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GENERAL PLASMA CHARACTERISTICS OF A BERKELEY
MULTIFILAMENT ION SOURCE*

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ABSTRACT

The general plasma characteristics of a Berkeley Multifilament Ion Source are presented. The measurements are obtained via a pulsed electrostatic probe data acquisition system, and in part conclude:

- A. The electron distribution function consists of a bulk component of thermal electrons ($kT_e \sim 3$ to 5 eV) comprising 90 to 97 percent of the total electron population (depending on operating conditions), plus a non thermal high energy tail, which is a monotonically decreasing function of energy, and contains a small but experimentally significant electron population at energy values 10 to 15 eV above maximum cathode fall.
- B. Overall source performance, i.e. the spatial distribution of plasma potential, plasma density, and ion current density, approximately follows steady state, low pressure discharge theory assuming spatially uniform ion production.

*Research supported by U.S. Department of Energy

INTRODUCTION

Plasma heating by neutral beam injection comprises a basic element of the world-wide Magnetic Fusion program. In conjunction with this effort, the Lawrence Berkeley Laboratory/Lawrence Livermore Laboratory Neutral Beam Group has undertaken the development of injection systems for several major U.S. Department of Energy fusion experiments.¹ Presently, the heart of the LBL/LLL program is the Berkeley Multifilament Ion Source.² The purpose of this paper is to present a general assessment of the basic plasma parameters such as electron distribution function, plasma potential and plasma density; which characterize the ion source discharge. A better understanding of these parameters, and the physics governing their behavior, will hopefully lend guidance for improving future source performance.

EXPERIMENTAL APPARATUS

I) The 10 Ampere Source

The 10 ampere source is basically a small version of the ion sources presently employed in the LBL/LLL neutral beam program. A cross sectional schematic is illustrated in Fig. 1. The source produces a plasma via a diffuse, low pressure, high current electrical discharge. Arc ionization is produced by primary electrons originating at the thermionic cathode (filament ring), and energized by their passage through the cathode-plasma sheath. The arc discharge occurs between the filament ring, consisting of 26 hairpin tungsten filaments connected in parallel, and the anode ring. A pulse line composed of iron core inductors and electrolytic capacitors, supplies roughly 10 to 60 kW of arc power for up to 100 msec. All source chamber walls electrically float at potentials such that the net random current due to

electron and ion bombardment is nulled. The main volume of the discharge is relatively magnetic field free, although both filament heater current and arc discharge current contribute to a field in the vicinity of the filaments. For this reason, the applied filament current is D.C. to minimize A.C. modulation of discharge conditions. To avoid formation of a substantial anode sheath, which increases discharge noise, the anode area is chosen such that the discharge arc current is supplied by the random electron flux striking the anode.

Experimental access to the plasma is via two radial probe ports near the source midplane, one radial probe port near the floating extractor grid, one axial probe port, and a section of axially symmetric floating wall which can be used as an extended wall probe.

II) Measurement Apparatus

The majority of source plasma measurements were obtained via a pulsed electrostatic probe data acquisition system. The system digitally records a probe characteristic and its first and second derivatives; the latter functions being proportional to the projected electron energy distribution function and the isotropic electron energy distribution function, respectively.³ Several distribution function measurements employed the second harmonic or intermodulation technique, which uses the nonlinearity of the probe current-voltage characteristic to obtain its second derivative.^{4,5} This technique was primarily employed as an auxiliary check on the reliability and accuracy of the pulsed acquisition system. A complete description and accuracy analysis of the two techniques are given in references 3 and 5.

Figure 2 schematically illustrates the pulsed probe driver/detection apparatus. An initial pulse, obtained from the source logic, operates the timing of various source inputs (e.g. application of arc power, filament

power, gas injection, etc.). The pulse is also applied to a variable delay gate (enabling data acquisition at any subsequent moment during source operation), amplified, and then used to trigger the probe driver and data recording system. The probe driver initially applies a large positive bias to the probe to insure a clean collection surface, followed by a linearly decreasing voltage ramp which sweeps the probe bias over its entire operating range. Sweep speeds of $.1 \text{ v}/\mu\text{sec}$ to $1 \text{ v}/\mu\text{sec}$ over a total range of 100 volts are typical. The probe current is differentially detected across a standard resistance and then processed by the differentiation network, which outputs the probe current and its first and second derivatives. These signals are digitally recorded by a Nicolet transient digitizer, which simultaneously samples the processed current signal and its corresponding bias voltage. The stored data is accessible both graphically and as a digitized set of points; each point consisting of two twelve bit words (e.g., (V,i) for probe characteristic measurements) with a maximum of 2048 points per data set. The digitized data is finally read by a Modcomp Systems computer via a direct I/O link, which subsequently executes an analysis algorithm providing on line data analysis.

THE ELECTRON DISTRIBUTION FUNCTION

Preliminary analysis of the electron distribution function in low pressure, hot cathode discharges was performed by Langmuir in 1925.⁶ Employing the technique of electrostatic probes,⁷ current-voltage characteristics were obtained for a variety of operating conditions in low current ($\sim 10\text{mA}$), D.C. mercury vapor discharges. These probe characteristics, in many ways similar to those obtained in the Berkeley source (a typical example is illustrated in

Figure 3A), were interpreted by Langmuir as being derivable from an electron distribution function composed of three main constituents:

1. Primary electrons: thermionically emitted electrons energized by their passage through the cathode-plasma sheath.
2. Secondary electrons: an isotropic, thermal constituent with a temperature considerably less than, but dependent on the primary electron energy. In Figure 3A, the electron probe current due to secondary electrons would roughly correspond to probe bias between 0 and 23 volts. Note that the secondary electrons appear thermal, due to the exponential dependence of probe current on probe bias in this range.
3. Ultimate electrons: a cool isotropic, thermal component constituting the bulk of the electron population with a temperature less than the secondaries, but fairly independent of primary electron energy. In Figure 3A, the ultimate's contribution corresponds to probe bias between 23 volts and the plasma potential. Again, note that the ultimate electrons appear thermal.

The secondary and ultimate electrons compose what is often called a two temperature or Bimaxwellian distribution function. However, the physical origin of this distribution function is difficult to resolve. For high energy electrons comprising a majority of the secondary population, the collisional mean free path is many times greater than the plasma's spatial dimension and hence, collisional relaxation is inadequate to account for thermalization. Several explanations of this apparent conundrum, oftentimes called "The Langmuir Paradox," have been proposed involving collective effects such as plasma-sheath oscillations.⁸ In recent years, subsequent experimental investigations of low current discharges have provided evidence that

questions pertaining to the resolutions of Langmuir's Paradox are possibly moot. Work by Rayment and Twiddy,⁹ involving direct distribution function measurement via the harmonic double differentiation technique in mercury vapor discharges, have shown that the electron distribution function is non-thermal, despite the thermal nature indicated by probe characteristic measurements.

With regard to the Berkeley source, distribution function measurements performed under relatively high discharge current conditions, confirms the non thermal nature of the distribution function tail. Figure 3B illustrates a logarithmic plot of the electron energy distribution function $f_e(\epsilon)$ ¹⁰, obtained by both real time and harmonic double differentiation of the probe characteristic shown in Figure 3A. Figures 3C and 3D plot the total electron energy distribution function $F_e(\epsilon)$, including phase space weighting (i.e. $F_e(\epsilon) \propto f_e(\epsilon)\sqrt{\epsilon}$ where $F_e(\epsilon)d\epsilon$ gives the relative number of electrons with energy between ϵ and $\epsilon + d\epsilon$). The distribution function, in contrast to Langmuir's interpretation, consists of two main constituents:

1. Thermal bulk electrons which constitute the majority of the total electron population (roughly 96% for the function shown in Figure 3C).
2. A non thermal high energy tail, which comprises the monotonically decreasing high energy component of the distribution function (Figure 3D)¹¹.

The break between the bulk electron component and non thermal tail, occurs at an energy roughly corresponding to the potential difference between the plasma potential and the source wall floating potential. Measurements made with cylindrical probes oriented in the axial and radial directions, and with spherical probes confirm the near isotropy of the distribution function; which is primarily due to the symmetry of the source chamber.

Qualitatively, distribution function structure is best understood by considering the source chamber as an electrostatic potential well. Excluding the anode, the chamber consists of several electrically isolated sections of conducting wall; each section floating negative with respect to the plasma potential such that the net random current due to electron and ion bombardment is nulled.¹² Source walls therefore form a potential well for electrons; the containment condition being that the projected energy of an electron normal to a wall surface ($\epsilon_{\perp}$), is less than the potential difference between the plasma potential and the wall floating potential ($\Delta\epsilon_{\text{WELL}}$). This containment condition can be employed to conceptually dichotomize the distribution function into the two constituents described above.

1. Electrons whose total energy is less than $\Delta\epsilon_{\text{WELL}}$, and which remain trapped until encountering the anode. Electrons in this group can be shown to have sufficient time to thermalize before escaping,¹¹ and hence constitute the bulk thermal electrons.
2. Electrons whose total energy is greater than $\Delta\epsilon_{\text{WELL}}$ (the high energy tail). Within this group, electrons where $\epsilon_{\perp} < \Delta\epsilon_{\text{WELL}}$ will remain trapped until collection by the anode, an inelastic encounter with a background neutral, or scattering into the "loss cone" defined by the condition $\epsilon_{\perp} > \Delta\epsilon_{\text{WELL}}$. The containment period, which for typical source operating conditions is .03 μ sec, is insufficient to allow thermalization,¹¹ but evidently sufficient to insure no overall depletion of the tail.

Spatially, the energy distribution of bulk electrons remains fairly constant over the majority of the source volume. Axial and radial scans of the the bulk electron temperature (Figures 5A and 5B) show a fair degree of

spatial uniformity. The high energy tail, however, exhibits a gradual population enhancement with increasing radial position from source center. This effect can be partially attributed to the high energy containment condition ($\epsilon_{\perp} < \Delta\epsilon_{\text{WELL}}$) which, for the cylindrical geometry of the source chamber, favors energetic electrons with small radial velocity components that can elastically scatter off the plasma-wall sheath.

Figure 3E illustrates the distribution function tail near the filaments at a radial position 6 cm off axis. The tail comprises $\sim 10\%$ of the total electron population as opposed to $\sim 4\%$ for Figure 3D obtained under the same operating conditions on axis. In terms of electron population capable of ionization, this relates to an off axis density of $\sim 1.6 \pm .2 \cdot 10^{11}/\text{cm}^3$ as compared to $1.2 \pm .2 \cdot 10^{11}/\text{cm}^3$ on axis; even though the total electron density maximizes at source center (see Figure 5). Hence, plasma ion production is essentially uniform throughout the source volume.

In conclusion, when computing bulk plasma properties such as electron Debye length, which sets the spatial scale determining sheath structure, the distribution function may be considered thermal at the bulk electron temperature. However, when computing dissociation and ionization rates, the high energy tail has profound influence. For example, the population of ionizing electrons in deuterium is typically 100% larger than expected from a Maxwellian at the bulk electron temperature. The enhancement of ionization rates is even greater due to cross section weighting. The spatial uniformity of ionizing electrons results in uniform plasma ion production, and performs the beneficial function of flattening the plasma's potential and density profile; a necessary condition for large area ion extraction.

THE HIGH ENERGY TAIL BEYOND CATHODE FALL

The existence of electrons with energy values exceeding the cathode fall in electrical discharges have been documented since the early days of vacuum tubes.¹³ An extensive study of this effect in low current, hot cathode discharges was initially performed by Langmuir.⁶ Using probe characteristic measurements, substantial electron currents were measured for probe bias values up to -20 volts with respect to cathode. Langmuir attributed this effect to primary electron scattering, and proposed an algorithm for determining the temperature by hypothesizing an isotropic Maxwellian, displaced in energy by cathode fall acceleration:

$$f_p(\epsilon) = n_e \left(\frac{m_e}{2kT_e} \right)^{3/2} e^{-(\sqrt{\epsilon - \epsilon_p})^2 / kT_p} \quad (1)$$

where $V_p \equiv$ Plasma Potential w.r.t. cathode

$T_p \equiv$ Primary Temperature

as the primary electron distribution function. For a 5mA low pressure mercury vapor discharge, with a cathode fall of 50volts, a primary temperature of .12 eV was sufficient to account for the experimental measurements.

Similar measurements performed on the Berkeley source, involving high resolution probe characteristics, generally concur with Langmuir's experimental results. Figure 4A is a computer plot of a probe characteristic obtained under conditions similar to those of Figure 3. Measurable electron current extends to probe bias values 20 volts negative of (-) filament. (Zero bias marks the negative leg of the cathode.) However, as previously mentioned, a more precise determination of the high energy tail at energy values exceeding cathode fall entails direct distribution function measurement. Measurements

performed in low current discharges by Rayment and Twiddy, reveal a monotonically decreasing, non-thermal function over a range 15 to 20 eV greater than cathode fall. The dominant mechanism for this primary scattering is due to a resonant interaction between the primary and bulk plasma electrons. The distance traveled by primaries before being strongly scattered is roughly 1/10 the collisional mean free path for electron-electron scattering, and corresponds to a plasma interaction time of approximately three plasma periods; indicating a strong beam-plasma effect.⁹

Analogous distribution function measurements on the Berkeley source, employing a section of axially symmetric floating wall as an extended wall probe, generally concur. Figure 4B illustrates an axially projected distribution function obtained for a background plasma density of $1.3 \cdot 10^{12}/\text{cm}^3$ (Discharge arc power = 10.3 kW). The results parallel those of Rayment and Twiddy, and consist of a monotonically decreasing function out of 20 eV above cathode fall. Models describing this distribution function structure for energy values greater than cathode fall, can possibly be inferred from similar measurements in low current discharges where beam-plasma interactions dominate. However, at present, no direct experimental confirmation of this mechanism in the Berkeley source exists.

THE SPATIAL DEPENDENCE OF SOURCE PLASMA PARAMETERS

The first comprehensive steady state theory of a low pressure, magnetic field free discharge was formulated by Tonks and Langmuir in 1929.¹⁴ The theory involved solution of Poisson's equation under conditions where:

1. electrons are assumed to have a Maxwellian distribution function;

their local density satisfying the Boltzmann relation

$n_e(X) \propto \exp(e\phi(X)/kT_e)$ where $\phi(X)$ is the local plasma potential.

2. ions are assumed created at rest throughout the plasma volume according to a specified generation function, and subsequently free fall without collisions in the local ambipolar electric field to the walls, where recombination with electrons occur. For the case of planar, cylindrical or spherically symmetric discharges ($\beta = 0, 1, 2$ respectively), the ion continuity equation under the free fall and steady state assumptions, yields the local ion density function:

$$n_i(X) = \left(\frac{M_i}{2e}\right)^{1/2} \frac{1}{X^\beta} \int_0^X \frac{G(Y) Y^\beta dY}{[\phi(Y) - \phi(X)]^{1/2}} \quad (2)$$

where $G(X) \equiv$ Ion generation rate per unit volume

$\phi(X) \equiv$ Local plasma potential (a monotonically decreasing function of X , with $\phi(0) = 0$).

$X \equiv$ Variable characterizing the spatial position in the discharge measured with respect to the center of symmetry (i.e., $X = Z$; r for planar; cylindrical or spherical discharges, respectively).

Thus Poisson's equation becomes:

$$\begin{aligned} \nabla^2 \phi(X) &= -4\pi e(n_i(X) - n_e(X)) \\ &= -4\pi e \left[\left(\frac{M_i}{2e}\right)^{1/2} \frac{1}{X^\beta} \int_0^X \frac{G(Y) Y^\beta dY}{[\phi(Y) - \phi(X)]^{1/2}} - n_{e0} e^{(e\phi(X)/kT_e)} \right] \end{aligned} \quad (3)$$

Langmuir termed this result "The complete plasma-sheath equation" and proposed solutions for two simplified but physically interesting cases:

1. The plasma approximation, where quasi-neutrality requires $\nabla^2\phi(X) = 0$.
2. The thin sheath approximation where volume ion production in the sheath region can be ignored.

The proposed solutions were in power series form, and were asymptotically correct in the limit of small Debye length.

Exact solutions of equation 3 for planar discharges; and asymptotic, thin sheath solutions of equation 3 for cylindrically and spherically symmetric discharges, were formulated by Self assuming plasma ion production spatially uniform, proportional to the electron density, and proportional to the square of the electron density.^{15,16} Since many relevant discharge parameters are calculable once the potential distribution is known, these solutions provide valuable input for predicting ion source performance. However, for most experimental discharge chambers, a two-dimensional generalization of the Self solutions is necessary in order to obtain a complete and accurate spatial mapping of the plasma potential.

An alternative approach to steady-state low pressure discharge theory proposed by Kino and Shaw,^{17,18} retains the Maxwellian assumption for electrons, but treats ion motion via transport equations obtained from moments of the Boltzmann equation. Hence, whereas the Tonks-Langmuir or Self method deals with an exact description of ion motion in terms of the ion distribution function and related local ion density (equation 2), the moment method employs a macroscopic fluid description of ion kinetics. The advantage of the moment equation method, is that it leads to differential equations which are easier to generalize and compute than the exact plasma sheath equation. The two-dimensional solutions conclude that for cylindrically symmetric discharges, spatial plasma profiles are dependent on R/L_z , the discharge chamber radius to depth ratio. However,

for the Berkeley source where $R/L \ll 1$, the one-dimensional solutions suffice for estimation purposes across the bulk of the discharge chamber.

Figures 5A and 5B illustrate axial and radial profile data for operating conditions previously illustrated in Figure 3. The ion free fall profile for plasma potential represents solutions to equation 3 for the case of spatially uniform ion production; as concluded from electron distribution function measurements. Ion free fall curves for plasma density are related to the plasma potential profile via the Boltzmann factor at the bulk electron temperature. Saturated ion current densities are defined in terms of the normalized value:

$$j_i)_{SAT} = \frac{1}{4} n_i e \sqrt{\frac{8kT_e}{\pi M_i}} \quad (4)$$

The experimental agreement with the one-dimensional solutions, although approximate, remain sufficient to conclude that overall source performance follows steady state low pressure discharge theory. In particular:

1. Plasma potential measurements exhibit the general ambipolar profile predicted by solutions of the collisionless plasma sheath equation (3) for spatially uniform ion production.
2. Local plasma density is related to local potential via the Boltzmann factor at the bulk electron temperature.
3. Extractable ion current density (which is equivalent to the outward ion flux crossing the Tonks-Langmuir Sheath Boundary) follows low pressure discharge theory predictions, and hence is essentially determined by the electron temperature and density at source center.

Admittedly, an exact determination of the effects of multiple ion species,¹⁹ finite ion temperature²⁰, and ion collisions on observable plasma parameters, requires numerical solutions of the appropriate moment equations. However, to within experimental uncertainties, measurements indicate that these effects are minor.

ACKNOWLEDGMENTS

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FOOTNOTES AND REFERENCES

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FIGURES

- Figure 1. Schematic cross section of the Berkeley 10 ampere neutral beam ion source.
- Figure 2. Probe driver-detection schematic.
- Figure 3A. Computer plot of the electron probe current characteristic.
- Figure 3B. Electron probability distribution function $f_e(\epsilon)$.
- Figure 3C. Total electron energy distribution function $F_e(\epsilon)$.
- Figure 3D. Electron energy distribution function - high energy tail: source center.
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- Figure 4B. Projected electron distribution function $f_e(\epsilon, \hat{z})$.
- Figure 5A. Axial plasma profile.
- Figure 5B. Radial plasma profile.

XBL 782-279

Figure 1.

XBL 782-284

Figure 2.

Arc Power: 16.3 kW

Gas Flow: 6.5 T-l/sec

Source Center

Bulk Electron Temperature: 3.8 ± 0.2 eV
Electron Density: $2.0 \pm 0.3 \cdot 10^{12} / \text{cm}^3$
Ion Density: $1.9 \pm 0.2 \cdot 10^{12} / \text{cm}^3$

XBL 785-8672 A

Figure 3A.

XBL786 - 1154

Figure 3B.

XBL 785 - 879

Figure 3C.

XBL786-1149

Figure 3D.

XBL786-1148

Figure 3E.

XBL 7811-12892

Figure 4A.

XBL787-1381

Figure 4B.

Plasma parameters vs. axial position
Arc power: 16.3 kW gas flow: 6 T- ℓ /sec

◻ Axial probe data ▲ Radial probe data

Figure 5A.

XBL787-1379

Figure 5B.

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