cross point of the wires (9 *mm* from the top of the electrode). Analysis suggested that two distinct regions were established for the axial propagating plasma. The first, close to the cross point, is below the ‘merger point’ (where the plasma from the wires merges on the axis) and the axial plasma is kinetically driven by the plasma ablating from the wires. The second region lies beyond the merger point and corresponds to distance at which the jet is freely propagating and no longer fed by the x-pinch limbs.

A study of the x-pinch limbs revealed that only  $\sim 60\%$  (4.2 *mm*) of the wire limbs, adjacent to the cross point, significantly contributed to the axial plasma column. This defined a lower limit for the plasma convergence region (where the plasma from the wires merges on the axis) and demonstrated that the jets were freely propagating for



distances of up to 19 jet radii. The region in which the jets are not driven is important due to the fact that the jets observed in astrophysics are freely propagating and therefore this is the region of interest in the experiments. Here the axial plasma was measured to have velocities of  $\sim 3 \times 10^6 \text{ cm/s}$  away from the cross point.

Once beyond the merger point the jet was free to expand radially at the sound speed of the plasma which was found to be  $5.5 \times 10^5 \text{ cm/s}$ . Through a CE model and a reasonable ionization estimate of  $\sim 5$  (appropriate for the coronal plasma) a  $T_e$  of  $\sim 7 \text{ eV}$  was calculated. This temperature did not contradict data recorded with the MCP diagnostic which recorded jet cooling lengths of 0.05 to 0.5 *cm*.

Finally an investigation into the validity of the scaling parameters revealed that while the Mach number ( $\sim 6$ ), cooling parameter (1-10), and localization parameter ( $1 \times 10^{-3}$ ), are close to those observed in astrophysical objects; however, the density contrast, Reynolds number, and Peclet numbers differ greatly between the laboratory and the astrophysical systems. As a result, scaling between the two systems appears possible, provided advances in a few parameters can be made. As an example, propagation of the jets into a gas or other medium will reduce the density contrast ratio ( $\eta$ ) aligning it more closely with the value observed in astrophysics. While an increase in  $Re$  and  $Pe$ , both of which have a strong dependence on density, elicit experiments with higher values of  $n_e$ . Despite the variation between the two systems estimates of the Euler scaling demonstrate that 100 years in astrophysical systems may be represented by 19 *ns* in the laboratory.

## Chapter 6

# Cross Point Evolution and Emission

Previous work has documented the backlighting capability of x-pinchs for high density plasmas as well as micron scale objects (see chapter one). However, as discussed in section 3.4 of chapter one, the mechanisms preceding the emission are not well understood. Although a complete understanding of the collapse and emission from the cross point is well beyond the scope of the research presented here, a more comprehensive knowledge of the emission is an integral part to understand the physics of pinch plasmas. The current chapter begins with an investigation of the time integrated, and then time resolved x-ray emission from the cross point. In this way, a correlation of the emission with the dynamics presented in the previous chapters can be made.

Due to the short-duration, small, and high-energy cross-point emission, the x-pinch is uniquely suited for the characterization of inertial confinement fusion (ICF) capsules. The later portion of the chapter chronicles the first use of x-pinch cross point radiation as a diagnostic tool for proposed ICF capsules. While the study of emission encompasses various materials and configurations (W ( $5\ \mu\text{m}$ ), W ( $7.5\ \mu\text{m}$ )), capsule imaging was performed with four  $5\ \mu\text{m}$  diameter tungsten wires strung between a  $1\ \text{cm}$

anode cathode gap. This arrangement was chosen due to the reproducible and high energy yields achieved in previous experiments.

## 6.1 Introduction to Cross point Compression and Emission

In an x-pinch the current is divided between the two (or four) legs of the wires. Taking a four wire x-pinch, at the cross point the full current is driven through a single column of plasma, quadrupling the limb current and yielding a sixteen fold increase in the magnetic pressure. This results in a radial collapse of the plasma at a localized location. Previous work has recorded the necking down of the plasma at the cross point and the formation of a  $300\ \mu\text{m}$  long plasma column, with a diameter of tens of microns. This column is similar to those observed in single wire z-pinch experiments [6-1] and is referred to as a ‘micro-z-pinch’. The continual current flow drives an  $m = 0$  instability in the column resulting in single or multiple points of high compression. These points attain a high temperature and high density and have been observed as the source(s) of energetic x-rays.

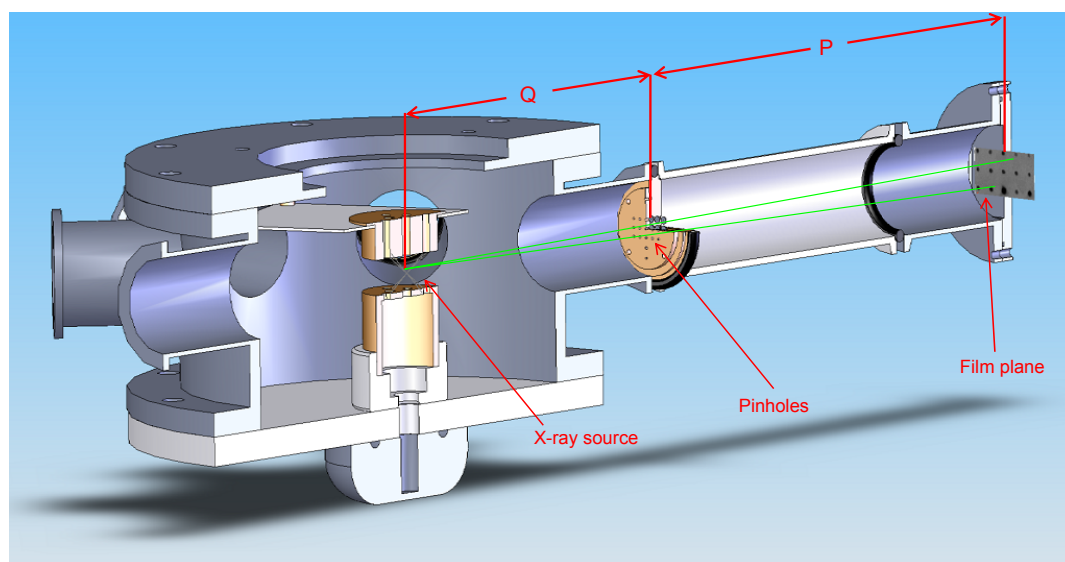
## 6.2 Experimental Setup

The electrode gap distance was fixed at  $1\ \text{cm}$ , with wire materials including Al, Mo, Fe, and W. The most useful (short duration, small source size, and high energy emission) was obtained using four  $5\ \mu\text{m}$  (diameter) tungsten wires with an anode-cathode separation of  $1\ \text{cm}$ .

### 6.2.1 X-ray emission

In order to study the emission from the cross point, a multi-pinhole holder was

designed and used to record the time integrated spectrum on calibrated Kodak DEF film [6-7]. This allowed the simultaneous recording of up to fifteen various filters at approximately the same orientation to the cross point. A schematic of the setup can be seen in Figure 6-1 where Q represents the distance between the x-pinch and the pinholes and P the length separating the pinholes from the x-ray film. For the system employed here, values of 16 cm, 20 cm, and  $< 50 \mu\text{m}$ , for P, Q, and the pinhole diameter respectively, were used. Each pinhole corresponds to a single exposed dark spot which appears on the film. The film calibration [6-7] was used to convert spot brightness to incident radiation. Incorporating the transmission of the filters and the solid angle of each spot reproduced the energy emission from the cross point. In conjunction with the time integrated film, a diamond photo conducting diode (PCD) was used to monitor the emission from the pinch. Although not quantitatively calibrated, this diagnostic was used to record the timing and duration of the radiation, for comparison with optical and XUV probing.



**Figure 6-1** Schematic of the 15 pinhole camera and time integrated film camera mounted to the x-pinch vacuum chamber. Green lines represent the path of the emitted x-rays.

Additionally, time resolved x-ray spectra were recorded with a set of seven silicon *p-i-n* diodes, each having a  $100\ \mu\text{m}$  thick Si layer and an active area of  $1\ \text{mm}^2$ . The sensitivity of the diode setup ranged from  $4\ \text{eV}$  through  $12\ \text{keV}$  and had a rise time of  $< 1\ \text{ns}$ .

In both of the aforementioned cases, spectra were compiled through the use of a set of seven Ross filter pair as described in detail in section 2.5.3.

The L and K edges of the filters clearly define energy transmission windows and plastics were added to match the transmission outside the designated energy window. The following tables lists the filters used and is ordered from hardest to softest, data was taken from the tables provided in reference [6-8]:

**Table 6-1 X-ray filters and their associated energy ranges, from hardest to weakest.**

| Filter material                                                          | Energy cutoff (keV) | Energy Range (keV) |
|--------------------------------------------------------------------------|---------------------|--------------------|
| 7.6 $\mu\text{m}$ Cu + 270 $\mu\text{m}$ Polypropylene                   | 9                   | 8.4-9              |
| 7.5 $\mu\text{m}$ Ni + 300 $\mu\text{m}$ Polypropylene                   | 8.4                 | 7.8.4              |
| 10 $\mu\text{m}$ Fe + 50 $\mu\text{m}$ Teflon ( $\text{C}_2\text{F}_4$ ) | 7                   | 6-7                |
| 15 $\mu\text{m}$ Cr                                                      | 6                   | 5-6                |
| 25 $\mu\text{m}$ Ti + 50 $\mu\text{m}$ Teflon ( $\text{C}_2\text{F}_4$ ) | 5                   | 3.9-5              |
| 15 $\mu\text{m}$ Sn                                                      | 3.9                 | 3.4-3.9            |
| 12.5 $\mu\text{m}$ Ag                                                    | 3.4                 |                    |

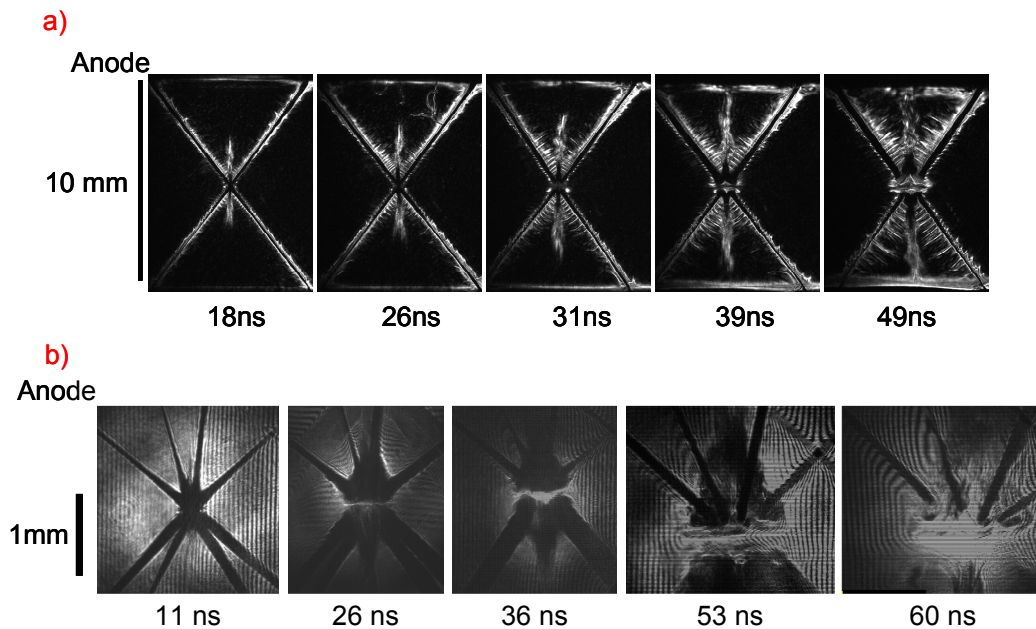
### 6.3 Cross Point Emission

Experiments were performed with two and four wires of various materials including Al, W( $5\ \mu\text{m}$ ), W( $7.5\ \mu\text{m}$ ), Mo; while anode-cathode separations of 10, 15, and 20 mm were utilized. The ‘best’ radiographic results (small spot size, short duration x-

ray pulse, and high energy photons) were obtained using four  $5\ \mu\text{m}$  diameter tungsten wires with an anode-cathode separation of  $1\ \text{cm}$ .

### Gap formation

Previous work has shown higher  $z$  materials to perform as better radiators. In response two setups of tungsten wires were studied to compare the influence of initial wire geometry. Here x-pinchs were composed of four  $5\ \mu\text{m}$  and two  $7.5\ \mu\text{m}$  tungsten wires. This enabled an increased level of symmetry with the four wire case while maintaining the material, anode-cathode gap ( $1\ \text{cm}$ ), and mass per unit length ( $2 \times 7.5\ \mu\text{m}$ :  $1.7 \times 10^{-5}\ \text{g/cm}$  and  $4 \times 5\ \mu\text{m}$ :  $1.5 \times 10^{-5}\ \text{g/cm}$ ) for the two setups.



**Figure 6-2** A side-by-side sequence comparison of two W x-pinch configurations having the same mass per unit lengths. Shown in (a) is a schlieren sequence of a two  $7.5\ \mu\text{m}$  W pinch, the images in (b) show interferometric images of the cross point from a four wire,  $5\ \mu\text{m}$  diameter x-pinch.

Figure 6-2 shows the development of the cross point for two and four wire tungsten x-pinchs. In the four wire experiments utilizing  $5\ \mu\text{m}$  diameter wires (b) the gap was observed to form  $\sim 20\ \text{ns}$  after the start of the current, which is approximately half of the gap formation time recorded from the sequence of two  $7.5\ \mu\text{m}$  wire x-pinchs

displayed in (a). The use of two larger diameter wires allowed the mass per unit length to remain consistent with the previous case. Above, the mass per unit length for four  $5\ \mu\text{m}$  wires was  $0.015\ \mu\text{g}/\text{cm}$  and for two  $7.5\ \mu\text{m}$  wires it was  $0.017\ \mu\text{g}/\text{cm}$ . Note: In most materials (Mo, Fe, Cu, Mo(Au)) the cross point became void of plasma around  $40\ \text{ns}$  after the start of the current, with an exception occurring in aluminum which recorded the formation of a gap at  $\sim 55\ \text{ns}$ . The use of a photo conducting diode (PCD) enabled the correlation of the emission of radiation with the physical formation of a gap in the plasma column, in the vicinity of the original cross point of the wires.

### 6.3.1 Time integrated emission

Initial studies of the pinch were done using film to capture the total emission from the pinch. In Figure 6-3a, the image of a calibrated DEF film displays the difference in transmission of the various filters combination. The remaining 6 pinholes (enclosed in green) were used for orientation of the film.

The plot in Figure 6-3b displays lineouts from various filtered pinholes. Variation in emission resulted in differences of pixel intensity on the film. Additionally, the narrower dip from the Ag filtered spot suggests that only a limited portion of the x-pinch was emitting in the associated energy range. From these profiles, and a visual inspection of the film, the contrast between the Ag ( $h\nu \leq 3.4\ \text{keV}$ ) and Sn ( $h\nu \leq 3.9\ \text{keV}$ ) spots is notable when compared with those of the harder filters; indicating that there was low as well as high energy x-ray emission. Additionally the darker appearance of the Cu filter ( $h\nu \leq 9\ \text{keV}$ ) over that of the neighboring Ni recorded the presence of x-rays with energies above  $8.4\ \text{keV}$ .

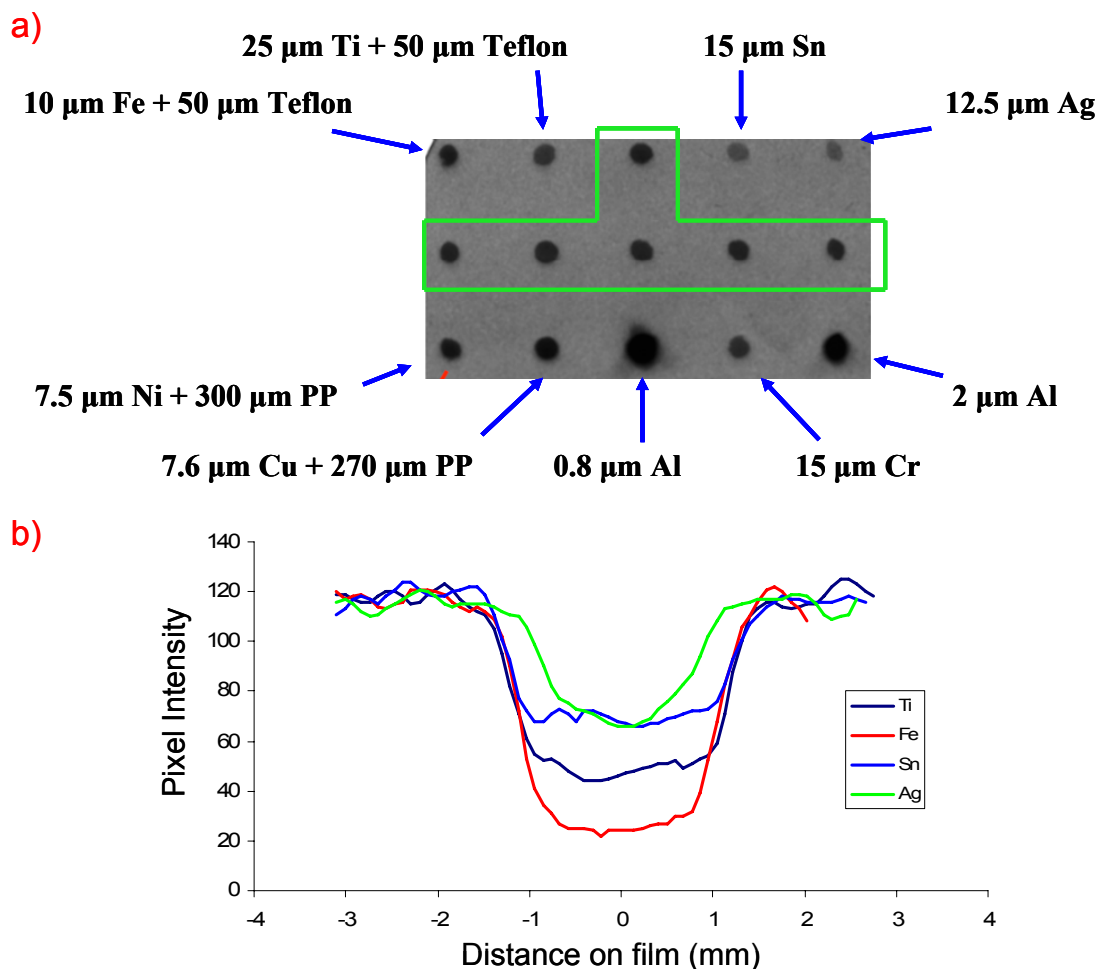


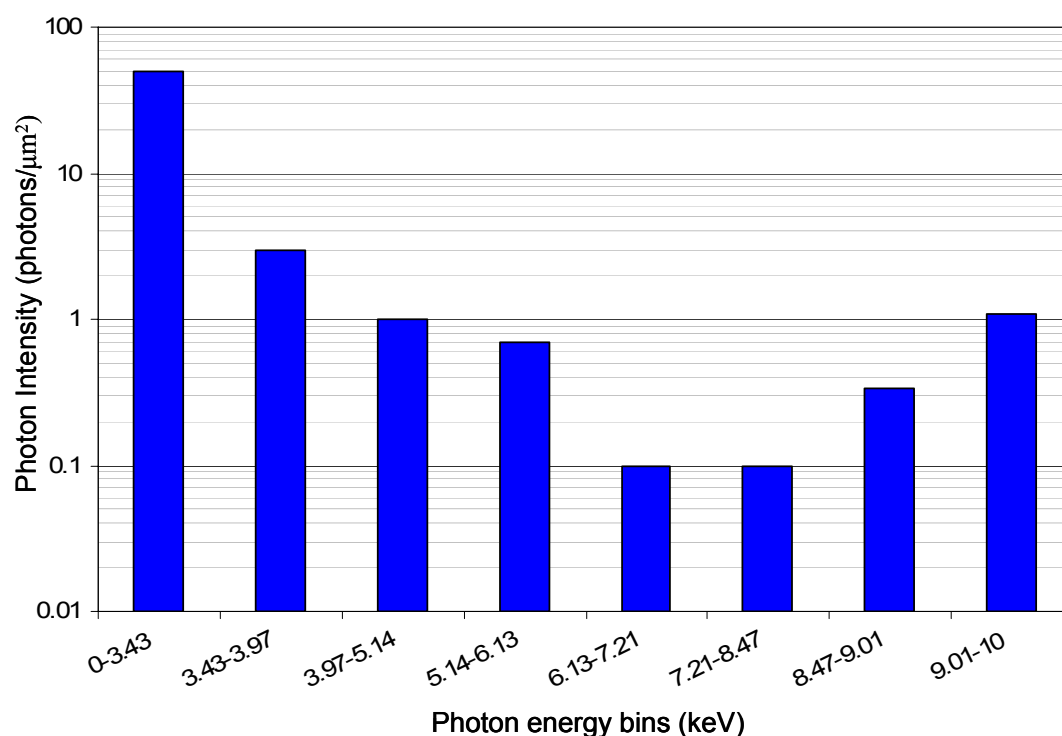
Figure 6-3 a) An image of a calibrated DEF film after exposure from a 5  $\mu\text{m}$  four wire W X-pinch. The spots in the green box were used in this shot as orientation markers for the film. B) contrasts the lineouts from various filtered spots in (a).

### Time Integrated Spectrum

The photon flux on the film was determined through an analysis of the recorded spots' intensity levels and the sensitivity date for the film. The spectrum radiated from the cross point of the x-pinch was calculated accounting for the system geometry and the filters placed on each pinhole. Figure 6-4 displays a histogram of the photon count for a four wire tungsten x-pinch. The presence of continuum radiation may be responsible for the low energy photons emitted from the compressed plasma and contribute to the

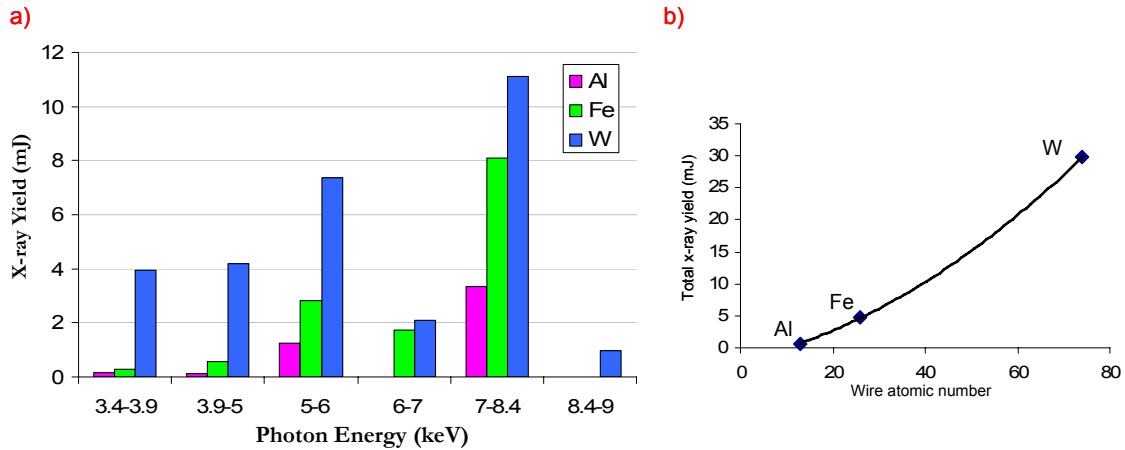


blackbody spectrum shape as discussed below. Additionally a possible source of the high energy emission  $> 8.4 \text{ keV}$  is copper  $K_\alpha$  line radiation ( $\sim 8.1 \text{ keV}$ ), a result of the heating of the brass electrodes. Similar emission profiles were generated for Al and Fe x-pinch, and the energies of the respective photon bins were then used to generate the energy spectra shown in Figure 6-5a. Note that here the x-ray yield energy is plotted; in comparison, Figure 6-4 was a plot of the photon intensity. The average emission of the tungsten x-pinch can be seen to dominate that of other materials from  $3.5 - 9 \text{ keV}$ .



**Figure 6-4** A typical time integrated spectrum (single shot) for a 4 wire  $5 \mu\text{m}$  diameter tungsten x-pinch.

Additionally emission from various materials varies, with the higher  $Z$  materials exhibiting the highest emission ie. Iron ( $Z = 26$ ) surpasses Al ( $Z = 13$ ) emission. From the requirement of  $> 5 \text{ keV}$  x-rays for imaging, a tally of the  $5 - 9 \text{ keV}$  tungsten emission yields a flux of  $\sim 1.8 \times 10^{13}$  photons.

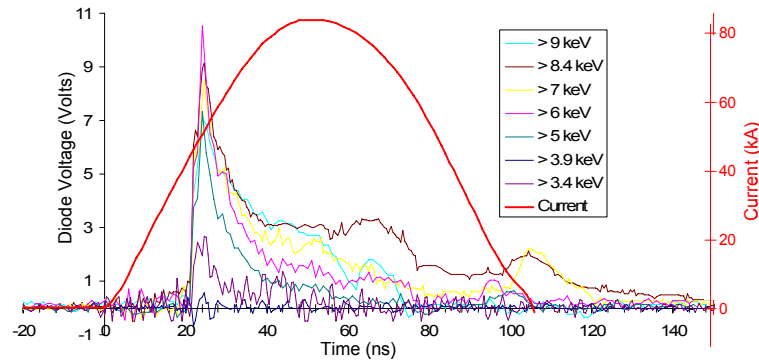


**Figure 6-5** a) Average x-ray yield from time integrated diagnostics for various wire material x-pinch as a function of emission energy. B) a chart of the total energy yield for the various materials from 3.4 – 9 keV as a function of atomic number. A second order polynomial trend is overlaid on the data.

Integrating the x-ray yield from 3.4 – 9 keV we find 3.0, 4.7 and 7.0 mJ for Al, Fe, and W respectively. A plot of the yields against atomic number appears in Figure 6-5b and a second order polynomial fit has been included to show the trend of the data.

### 6.3.2 Time resolved emission

To temporally characterize radiation from the cross point, in various energy ranges, a set of PIN diodes were filtered with Ross filter pairs. The diode signals displayed in Figure 6-6 were captured from a single four-wire 5  $\mu\text{m}$  tungsten x-pinch, and serve as a typical example of the output obtained for this configuration. The most prominent feature is a sharp initial peak appearing approximately 20 ns after the start of the current. Here, all the diodes recorded emission. This peak correlates well with the observed gap opening observed in the optical probing sequences discussed above. Progressing in time, a second peak was recorded ~50 ns after the first peak; in contrast to the first, only a rise in the signals from diodes F, D, and B was recorded.

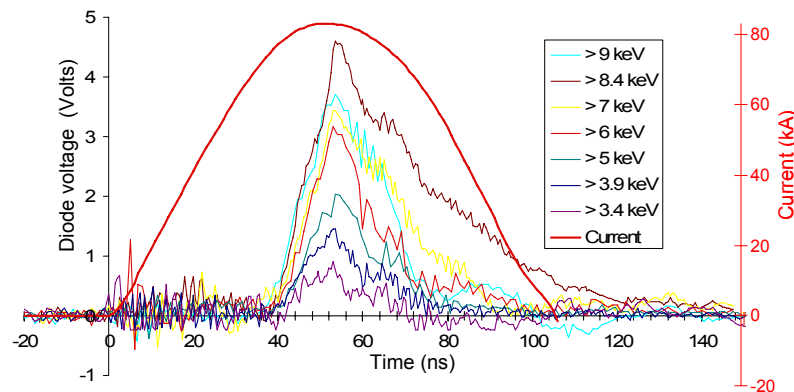


**Figure 6-6** A temporal evolution of the x-ray emission from 1-9 *keV* for a four wire, 5  $\mu\text{m}$  diameter, tungsten x-pinch as recorded by silicon diodes. The current profile is included (red) plotted with arbitrary units.

A third peak appears approximately fifty nanoseconds later and is captured exclusively by the Fe ( $\leq 7 \text{ keV}$ ) and Ni ( $\leq 8.4 \text{ keV}$ ) diodes.

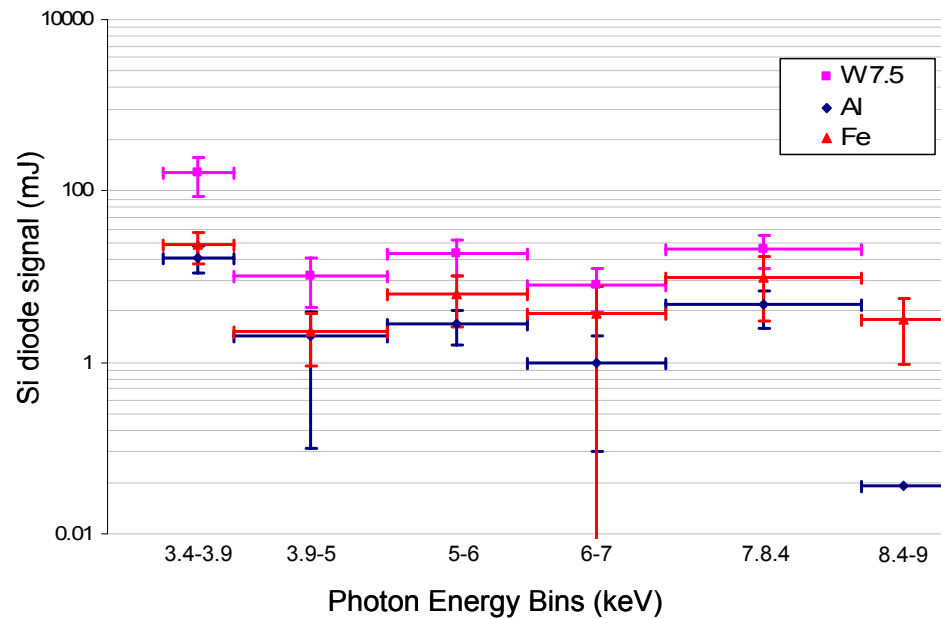
The variation in diode signals (by peak) captures the temporal evolution of the pinch, showing that earlier peaks radiate from 3-9 *keV* while later peaks exhibit radiation in only one or two energy bands. The variability of peak emission is addressed below.

In contrast to the sharp initial peak shown above, diode traces from low *Z* materials display a broad initial peak as the recorded emission from a two wire aluminum x-pinch demonstrates in Figure 6-7. Here a FWHM of  $\sim 42 \text{ ns}$ , and the absence of later peaks, further distinguishes it from the traces presented above for W wires.



**Figure 6-7** Diode traces from a two 15  $\mu\text{m}$  diameter, aluminum wire x-pinch. The current profile is included (red) plotted with arbitrary units.

Paralleling the analysis used for the time integrated emission, analysis of the diode signals was performed to recover the photon flux in various energy bins emitted by the x-pinch. A time integrated analysis of the signals was done to compare with the results obtained with the calibrated DEF film discussed above. Figure 6-8 plots the spectra from three materials with varying atomic numbers; different diameter wires were used to keep the mass per unit length approximately constant at  $\sim 0.01$ ,  $0.012$ , and  $0.015 \mu\text{g/cm}$  for Al, Fe, and W respectively.



**Figure 6-8 Emitted photon energy comparison for tungsten, iron, and aluminum x-pinchs. (Note: The designation of W 7.5 is used to identify a two wire tungsten x-pinch made with 7.5 micron wires, Al and Fe are standard wire diameters noted above)**

In this figure, horizontal error bars are used to bracket the various energy ranges of the filter combinations while vertical error bars are determined from the error associated with the diode traces. For all energy bins the radiation from the tungsten x-pinch was the highest of the three materials. In most bins, iron shows a higher level of emission when compared with that from the aluminum wires; however for the  $3.4\text{-}3.9 \text{ keV}$  and  $3.0\text{-}5 \text{ keV}$

ranges the emission amplitudes are very similar. For the high energy radiation (8.4-9  $keV$ ), a large discrepancy was found, with the Al emission an order of magnitude below that of Fe.

### 6.3.3 Individual Peak Emission

As noted above, the ratio of the diode signals from various time resolved peaks is not consistent, and therefore prompted an analysis of each successive emission. Due to tungsten's highest overall emission a more thorough analysis was performed on these x-pinch. In Figure 6-9a, the diode traces of a W x-pinch, show a fast rise-time, short-duration (FWHM  $\sim 10$ -30  $ns$ ) first peak (around the time of maximum current), and a subsequent slower-rise, broader peak. Shown in (b) is a schlieren image of the cross point just before peak current. Here the necked plasma is shown immediately preceding the maximum compression and breakup of the plasma column. A comparison with the diode traces shows that this is well correlates with the fist emission peak. The bar graph is (c) plots the spectrum obtained from the first peak, displaying a Plankian trend, with intensity falling off with increased photon energy. Here a large contribution is seen in the photon bins below 5  $keV$ , with only a small amount above 7  $keV$ . The peak of this distribution is centered between 3.9 and 5  $keV$ .

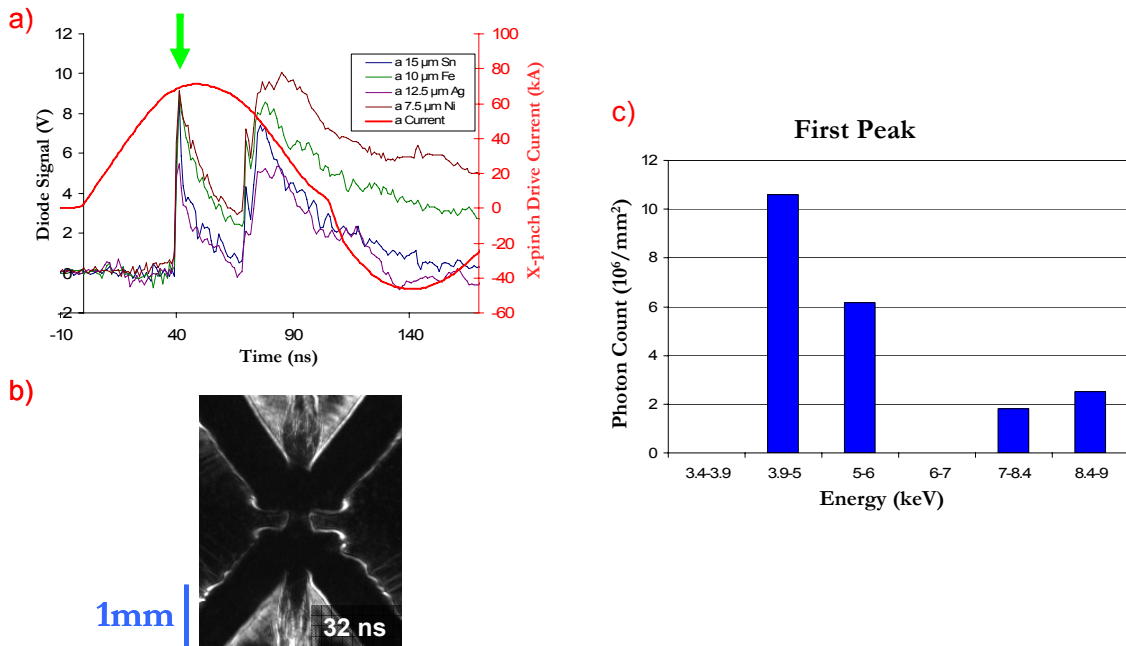
Due to tungsten's high atomic number it can be considered a good radiator and therefore it is appropriate to apply Plank's law for black body (BB) radiation [6-11]:

$$I(\nu, T) = \left( \frac{2hc^2}{\lambda^5} \right) \frac{1}{e^{hc/\lambda kT} - 1}. \quad (6.3.1)$$

Above  $h$  is Plank's constant ( $J \cdot s$ ),  $\lambda$  is the radiations frequency ( $Hz$ ),  $k$  is the Boltzmann constant ( $J/K$ ), and  $c$  is the speed of light ( $m/s$ ). For a BB energy spectrum the peak will occur at:

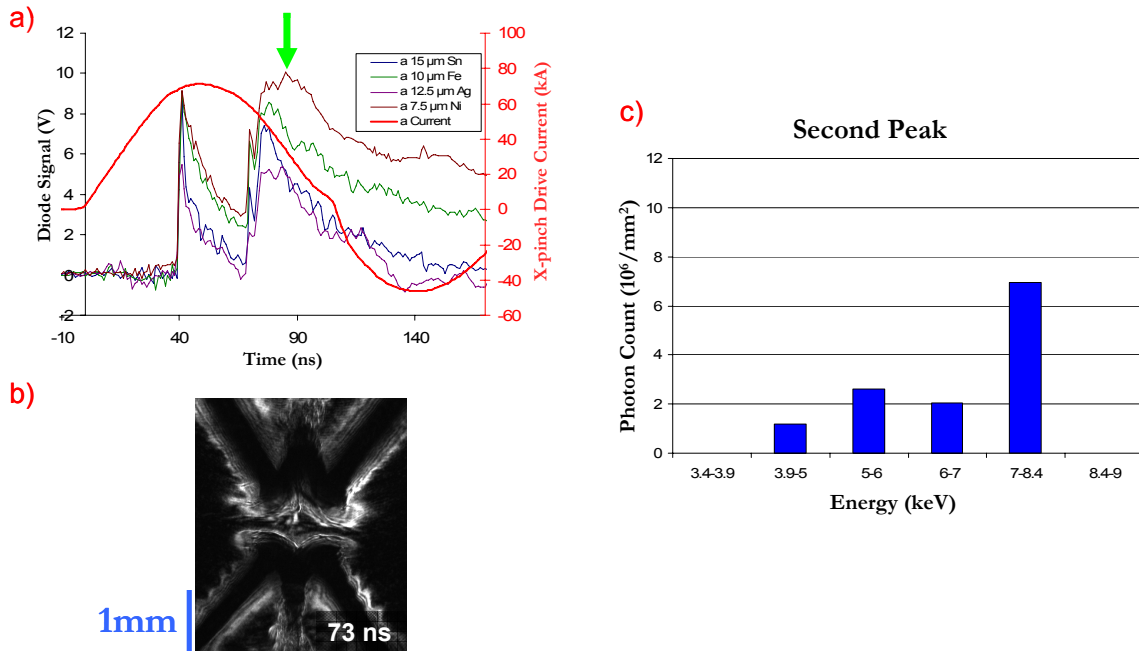
$$\lambda_{\max} = \frac{2.9 \times 10^3 (m \cdot K)}{T}, \quad (6.3.2)$$

where  $T$  is in Kelvin. For the spectrum centered at  $4.6 \text{ keV}$  a plasma temperature of  $917 \pm 118 \text{ eV}$  is found. The large error comes from the width of the Ross filter pair window. This value does not contradict previous cross point estimations of  $\sim 1 \text{ keV}$  for  $1 \text{ MA}$  drivers [6-12].



**Figure 6-9** X-ray emission from the first peak from a two wire  $7.5 \mu\text{m}$  diameter tungsten x-pinch. (a) shows a selection of the diode traces, (b) displays a dark field schlieren image at approximately the same time as the first emission peak, and (c) displays the spectrum extracted from the diode signals.

From the same experiment, an examination of the late emission is displayed in Figure 6-10. The second peak occurred 70-90 ns after the start of the current and exhibited a FWHM of 30-50 ns. This radiation took place well after the formation of a gap in the plasma, as depicted in the concurrent probing image in (b).



**Figure 6-10** X-ray emission analysis of the second peak from a two wire,  $7.5 \mu\text{m}$  diameter tungsten x-pinch. Here (a) shows a selection of the diode traces, (b) displays an optical probing schlieren image at approximately the time of the second emission, and (c) displays the spectrum extracted from the diode signals.

The spectrum emitted late in time was centered about the  $7\text{-}8.4 \text{ keV}$  range as evident in (c). From equation (6.3.2) the black body spectrum will be peaked at  $8.4 \text{ keV}$  for a plasma with a temperature of  $1.6 \pm 0.13 \text{ keV}$ . A further discussion of the temporal evolution of the emission follows.

### 6.3.4 Emission Discussion/Conclusions

Time integrated emission spectra displayed dual peaks at  $3 \text{ keV}$  and  $> 8.4 \text{ keV}$ . The contour of the lower energy emission is indicative of black body radiation where the emission decreases as the wavelength increases. However this does not account for the high energy emission peak. The break in continuum from the lower energies indicates that the  $h\nu \sim 8.5\text{-}10 \text{ keV}$  emission may be attributed to line radiation rather than thermal emission. A more through explanation is presented in conjunction with the temporally

resolved analysis.

### **Individual Peak Spectrum**

In the tungsten spectrum analyzed, the first peak occurred at  $\sim 40$  ns and was correlated with the presence of a small, dense plasma (optical probing) at the original cross point of the wires. The emission and high compression of the plasma at the location of maximum magnetic pressure indicated that the short duration emission could be attributed to the formation of a plasma hot spot and the resulting thermal emission. A blackbody spectrum was compared with spectrum recorded and corresponded to a  $T_e$  of approximately  $917 \pm 118$  eV which is well within the accepted values of previous hot spot temperatures.

After the plasma compression, the plasma column breaks forming a gap around the original cross point of the wires. The radiation which begins  $> 80$  ns after start of the current occurs well after this formation and therefore is not associated with a compression of plasma on the axis. For this late time emission a temperature of  $\sim 1.6 \pm 0.13$  keV is calculated, well above reported values and not likely to occur after the peak of the current. Instead an acceleration of particles by the electric field is more probable.

On either side of the formed gap two virtual electrodes maintain a high voltage potential as a result of the continued current drive. Within the gap, free electrons undergo an acceleration by the electric field. These electrons are driven along the axis encountering the remaining plasma or the anode. At this point, they deposit their kinetic energy. This mechanism, known as an electron beam, has the potential to create a broad spectrum of energetic electrons, up to 100 keV [6-10], and may be responsible for the slow-rise, long-duration, radiation recorded after the current maximum.



Additional support stems from the fact that for tungsten wires,  $h\nu$  values of  $> 7$  *keV* correlate to the 62<sup>nd</sup> ionization. Rather than such a high degree of ionization, a more plausible explanation comes from copper  $K_\alpha$  emission ( $\sim 8.1$  *keV*) generated when energetic electrons collide with the brass electrodes.

Individual peak analysis of various wire materials, although highly useful, and the evaluation of other wire materials is yet to be completed and may serve as the focus of future work.

## 6.4 Point Projection Radiography

The characterization of time integrated emission from various x-pinchs aided the selection of the correct wire material for use as a backlighting tool. From the results in the previous section the highest intensities of hard ( $> 5$  *keV*) radiation were obtained with tungsten wire x-pinchs, which established their use as an effective backlighter for capsule imaging.

### 6.4.1 Applications

As previously reviewed in chapter one there are a multitude of applications which utilize the small, bright x-ray emission generated at the cross point, extending from lithography to time resolved high density plasma radiography.

Central to the National Ignition Facility's (NIF) [6-1] Inertial Confinement Fusion (ICF) ignition target concept [6-3] are millimeter scale Be coated shells, containing moderate levels ( $> 0.25$  %) of a copper dopant. Their composition has emerged from their favorable energy absorption characteristics (pre-implosion), and hydrodynamic

properties during the plasma implosion phase; while the dopant serves to increase the stability of the ablator/D-T interface [6-4]. Once the outer plastic layer, of the capsules, is formed, a mixture of deuterium-tritium (DT) gas is introduced into the shell and then frozen to form an ice layer of uniform thickness inside the plastic shell. This is achieved through the slow lowering of the shells' temperature.

The primary limitations affecting the yield achieved from a capsule implosion is the uniformity and morphology of the outer beryllium ablator as well as the DT ice layer formed on the inside of the capsule. In response, an accurate micron-scale non-destructive characterization of the DT layer is crucial. The opaque nature of beryllium to visible light necessitates x-ray imaging techniques to examine the thickness and roughness of both the Be and DT ice layers. Traditional radiographic methods achieve the required phase contrast images with long exposures of a minute or more. Vibrations from the various systems, including cryogenic (necessary to keep the shells cold) introduce motion blurring in the images degrading resolution. The amplitude and frequency of vibrations are dependent on the mounting and amount of material contained in the capsules, with typical periods of vibration less than a quarter of a second. The reproducibility of the short duration, bright, micron-size x-ray source makes the x-pinch an ideal device for the characterization of Inertial Confinement Fusion (ICF) capsules.

#### **6.4.2 Capsule Imaging**

Due to the cryogenic restrictions associated with NIF shells, DT-ice filled capsules were substituted with low density CH foam shells which enabled storage and testing at room temperature conditions. In order to ensure viability of the results, the

parameters of the CH shells were kept as close as possible to the DT targets and are summarized in the Table 6-2 below, data was compiled from references [6-3], [6-4] and [6-6]:

**Table 6-2 Description of ICF D-T capsules and mock CH capsules**

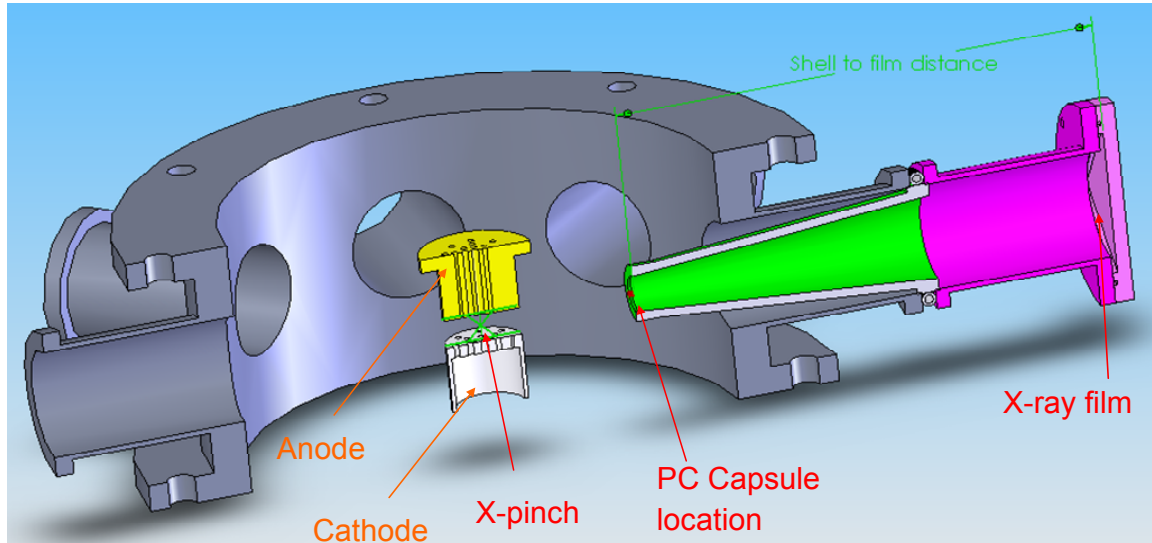
|                                     | <b>Purposed NIF (DT capsule)</b> |            |      | <b>CH plastic shell (no liner)</b> | <b>CH plastic shell (with CH foam liner)</b> |
|-------------------------------------|----------------------------------|------------|------|------------------------------------|----------------------------------------------|
|                                     |                                  |            |      |                                    |                                              |
| <b>Capsule diameter (mm)</b>        | 1.1                              | 1.19       | 1.37 | 2                                  | 1                                            |
|                                     |                                  |            |      |                                    |                                              |
| <b>Outer Layer</b>                  |                                  |            |      |                                    |                                              |
| Material                            | CH+0.25%Be                       | Be+0.9% Cu |      | CH                                 | CH                                           |
| Thickness ( $\mu\text{m}$ )         | 160                              | 160        | 113  | 20                                 | 20                                           |
| Density ( $\text{mg}/\text{cm}^3$ ) | 1,050                            | 1,943      |      | 1050                               | 1050                                         |
|                                     |                                  |            |      |                                    |                                              |
| <b>Inner Layer</b>                  |                                  |            |      |                                    |                                              |
| Material                            | Solid DT                         |            |      | N/A                                | CH foam                                      |
| Thickness ( $\mu\text{m}$ )         | 80                               | 50         | 92   | N/A                                | 80 $\mu\text{m}$                             |
| Density ( $\text{mg}/\text{cm}^3$ ) | 250                              |            |      | N/A                                | 100                                          |
|                                     |                                  |            |      |                                    |                                              |
| <b>Center</b>                       |                                  |            |      |                                    |                                              |
| Material                            | DT gas                           |            |      | Vacuum                             | Vacuum                                       |
| Density ( $\text{mg}/\text{cm}^3$ ) | 0.3                              |            |      | $\sim 0$                           | $\sim 0$                                     |

#### 6.4.2.1 Contact radiography

Initial experiments were performed using contact radiography; the capsule was placed directly in front of the film located in the x-ray camera (pink) pictured in Figure 6-11 below. This method relies exclusively on the transmission properties of the object, where the transmission is defined by:

$$T = \frac{I}{I_0} = e^{-\sigma l N}.$$

Above  $l$  is the path length through the object,  $\sigma$  is the cross section of light absorption for a single particle, and  $n$  is the number density per unit volume.



**Figure 6-11** Cut-through of the experiment vacuum chamber model showing the capsule imaging diagnostic setup. The cone (green) enabled proximal placement of the shell to the pinch source for phase contrast imaging; while The x-ray film camera (pink) was located outside the chamber, allowing the removal and relocation of the film to the darkroom (for processing) with minimal additional exposure.

Comparing the calculated transmission of 8 *keV* photons through a 200  $\mu\text{m}$  sample of Be ( $1.84 \text{ g/cm}^3$ ) and one of solid DT ( $0.25 \text{ g/cm}^3$ ) yielded values of 96.3% and 99.9% respectively. The similar low absorption characteristics of the shell materials will be indistinguishable in practice, and demonstrate that contact radiography is not an effective method to image the inner DT ice layer.

In response, phase contrast (PC) imaging was employed to capture the low density interfaces by leveraging the variation in diffraction properties of the different shell layers. Before proceeding it is important to note that the low density CH foam has a similar refractive index to solid DT making it a suitable substitution choice.

### 6.4.2.2 Phase Contrast (PC) Radiography

Phase contrast (PC) imaging, relies on the contrast of phase delay, and refractive index of the capsule layers to construct an image. For the shells discussed above; the phase delay of D-T ice is of the same order as beryllium. A cartoon of the x-ray propagation is shown below in Figure 6-12. In contrast to contact radiography, the film (v) is located away from the capsule (iv) allowing the propagation of the x-rays after they have emerged from the capsule.

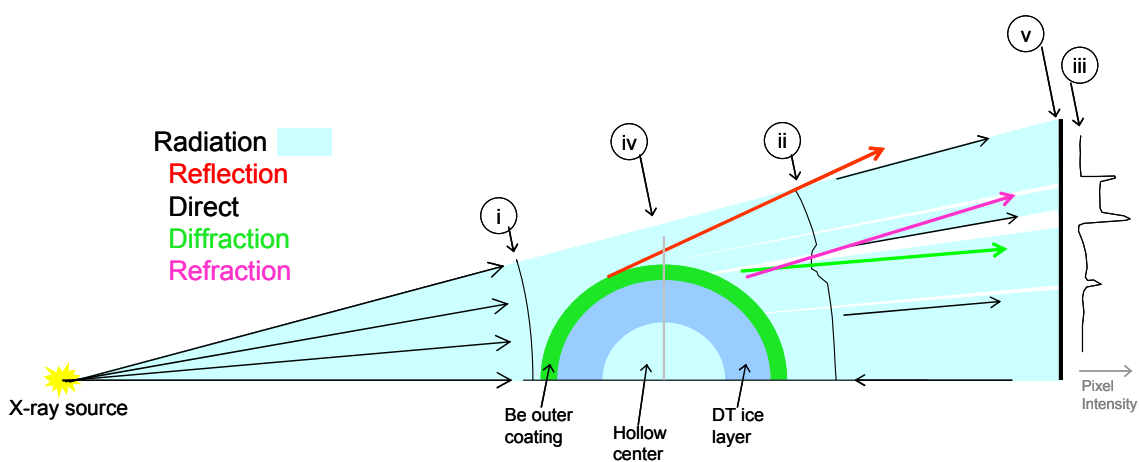
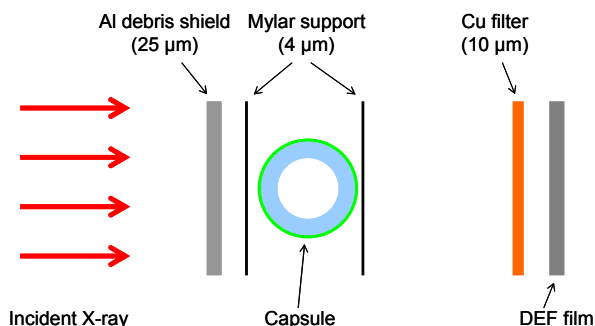


Figure not drawn to scale

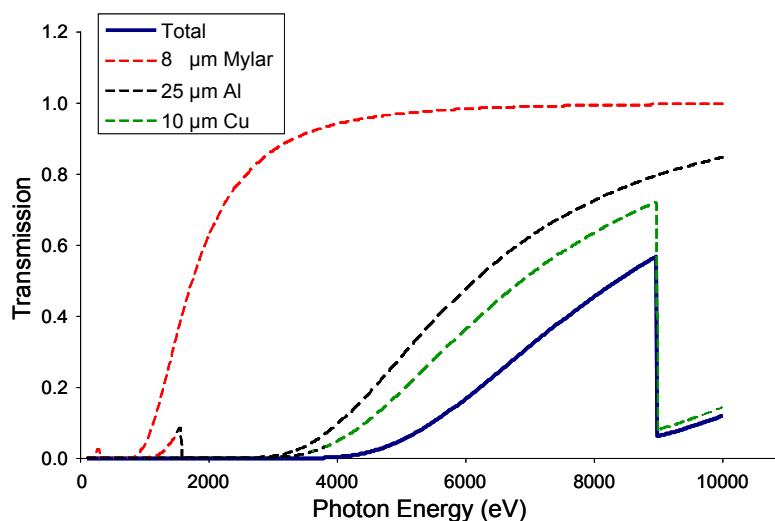
**Figure 6-12** A cartoon illustrating Phase Contrast, x-ray backlighting. (i) designates the spherical wave-front emitted by the x-ray source, (ii) the radiation intensity immediately behind the shell where intensity fluctuations are due to absorption, and (iii) an intensity profile far from the shell where phase contrast effects have been highlighted the boundaries of the various density layers. (iv) the central plane of the capsule and (v) the location of the detector plane for phase contrast imaging.

After the x-rays are generated they propagate as a spherical wave front (i) until they intersect the capsule, where the various materials decrease the group velocity at different rates. Absorption in the opaque outer layers attenuates the incident radiation creating a contact radiography image immediately behind the shell (ii). Refraction within the target layers redirects the rays forcing their interaction as they propagate away from the shell. As the distance to the film plane increases (v), so do the magnification and the diffraction effects, which manifest as peaks in the intensity profile (iii).



**Figure 6-13 Cartoon showing the x-ray filters between the radiation source and the film**

In order to perform the PC imaging of the shells, the configuration depicted in Figure 6-11 was used. The implementation of metallic filters to protect the capsules from debris, and filter out low intensity radiation was as follows. Between the source and the shell is a  $25\ \mu\text{m}$  Al filter to block debris. The shell is held in place by two  $4\ \mu\text{m}$  mylar sheets on both sides and finally a  $10\ \mu\text{m}$  thick copper filter was placed in front of the film to filter out x-ray energies below  $5\ \text{keV}$ , an illustration of the x-ray path is shown in Figure 6-13



**Figure 6-14 Plot of the transmission values for the various filters used to image CH capsules. Prominently displayed is the  $\sim 8.4\ \text{keV}$  energy cutoff of the Cu filter.**

The filters were taken into account when analyzing the flux recorded on the film.

The respective transmissions are plotted as a function of photon energy; the total

transmission is shown in dark blue. A strong influence of the Cu filter  $\sim 8.4$  keV energy cutoff is observed in the overall transmission of x-rays to the film.

### 6.4.3 Contact Radiography Imaging

Initial experiments with W x-pinchs, set plastic capsules directly on x-ray film and yielded the radiograph shown in Figure 6-15a. The center of the capsule was determined and a series of radial lineouts were taken at angles which correspond to the black spots superimposed on the film.

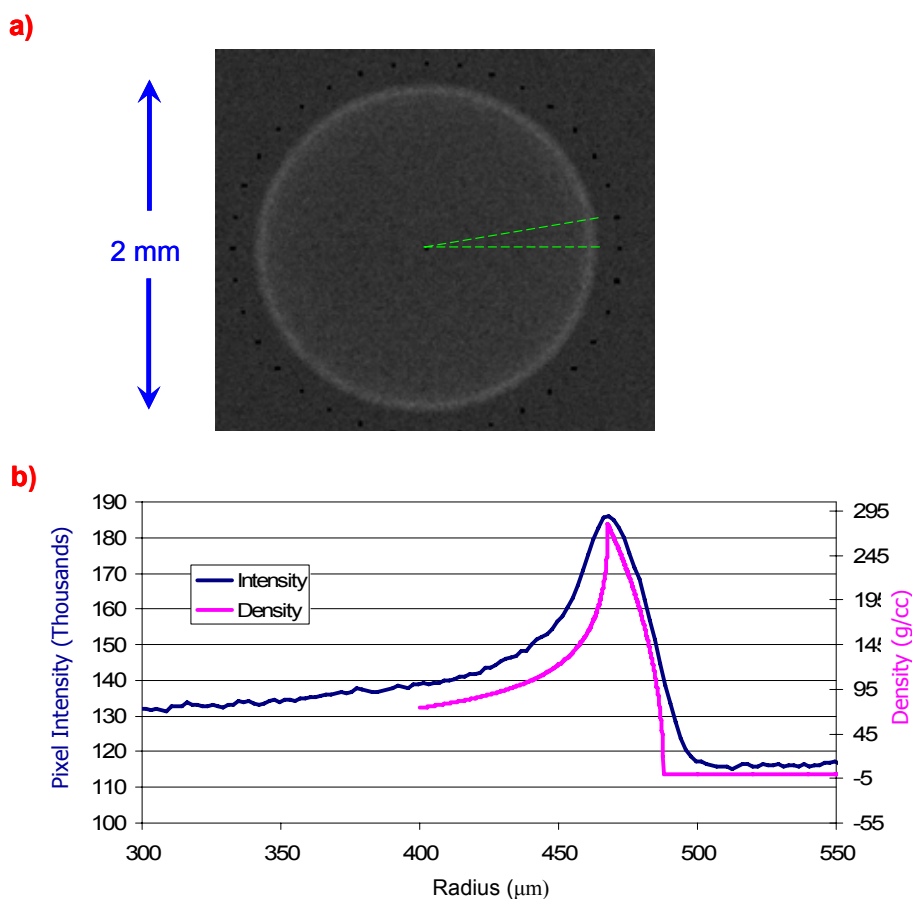


Figure 6-15 Contact radiography data for a 2 mm diameter, CH plastic, shell with a wall thickness of 49 μm. The image in (a) is an image created by placing the shell directly on the radiographic film. The black dots indicate the end location of lineouts taken from the center along the radii of the shell. The plot in (b) includes the average pixel intensity, as a function of radius, from the lineouts taken in (a) (blue) as well as the density profile encountered by a photon traveling through the shell (pink).

Two examples are highlighted by dashed green lines in the figure. The average of the lineouts was taken and is plotted in blue in Figure 6-15b. Plotted in pink is the calculated density encountered by a photon as it travels through the capsule. Due to the placement of the capsule directly on the film, the only notable effect on the photons is absorption from the plastic. In the plot, the intensity on the film is seen to closely follow the density profile as expected. Deviations between the two curves may have resulted from a non-symmetrical shell or a small misplacement of the central spot.

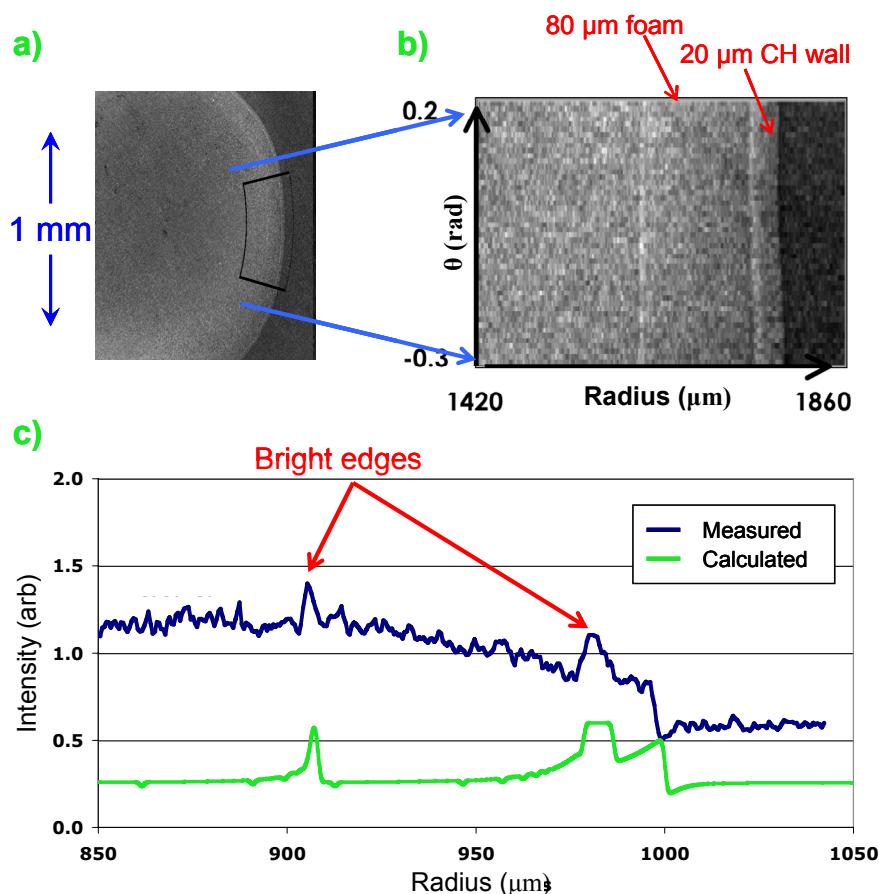
#### 6.4.4 Phase Contrast Radiographic Imaging

To identify the boundaries between the different layers of the capsules, the shells were moved away from the film, closer to the x-pinch source, and positioned as described in section 6.4.2.2.

The image appearing in Figure 6-16a is a radiograph of a 1 mm diameter CH shell with a 20  $\mu\text{m}$  thick outer layer and an 80  $\mu\text{m}$  thick low density foam layer. The x-ray film results in dark regions with high photon flux, and light regions that are not heavily exposed. The left side of the image appears lighter when compared to the right due to the absorption properties of the plastic but does not effect the short variations in intensity which are investigated. As expected, the center of the shell appears slightly darker than the perimeter, as photons passing through the center of the shell encounter the least amount of material, reducing absorption.

A black outline identifies a region close to the edge of the capsule which is re-plotted in (b) as theta vs. radius. In this plot, four regions are identifiable: the shell interior, the foam layer, the opaque shell wall, and the region outside the capsule.





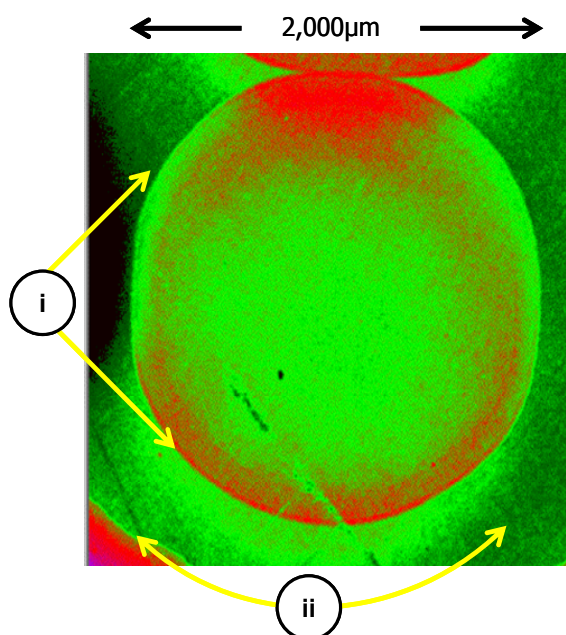
**Figure 6-16** Results from phase contrast imaging of a CH shell with a low density foam liner. Shown in (a) is a portion of a shell radiograph produced from a single shot, an expansion of the region outlined in black appears in (b) plotted as theta vs. radius. An average across theta is plotted in (c) in blue and compared against a theoretical of intensity vs. radius.

In the figure appearing in (b) the regions inside the shell appear to have the same pixel intensity; however, they are separated by bright pixels appearing as vertical while lines in the plot. An average across theta was taken to generate the ‘measured’ (blue) curve appearing in Figure 6-16c. A gradual downward trend is observed in the intensity and can be attributed to the absorption of the plastic; however this does not show a clear interface. More importantly are the intensity spikes appearing at the interfaces of the various layers (marked with red arrows). These peaks correspond with those appearing in the ‘calculated’ intensity profile shown in green. The calculations for the generated

intensities were done using a ray tracing program [6-14] developed in collaboration with General Atomics. Another feature of the PC imaging, and appearing in both profiles, is the dip in intensity around  $1000\ \mu\text{m}$  at the outer edge of the capsule.

#### 6.4.5 The Presence of Multiple Emission Sources in Capsule Imaging

As previously shown, often x-pinchs generate multiple x-ray emissions. Figure 6-17 shows a false color radiographic image of a non spherical  $2\ \text{mm}$  diameter shell.



**Figure 6-17** A false color image of radiograph of a non spherical capsule showing the recording of multiple images. (i) Identifies the sharp boundary image obtained from a small x-ray source while (ii) highlights the diffuse shell outline produces from a large source.

Here two images are superimposed, the first (i) exhibits a sharp boundary for the  $20\ \mu\text{m}$  outer layer indicating a small x-ray source, while the second image (ii) shows a very diffuse boundary indicating a large source size. Additionally, the two shell images are offset (not concentric) indicating that the two sources were offset in the vertical direction. From the sharpness and position of the secondary image the second source had a diameter of  $\sim 100\ \mu\text{m}$  and was offset from the first by  $\sim 130\ \mu\text{m}$ . This results does not contradict

the results presented in [6-13] in which micro z-pinches were recorded with lengths of  $150 \mu m$ .

#### 6.4.6 Limitations of Capsule Imaging

For the profile presented in Figure 6-16 the signal to noise ratio is approximately one with the position of the edges determinable to  $\sim 0.5 \mu m$ . Due to the low resolution the uniformity of the inner layer can only be found for the first few modes. The relatively high noise levels observed in the shell images arises from the large grain size of the Kodak Industrex film used to record the image. The resolution of the image is ultimately limited by the shot noise arising from the limited number of photons that are available to form the image. The image used for analysis was captured  $55 mm$  from the source, resulting in a flux of  $\sim 500 \text{ photons} / \mu m^2$  at the film. Approximating the film as an ideal recording medium, this results in a 20% high (FWHM)  $2 \mu m$  wide edge, superimposed over  $\sim 4\%$  noise fluctuations. Here the ideal signal to noise ratio (SNR) would be 5. For  $1 \mu m$  pixels (at the capsule) and a  $2 mm$  diameter shell the number of pixels along the circumference  $N_{pts}$  is  $\sim 6000$ . From the analysis by Montgomery *et al.* (see reference [6-9]) the highest theoretical resolution or ‘noise floor’ is defined as:

$$noise \quad floor = \frac{25}{N_{pts}} \left( \frac{\Delta x}{SNR} \sqrt{\frac{FWHM}{2}} \right)^2 \quad (6.4.1)$$

Where  $\Delta x$  represents the microns per pixel and the FWHM is given in pixels. Taking the above parameters yields a noise floor of  $0.17 nm$  which is sufficient to characterize the DT ice layer described in [6-4].

### 6.4.7 Summary

An initial investigation into the emission of the cross point revealed time integrated spectra with peaks at 4.5 and 8.5 keV. The overall x-ray yields from various materials increased directly with the atomic number, producing 3.0, 4.7 and 7.0 mJ for Al, Fe, and W respectively.

In order to further investigate the cross point emission, Si diodes (in conjunction with Ross filter pairs) were used to record time resolved spectra. Signals, recorded variations in peak emission with high Z materials having short, fast rise-time peaks around the peak current (40 ns); while broader, long rise-time peaks were associated with lower Z materials such as Al. Additionally, Al emission typically occurred 15 ns later than other materials or 55 ns after the start of the current.

The silicon diodes also revealed the presence of a late time emission well after the formation of a gap in the x-pinch plasma at the cross point. This prompted individual analysis of the primary emission ( $\sim 40$  ns) and the late time emission  $\sim 80$  ns after the start of the current. Results from the first peak indicated a Plankian BB spectrum centered around 4.5 keV which gave a plasma temperature of  $\sim 900$  eV. The second peak showed very little low energy emission and a peak in the 7-8.4 keV range. Analysis concluded that the most probably mechanism for the later emission is an electron beam along the axis of the pinch.

The use of the x-pinch as a backlighter has been well documented however very few of those utilize its short-duration and small source-size characteristics. Above the use as an ICF capsule diagnostic was developed. Initial results from contact radiography demonstrated the ability to produce a clear, detailed image from a single shot exposure.

The extension of the work to phase contrast imaging, demonstrated the ability to image internal shell layers whose low density made them insensitive to absorption imaging. Additionally, a small x-ray source size (micron scale) enabled the imaging of the 20  $\mu\text{m}$  thick shell outer layer. This work serves as the first demonstration of the x-pinch as a viable tool for the non-destructive diagnosis of opaque ICF capsules requiring micron scale resolution.

# Chapter 7

## Summary and Future Work

The work presented in this thesis has demonstrated that the geometry of an x-pinch comprises an extensive range of plasma physics, generated by a simple multi-wire configuration having a single cross point. Additionally, the ability to create and study High Energy Density Plasmas on a compact, university scale, pulse power driver was demonstrated.

Research into the ablation (chapter three) and dynamics of the coronal plasma (chapter four) has furthered the understanding of the physics involved in this high energy density system. While characterization of the plasma jets formed (chapter five) as well as the x-ray emission (chapter six) has advanced the role of the x-pinch as a tool useful in the study of astrophysical plasma jets and the characterization of the next generation of energy resources. The work presented is paramount in linking the plasma physics observed in wire arrays with that present in x-pinch.

The first comparison of Rocket model to the wire ablation in x-pinch was well correlated, verifying that the physics governing multi-wire pulse power experiments is applicable for various configurations. The use of simultaneous, complimentary,

diagnostics provided information of the location of the current during the experiment for various wire materials. Additionally, an investigation of the jets produced, found that while the physical parameters show vast differences, both systems can be treated hydrodynamically, with their scaling parameters falling above the critical transition values. As a result, estimates of the scaling parameters necessary for the study of astrophysics were calculated, demonstrating the applicability of laboratory results to interstellar plasma jets. Finally, the first use of an x-pinch as an effective ICF capsule diagnostic was demonstrated. The results from each topic covered in this thesis are summarized below, followed by prospects of future work in each of the respective topics.

## 7.1 Ablation

The modulated wire ablation observed in x-pinchs is similar to that observed in experiments subjecting ablating wires to a global as well as local magnetic field. Examples include cylindrical, conical, and planar wire arrays. Although the cause of the periodic density structures has not been determined experimentally, simulations have been able to reproduce the results captured in the laboratory.

The work presented in chapter three marked the first investigation of the non-uniform coronal plasma exhibited in x-pinchs. By 49 *ns* electron densities reached  $1.1 \times 10^{18} \text{ cm}^{-3}$  as distance of 0.25 *mm* from the wire core. The wavelengths observed for tungsten and iron x-pinchs correlated well with the same materials on alternate generators with varying maximum currents and risetimes. Because of the independence of experimental parameters ( $I_{\text{max}}$ , array radius, risetime) a comparison with the Rocket Model (previously developed for wire arrays) was performed. The resulting good

agreement supported the notion that the wire ablation is dominated by the current rise rate and is insensitive to the maximum current or experimental geometry imposed.

The first analysis of the density profiles from the x-pinch limbs matched well with the density profiles predicted by the Rocket Model validating its applicability to x-pinches. The density contrast ratio was found to increase as the distance from the wire increased, correlating well with 3D resistive MHD simulations indicating that the perturbation is likely due to an  $m = 0$  magnetohydrodynamic instability.

### **Future work**

The presence of the density perturbations is exhibited in experiments that impose a global as well as local magnetic field on an ablating plasma. In contrast, single wire experiments do not display the same ablation features. The modulation first developed adjacent to the cross point of the wires and then develop at greater distances as time progresses. This may be due to minimum global field required to drive plasma off of the wires. Experiments with the ability to alter/monitor the magnetic field topology may provide useful information regarding their formation mechanisms.

In response, ablation studies for varying ratios of global to local magnetic fields would prove informative, determining if there is a critical value at which the periodic structures appear. The geometry of the x-pinch lends itself to such work as the wire distance to the axis rapidly changes as a function of distance from the cross point. Currently experiments studying the profiles of the density flares are being performed at various distances from the cross.



## 7.2 Coronal dynamics

Following the ablation the wires are surrounded by a low density corona. This hot conducting plasma influences the current distribution, and as a consequence is responsible for a majority of the subsequent x-pinch dynamics.

Chapter four examined the dynamics of the coronal plasma ablated along the limbs of an x-pinch. The corona as well as the overdense plasma followed a trend in which the wire material governed the expansion speed, with higher  $Z$  materials expanding at slower rates. In the case of the overdense plasma, aluminum exhibited velocities of  $\sim 9 \times 10^5 \text{ cm/s}$ , well above those seen for Fe and W of  $\sim 3$  and  $\sim 2 \times 10^5 \text{ cm/s}$  respectively. The discrepancy was present, although less pronounced, in measurements of the low density coronal plasma. As in the previous case aluminum exhibited the highest expansion rate followed by iron and then tungsten. This disparity can be attributed to the wire material's ability to radiate the deposited energy. Lower  $Z$  materials do not radiate as efficiently resulting in a higher thermal energy.

A comparison of the expansion rates for various materials with the theoretical sound speed values at  $15 \text{ eV}$  (reasonable for the corona) indicated that the plasma expansion is heavily influenced by the sound speed of the wires. A more detailed inspection of the wire expansion data highlighted a transition, around  $30 \text{ ns}$ , to a slower expansion rate. The kinetic pressure ( $P = 9.3 \times 10^7 \text{ Pa}$ ) agreed well with the magnetic pressure ( $8.3 \times 10^7 \text{ Pa}$ ) calculated for the location indicating that a balance of the pressures was responsible for a confinement of the plasma around the x-pinch limbs.

The presence of an axial plasma unconnected to the pinch limbs, as well as, no visible flare structures present in the optical Al images prompted the use of simultaneous

self emission imaging to visualize the coronal plasma below the density detection threshold of the optical probing system. In high  $Z$  materials (W) the hot emitting plasma and hence the current remained in the vicinity of the wire core for a majority of the experiment; only late in time did the current transition to the axis. In contrast XUV imaging of low  $Z$  materials (Al) captured an emitting plasma connecting the wires and the axis, indicating that the current was traveling through the low density plasma to the axis. In this case the current was frozen in the plasma and as it was swept to the axis by the global B-field.

Results from bare molybdenum wires paralleled those from aluminum, while Mo wires coated with a thin layer of gold demonstrated behavior similar to the high  $Z$  material wires. The variation in behavior of the plasma was explained by the difference in resistivity of the wire materials. In the analysis resistivity was found from the Spitzer model and the Coronal Equilibrium model was used to determine the discrete ionization state of the plasma as a function of temperature. The material's resistivity dictated the magnetic Reynolds number which was a strong indicator of whether the current was frozen in the plasma or had the ability to diffuse. For the higher  $Z$  materials a higher resistivity ( $Re_m < 1$ ) and was associated with a diffusive plasma the consequences of which were verified in experiments. Alternatively, low  $Z$  materials exhibited lower resistivity values ( $Re_m > 1$ ), describing a plasma in which currents which were not able to diffuse. This was also exhibited in the experimental results. The magnetic Reynolds number has historically been difficult to measure and this work marks the first estimation of  $Re_m$  in the plasma produced from the x-pinch wire geometry.

## Future work

As presented, the corona is responsible for the distribution of the current in the experiment. At this time, only an inference of the current path is possible, however a complete picture of the current would prove immensely useful in the understanding of prevailing physics as well as a benchmark for 3D resistive MHD simulations. It would also be of potential interest to investigate a variety of bare and coated wire materials to determine the effects of radiation on the coronal behavior.

The use of an insulated concentric ring electrode equipped with individual current monitors would enable the tracking of the current path within the x-pinch during an experiment.

## 7.3 Plasma jets

Approximately 10 *ns* after the start of the current a plasma is seen to form on the axis of the x-pinch. As time progresses this is seen to propagate on along the axis, away from the cross point of the wires. The work in chapter five is the first investigation of freely propagating x-pinch jets and their scalability to the large scale plasma jets ubiquitous in astrophysics.

Through the  $\mathbf{J} \times \mathbf{B}$  force, plasma from the legs of the pinch is accelerated radially inward, upon reaching the axis its radial momentum is thermalized while the vertical momentum carries the plasma away from the cross point. Initial results recorded the formation and propagation of the jets and found that various materials produced jets of similar velocities of  $\sim 8.8 \times 10^6 \text{ cm/s}$  (optical probing) between the cross point and the electrodes.

An ongoing source of contention is the source of the plasma making up the x-pinch jets, previous work has supported contributions from both the wire limbs and the hydrodynamic ejection of material from the cross point of the wires. However, velocity measurements from self emission imaging ( $\sim 1.1 \times 10^7 \text{ cm/s}$ ) matched well with the calculated plasma ‘zipper’ velocity, indicating that the axial plasma is dominated by the flow of plasma from the x-pinch limbs.

Once formed, the jets were observed propagating up to 16 *mm* from the cross point of the wires (9 *mm* from the top of the electrode). Analysis suggested that two distinct regions were established for the axial propagating plasma. The first, close to the cross point, is below the ‘merger point’ (where the plasma from the wires merges on the axis) and the axial plasma is kinetically driven by the plasma ablating from the wires. The second region lies beyond the merger point and corresponds to distance at which the jet is freely propagating and no longer fed by the x-pinch limbs.

A study of the x-pinch limbs revealed that only the 65 % of the wire limbs (adjacent to the cross point) significantly contributed to the axial plasma column, demonstrating freely propagating jets for distances of up to 19 jet radii. Here the axial plasma was measured to have axial velocities of  $\sim 3 \times 10^6 \text{ cm/s}$ .

The propagation of the jets into vacuum allowed the jet to expand radially at the sound speed of the plasma (found to be  $5.5 \times 10^5 \text{ cm/s}$ ), and established a Mach number of 6 for the x-pinch jets. Through a CE treatment, an electron temperature of  $\sim 7 \text{ eV}$  was calculated. This temperature did not contradict data recorded with the MCP diagnostic. Additionally, self emission images enabled estimates of the jet cooling lengths of 0.05 to 0.5 *cm*.

Finally, an investigation into the validity of the scaling parameters revealed that while the Mach number, cooling parameter, and localization parameter were in the correct regime, however the density contrast, Reynolds number, and Peclet numbers differ by orders of magnitude for the two systems. Initial estimates of the Euler scaling parameters revealed that 100 *years* in the astrophysical systems may be represented by 19 *ns* in the laboratory system allowing an extended study of plasma jet formation and propagation.

### **Future work**

At this time it is believed that a combination of sources contribute to the jets, however a full understanding of their contributions has yet to be determined. Understanding would be enhanced though more accurate/direct measurements of temperature this would also provide a greater certainty of the cooling length of the jet and can be achieved through axially resolved spectroscopy. Additionally, interferometric imaging of various material jets above the anode would aid comparisons with results on conical wire arrays. More sensitive density measurements would reduce the errors associated with the determination of the tip and thus the overall length of the jet.

A thorough understanding of these jets will most likely be attained through comparisons with 3D MHD simulation results. At UCSD, work has already begun to study the jets through simulations (see D. Haas et al.; Supersonic jet formation and propagation in x-pinch, *Astrophysics and Space Science*, submitted).

An extension of the work related to the astrophysics would propagate the jets into gas clouds or other plasma so simulate the propagation of astrophysical jets into solar winds and the inter-stellar medium (ISM). This would also serve to reduce the density

contrast ratio ( $\eta$ ) aligning it more closely with the value observed from astrophysics. Additionally, increased accuracy of the scaling parameters (Re and Pe numbers) may be achieved through an increase in the jet density which may be achieved with larger drive currents. As a result, accurate scaling between the two systems appears possible provided advances in a few parameters can be made. Experiments at mega-ampere facilities have been performed to investigate astrophysical jets through those produced in the laboratory as referenced in chapter one and five.

#### **7.4 X-pinch cross point emission and x-ray radiography**

The culmination of the plasma dynamics investigated above occurs around the peak of the current pulse through the emission of x-rays from the cross point of the wires. Although previously studied for use as an x-ray backlighter the work in chapter six extended this work by investigating the temporal evolution of the spectrum as well as exploring the viability of the x-pinch as an x-ray backlighter for ICF capsules.

Integrated emissions for the entirety of a tungsten wire experiments revealed a spectrum with two peaks at 4.5 and 8.5 *keV*. The overall x-ray yields from various materials increased directly with the atomic number, producing 3.0, 4.7 and 7.0 *mJ* for Al, Fe, and W respectively.

Time resolved signals, recorded variations in peak emission with high *Z* materials having short, fast rise-time peaks around at  $\sim 40$  *ns*; while broader, long rise-time peaks were associated with lower *Z* materials such as Al. Additionally, Al emission typically occurred 15 *ns* later than other materials or 55 *ns* after the start of the current.

Analysis showed a difference in the primary emission ( $\sim 40$  *ns*) and the late time

emission ( $\sim 80$  ns). Spectra from the first peak indicated a BB Plankian spectrum centered around  $4.5$  keV which giving a plasma temperature of  $\sim 917$  eV. The second peak displayed minimal low energy emission and a peak in the  $7\text{--}8.4$  keV range. Analysis concluded that the most probably mechanism for the later emission was an electron beam generated late in time along the axis of the pinch.

The second part half of chapter six developed the use of the x-pinch as a radiographic source for the characterization of ICF capsules. Results from contact radiography were able to produce a clear, detailed image of an absorbing ICF shell from a single shot exposure. Phase contrast imaging demonstrated the ability to image low density internal shell layers whose which were transparent to the incident x-rays. Additionally, a small x-ray source (micron scale) enabled the clear imaging of the  $20\text{ }\mu\text{m}$  thick CH outer layer. This work serves at the first demonstration of the x-pinch as a viable tool for the non-destructive diagnosis of opaque ICF capsules requiring micron scale resolution.

### **Future work**

While the development of the x-pinch as a backlighter has extensively optimized the physics driving the radiative collapse of the cross point is still not well understood. As technology advances to meet the requirements of scientists in the laboratory, higher spatial resolution and shorter temporal resolution will aid in the understanding of this very fast unstable collapse and consequently the physics involved.

Future work to optimize the x-pinch as a radiographic tool is constantly being performed. Efforts to minimize multiple x-ray burst and tailor the energy of the emission will be attained from the investigation of new wire materials.

Finally, a major improvement which is currently under development at UCSD is the use of a pre-cut x-pinch cut from a single metallic foil. This would eliminate the individual twist needed for each experiment, and ultimately facilitate an automated experiment as well as providing a consistent short duration hard x-ray source.



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