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ECR Plasma Source for Heavy Ion Beam Charge Neutralization*

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Highly ionized plasmas are being considered as a medium for charge neutralizing heavy ion beams in order to focus beyond the space-charge limit. Calculations suggest that plasma at a density of 1 - 100 times the ion beam density and at a length ~ 0.1-2 m would be suitable for achieving a high level of charge neutralization. An ECR source has been built at the Princeton Plasma Physics Laboratory (PPPL) to support a joint Neutralized Transport Experiment (NTX) at the Lawrence Berkeley National Laboratory (LBNL) to study ion beam neutralization with plasma. The ECR source operates at 13.6 MHz and with solenoid magnetic fields of 1-10 gauss. The goal is to operate the source at pressures ~ 10^{-6} Torr at full ionization. The initial operation of the source has been at pressures of 10^{-4} - 10^{-1} Torr. Electron densities in the range of 10^{8} - 10^{11} cm^{-3} have been achieved. Low-pressure operation is important to reduce ion beam ionization. A cusp magnetic field has been installed to improve radial confinement and reduce the field strength on the beam axis. In addition, axial confinement is believed to be important to achieve lower-pressure operation. To further improve breakdown at low pressure, a weak electron source will be placed near the end of the ECR source.

I. Introduction

A possible heavy ion fusion reactor design is the HIBALL-II design [1]. The final focusing magnets must focus multiple heavy ion beams to a small spot size in the target chamber at the emittance limit. This will require a deliberate charge neutralization of the ion beams before they reach the emittance limit. The planned near-term Neutralized Transport Experiment (NTX) [2] will investigate the most promising neutralization methods. One reactor design concept utilizes multiple heavy ion beams, charge neutralized by large-volume plasma. The charge neutralization was modeled as a heavy ion beam propagating through a highly ionized cylindrical plasma column [3]. The cold plasma ion motion is neglected, and electrons from the cylindrical plasma move into the beam channel, reducing the net positive beam charge over the larger volume of the plasma channel. For NTX, ion beam densities will be in the range of $10^8 – 10^9$ cm^{-3}. Present calculations require the plasma to be in the range of 0.1- 2 meters in length with an electron density comparable to 1-100 times the beam density. The operating pressure for the plasma needs to be in the range of $10^{-6} – 10^{-5}$ Torr to prevent neutrals from stripping the beam ions to higher charge states. In this paper, we describe a progression of plasma sources toward lower operating pressures that are capable of producing large-volume plasmas to support neutralization experiments. To achieve neutralization, plasma will be created or injected into the drift section between the last magnetic lens and the reactor chamber. These sources are versions of those applied to plasma processing of semiconductor devices for pressures above 1 mTorr and those applied to some particle accelerators at 10^{-6} Torr. All of the sources under consideration are Electron Cyclotron Resonance (ECRsources and are driven at radio frequencies (rf) of 1-50 MHz or at the microwave frequency of 2450 MHz.

II. Wave Damping Theory

(a) Collisional Damping near 1 mTorr Pressure

Plasma processing sources routinely operate near 1 mTorr pressure. The wave damping is collisional at this pressure. Consequently, the volume of the plasma is limited by the plasma skin depth. Fortunately, increasing electromagnetic wave penetration in collisional plasmas with magnetic fields has been theoretically studied [4] and has identified the whistler wave as favorable for the creation of large-volume plasmas for semiconductor processing. The whistler wave propagates along magnetic field lines ($k \,||\, B$). The approximate dispersion relation for whistler waves is

$$N^2 = [1 + \omega_{pe}{}^2/(\Omega_{ce}\,\omega(1-\omega/\Omega_{ce}))]\; F(\nu/(\omega-\Omega_{ce})), \qquad (1)$$

where N is the index of refraction, ν is the collision frequency, Ω_{ce} is the electron cyclotron frequency, $F(x) = (1- jX)/(1+ X^2)$,and $\omega < \nu, \Omega_{ce}$. The propagation characteristics and wave damping can be examined from the real and imaginary components of the index of refraction. The real part of the index is continuous and is always greater than zero for all densities, indicating that there is no resonance or cutoffs to limit wave accessibility at any density. This is a unique characteristic that allows access to all density ranges with one heating frequency. Control of the skin depth of plasmas is directly observed in the electron absorption power density, P_{abs}, including collisionality and magnetic field. Here , P_{abs} is defined by

$$P_{abs}=\frac{e^2E^2}{4m\nu}\left(\nu^2/((\omega - \Omega_{ce})^2 + \nu^2) + \nu^2/((\omega + \Omega_{ce})^2 + \nu^2)\right) , \qquad (2)$$

where e is the electron charge, E is the wave electric field, and m is the electron mass. For the whistler wave, $\omega \ll \nu, \Omega_{ce}$, and therefore the absorbed power density can be reduced by increasing the cyclotron frequency until it is comparable to the collision frequency ($\nu \sim \Omega_{ce}$). The absorption for 13 MHz waves at 1 mTorr can be affected by introducing 10's of gauss of axial magnetic field. The density scale length can be increased 10-100 fold. This level of axial magnetic field will not adversely affect beam focusing. By changing the magnetic field, the plasma length can be adjusted to achieve beam neutralization. Similar results were obtained by Mantei [5] in plasmas produced with microwaves.

(b) Collisionless Damping Below 1 mTorr Pressure

At low pressure, the plasma is collisionless compared to the wave frequency and cyclotron wave damping is required, where $\omega \sim (1\text{-}2)\ \Omega_{ce}$. Wave damping depends upon the plasma temperature, density, collisionality, and the proximity of the wave frequency to the cyclotron frequency. Cyclotron damping ($\omega \sim \Omega_{ce}$) has the imaginary wave vector, k_{Iii}, given by

$$k_{IIi} = (\pi)^{1/2}\, \omega_{pe}^{2} /(2c^{2}\, k_{II}^{2})\, \zeta_0 \exp\{ - \zeta_1^{2}\},$$

$$k_{IIi} =\zeta_1 = (\omega - \omega_{ce})/(k_{II}v_{th}). \qquad (3)$$

The ECR wave requires a magnetic field, but it can be modest (~ 10 gauss) if the source frequency is at 13 MHz. Similar plasmas have been produced using whistler waves by Stevens [6].

III. ECR Solenoid Sources

The first source examined was a simple ECR solenoid source. It is a 4” diameter cylinder and is approximately 12” long. Simple 16-gauge wire is wound around the cylinder to create a solenoid field. Up to 15 amperes of current can be applied to the coil to create a 30 gauss field. A radio frequency antenna couples power into the cylinder through a quartz window mounted at one end of the cylinder. The antenna is a simple 3-turn spiral. The spiral antenna is cooled with water and mounted in an enclosure against the window to prevent wave leakage. The source operates at 13 MHz frequency and at nominal power levels of 1 kW. The spiral antenna is impedance matched to the 13 MHz radio frequency source with a pair of tunable capacitors arranged in series and parallel to the antenna. Figure 1 is a photograph of the source. In the photograph, a window is mounted for viewing the plasma. Through a vacuum tee is mounted a Langmuir probe.

The first operation of the source was at pressures near 5 mTorr in Argon gas. In this regime the damping is expected to be collisional and the weak solenoid magnetic field is expected to effect the skin depth. The Langmuir probe was moved from the side of the cylinder source to the end where the viewing window is shown in Figure 1. The Langmuir probe is programmed to scan the length of the source on its axis. Figure 2 shows a plot of the electron density (dashed lines) and the ion density (solid) as a function of position from the antenna window for different values of magnetic field. In going from zero magnetic field to 4.3 gauss, the plasma density increases from 10^{8} cm^{-3} to over 10^{10} cm^{-3} at a distance of 25 cm from the antenna. The skin depth is greatly extended and the data fits the theory for collisional damping in Eq. (2).

The situation is much different at pressures near 0.5 mTorr. When varying the field, the plasma density is a maximum when $\omega \sim \Omega_{ce}$ at 6.2 gauss. This is an indication that the wave damping is now cyclotron damping at a pressure of 0.5 mTorr. The magnetic field scan at 0.5 mTorr is shown in Figure 3.

The operation of this source behaves like similar sources studied in the literature. It has an operating range down to 0.5 mTorr. Below this pressure the source would extinguish.

IV. Cusp ECR Source

We have used an alternate magnetic field configuration to improve the confinement of the source by increasing the magnetic field without raising the field on axis where an ion beam would propagate if it were to be integrated co-linear with the plasma source. The simple solution is to substitute a cusp magnetic field for the solenoid. The magnets are arranged in an eight-pole configuration with the field perfectly nullified on axis and building up to a value near 1 kG at the cylinder inner wall. Consequently, there is a cyclotron resonance near the axis for strong wave damping and a strong field near the wall to provide confinement. In this configuration, the plasma source ran well at pressures down to 0.5 mTorr. However, the source did not operate at lower gas pressure. The plasma electron density on axis is on the order of 10^{11} cm^{-3} near the antenna and approximately 10^{10} cm^{-3} at a distance of 20 cm away. This is very similar to the solenoid ECR source.

V. Source with Mirror Coils

The operating pressure for plasma sources is a balance of ionization rate and particle loss rate. Both solenoid and cusp ECR sources have limited confinement because they are open on each end, and there is no attempt to plug the ends to reduce the loss. To reduce the particle loss rate, mirror field coils were wound on the ends of the source. There is approximately 80 gauss field in each end coil. An initial attempt to operate the source with the mirror coils on the end did not improve performance and actually extinguished the plasma when the mirror fields were above 80 gauss. It was determined that the two mirror coils removed the cyclotron resonance everywhere in the source. The solution was to install a coil in the center of the source to null out the mirror coil contribution in the middle of the plasma source. This change allows the mirror coils to operate at all mirror field values, and allowed the plasma source operation to continue down to $2x10^{-4}$ Torr. The plasma was observed to be smaller in size and had a very blue hue. Langmuir probe measurements showed that the confinement zone was only 2-3 cm long in the middle of the source and the density was below 10^9 cm^{-3}. The electron temperature in that region was 15 eV. A higher level of ionization would be expected at that electron temperature. It is been concluded that the central coil to null out the effects of the end mirror coils needs to be lengthened. A 2-3 cm length is not sufficient for wave damping and plasma confinement.

VI. Future Plans

Future plans include increasing the length of the cyclotron resonance region in the source by redesigning the central coil. Consideration is also being given to converting to a microwave frequency of 2450 MHz to achieve a higher level of ionization. Sources in the literature that operate near 10^{-6} Torr pressure all use microwaves instead of radio frequencies [7]. The present cusp magnets have a field near the wall for cyclotron resonance.

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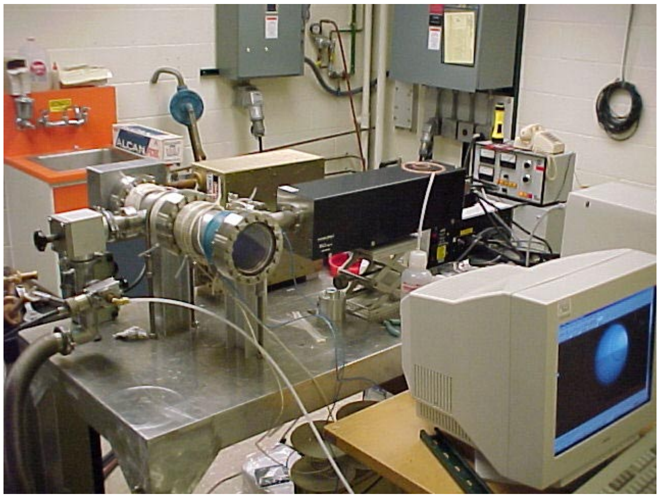

Fig. 1 Photograph of the ECR solenoid plasma source and the Langmuir probe.

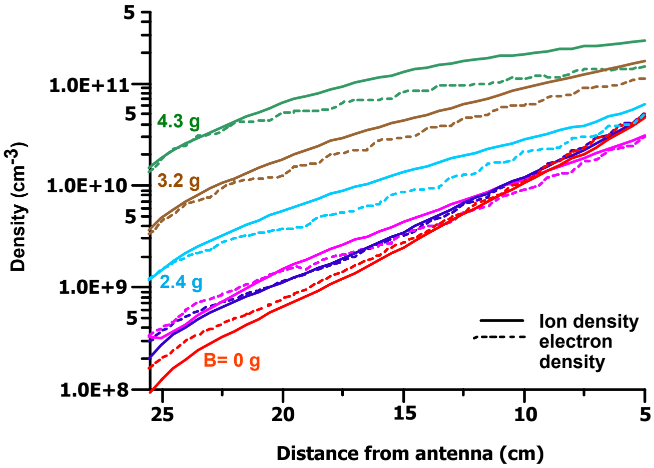

Fig. 2 Electron density as a function of position relative to the antenna for different magnetic fields.

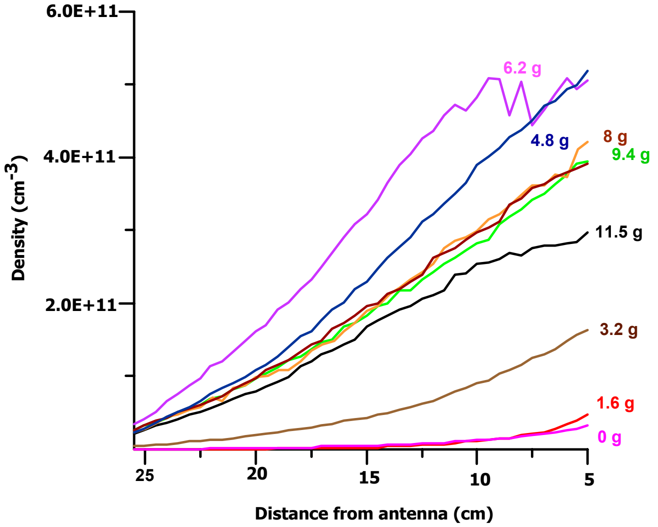

Fig. 3 Electron density as a function of position relative to the antenna for different magnetic fields at low pressure. A distinct cyclotron resonance can be viewed.