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Emission Reconstruction As A
Plasma Diagnostic

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July 1977

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TWO DIMENSIONAL SPECTRAL LINE EMISSION RECONSTRUCTION AS A PLASMA DIAGNOSTIC*

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Abstract

A technique for reconstructing point by point light emission from a plasma using a series of one dimensional, line of sight measurements is described. The method, an adaptation of tomographic x-ray scans, does not assume any symmetry in the plasma, unlike an Abel inversion. Results from the Tormac IV toroidal bicuspid device are presented, in which plasma light was collected by a 16 channel polychrometer with $0.4 \text{ \AA}$ resolution and a one microsecond time response. Reconstructed plasma light emission with spatial, temporal and wavelength resolution is then calculated. The profiles of reconstructed spectral line (Stark broadened H_{β} and Doppler broadened $HeII \text{ } 4684 \text{ \AA}$ lines from the 90% H, 10% He plasma) are used to monitor local plasma density and temperature. A spatial resolution of 2 cm in a 14 x 24 cm vessel, which is determined by the number of angles that the plasma is viewed from, is realized. This technique is particularly useful when a high temperature plasma is surrounded and obscured by a low temperature, highly emissive plasma near the vessel walls.

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INTRODUCTION

An experimental technique for spatially resolving spectral line emission profiles in two dimensions from a set of one dimensional projections has recently been developed as a plasma diagnostic tool for the Tormac devices.¹ Light emitted from the plasma is collected in a light pipe with a narrow acceptance angle at various positions around the plasma, and is transmitted to a polychromator where it is broken up into wavelength increments. Time resolved amplitudes are then recorded by a computerized data acquisition system. A computer code, using the data from many different light pipe positions, then calculates the self consistent point emission of light from the plasma as a function of time and wavelength. Broadening of spectral lines by Doppler and Stark effects is then used to determine spatially resolved plasma temperature and density. The computer techniques used here were borrowed from the fields of nuclear medicine and astronomy, where techniques for two-dimensional image reconstruction were originally developed.²⁻⁶ Unlike other techniques, such as Abel inversion, no symmetry in the object viewed is assumed a priori and the technique can be applied to a plasma of arbitrary shape. Reconstructed line profiles are particularly valuable when the high temperature plasma of interest is obscured by a blanket of colder, highly emitting plasma near the vessel walls.

MATHEMATICAL METHOD

In recent years a large number of computational techniques have been developed for reconstructing a function of two variables $f(x,y)$ over a domain from a set of one dimensional projections $P_k (k=1,2...N)$ where

$$P_k = \int_{\ell_k} f(x,y) d\ell \quad (1)$$

and ℓ_k is some path (usually a straight line) through the domain of interest. These techniques have been widely used in medical x-rays, where the fractional absorption of a highly collimated beam of x-rays gives a measure of the density of material along the path of the beam. A series of these measurements (typically several thousand) is taken and stored in a computer. Upon completion of the measurements an algorithm computes density as a function of position. This technique can be adapted to plasma spectroscopy, since emitted plasma light viewed with a narrow acceptance angle, closely approximates a line integral of light emission along the acceptance cone. Thus, in principle, point by point emission within the plasma can be calculated. If the collected light is split into a number of wavelength increments, then emitted spectral line profiles at points within the plasma can be calculated, giving a wealth of information on the internal structure of the plasma.

A brief review of reconstruction algorithm is given here. For a more complete description, the interested reader is referred to the collection of review articles given in the references.²⁻⁶

Let space be divided up into finite size squares, each with intensity a_{ij} (assumed isotropic) where i, j , are coordinates of the squares as shown in Fig. 1. A spectrograph aperture is placed as shown in the figure and it measures light (P_1) given by

$$P_1 = \alpha(a_{1,1} + a_{1,2} + \dots a_{1,6}) \quad (2)$$

where α is a calibration constant for the apparatus. When the spectrograph aperture is moved to position #2, a different equation is obtained,

$$P_2 = \alpha(\sqrt{2} a_{1,3} + \sqrt{2} a_{2,4} + \sqrt{2} a_{4,6}), \quad (3)$$

where the factor $\sqrt{2}$ accounts for the longer transverse of each element.

The above equations can be written in matrix form;

$$P_k = \sum_{i=1}^n \sum_{j=1}^m C_{ijk} a_{ij}. \quad (4)$$

C is, in general, a sparse matrix since the spectrograph sees only a small fraction of the total area at each position. The only non-zero elements of C are those such that the element ij is "seen" by the k^{th} projection. In addition to Eq. 4, the constraint $a_{ij} > 0$ is imposed (negligible self absorption of light by the plasma is assumed).

The algorithm used here to reconstruct the array a_{ij} is the multiplicative algebraic reconstruction method of Gordon et.al.⁶ It is chosen because of its suitability for emission reconstructions. To initialize the calculations a "guess" $(a_{ij})_0$ is made by dividing up the light seen by each projection evenly among all the array elements transversed by that projection and then appropriately normalizing by the number of

viewing angles. P_1' is then calculated by Eq. 4, using $(a_{ij})_0$ and dividing into the measured value P_1 . All the elements a_{ij} seen by this projection are then normalized by this factor. The procedure is then repeated for all N spectrograph positions, and at the conclusion a new array $(a_{ij})_1$ has been estimated. The above procedure is repeated a number of times until convergence is realized after ℓ iterations. Convergence is monitored by the parameter δ , where

$$\delta = \left[\sum_{k=1}^N \left(P_k - \sum_{j=1}^n \sum_{i=1}^m c_{ijk} (a_{ij})_{\ell} \right)^2 \right]^{\frac{1}{2}} \quad (5)$$

and is a measure of the agreement between the original data and the reconstructed array. Typically δ initially decreases with each iteration, reaches a minimum and then begins to increase slowly.⁶ The iteration process is cut off at this point (typically after a few iterations) and the values of $(a_{ij})_{\ell}$ are taken as the final values. This iteration procedure "automatically" assures that $(a_{ij})_{\ell} > 0$ if the initial $(a_{ij})_0 > 0$ since the normalization procedure described above cannot change the sign of any element a_{ij} .

NOISE AND ACCURACY

Two questions arise upon consideration of the above process. The first is how many projections P_k must be measured to achieve some desired spatial resolution in the plasma interior, and the second is what are the errors in the final computed values of $(a_{ij})_{\ell}$ given the grid spacing, number of the projections and noise on the measured projections. The two questions are interrelated as will be shown. This is particularly relevant to plasma experiments, where limited access to the region of interest

and the difficulties in achieving a large number of repeatable plasma shots may be the limiting factors in achieving a desired resolution. These questions are addressed briefly, and somewhat heuristically since the interested reader will doubtless wish to pursue the relevant literature on the subject. A search of the literature has revealed no general criterion for resolution, accuracy and noise sensitivity. They are, in general, functions of the domain shape, number and positions of the projections P_k , shape of the object viewed and the reconstruction algorithm used. A set of test arrays were used prior to the work described here to determine the optimum number and positions of the projections.

In reconstructing emitted light from a plasma some sort of structure is expected. The reconstructed emission intensities will thus not be random values, but will have some fairly simple form, or shape, in the region being reconstructed. The emission $I(x,y)$ over the space (corresponding to the grid averages a_{ij}) can be represented by a Fourier series. The reconstruction technique used here will typically reproduce (or reconstruct) the lowest order Fourier components quite accurately, while the error in the algorithm increases with the order in Fourier series. The eigenfunction analysis of Klug and Crowther⁷ demonstrates this phenomenon quite clearly. Let the emission from the plasma be $I(x,y)$ and the reconstructed intensity be $I'(x,y)$. If we denote the reconstruction process as an operator F , then

$$I'(x,y) = F(I(x,y)) \quad (6)$$

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It can then be shown⁷ that the operator F will have a set of eigenfunctions ψ_n , where

$$F(\psi_n) = \lambda_n \psi_n. \quad (7)$$

These eigenfunctions will be determined by the particular reconstruction technique used, the boundary conditions (i.e. the shape of the vessel) and the orientations of the various projections P_k . For a finite number of projections P_k only a limited number of eigenfunctions are reliably represented in the reconstruction. This is because the λ_n 's for increasingly "finer", or higher order eigenfunctions tend to zero. Thus if $I(x,y)$ is expanded in terms of the eigenfunctions;

$$I(x,y) = \sum_{n=0}^{\infty} a_n \psi_n(x,y), \quad (8)$$

the reconstructed image will be given by

$$I'(x,y) = \sum_{n=0}^{\infty} a_n \lambda_n \psi_n(x,y). \quad (9)$$

The terms in the above series with small eigenvalues will be attenuated. In practice this limits the spatial resolution of the reconstruction. The spatial resolution of a reconstruction is thus not in general determined by the grid spacing alone, particularly when the system of Eq. 4 is underdetermined. While no general criterion for resolution has been found in the literature, a series of tests were run on the computer with variously shaped "test arrays" for the set of projections used in this work. The results of these runs indicated that a 2 cm resolution is to be expected in the reconstructions described later in this work.

The reconstruction is performed using the measured quantities P_k and any noise or uncertainty in these quantities will be reflected in the reconstruction. Given noise or uncertainty that is statistically independent from the signal, then the relative uncertainty in the amplitude of a reconstructed eigenfunctions, ψ_n , is proportional to $1/\lambda_n$. Thus, in the presence of noise on the input data, the coarser structures in the reconstruction are more reliable than the fine details, as might be expected.

In the work described here, the uncertainty in the reconstruction was evaluated by a technique different from the above described eigenfunction approach, to facilitate computation. Since several shots of the machine are used to determine each P_k , the statistical variation (standard deviation) of each P_k is known. Noise (generated by a random number generator in the computer) is artificially added to the input data and the reconstruction is performed. This reconstruction is of course, somewhat different from the original reconstruction without the added noise. Repeating this process a number of times with "new" noise each time, an estimate of the uncertainty of each a_{ij} is found.

A reconstruction resolution of the order of 2 cm is desired in the Tormac IV experiment described here. With a rectangular vessel cross section 14 cm $\times$ 24 cm, scans of the plasma were made at angles to the major axis of 0° , 45° , 90° , and 135° as shown in Fig. 2. At each angle, a sweep was made at intervals of 1.25 cm. At each of the angles 45° , 90° , and 135° , measurements were made at 24 positions.

At 0° , a total of 12 positions were viewed. Three to five shots were made at each position to average out noise and to determine the shot-to-shot variation in the measurements. The grid spacing used in the reconstruction is 1.25 cm, although the reconstruction resolution is somewhat coarser than this.

APPARATUS

Plasma light was viewed through the glass vacuum vessel with the light pipe assembly shown in Fig. 3. The acceptance angle ($\sim 5^\circ$) is fixed by the position and diameter of the lens L1 and the viewing angle θ is determined by the mirror angle ϕ . Three mirrors with angles ϕ of 22° , 45° and 67° were used in this work. Light collected by the assembly is transmitted through 3 m of fiber light guide to a spectrograph as shown in Fig. 4. Light is dispersed in wavelength and split into 16 channels separated by $0.39 \text{ \AA}$. Since a large number of shots is needed to collect data for a reconstruction, the instrument wavelength setting and photomultiplier gains must remain constant with time. It was found that the main source of drifts in these parameters was variation in temperature. The entire instrument was insulated with a 5 cm thick layer of styrofoam (polystyrene foam) and the interior maintained at a constant temperature of $38^\circ \pm 0.1^\circ\text{C}$ with a thermostat and heater. This reduced the wavelength calibration drift from several angstroms per day to about $0.06 \text{ \AA}$ per day, and the photomultiplier gain drift from $\sim 20\%$ per day to $\sim 2\%$ per day. The relative gains of the 16 polychrometer channels were normalized by using a xenon arc lamp source with a relatively flat spectrum over the instrument range. The gains of

the various channels were equalized to within a few percent using gain adjustments on the amplifiers. An additional calibration was made to calculate normalization factors which were stored in the computer and later used to make small final corrections ($\sim 1-2\%$) to the collected data.

The separation between channels of $0.39 \text{ \AA}^0$ was chosen to match the widths of the spectral lines of interest. The plasma in the Tormac IV device is 10% He, 90% H, with peak ion temperatures of $\sim 300 \text{ eV}$. Doppler broadening of lines from these elements ranges from $\sim 1-6 \text{ \AA}^0$ (fwhm). Stark broadening of the H_β line of the order of $3 \text{ \AA}^0$ (in this experiment) is used to measure plasma density and turbulence. Since the total range of the instrument is 16×0.39 or $6.2 \text{ \AA}^0$, well resolved line profiles can be measured with single shots.

WALL REFLECTIONS

The Tormac IV vacuum vessel is a glass toroid of rectangular cross section, and views of the plasma light contain light reflected from the glass walls and surrounding structures as well as unreflected light. Although specular reflection of light from glass is small ($\sim 4\%$ for normal incidence at each interface) a correction must be made for accurate reconstructions.

The reflections encountered in the Tormac IV device are illustrated in Fig. 5, where Θ is the acceptance angle of the light pipe and ϕ is the acceptance angle for the reflected light. For the cylindrical problem at hand, the indicated magnification of the acceptance cone takes place only in a plane perpendicular to the major axis. In the plane

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parallel to the major axis shown in Fig. 5 the acceptance angle is unchanged by reflection (for small θ).

For $\theta \ll r_2 / (r_2 - r_1)$

$$\phi \approx \theta \left(\frac{2r_2 - r_1}{r_1} \right) \quad (10)$$

The net effect of this phenomenon is to include light from a wide toroidal region. Since Tormac IV is a toroidally symmetric plasma device the spreading of the acceptance cone in the azimuthal direction causes no loss of information. The plasma cross section in a plane containing the major axis of the device is sought, and for small θ the light pipe resolution in this plane is unaffected by the curvature. Spatial resolution is thus maintained in this plane. Subsequent reflections off the glass can be shown to be inconsequential and are ignored. The reconstruction algorithm is easily corrected to include the reflected light. It is simply necessary to include the array elements seen by reflection in the matrix C_{ijk} , multiplied by the appropriate reflection coefficient for the two glass surfaces.

EXPERIMENTAL RESULTS

A series of typical experimental results are presented in Fig. 6 through 14. Shown in Fig. 6 are plots of the intensity of H_β light emission (i.e. the sum of the 16 polychrometer channels) as functions of distance along the machine major axis at different radii from the major axis. Data here was averaged over a 2 μ sec time interval 20 μ sec into the preionization phase of the experiment, prior to plasma compression. The plasma is preionized by applying a rapidly

changing poloidal magnetic field with external coils. This generates a toroidal electric field that initiates the avalanching and breakdown of the gas fill in the chamber (80% H_2 , 20% He at $\sim 10 \mu$ Hg). At the time of the reconstruction in Fig. 6 a toroidal pinch, hotter than the surrounding plasma, has formed in the center of the chamber. The hot "burned out" region of plasma is clearly indicated. Shown in Fig. 7 are a series of reconstructed spectral lines (H_β) at various positions along the major axis at constant radius ($r = 14$ cm). Although the relative errors are small in the region of high emission ($Z < 5$ cm), they become prohibitively large in the region of low emission ($Z > 5$ cm). To overcome this problem an average of the spectral emission over a number of grid points in the pinched region was made and is shown in Fig. 8. The relative errors in this profile are tractable even though the average H_β emission over this region is only a few percent of that in the colder outer region. Although the inner region is completely surrounded by a region of high emission, a useable line profile has been extracted.

The H_β line emitted from the bright regions has a width (fwhm) of $\sim 1 \text{ \AA}$, indicating the limiting plasma parameters $n_e \lesssim 3 \times 10^{14} \text{ cm}^{-3}$ and $T_i \lesssim 6 \text{ eV}$, while that from the inner pinched region, with a width $\sim 2 \text{ \AA}$, shows that $n_e \lesssim 10^{14} \text{ cm}^{-3}$ and $T_i \lesssim 30 \text{ eV}$.⁸ In addition, this profile shows evidence of plasma satellites. Satellites, separated by the plasma frequency from the center of H_β , have been observed before at higher filling pressures (30 μ Hg) in Tormac devices during preionization.⁹

A second example of reconstruction results is with the HeII (singly ionized Helium) $4686 \overset{0}{\text{\AA}}$ spectral line. A series of plots of light emission intensity (i.e. the sum of the 16 polychrometer channels) at different times is shown in Figs. 9 - 14. Times shown are during and after plasma compression. In the initial phases of compression the light peaks up in the center of the chamber and shortly burns out. Ion temperatures, indicated by Doppler broadening of this line prior to burn out are of the order of ~ 100 eV. The flux of hot plasma out the cusp points heat the plasma in these regions, as is indicated by the increase of light coming from the cusps late in time. The thin "shell" of light surrounding the centrally, containing plasma late in time is presumed to be due to a flux of neutral gas impinging on the hot plasma, where it emits briefly before becoming fully ionized in the high temperature region.

CONCLUSION

A plasma diagnostic technique is presented here that provides spatially resolved information such as temperature, density and a monitor of plasma turbulence. The method is non-perturbing and requires only a moderate investment in equipment. Presumably the technique could be extended to reconstruction of continuum plasma emission (bremsstrahlung), Zeeman split lines and impurity lines, although these are not described in this work.

The authors are grateful for the efforts of Ludmilla Soroka, who performed much of the computational work and plotting of the final results.

CAPTIONS

Figure 1

Simplified reconstruction array. Two spectrograph viewing positions are shown. The region viewed is divided up into squares and the spectrograph placed so that it views rows, columns, and diagonal lines of sight. The data from a large number of different projections are then used to find the self-consistent light emission from the plasma in each array square.

Figure 2

Lines of sight used in the reconstruction of plasma light in the Tormac IV experiment. Tormac is a toroidal bicuspid device¹ and the final plasma shape, after construction, is shown by the shaded area. Plasma streaming out of the cusps impinges on the glass walls at the points marked by "x", and a cold, dense plasma builds up in these regions following plasma compression. The lines of sight for the reconstruction used here are at 0° , 45° , 90° , and 135° . At each angle measurements are made at intervals of 1.2 cm.

Figure 3

Light collector assembly. Plasma light is viewed through the glass vacuum vessel. The acceptance cone of the assembly is fixed by the diameter of the lens L1 and the distance ℓ , the focal length of the lens. The viewing angle θ is fixed by the mirror M1. Three separate mirrors were used for these measurements with angles ϕ of 22° , 45° , and 67° respectively,

and were constructed of polished glass coated with evaporated aluminum and a protective coating. The fiber light guide is made up of 64 fibers, each 250μ in diameter.

Figure 4

Spectrograph (polychrometer) used in the measurements described here. Light from the plasma, carried by the input fiber light guide, is defined by the entrance slit (25μ). The light is reflected from the spherical mirror M_2 , and dispersed by the grating G_1 . The dispersed light is reflected and focused by the spherical mirror M_3 . The image of the entrance slit is then magnified by the cylindrical lenses L_2 and L_3 focused onto a set of 16 rectangular Lucite light guides. The light guides are $125\mu \times 1.5$ cm in cross section, and are stacked together in a row as shown. The guides are separated by a thin ($\sim 20\mu$ thick) layer of transparent silicone rubber to eliminate cross-talk between guides. Dispersed light entering the guides is then transmitted to individual photomultiplier tubes and amplifiers. Signals from the 16 amplifiers are recorded by a data acquisition system with a sampling frequency of 2 MHz (each channel). The assembly consisting of mirrors M_2 , M_3 and grating G_1 is a modified Spex 0.75 monochrometer. The separation between channels is $0.39 \text{ \AA}$, and the entire device is thermally insulated and held at a constant temperature ($\sim 38^\circ\text{C}$) to minimize thermal drifts in the wavelength setting and photomultiplier gains.

Figure 5

Reflection of light from the glass-vacuum interface in the Tormac IV vessel. Reflected light must be accounted for in the reconstruction algorithm as described in the text. Here light from the inner glass cylinder effectively spreads the region viewed in the toroidal direction. Since the plasma is toroidally symmetric no resolution is lost in the reconstruction by the spreading. The side view (b) shows reflected light in a plane containing the major axis of the device.

Figure 6

Reconstructed H_{β} light emission as a function of position during the preionization phase. Intensities are calculated by integrating over the 16 polychrometer channels. The four graphs, each at a different radius from the major axis of the machine, show emission intensity as a function of distance (Z) along the major axis. The center of the device is at $Z \approx 13$ cm, and the plot shows asymmetry in the plasma at this time, the source of which is unknown at present. The inner glass cylinder of the chamber is at $R = 7.5$ cm, and the outer cylinder at $R = 22$ cm. The toroidal pinch, which is seen by the region of depressed light emission, is centered at $R \approx 14$ cm. and $Z \approx 13$ cm.

Figure 7

Reconstructed spectral line emission from various points within the preionized plasma. The points are all at constant radius ($R \approx 14$ cm) at different distances along the Z axis, starting at $Z = 1$ cm at the side wall of the vessel proceeding to $Z = 10$ cm near the center of the plasma.

Relative errors in the line profiles are small for the plasma near the wall ($r < 5$ cm.), but become quite large for lines near the center (note that (g) and (h) have expanded vertical scale) where the emission intensity drops.

Figure 8

H_β line profile averaged over a 4 cm x 5 cm region in the center of the plasma. The relative errors are reduced and satellites are apparent on the side of the line profile.⁹

Figures 9 - 14

Plots of HeII 4686Å⁰ light density as a function of position at different times. The inner glass wall is $r \approx 7.5$ cm and the outer wall at 22 cm. These plots, unlike the preceeding H_β plots have been symmetrized to improve the signal noise ratio. Typical asymmetries of $\sim 10 - 15\%$ were seen in the original unsymmetrized reconstructions. Note that in these plots the midplane of the plasma is located at $Z = 0$ cm.

Fig. 9. $t = 30$ μ sec after preionization, just prior to plasma compression - very little light is visible.

Fig. 10. $t = 34$ μ sec, approximately halfway through plasma compression by the bicuspid containment field. A large amount of emitted light is visible in the center of the chamber.

Fig. 11. $t = 38$ μ sec, peak compression.

Fig. 12. $t = 42$ μ sec after peak compression. Light is "burning out" as ionization of the HeII species proceeds. Some heating of the cusp regions is evidenced by the increase in light emission.

Fig. 13. $t = 52 \mu\text{sec}$. Burnout of the central region is complete and light intensity at the cusps continues to increase. A ring of bright emission can be seen around the central plasma.

Fig. 14. $t = 62 \mu\text{sec}$, little change except total light emission is beginning to drop.

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Figure 1

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Figure 2

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Figure 3

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Figure 4

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Figure 5

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Figure 6

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Fig. 7

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Fig. 8

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Fig. 9

Fig. 10

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Fig. 11

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Fig. 12

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Fig. 13

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