3D Isosurface Visualization of Electron Density and Temperature Distribution in a Magnetized Sheet Plasma Ion Source

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A 3D visualization of argon and nitrogen-argon plasma electron density (n_e) and effective temperature (T_{eff}) distributions were constructed using the I-V curves from Langmuir probe traces at specific discrete positions in the extraction region of a magnetized sheet plasma ion source. Argon and mixed N_2-Ar sheet plasmas are characterized using the calculation of the electron energy distribution function (EEDF). By taking the current vs. voltage reading of a single probe in 68 discrete locations of the plasma, a 3-dimensional map of the electron density and electron temperature were constructed. The map was constructed to understand the global condition of the extraction region of the source. The technique can be applied to the determination and understanding of edge plasma parameters in magnetic confinement devices.

Keywords: Magnetized Sheet Plasma Ion Source (MSPIS), sheet plasma, plasma visualization, Langmuir probe, magnetized plasma

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1. Introduction

Plasma visualization has been an important tool for edge plasma kinetics in fusion devices [1].

A Magnetized Sheet Plasma Ion Source (MSPIS), originally designed for H^- production [2–4], is used for wide-area epitaxial deposition of hard films such as titanium nitride (TiN) [5, 6], and synthesis of amorphous silicon [7]. A 3D map of the plasma is constructed to understand the behavior of the plasma and examine the effect of a biased metallic device inside the chamber. The magnetized sheet plasma is several millimeters thick and has an area of $13 \times 20\,\text{cm}^2$. The MSPIS is designed with a pair of Helmholtz coils and a pair of strong dipole magnets creating a magnetic mirror field. A coreless magnetic coil and plasma limiters encasing a ferrite magnet add to the magnetic mirror enhancing stability of the plasma.

Argon and mixed N_2-Ar sheet plasmas are characterized using the calculation of the electron energy distribution function (EEDF) [8, 9]. By taking the current vs. voltage (IV) curve using a single Langmuir probe in 68 discrete locations of the Argon or N_2-Ar plasma, a 3D map of the electron density and electron temperature were constructed. Three types of Langmuir probes of different L-lengths were used to determine the plasma electron density and temperature

Ar and N_2-Ar plasmas are used to determine the effect of single and dual gas plasma on the electron configuration. Argon served as the single gas parameter. Nitrogen gas was introduced as reactive gas into the system using argon as carrier, and was compared to the argon only plasma. The plasma, assumed to be of uniform electron density and effective electron temperature along the sheet, should exhibit a sheet like configuration on the visualization. The actual 3D map, however, demonstrates otherwise.

2. Methodology

Argon and mixed nitrogen-argon plasmas were probed in this experiment. Tables 1 and 2 are summaries of the discharge parameters.

Figure 1 is a schematic diagram of the MSPIS. Details of the machine are presented in references 4-6. A 1D scan of the magnetic field strength of the Helmholtz coils was done along the center of the extraction chamber perpendicular to the sheet plasma, that is, along the z-axis.

Attached on the side of the extraction chamber opposite the vacuum pump is a Langmuir probe mounted on adjustable bellows. These bellows adjust the distance of the Langmuir probe tip from the sheet plasma plane. A biased substrate holder is positioned at the base of the extraction chamber, adjacent to the adjustable bellows and pump. The origin of the coordinates in figure 1 is located at the center of the extraction chamber having dimensions of $21.1 \times 13.4 \times 13.4\,\text{cm}^3$. The x-axis spans the position of

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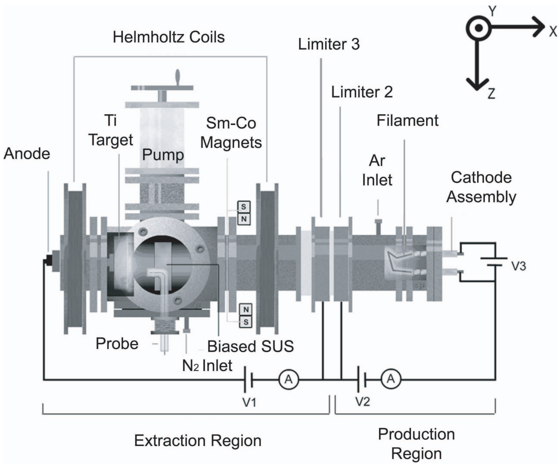

Fig. 1 The Magnetized Sheet Plasma Ion Source.

Table 1 Argon plasma discharge parameters.

Argon plasma – Sputtering		
Extraction current and voltage	50 V - 80 V	4 A
Production current and voltage	5 V - 10 V	4 A
Filament current and voltage	10 V - 14.9 V	11 A - 15 A
Helmholtz coils	32 V	12 A
Base Pressure	7.4×10^{-5} Torr	
Gas Filling Pressure	12 mTorr	
Flow rate (Ar)	20 sccm	
Time duration	1 hr	

Table 2 N_2-Ar plasma discharge parameters.

N_2-Ar plasma – Nitriding		
Extraction current and voltage	50 V	1 A
Production current and voltage	20 V	8 A
Filament current and voltage	15 V	11 A -13 A
Helmholtz coils	31 V - 32 V	12 A
Filling Pressure	3.5×10^{-2} Torr	
N_2:Ar ratio	1:4	
Flow rate (Ar)	71-75 sccm	
Flow rate (N_2)	8.5-9.4 sccm	
Time duration	1 hr	

the Ti target to the production chamber; the y-axis extends from the base of the extraction chamber to the view port; and the z-axis' becomes more negative towards the pump side.

Three kinds of Langmuir probes are used in the experiment; one straight-tipped and two L-shaped probes. The shorter legs of the L-shaped probes are edges exposed to the plasma with lengths 2 cm and 3.5 cm. The probe's wire diameter is 0.5 mm. The straight-tipped probe can only be varied along the z-axis while the L-shaped ones can be rotated. The 2 cm bent tip probe collected reading at 45° interval in one plane, and at ~ 22.5° interval for the 3.5 cm bent tip. The total number of localized points used for interpolation was 68. The probe distance from the z-axis is varied at increments of 1 cm.

The region between the ion saturation current and the electron saturation current of the IV curve collected from the Langmuir probe were analyzed using the Druyvesteyn method to obtain the electron energy distribution function (EEDF) [8, 9]. The discrete data points were processed in Matlab's Interp3 (linear) [10] built-in program.

Usually the positive ion contribution can be neglected since it is in most cases much less than the electron contribution [11, 12]. However, in the evaluation of plasma parameters, the positive ion contribution is still eliminated by subtracting the ion saturation current.

Electron density and effective electron temperature values were then programmed using the Visualization Toolkit (VTK) [13] for imaging. This method applies to 3D mapping that includes interpolation of data along the adjacent planes using Matlab's 7.0 interpolation function.

3. Results and Discussions

The term "moving away from the plasma sheet center" pertains to the value as the position along the positive z-axis is increased.

The sheet plasma is perpendicular to the z-axis with a few cm thickness if no biased perturbing material is present.

Isosurfaces of the T_{eff} can be observed by changing the lowest recorded data. T_{eff} below the set point are excluded in the graph leaving the hotter electrons. This capability of the system pinpoints the areas where the energetic electrons are concentrated. The color bar at the bottom of each figure is the temperature of the electron, increasing from blue to red.

Figure 2 shows a screenshot of the varying T_{eff} as colored isosurfaces of the plasma inside the extraction chamber. As can be seen, T_{eff} is not uniform at a plane with respect to the x- and y-axes. With reference to several positions inside the chamber, the electron temperature increases at the periphery of the substrate holder, the anode and areas near these surfaces. The increase in electron acceleration due to biasing results to high current density and increased electron temperature in the substrate periphery. The anode and the substrate holder both have the same bias voltage.

The images shown in Fig. 2 are viewed in a stationary perspective. An option to rotate the map in 3D as a zoom in and out is integrated into the system. From the map, 13.0 eV is the highest recorded electron temperature. This is significant in the dissociation process of nitrogen when added to the plasma. The map also shows a higher concentration of hotter electrons at the substrate compared to the anode despite the fact that both are of the same bias potential.

Figure 3 shows the results with the addition of nitrogen. The overall effect of the introduction of the neutral gas Nitrogen (N_2) into the system is to significantly lower the T_{eff} inside the extraction chamber due to the increase

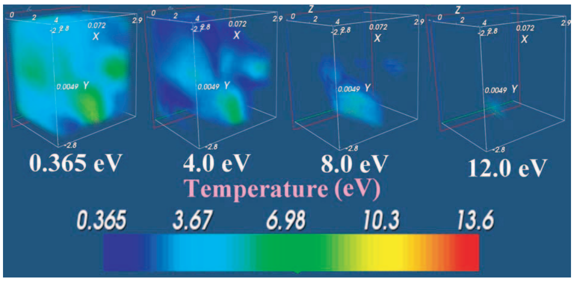

Fig. 2 Isosurface of the effective temperature of Ar plasma for various set points of effective electron tempterature.

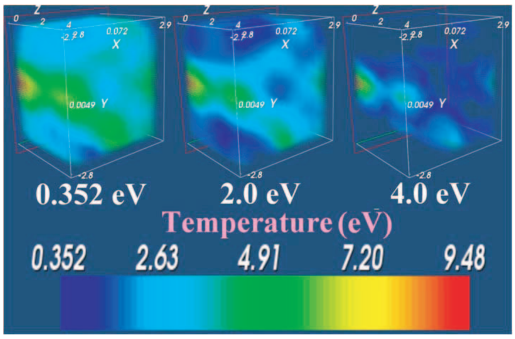

Fig. 3 Isosurface of the effective temperature of N_2-Ar plasma for various set points of effective electron tempterature.

in total filling pressure and increased inelastic collisions. The increase in pressure leads to lower mean free path and lower current density at the biased substrate, which consequently lowers the electron temperature. The shorter mean free path signifies more collisions and loss of energy when electrons dissociate N_2. With argon alone, the highest electron temperature is 13.6 eV, while the addition of nitrogen lowers this to about 9.48 eV. These are shown in Fig. 4 and 5.

The non-uniformity of the T_{eff} distribution inside the extraction chamber is also apparent like in the case of argon plasma. The anode and biased substrate holder give rise to different current distributions compared to other locations. The positively biased substrate holder at positive 50-80 V attracts the negatively charged electron. The opposite polarity accelerates the electrons and collide the neutrals and ions along its path. Therefore, higher electron temperatures are thus expected near their locations due to higher frequency of ion bombardment.

It would be expected that near the gas feed-through locations, the initial high pressure due to the diffusing flux of neutral atoms leads to lower electron temperatures. Nitrogen gas is fed at the extraction chamber while argon gas is via the production chamber.

The non-uniform radial and axial distribution of electron density of the Ar plasma is observed in Fig. 4. There is no discernible pattern in the effective electron temperature's relation to the density. However, there is an apparent decrease (although non-uniform) in density as the probe is positioned away from the center of the extraction cham-

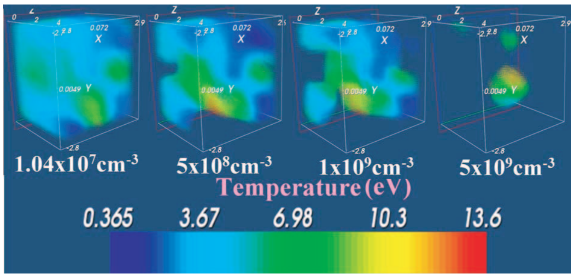

Fig. 4 Isosurface of the electron density of Ar plasma for various set points of electron density.

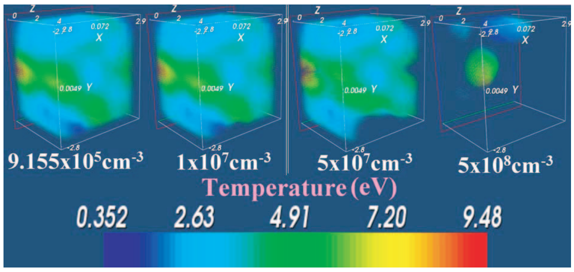

Fig. 5 Isosurface of the electron density of N_2-Ar plasma for various set points of electron density.

ber as seen in the $5 \times 10^8\ \mathrm{cm}^{-3}$ isosurface. In general, a non-uniform decreasing pattern is observed as the probe is moved away from the sheet center. However, the highest concentration of electrons is about 3.5 cm away from the sheet center. Compare this to Fig. 5.

It is apparent in Fig. 5 that the electron bulk of N_2-Ar plasma is found at the center of the extraction chamber as opposed to the periphery. This difference is explained by the presence of the streaming neutral gas injected directly into the extraction chamber. The additional gas differentiates the working filling pressure in the chamber. Pressure can dictate the diffusion of charged elements in the presence of a magnetic field [14]. Higher pressure can lead to stronger confinement, thus a more sheet-like geometry is observed.

4. Conclusion

Electron density (n_e) and effective electron temperature (T_{eff}) distributions were constructed using the I-V curves from Langmuir probe traces at specific discrete positions in the extraction region of a magnetized sheet plasma ion source (MSPIS). These values were then programmed using the Visualization Toolkit (VTK) for 3D imaging. To elucidate the effects of changing plasma parameters, slices of the n_e and T_e space were taken. Non-uniformity of n_e and T_e along the sheet plane was observed. This non-uniformity of the plasma inside the source is a machine limitation. To increase the performance of the machine's plasma uniformity, the magnetic field strength of the source should be replaced from an operating current at 12 A to 30 A, the designed operating condition.

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