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A DIPOLE ASSISTED IEC NEUTRON SOURCE

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Abstract

A potential opportunity to enhance Inertial Electrostatic Confinement (IEC) fusion exists by augmenting it with a magnetic dipole configuration. The theory is that the dipole fields will enhance the plasma density in the center region of the IEC and the combined IEC and dipole confinement properties will reduce plasma losses. To demonstrate that a hybrid Dipole-IEC configuration can provide an improved neutron source vs. a stand alone IEC, a first model Dipole-IEC experiment was benchmarked against a reference IEC. A triple Langmuir probe was used to find the electron temperature and density. It was found that the magnetic field increases the electron density by a factor of 16, the electron temperature decreases in the presence of a magnetic field, the discharge voltage decreases in the presence of a magnetic field, the potential of the dipole strongly influences the densities obtained in the center. The experimental set-up and plasma diagnostics are discussed in detail, as well as the results, and the developmental issues.

1 Introduction

Inertial Electrostatic Confinement (IEC) fusion, was first proposed by Salisbury in the 1940's as a means of electrostatically confining a plasma. In a typical IEC device, a high voltage (~50-200 V) is applied to nearly transparent grids which accelerate ions down an electrostatic potential hill where the charged particles converge and fusion occurs. The IEC may be particularly well suited for advanced fuel fusion since high ion energies can be achieved with ease. However, for the successful development of IEC of plasmas for fusion power, electrical production, spacecraft production, or higher yield neutron source applications, the IEC must overcome several physics issues such as electron confinement, ion loss rates, charge exchange limitations, ion collision time scales, and ion source profiling [1]. A potential opportunity to enhance the IEC exists by augmenting it with a magnetic dipole configuration. Some of the aforementioned issues and challenges may be reduced or eliminated in the resulting dipole-assisted IEC (DaIEC). The theory is that the dipole fields will enhance the plasma density in the center region of the IEC and the combined IEC and dipole confinement properties will reduce plasma losses.

To demonstrate that a hybrid Dipole-IEC configuration can provide an improved neutron source vs. a stand alone IEC, a first model Dipole-IEC experiment was benchmarked against a reference IEC. Two half-bowl shaped cathode grids are put into the upper and lower sides of the dipole, to accelerate ions toward the center of the IEC. The dipole is electrically isolated from the grids, with four separate supports. The magnetic flux along the z-axis of the magnetic coil will provide a preferred path for the weakly ionized plasma. When the B-field lines exit the IEC grid, the electrostatic field dominates and reflects most particles back inside the grids, where the magnetic field once again dominates. Thus particles oscillate much as they would in a normal IEC with the added benefit of having a preferential particle trajectory to focus the plasma similar to an IEC based jet mode configuration. A triple Langmuir probe was used to study the electron temperature and density.

2 Experimental Set-up

2.1 Coil Design

The Dipole Assisted IEC experiments were performed in the Fusion Studies Laboratory vacuum chamber facilities. A schematic of the experimental set up is shown in Fig. 1.

The dipole coil is the main feature in the DaIEC experiment. The dipole coil is installed inside the IEC and placed at the center of the two bowl shaped grids. When a current is applied to the coil, the magnetic field produced by this coil is expected to trap charged particles along its magnetic field lines. These trapped particles are better focused at the center region of the spherical IEC device. Theoretical estimation of the increase in ion density in the presence of a magnetic field will be considered based on the effect of focusing plasma. The ion density is increased in such way that magnetic field compresses plasma into small volume. Therefore, we can estimate the theoretical increase in density by taking the ratio of number of particles in volume before and after the compression. The assumptions made in this estimate are 1) the radial density profile before compression is exponential. 2) the density is constant readily after the compression.

Fig. 1: A schematic view of the experimental set-up.

The number of ions when there is no magnetic field in the cylinder with small height Δh ,

$$N_0 = 2\pi \int r \rho_r(r) dr \cdot \Delta h \quad (2.1)$$

$\rho_r(r)$ is the ion density as a function of radius. At the center, density is equal to $\rho_r(0)$ and boundary condition is set as constant A. Therefore the equation becomes

$$\rho_r(r) = \rho_r(0) e^{\frac{-r^2}{A}} \quad (2.2)$$

Now, number of ions when magnetic field is turned on is simply,

$$N_B = 2\pi r_B^2 \rho_r(0) \cdot \Delta h \quad (2.3)$$

Where, r_B is radius of compressed cylindrical volume. Therefore, ratio is

$$\frac{N_0}{N_B} = \frac{2\pi\rho_r(0)\int re^{\frac{-r^2}{A}} dr \cdot \Delta h}{2\pi r_B^2 \rho_r(0) \cdot \Delta h} = \frac{1}{r_B^2} \int re^{\frac{-r^2}{A}} dr \quad (2.4)$$

$\frac{1}{r_B^2} \int re^{\frac{-r^2}{A}} dr$ is the factor of density increase due to a presence of magnetic field. We will estimate boundary condition for potential profile to determine A and r_B from the experiment.

2.1.1 Operation Conditions.

The effect of adding a magnetic field is examined in low voltage IEC operation and these voltages are varied from 500 V to several kV. It is obvious that in the low voltage regime, ions have low energy compared to those in high voltage operation. Therefore, to trap those ions and elections, several hundred gauss of magnetic field is first considered. The actual size of dipole coil is determined by aiming to produce 1000 gauss at the center of our IEC device; this is achieved with 20 A of applied current and 16 x 25 turn of the dipole coil (Fig. 2).

Fig. 2: A completed dipole coil (Ri=4cm, and Ro=8cm h=4cm).

2.1.2 Effect of Potential

Since the dipole coil is inserted and tested within the plasma, an examination of the effects of adding another potential (potential of dipole coil) needs to be investigated. In a typical IEC

operation, since there is only a cathode grid causing ions accelerating toward the center, the potential within the cathode grid is only estimated due to this space charge effect. However, in this dipole assisted IEC, by changing the potential of coil, it is possible to control the potential at the center region of IEC regardless of the space charge. In other words, by fixing potential to coil around cathode potential, we can decrease potential barrier built up by space charge at the center of IEC device. However, since applying kV range of negative potential to coil is not easily achieved, in the first model of Dipole assisted IEC, potential of dipole coil is adjusted to few hundreds of voltage. In addition, although it is obvious that negative potential to coil is favorable, we will examine the effects of applying positive voltage and zero voltage. A floating condition of coil is achieved by connecting isolation transformer between power supply for dipole and electrical outlet.

2.2 Grids

Two 20 cm diameter grids were constructed of 0.5 mm diameter stainless steel wire with a spacing of approximately 1 cm. The grid acts as a cathode and is placed at a large negative potential with respect to the chamber. The bowl shaped geometry was chosen for ease of construction, otherwise it would have been difficult to build and support a spherical grid outside of the magnetic dipole. In addition, since we are interested in focusing the charged particles through the top and center of the dipole, there was no reason to accelerate ions to the sides of the dipole, which would have resulted in further deterioration of the dipole. A picture of the grid is shown in Fig. 3.

Fig.3: An overall view of the Grid.

2.3 Plasma Diagnostics

Electrostatic, or Langmuir probes were the first diagnostics developed capable of taking measurements inside of a plasma. Physically they are very simple consisting only of an exposed wire in a plasma that is biased to some potential. Langmuir and Mott-Smith [2] have described a single probe technique for measuring electron temperatures as well as other quantities such as electron density and wall and space potentials. However, in any case, unless its area is extremely small, the probe may draw sufficient electron current when operated close to space potential to disturb the plasma conditions which it is designed to measure [3]. Therefore, “floating probe” methods have been invented for determining plasma properties with minimum disturbance. For the experiment at hand, a floating double probe and triple probe have been used.

The double probe method makes use of two probes, each similar to the single probe of the single probe method. They are interconnected as shown in Figure 4.

Fig 4 (a) Double Probe Circuit, (b) Triple Probe Circuit

In the double probe circuit, the potential V_d is termed the differential voltage and its associated current i_d the circuit current. By plotting these two parameters (V-I characteristic), the electron temperature, electron density and wall potential can be determined. The actual shape of the double probe characteristic is very important for two reasons. The effect of the electric and magnetic fields can make the electron distribution non-Maxwellian, which would invalidate

much of the theory from which probe theory is built. Also, since there are high energy ions present in our experiment, saturation may never occur, which would make the probe analysis extremely difficult, if not impossible.

Although the triple probe is the main diagnostic used in this experiment, it is useful to first briefly discuss the double probe trace. We will thus consider a characteristic curve taken from our experiment. The V-I trace shown in Fig. 5 was taken at a pressure of 20 mT, with a discharge voltage and current of 3 kV and 20 mA, respectively. Using the values found from this figure, and the “equivalent resistance” method outlined by Johnson and Malter [3], $T_e = 1.32$ and $n_e = 2 \times 10^9 \text{ cm}^{-3}$ is found.

The points AB and CD correspond to the ‘saturation regions’ of the curve; meaning a sheath forms around the probe which further repels ions. Ideal saturation (completely horizontal AB and CD regions) does not occur in practice unless $r_p / \lambda_D \rightarrow \infty$. Otherwise, the sheath surrounding the probe increases with increasing applied potential, therefore the ion current also increases. The implications of this will be discussed in the following section. However, the existence of the saturation regions imply the ions can be captured by the probe, which was essential for operation of the triple probe.

The most sensitive procedure for checking whether the electron energy distribution function is Maxwellian is to observe whether a plot of $\ln(dV_d / dI_d)$ vs. V_d is linear [4]. Since this is true for our case, we are able to assume the electrons are Maxwellian, which was necessary for triple probe operation.

Fig. 5: V-I Graph at pressure 20mT, discharge voltage 3kV and current 20mA.

2.3.1 Triple Probe Method (TPM)

One of the drawbacks of double Langmuir probes is that a current vs. voltage curve is needed to properly determine plasma properties from the probe measurements. The symmetric triple probe solves the problem of this voltage sweep allowing for the instantaneous measurement of electron temperature (T_e) and density (n_e), where previously, tedious curve fitting was required [4]. The symmetric triple probe consists of three exposed wire of equal area in the plasma. By correctly biasing the probes, and using the theory outlined by Chen [5], T_e and n_e can be found. There are several other advantages associated with triple Langmuir probes. As with the DPM, the circuit is floating, such that no net current is transferred between the probe and the plasma, so relatively little disturbance of the plasma results. Also, with single Langmuir probes, analysis of magnetoplasmas can be rather difficult and cumbersome since the ion current falls off rapidly in the region of the floating potential, and the probe characteristic curve no longer remains a straight line. The slope of this straight line is what is typically used to find T_e . In the triple probe

system, the problem of the correction of the ion current is removed since the system is operated on the basis of the difference and ratio of the three probe currents.

In the TPM, a fixed voltage is applied between two of those wires, generating a current in that circuit, which is measured. The voltage difference between the positive wire and the third wire, which is electrically floating is also measured. Using the methods outlined by Chen [5], these two values (V_{d2} , I) allow for the evaluation for the electron temperature and subsequently the electron density.

The current V_{d3} is fixed and is provided by a 9 V battery. The current I is determined by means of a high impedance ammeter. The voltage V_{d2} is measured by means of a voltmeter.

Because all the wires have the same radius, the assumption that all probes collect over the same area can be made. This simplification yields the following expression for the electron temperature:

$$\frac{1}{2} = \frac{1 - \exp\left(-\frac{eV_{d2}}{kT_e}\right)}{1 - \exp\left(-\frac{eV_{d3}}{kT_e}\right)} \quad (5)$$

V_{d3} is a constant input to the probe and V_{d2} is measuring output, therefore (5) can be used to find T_e . By using the Bohm sheath criteria [6] and algebraic manipulation of the current equations to each probe, the electron density is given by:

$$n_e = \left(\frac{\sqrt{m_i}}{S} I \right) \frac{\exp(1/2)}{e\sqrt{kT_e} [\exp(\phi V_{d2}) - 1]} \quad (6)$$

2.3.2 Magnetic Field Effects

The magnetic field influences the measurements of the plasma parameters since it constrains the motion of the charged particles, and account has to be taken of the anisotropy of space caused by the different diffusion coefficients parallel and perpendicular to the magnetic lines of force [7]. The extent of the magnetic field effects is measured through the electronic and ionic Larmor radii. Since the triple probe assumes operation in the region of ion saturation, the effects of the magnetic field on the electron current can be neglected. Studies have been done on the effects of the magnetic field on ion current [8 - 11]. The main result of the studies is that the ‘channeling effect’ of the field lines on the streaming plasma reduces the effective collection area of the probe to $2r_p$ per unit length whereas for vanishing B-fields, this area is $2\pi r_p$ per unit length. Therefore in the limit of large B, the area changes by a factor of $2/\pi$.

3 Results and Discussions

The electron densities and temperatures were determined using equations (5) and (6). The validity of our assumptions were also examined in this experiment. Experiments were performed in a pressure range between 25 and 80 mTorr. The magnetic field was varied from 0 to 700 gauss at the measurement positions. The potential of dipole coil was varied from -100V, grounded and 100V. We have only considered the lower pressure regime in this report.

Fig. 6: When current is on the charged particles are applied in the center of the spherical IEC device

Fig.6 shows the how plasma focus is achieved when magnetic field is turned on. The left picture is before the magnetic field is turned on, and right picture is when magnetic field is turned on. Compression of plasma at the center region is well achieved by the dipole magnetic field. Fig. 7 shows how the electron density changes with increasing magnetic field measured at various coil potentials.

Fig. 7: Electron Density vs. Dipole Magnetic Field Strength at 25mTorr, 20mA.

It can be seen that applying a negative potential to the dipole coil reduces the effect of the magnetic field on the density. It only increases the electron density by a maximum factor of 9 when magnetic field is tuned on. For the both case of ground potential and positive potential of coil, the electron density increases by a factor of 15 and 17, respectively. Theoretical estimation of electron increase is about 20 times with r_b and A determined in experiment. So, our result is within the theoretical estimation and it is good. However, this does not conclude that we have increased density at the center region of IEC device since we have measured density only at the surface of dipole coil. In addition, especially in the case of positive and ground potential to the coil, it is obvious that fewer electrons can reach the center because these applied potential acts as potential barrier and reflects electrons back. Therefore, density is lower at the center than on the surface of the coil. It is previously stated that the purpose of controlling potential at the center is to decrease the potential build up by space charge. So, further discussion of effect of potential of coil will be carried over the next model of dipole assisted IEC experiment.

It is also observed that the electron density is maximized in lower magnetic field strength for the three coil potentials measured. This indicates that optimum magnetic field strength exists for maximizing the density. This is not first expected since in lower magnetic field, the ions Larmor radius become as large as inner radius of coil, and the electron loss is significant. Therefore, it was expected that stronger magnetic field strength is necessary to increase electron density. The reason of this optimum magnetic field strength can be interpreted as follows. In a strong magnetic field, most of the particles are trapped along the field lines, however, as electrons approach the center region, the magnetic field is too strong for low energy electron. It reflects these electrons back to outside, in a so called 'mirror effect'. Therefore, the electron density decreases with increasing magnetic field strength. For the case of low magnetic field strength, the magnetic field is not strong enough to confine electrons along its magnetic field line. Electron loss due to the magnetic drift is significant. Therefore, an optimum magnetic field exists for maximum electron density at the center of IEC device. It is noted that this effect can only be observed in low pressure operation of IEC. For high pressure operation, since particles are so collisional compared with low pressure operation, the effect of particle collision dominates the particle motion. Therefore, optimum magnetic field strength is shifted to higher magnetic field strengths. This effect is actually observed in higher pressure regime as maximum electron density occurs at 700 G.

The electron temperature variation with different magnetic field is shown in Fig. 8. Electron temperatures are almost nearly constant in higher magnetic field.

Fig. 8: Electron Temperature vs. Magnetic Field Strength.

When magnetic field is turned on, discharge voltage drops with increasing magnetic field. This is observed independently from central potential. A plot of this trend is shown in Fig. 9.

Fig. 9: Discharge Voltage vs. Magnetic Field Strength.

This implies that the existence of magnetic field lines increase the distance traveled by electron from cathode to anode. Since ionization take place between cathode and anode and electron created from ionization will be trapped along the magnetic field line and travel longer distance than that without magnetic field. Therefore, a discharge voltage drop is observed. This is advantageous because higher densities are obtained at a lower discharge power levels.

4. Error Analysis

The plasma conditions are not entirely reproducible when running the dipole assisted IEC. The differences in measured parameters could be attributed to wall outgas, uncertainties in equipment readouts, probe contamination, etc. Another source of error is that probe theory assumes that the probe's influence on the plasma is negligible, which is rarely the case. Much of the error in traditional Langmuir probe analysis arises from the curve fitting required from the V-I trace. While the triple probe eliminates the need for curve fitting, it does contain an essential error because the ion saturation currents flowing in the three probes are not equal. This is because the ion saturation current increases as the magnitude of negative probe potential increases, as mentioned in section 2.3. It should be mentioned that in an effort to quantify this error, Chen [5] introduced a dimensionless parameter which is dependant on the ratio of the probe radius and Debye length ($\xi = r_p / \lambda_D$). However, an in depth analysis of such theoretical errors is not necessary in our case, since we are primarily interested in the *ratio* of electron temperatures and densities. Therefore, we are interested in the statistical sources of error, which can be estimated by taking the data several times and observing the change between consecutive measurements.

5. Conclusions

The successful construction and operation of the dipole assisted IEC was demonstrated in this first model of experiment. It was found that a magnetic field increases the electron density by a factor of 16, the electron temperature decreases in the presence of a magnetic field, the discharge voltage decreases in the presence of a magnetic field, the potential of the dipole strongly influences the densities obtained in the center. Overall, there is a strong indication that the presence of magnetic field affects not only plasma parameters but also operation conditions such as discharge voltage. However, the effect of dipole magnetic field cannot be observed separately from potential barrier we had at the center of IEC device in this experiment. In order to examine the effect of magnetic field only, coil potential needs to be lowered as same potential as cathode potential. Then, we can also see the effect of controlling potential by decreasing it further from grid potential. Therefore, further investigation on this needs to be carried over in next model of dipole assisted IEC and they are of high interest to study in greater detail.

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7. Appendix A

Triple probe data at 25mTorr, 20mA with different central potentials.

Average

$V_c=0V$

B(gauss)	$T_e(eV)$	Density(cm- 3)	Increase
0	1.248	2.03E+08	
70	5.011	6.62E+08	3.3
140	2.046	2.28E+09	11.2
210	1.011	3.09E+09	15.2
350	0.808	2.67E+09	13.1
525	0.721	2.39E+09	11.7
700	0.684	2.02E+09	9.9

$V_c=+100V$

B(gauss)	$T_e(eV)$	Density(cm-	Increase
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		3)	
0	1.124	1.96E+08	
70	3.298	5.53E+08	2.8
140	1.388	2.31E+09	11.8
210	0.891	3.25E+09	16.6
350	0.731	3.11E+09	15.8
525	0.778	2.85E+09	14.5
700	0.704	2.52E+09	12.9

V_c=-100V

B(gauss)	Te(eV)	Density(cm- 3)	Increase
0	0.931	2.13E+08	
70	4.571	6.38E+08	3.0
140	2.201	1.95E+09	9.2
210	1.556	2.10E+09	9.8
350	1.526	1.54E+09	7.2
525	1.326	1.28E+09	6.0
700	1.251	9.97E+08	4.7

B(gauss)	Vd(kV)
0	3
70	2.8
140	2.2
210	1.6
350	1.2
525	1.1
700	0.9

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9. Publications

Monthly Reports to D. O.E.

- Dipole Monthly Report, Report No. 1-5.

US- Japan Research Meeting

- Abstract: G.H. Miley, H. Momota, R. Thomas, Y. Takeyama, “Dipole Assisted Inertial Electrostatic Confinement”, 7th US – Japan Workshop on Inertial Electrostatic Confinement Fusion, Los Alamos, NM, Mar 14-16, (2005).
- Poster: Y. Takeyama, R. Thomas, G.H. Miley, “Dipole Assisted Inertial Electrostatic Confinement”, 7th US – Japan Workshop on Inertial Electrostatic Confinement Fusion, Los Alamos, NM, Mar 14-16, (2005).

APS Meeting

- George H. Miley, Prajakti J.Shrestha, Yang Yang and Robert Thomas, “Electrostatic-Dipole (ED) Fusion Confinement Studies”, 46th Annual Meeting of the Division of Plasma Physics, Savannah, Georgia, November 15-19, (2004).

10. Distribution List

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