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Convective flow zones in filament-discharge plasma sources

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ABSTRACT: Convective flow zones were found to surround the discharge current in an electron-beam generated argon plasma. Flow zones were created by the electric field associated with the injected electron beam. A sheet-beam was injected along a confining magnetic field. The discharge current and voltage were varied, and the ion flow near the beam was studied via laser-induced fluorescence. It was observed that the drift velocity, and thus the inferred electric field, was nearly constant even with increasing current, yet the electron density of the beam did increase.

KEYWORDS: Plasma generation (laser-produced, RF, x ray-produced); Plasma diagnostics - interferometry, spectroscopy and imaging .

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1. Introduction

Discharge plasma sources are in wide use industrially from high intensity mercury lamp discharges to metal halide lamp sources and many others. The lamp sources come in several configurations, often relying on the flow of electrons due to an electric field in the source for production of the plasma and associated light output. Laboratory plasma sources frequently use filament discharge sources for producing argon, xenon, neon, and other plasmas for basic and applied plasma physics research. These discharges may be produced from an electron beam made via thermionic emission from a filament biased below the surrounding vacuum vessel. Such configurations also are used in ion beam sources for plasma etching and deposition processes.

Traditionally probes such as Langmuir probes have been used for plasma diagnostic purposes. These probes have several advantages, in that they allow for an in-situ measurement of several important plasma parameters, but they are also invasive and can alter the plasma properties they are intending to measure. Tunable diode laser-induced fluorescence is a technique for measuring the velocity distribution function of the ions without causing any major disruption to the plasma [1]. The technique can be used to acquire a spatially-resolved measurement of the ion velocities in any direction, thus allowing flexibility in addition to being less disruptive.

In this experiment laser-induced fluorescence (LIF) was used to measure the ion velocity distribution in the plasma in the region of the discharge electron beam. A fast electron beam sheet caused an electric field not shielded within a Debye length to be created in the plasma. These unshielded electrons produced an electric field in the plasma and combined with the steady external magnetic field to produce an $\mathbf{E} \times \mathbf{B}$ drift near the beam [2].

These electric fields caused a convective zonal plasma drift velocity, yet the work presented in the present paper shows that the electric field in the region of the beam does not increase significantly with the beam current. It may be that, with increasing plasma density, the plasma shielding of the beam-produced electric field increases with beam current. A change in electric field was only observed at very low plasma densities where the experimental setup was no longer precise enough to produce a credible measurement of the zonal flow. In other words, some mechanism nearly clamps the zonal flow, the zonal flow saturates as the beam current density is raised.

Figure 1. Experiment geometry. Electron beam sheet is represented by central rectangle, and electric field by small arrows pointing into beam along y-axis. Magnetic field is in z-direction into the figure, and $E \times B$ drift is represented by large arrows along x-axis.

2. Experimental arrangement

The experiment was conducted on the Irvine Torus [3], which produces an argon plasma using a filament source to ionize the argon atoms. The vacuum vessel has a major radius of 56.5 cm, with a minor radius of 10.5 cm, with a toroidal magnetic field (z-direction), which was typically run at 1 kG. The filament, biased below vacuum vessel ground potential, was set up to be parallel to the major radius and perpendicular to the magnetic field. The beam was a sheet in the x-direction of extent 12 cm made with a 0.013 inch tungsten wire. A typical emission current was 100 mA, but this could be varied between 15 mA, at which the plasma disappeared, and 200 mA, at which time the filament would burn out in a matter of minutes. The argon neutral pressure in the chamber was typically 5×10^{-4} torr, which could be varied from 10^{-4} - 10^{-3} torr. About 1% of the background neutrals were ionized by the electron beam, resulting in a plasma density on the order of 10^{10} - 10^{11} cm^{-3} . Plasma electron temperatures were around 4 eV, whereas the ions were slightly above room temperature due to charge exchange. The ion and electron gyro-radii were approximately 3 mm and 0.1 mm, respectively, and the Debye length approximately 0.3 mm. The Irvine Torus is large enough that the toroidal magnetic field curvature is not likely to affect the present experiment results, and thus a Cartesian coordinate system is used throughout the rest of this paper as shown in figure 1.

Figure 2. Schematic of optical apparatus.

The plasma was diagnosed using laser light generated by a system of a seed laser amplified by a single pass optical amplifier [1]. The seed laser was a New Focus Vortex 6009 diode laser, with a frequency that could be adjusted by applying a variable piezo voltage, which could be swept between a wavelength of 668.10 and 668.19 nm. The seed laser output of about 5 mW was then passed through an SDL 8260 amplifier, which has a gain factor of up to 100. The beam then passed through an iodine cell with a photodiode attached. This allows absolute calibration of the laser frequency, as the iodine absorption peaks can be compared with an iodine atlas [4]. The beam was then passed through a chopper fan which allowed the signal to be detected in the presence of the background light from the plasma via lock-in amplifier. The laser beam was directed through a window of the vacuum vessel into the plasma.

Fluorescence was detected by a photomultiplier with a 432 nm filter (the emission wavelength of the argon excited by the laser), which was directed into a different window outside the vacuum chamber. This signal was processed by a lock-in amplifier at the frequency of the chopping fan. The argon fluorescence signal was taken simultaneously with the iodine signal, as the frequency of the laser was adjusted, which provided a trace from which an ion velocity distribution could be determined. A circuit diagram for the system used in this experiment is presented in figure 2.

3. Results

The frequency of the laser was swept through approximately 10 GHz for each scan. Within this range, both the argon LIF and an iodine peak were observed. Using a broader scan encompassing several iodine peaks for comparison with an iodine atlas [4], a linear conversion was made between the piezo voltage applied to the seed laser and the frequency emitted. The broader iodine scans showed that the frequency range covered by each volt applied to the piezo was nearly constant over the measurement range. The wavelengths were then converted into velocities, relative to the known transition wavelength for argon ions [1]. The Iodine and LIF peaks were observed to be approximately Gaussian, and thus were fit with a Gaussian approximation. A sample processed scan is shown in figure 3.

A vertical scan of the horizontal ion drift was taken by moving the laser in the y-direction (vertical) while the laser beam was going into the plasma in the x-direction (horizontal). The photomultiplier optics were focused at a particular x-value near the plasma center. By varying the y-position of the laser beam and collection optics, the successive scans offered a vertical profile of the x-direction plasma ion velocity distribution function in the area of the injected electron beam to a millimeter resolution. This showed that the expected $E \times B$ drift was observed above and below the beam, as seen in figure 4. The drift speeds and convective flow zones near the electron beam were similar to those observed in earlier experiments [2], with the maximum

Figure 3. Sample LIF scan. Velocity scale is in positive x-direction, showing drift horizontally outward in this scan, taken below electron beam.

Figure 4. Drift velocities near electron beam varied by about 300 m/s from an average radial drift outwards of approximately -200 m/s. Vertical position (x-axis of graph) has an arbitrary zero, sweeping up through beam centered at about 3 mm on graph.

ExB drift being about 300 m/s above and below a horizontal baseline drift around -200 m/s on this graph as observed away from the convective zone.

Once the vertical profile was obtained, the laser was set to the position of maximum drift above the beam, and the plasma parameters were varied to determine effects on the ExB convective drift. Varying neutral pressure and the energy of the electrons in the beam had no effect on the ExB drift. A factor of 7 increase in the injected beam current produced no

Figure 5. Drift velocity versus emission current. Drift speeds for currents below 20 mA are not precise enough to determine a trend due to low plasma density.

significant change in drift speed, as shown in figure 5. It was observed that, for beam currents between approximately 30 and 200 mA, the drift speed was approximately constant, but when the emission current was reduced below 30 mA, a slight shift may have occurred. The LIF signals were weak enough at this low plasma density to make this result unreliable however, so this low-density effect could not be verified.

At first glance, it might be surprising to see little change in ExB drift with discharge emission current. However, one should note that the beam energies are such that shielding within a Debye length is not expected. Further, the electron beam discharge, in argon here, has some similarity with mercury discharge lamps [5]. For mercury discharges, Elenbaas performed experiments and produced theories which showed that the axial electric field sustained in a mercury discharge goes as the discharge current to the one-fifth power [6], a weak dependence on discharge current (and within the error bars of the present LIF observations). Elenbaas obtained this result via power-balance considerations. While this derivation is done for mercury, the arguments carry over to argon filament plasmas. The basic result of the observations of figure 5 is that there is not much one can do via beam discharge current to vary the ExB drifts surrounding the electron beam in the argon discharge.

To examine further what effects increased electron beam current had, a vertical scan of the plasma was taken using a “T” probe, with a T shaped piece of wire inserted into the plasma and biased 150 volts below ground to collect ions and beam electrons with an energy of 250 eV, but exclude the main plasma electrons. These scans showed that there was very little broadening of the beam, and the ion density was proportional to the emission current. The data are shown in figure 6, with a negative current corresponding to ion density. Outside the inverted peaks, where ion density is much lower than in the ionization path of the electron beam, one may see the ion density is proportional to beam current as expected. Within the beam path, however, the total collected probe current increases with reduced rate as the discharge current is increased. From 50 to 100 mA discharge current, we observe only an 80% increase within the beam path instead

Figure 6. T-probe current versus vertical position, probe biased at -150 V.

of an expected 100%. From 100 to 150 mA discharge current, only a 10% increase in probe current is seen instead of the expected 50%. The beam did not broaden significantly over this current range, and thus it is unlikely that the increased density is spread over a greater area.

A vertical scan of the floating potential did not show increased vertical electric field near the beam at higher emission currents. Figure 7 shows the vertical scan of floating potential at several different emission currents. The slope in the region of the beam appears nearly constant across the scans at emission currents above 50 mA, which indicates that the vertical electric field in this region is not increasing with the increased discharge current in the beam. The magnitude of the vertical electric field (estimated via the $E \times B$ drift observation or the floating potential spatial variation) was consistent with earlier work, with an electric field of approximately ± 25 V/cm [2]. Only at emission currents less than 30 mA does the slope become shallower, showing that the electric field decreases.

Given a long-enough path length, the plasma may be expected eventually to neutralize the beam. Additional observations about the un-neutralized nature of the plasma in the electron beam path can be adduced. Considering Laplace's Equation guides the understanding that the electron beam has reached nearly its full velocity within approximately 15 cm of the biased filament beam source since the vacuum vessel has a radius of 10.5 cm. Hence, the electron beam current is carried into the plasma around the 3.5 m circumference toroid at the full beam velocity from very near the source. The beam then decelerates from collisions. In figure 6 we see evidence of successive passes of the beam at increasing vertical heights due to grad-B, curvature, and toroidal field design considerations. The potential drop from the first to second beam passes is about 5 volts along the 3.5 m toroidal path (E -parallel ~ 1.4 V/m). For the second to third beam pass the potential drop is about 3 volts (E -parallel ~ 0.87 V/m) and the overall potential is closer to ground than the first beam pass position. Even though the overall beam energy is not greatly reduced by the parallel electric field, the floating potential in the beam region is brought 25% closer to ground after these two passes following the initial-pass plasma potential. As well, figure 7 shows how the floating potential in the beam region becomes

Figure 7. Floating potential versus vertical height. Only at 10 and 20 mA does the slope of the floating potential appear to change significantly at the electron beam region, where at higher emission currents the potential appears almost constant with varying current with an offset of the plasma potential.

more similar to the surrounding region with each pass of the beam. The plasma increasingly neutralizes the electron beam with increasing beam distance from the source.

There is qualitative evidence of high energy ions near the filament. Though we have not seen high energy ions with LIF at the filament (the filament is very bright) and an ion energy analyzer would block the accelerating potential causing the high energy ions, we can examine the filament directly. The filament has a lifetime in these experiments typically of some hours. The filament fails when all the filament is etched away at a point along the filament. Incoming ions accelerated up to the beam potential etch the filament. The filament lifetime reduces as the accelerating potential or filament emission are increased, both of which increase ion etching.

4. Conclusions and recommendations

Electron beam argon discharges are accompanied by ExB convective flow zones surrounding the electron beam. The ExB convective drift zones extend many Debye lengths from the electron beam path, as the superthermal electrons are not shielded in the same manner as thermal electrons. The convective speeds do not change much with increased discharge beam current in the range studied. The electric field associated with the argon zonal flows does not change much with discharge parameter variation, perhaps for reasons similar to observations and theories of mercury discharges.

A further investigation into the shielding outside the Debye sheath would require a more sensitive and precise experiment, which could achieve lower plasma densities and still take an accurate measurement of the drift speed. In the present experiment, at lower plasma densities the noise became significant enough such that the uncertainty in the drift speed was more than 150 m/s, thus obscuring any trends in the low-density results. A refinement of the optics used in

the experiment would allow the results to be compared more conclusively to the model presented by Elenbaas.

This experiment would also benefit from a more precise method of measuring the vertical position of the laser in combination with altered discharge filament design. The filament expanded slightly when it was heated to operating temperatures, thus sagging slightly in the presence of the magnetic field, yielding a beam that had a slightly curved shape, and thus the laser's height above the beam had a horizontal dependence. Measurements were taken near the center of the beam but a flatter beam would improve the experiment.

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