A Multi Magnetic Mirror Machine for Plasma Production with Electron Cyclotron Resonance

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A magnetic multi mirror machine is been developed for plasma production with electron cyclotron resonance (ECR) in the UHF frequency range and low RF power. The machine is mainly designed to be used for investigation of basic magnetized plasma phenomena. Particle loss through mirror cusp fields during electron cyclotron resonance heating has been measured in several conditions. Experimental studies of electron and ion diffusion through the magnetic cusps and its relation with plasma and machine working parameters are presented. The relations between the obtained ECR plasma with the desired characteristics of material plasma processing reactors are also studied. Observations of localized electron cyclotron resonance heating in the magnetic mirror cusp fields are related to several physical situations reported in space and fusion plasmas. A description of the experimental setup and experimental results are presented.

1 Introduction

Plasma magnetic confinement with mirror type fields has been used to investigate fusion [1] and space plasma [2] phenomena for many years. Plasma heating with electron cyclotron resonance (ECRH) is today a successful method used in most of the controlled thermonuclear fusion experiments [3]. Theoretical and experimental developments were also made in order to clear basic plasma processes such as the kinetic instabilities generated by the mirror loss cone distribution function. Electron and ion diffusion to the mirror cusps fields are strongly dependent on kinetic and collision processes. One of the main process is connected with the electron cyclotron plasma waves [4] trapped in the mirror throats during the resonant electron heating. In this work, we found, once more, experimental evidence of momentum and energy transfer from electron cyclotron waves to particles. This is the physical mechanism responsible for particle acceleration toward the mirror throats, as shown by many authors in the plasma literature.

Electron cyclotron waves studies are still important today to improve mirror confinement schemes. In particular ECRH is used for plasma heating and production of large electrostatic potentials in the end plug barrier region of tandem mirrors. Therefore, it is of interest to study resonance heating and the energy transport of hot electrons from the resonant zone [5]. Electron cyclotron wave particle interaction is also observed in space and astrophysical plasmas in the intense radiation regions of magnetospheres [6]. In particular these phenomena lead to nonlinear dynamics governing the individual particle motion in the neighborhood of the electron cyclotron resonance zone. It also can give rise to wave-particle interactions in the weakly collisional plasma regime [7].

Recently, numerous material surface treatments with improvements on the methods of film deposition, ion implantation and plasma etching were made by using different types of electron cyclotron resonance in plasmas [8]. Semiconductor components development by using ion sputtering and etching have grown up extensively in the past twenty years. Plasma materials processing requires large volume, low ion temperature, high density and a uniform plasma in order to keep the ion flux to the substrate constant [9].

Early experiments on surface treatment [10] have demonstrated that ECR discharges can be operated at low neutral pressures 10^{-3} to 10^{-4}mbar, low RF power 1W to 100W, 1% to 10% of degree of ionization, with plasma densities as high as 10^{12} cm^{-3} and low plasma potentials. Under these process conditions, the ions become an important fraction of the chemically active species in the discharge, and the ion mean-free-path is larger than the width of the ion sheath. Lifetime limitations on the operation of ion sources based on electron emission by the thermionic effect is also a reason to use plasma production with electron cyclotron resonance sources. This is also specially relevant for several schemes of electrostatic propulsion based on ECR plasma sources [11].

This work will describe a mirror machine designed to generate plasmas using thermionic discharge in the preionization phase and an RF source for plasma heating and density increase in the ECR range. Special attention will be given for the electron density and temperature diagnostics with Langmuir probes and the magnetic field space profiles made with magnetic field Hall probes. Ion and electron flows to the loss-end fields are also measured with an end-mirror particle collector. Measurements of electron and ion diffusion through the mirror throats are indicating a high diffusion for ions and electrons during the RF excitation of the electron cyclotron resonance.

2 Description of the machine and its diagnostics

On Fig. 1a an schematic diagram of the mirror machine is shown, Fig. 1b shows a picture of the machine as it is at the Laboratório de Plasmas of UnB. The vacuum system contains two cylindrical Pyrex (Diam. = 0.15m, Length = 1.2m) glass tubes connected by a stainless steel flanged tube, which also allows the system connection to an Edwards vacuum cryogenic system (CR130), responsible for 8×10^{-7} mbar as background pressure. This central flanged tubeis assembled with three radial access windows which provide vacuum measurements, gas injection and filament electrical supply. Argon gas (99.995% pure) into the mirror machine can be varied with a leaking needle valve allowing a precise working pressure adjustments of 10^{-6}mbar in the 10^{-4}mbar range. The plasma is produced by thermionic discharge with hot tungsten wire cathode with a barium oxide layer. The loop 7cm diameter filament is positioned in the center of the chamber to produce a symmetric plasma. Two end metal flanges are equipped with vacuum feedthroughs to allow metal probes to move inside the mirror machine. Langmuir probes and particle collectors are assembled on them.

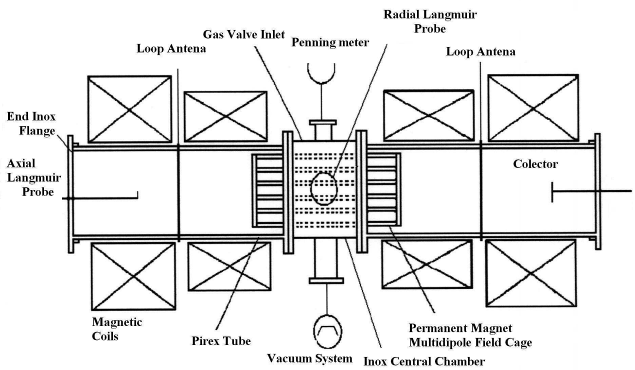

Figure 1a. Magnetic mirror machine, general shematic.

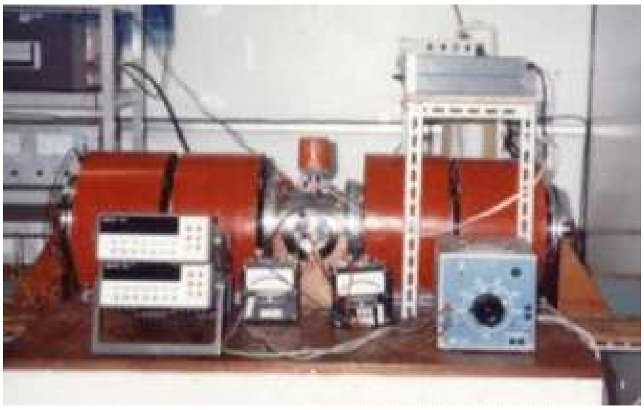

Figure 1b. Picture with general view of the Magnetic Mirror Machine.

The mirror machine used in this experiment has a scheme of mirror field arragement within four magnetic coils (see Fig. 2a) to generate a double pick of in the mirror fields throats (see Fig. 1a and 1b). The main magnetic field, with controllable mirror ratio is produced by four magnetic coils symmetrically located around the metal chamber. Fig. 2a also shows the axial spatial profile of the main magnetic field, for several DC coil currents, produced by two end coils with 912 turns of 3.5mm diameter cooper wire and two center 730 turns coils with 24cm averaged radius. The magnetic fields are measured by transversal and axial Hall probes of Walker Scientific Company Gauss meter model MG-3D. In the central metal chamber there is a multi dipole magnetic field made by permanent ceramic magnets, this radial field has its maximum 100Gauss at r = 5cm (see Fig. 2b) and it acts on the plasma boundary as a surface field. It is responsible for a significant improvement on the total particle confinement. The lifetime of the primary electrons produced by the thermionic discharge increases because they are better confined by the surface magnetic field. The result is the enhancement on the ionization efficiency of the discharge. It also decreases the plasma electron losses due to diffusion perpendicular to the lower axial magnetic mirror field in the central part of the chamber.

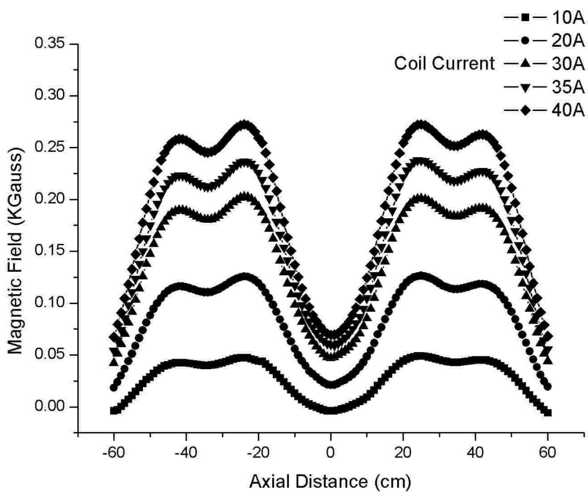

Figure 2a. Axial space profile of magnetic field measured by Hall probes.

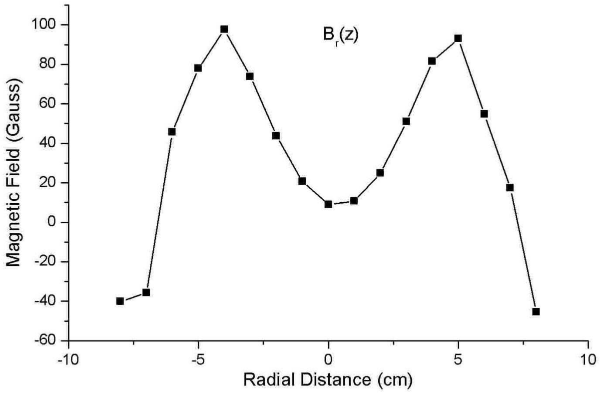

Figure 2b. Radial space magnetic field profile.

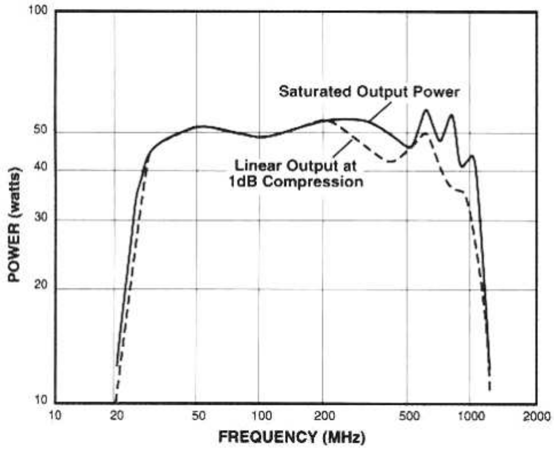

Figure 3b. RF amplifier power curve.

Electron cyclotron resonance is obtained by using radio frequency (RF) induced on the plasma by two 15cm diameter loop antennas assembled in an N type configuration scheme [12]. They are positioned externally around the glass vacuum tubes at a distance of 35cm on each side from the center of the machine. This antenna configuration allows a better coupling between induced electric fields and the plasma electrons in cyclotron orbits in the mirror throat magnetic fields. The RF wave is primarily produced by a Hewlett Packard HP 8648A generator within frequency range from 100KHz to 1000MHz and power of 1Db typically. The RF signal is increased by a ultra-broadband amplifier model 25 1000M7 made by Amplifier Research Company. The RF circuit is schematically showed in Fig. 3a and the power response curve of the amplifier on Fig. 3b. Notice a fairly flat response of the RF generation system for the working frequency range of this experiments, between 100MHz to 500MHz.

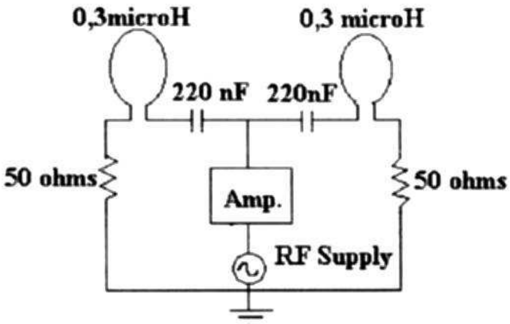

Figure 3a. Schematics of RF circuit with loop antennas.

Plasma diagnostics are made by using two different kinds of simple probes. Cylindrical Langmuir probes (d = 0.5mm and l = 0.5cm) are used to measure plasma parameters along the mirrors axis of the machine and in its central multi dipole cage chamber. Ions and electron flow through mirror throats are measure by a disk end probe made by a molybdenium 4.5cm diameter plate fixed at z = 58cm, outside the mirror throat.

3 Experimental results

3.1 With Thermionic Discharge

The electron cyclotron plasma production and heating data were taken with 2×10^{-4}mbar of Argon pressure, mirror throat (mid-plane) magnetic field going from 120 to 130 Gauss with coil current of 25A. A DC (50V, 1A discharge, typically) thermionic discharge produce pre-ionization within plasma parameters, electron temperature T_e and density n_e given respectively by $T_e = 2$eV and $n_e = 2 \times 10^9$cm^{-3}. Maximum density and electron temperature $T_e = 2.4$eV and n_e = 5.8 x 10^9cm^{-3} are found on the mirror cusps as expected for a magnetically confined quiescent collisionless plasma within electron Larmor radius of 0.3mm and Argon ion Larmor radius of 7cm. Only electrons are confined by these low magnetic fields.

A symmetric plasma is formed as shown in Fig. 4a and Fig. 4b, electron density and temperature space profiles. As expected, the peaks on the plasma density and electron temperature occurs in the mirror maximum field region at the cusps between $z = 30$cm and $z = 40$cm. The combined main axial magnetic field with the cage multi dipole magnetic field at the center of the mirror machine provides efficient primary electron confinement, allowing a good gas pre-ionization level (0.1%).

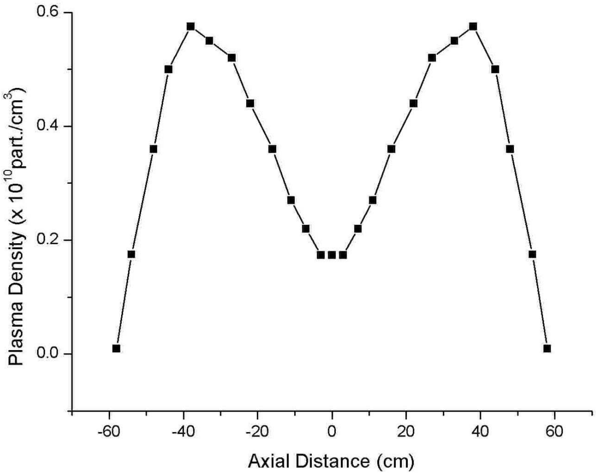

Figure 4a. Axial plasma electron density profile:Thermionic discharge.

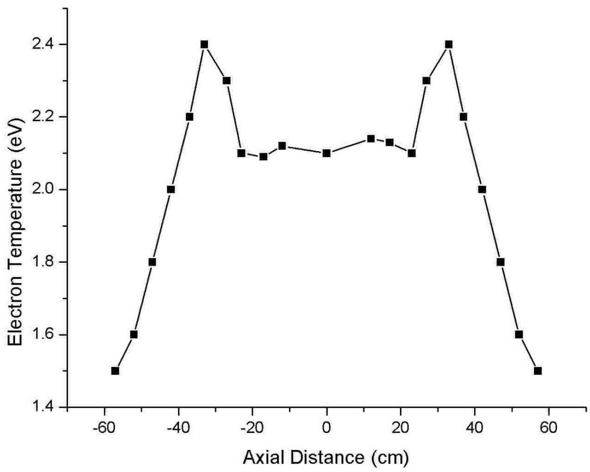

Figure 4b. Axial electron temperature profile: Thermionic discharge.

There is a small variation on the mirror ratio as the main magnetic field is changed, as shown on Fig. 5. A study of the electron loss current through the mirror as a function of the mirror ratio $B_{max.} / B_{min.}$ shown a minimum electron loss for a mirror ratio of 3.5 corresponding to a coil current of 15A. However in this condition of lower magnetic field, the pre-ionization plasma level has a much lower density. So it is more suitable to use a higher field with mirror ratio of 3.6 which is still close to a low electron loss condition.

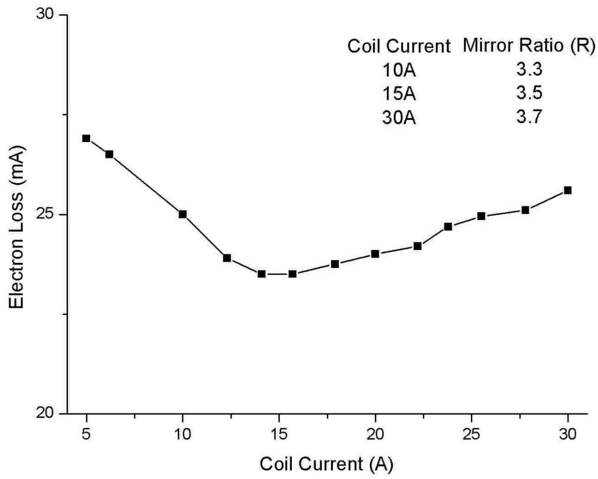

Figure 5. Electron axial flow collected by positive bias end disk as a function of mirror ratio.

3.2 With Radio Frequency

When low power (10W) Radio frequency is injected, with frequency at 350MHz (electron cyclotron resonant plasma frequency for 125Gauss field), on the pre formed DC plasma, electron density and electron temperature parameters are increased. In Fig. 6a it is possible to see that the N type configuration antenna design maintain the previous symmetric characteristics of the plasma, because the RF is also symmetrically injected. The plasma density in the center of the machine increase by an order of magnitude due to the RF induced electric field acceleration of free slow electrons generated by the thermionic discharge. An avalanche ionization process then occurs increasing mainly the plasma density of the magnetic throats where the electromagnetic antenna coupling is more efficient.

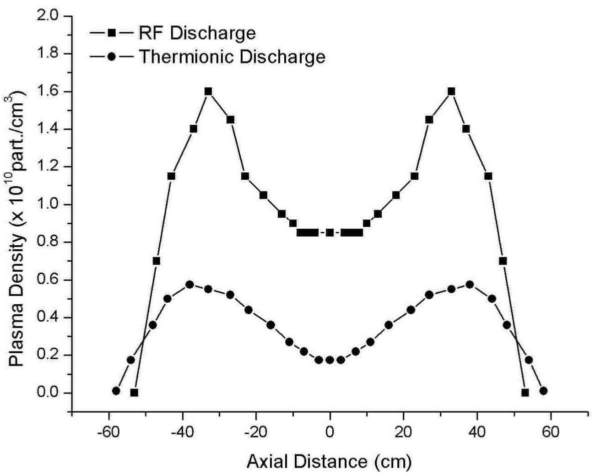

Figure 6a. Axial plasma density profile for RF discharge compared with thermionic discharge.

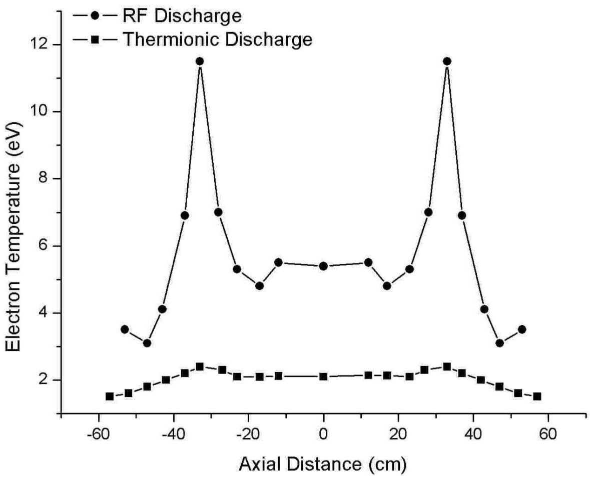

Figure 6b. Axial electron temperature profile for RF discharge compared with thermionic discharge.

The strongest effect of the RF injection on the plasma can be seen on the electron temperature space profile plot on Fig. 6b. The electron temperature doubles on the machine center and is five times bigger due to the good antenna electromagnetic coupling of the RF induced electric fields on the mirror throat plasma. Another important effect is the formation of a non Maxwellian (see Fig. 7) plasma, in which the coexistence of two populations of cold and hot electron plasma, can be distinguished by the movable Langmuir axial probe. In Fig. 7 it is possible to see the hot and cold electron plasma population splits as the probe moves to the mirror ends. As measured in many mirror plasma machines, including Tandem mirrors, the hot electrons became trapped in the mirror cusps and the cold electrons diffuses out from the confinement regions.

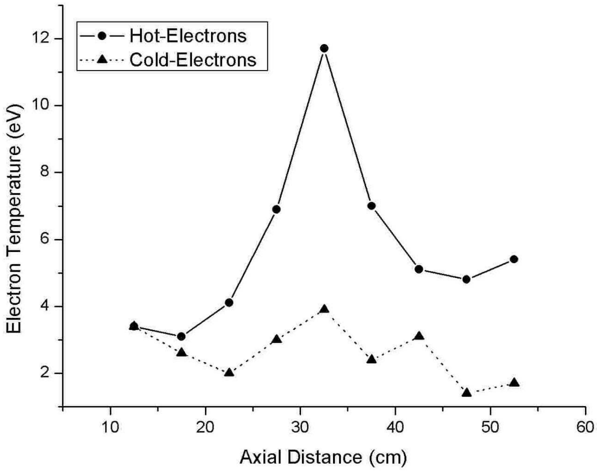

Figure 7. Two electron temperature plasma at the mirror throat.

We also study the effect of the electron cyclotron resonance on the ion and electron diffusion through the magnetic mirror cusps. On Fig. 8a the electron axial diffusion current collected by the positively polarized disk plate as a function of the RF injected frequency is shown. The disk is polarized with voltage value ($+5$Volts) at the Langmuir probe electron saturation current region, to minimize pertubation effects on the plasma. At the electron cyclotron resonance frequency ($f_{ce} = 345$MHz) the electron flow current is maximum, increasing from 20mA within thermionic discharge to 800mA with RF at f_{ce}. The correspondent electron diffusion rate is as high as 13.6m^2/s, bigger than the highest theoretical diffution rate. The Bohm diffution coefficient for electrons in this conditions is 7.2m^2/s.

With the same experimental conditions the ion flow current with disk plate polarized at the Langmuir probe ion saturation (-40Volts) was measured as a function of the RF frequency. Although the measured diffusion ion current curve doesn't exactly follow the electron flow current, they both have a maximum at an RF frequency of 345MHz. However the ion current increase from 1mA to 250mA was not expected. The measured diffusion rate for this condition was 3m^2/s, much bigger than the ambipolar diffution coefficient (0.1m^2/s) calculated for these experimental conditions.

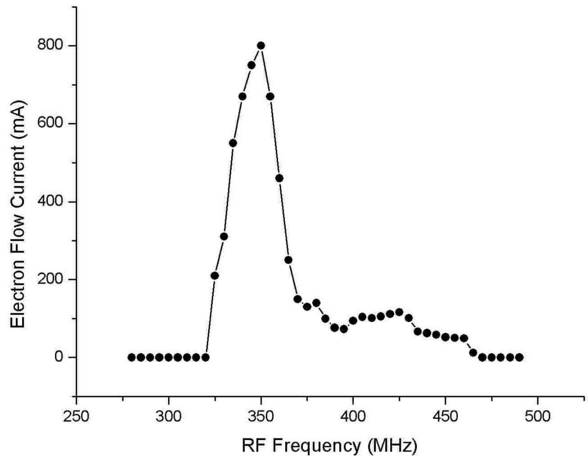

Figure 8a. Electron axial flow collected by disk positively bias probe versus RF frequency.

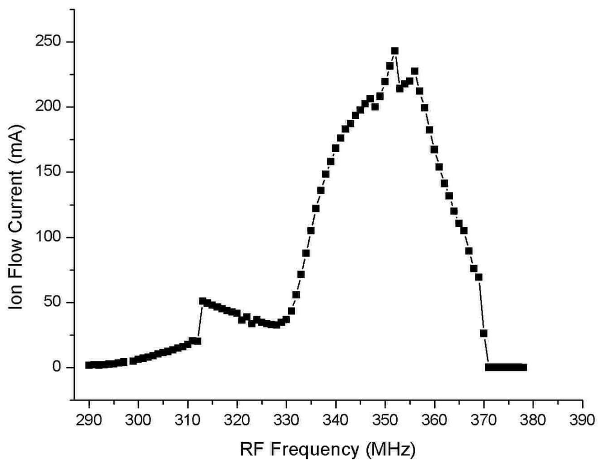

Figure 8b. Ion axial flow collected by a disk negatively bias probe versus RF frequency.

4 Conclusion

A magnetic mirror machine operating in the UHF frequency range was constructed and developed at the Laboratório de Plasmas of UnB. Magnetic field measurements are in good agreement with the designed characteristics of the magnetic coils. Density and temperature measurements in the pre-ionization phase with a Langmuir probe in the thermionic discharge are also in the expected range for a quiescent low density and warm and weakly magnetized plasma. A significant increase of electron density and electron temperature was measured during RF injection in the electron cyclotron resonance frequency. The good inductive coupling of the N type double loop antenna arrangements are the main reason for the measured improvements on the plasma parameters. The electron diffusion rate is bigger than expected indicating possible anomalous diffusion transport process due to turbulent electron cyclotron wave particle interaction in the resonant region. The observed increment in the ion flows current was also unexpected. The formation of double charge layers and electric fields connected with bootstrap currents in magnetic mirrors is a well known process, and can be related with these large ion current flows. Further investigation should be made to clear the physics and apply the effect on the improvement of plasma material processing with mirror machines.

Acknowledgments

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