INVESTIGATION OF 2.45 GHz MICROWAVE RADIATED ARGON PLASMA UNDER MAGNETIZED CONDITION

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Abstract

Permanent magnet based ECR ion source (PMECRIS) is a compact microwave discharged ECR ion source. This work models microwave plasma coupling in 2D axis symmetric configuration to investigates plasma parameters and corresponding influence of electric field in plasma environment. A microwave field of the order of 1.3 x10^5 V/m is obtained at the Centre of the plasma chamber cavity for an input microwave power of 500 W. Present microwave coupled plasma has a maximum density of 9.04×10^{16} / m^3. The steady state peak electron temperature is around 3 eV under various pressure (1mbar-10^{-3} mbar) conditions of argon gas. Most of power deposition takes place on the ECR surface zone which corresponds to 0.0875 T contour. Steady state argon plasma results show that beyond a critical plasma density of 7.4×10^{16} /m^3 most of the microwave power is deposited at the plasma edge.

INTRODUCTION

Since last few decades, dipolar and multipolar based microwave plasma based ECR ion source have been studied[1 and 2]. Hagelaar et.al [3and 4] and J Pelletier group [5] obtained a uniform high density plasma up to gas pressures 10^{-2} mbar.

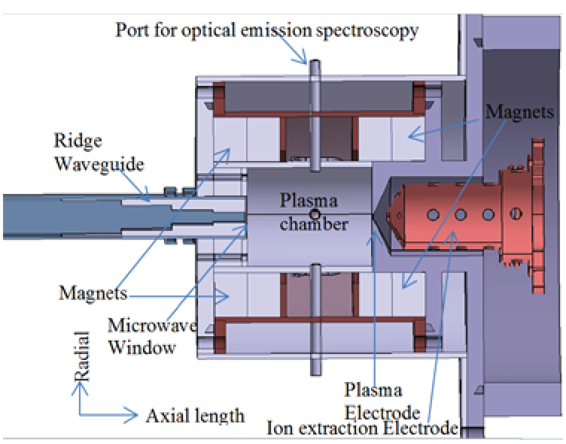

Figure 1: Cut section of negative hydrogen PMECRIS.

A detailed insight on microwave fed ion source physics is discussed for different absorbed power conditions by Hagelaar. Microwave heated ECR plasma is growing its interest in numerous number of applications under low pressure conditions, in plasma electron heating and power deposition by microwave electric field infusion plasma. A recent trend in the ion source technology aims at decreasing the gas pressure in the 10^{-3}mbar range using the same resonance heating by creating MW plasma.

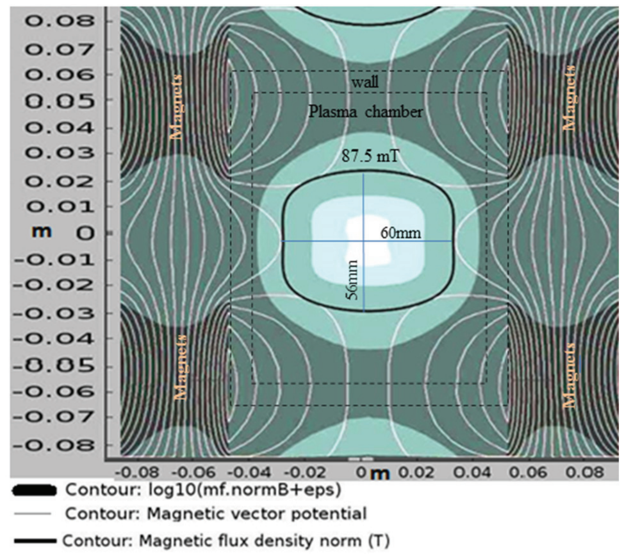

Figure 2: ECR contour for 2.45 GHz frequency.

At high pressures, ohmic heating (collision based) occurs in which gyrating electron motion is randomized by collisions with background gas molecules[6, 7 and 8]. With spatially varying electric fields in resonance zone, phase randomization can also happen due to thermal electrons motions even in the absence of collisions. This collision less heating dominates under low pressures. Under low pressure conditions plasma can be maintained uniformly and parameters can be well controlled [4-9]. However, in low pressure (10^{-3} mbar range), sufficient database is not available for negative ion source in R&D sectors.

This paper investigates a microwave coupled PMECRIS plasma under low gas pressure (≤10^{-2}mbar), which finally will be used as a negative hydrogen ion source for an RFQ accelerator. Effect of time scale dependent microwave propagation into the plasma is also discussed. A further study on how the power deposition is taking place with time into the plasma volume has been done. A detailed picture of time varying electric field distribution in plasma environment has been demonstrated clearly.

MICROWAVE PLASMA MODEL

This model is based on the finite element method (FEM) considering fluid approach with drift diffusion approximation. Ion motion is negligible w.r.t the electron motion in microwave timescale (ns). Electron density is

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constant in space in ECR zone. Electric field throughout the plasma is solved by following equations [3, 4 and 9].

$$\nabla \times \mu_0^{-1}(\nabla \times E) - \kappa_0^2(\epsilon_r - \frac{\iota\sigma}{\omega\epsilon_0})\nabla . E = 0 \quad \text{……… (1)}$$

σ is full tensor plasma conductivity. Perfect electric conductor boundary conditions are chosen on plasma chamber wall. All three components of electric field are computed despite the fact that only excitation occurs in the r-z plane from the coaxial port. Electron velocities, parallel to magnetic field, obtained from local momentum equation as follows [3, 4 and 9].

$$\frac{\partial \tilde{v}_e}{\partial t} = -\frac{q}{m_e}\tilde{E} + \nu_m \tilde{v}_e \quad \text{………..(2)}$$

The above equation is linearized by neglecting permanent magnetic force so that we can take a fourier transform of equation(2). In microwave plasma interaction time scale (time-scale:10^{-8}s, $10^{-7.4}$s, $10^{-6.8}$s, $10^{-6.2}$s, $10^{-5.6}$s, 10^{-5}s, $10^{-4.4}$s, $10^{-3.8}$s, $10^{-3.2}$s, $10^{-2.6}$s, 10^{-2}s), gyrating electrons do not travel appreciable distance, so space derivative components are not included in equation (2), assuming uniform pressure within the plasma volume. However, before coming to steady state, microwave plasma interaction ontinues over many microwave periods and electron's velocity is established after many periods.That's why electrons encounter appreciable electric field variations while passing through the ECR resonant surface zone in a very short time interval with their thermal motion along magnetic field lines. This is non-local kinetic effects which does not obey the above momentum equation (2). As a consequence, phase coherence between electron velocity and E-field oscillations is destroyed and electron faces spatial field variations. During stay at resonant surface electrons is accelerated in very short time and at next pass electron is accelerated from zero again. One of the methods to include this non-local kinetic effects is to add one component (doppler shift component) to the momentum collision frequency.

$$\nu_{eff} = \nu_m + \frac{\omega}{\delta} \quad \text{…….(3)}$$

δ is doppler broadening parameter [4 and 9], ν_{eff} is effective collision frequency. ν_m is the normal electron momentum collision frequency. From Fig. 2,width of resonant surface is obtained as ~1 mm and for λ=122.2 mm. For 3 eV electron temperature , the thermal velocity of electron is ~10^6 m/sec. For k=0.5 cm^{-1},we get an effective collision frequency in resonance zone as $\frac{v_T\omega}{\delta}$~10^9per second[4]. v_T is electron's thermal velocity. The normal electron collision frequency (ν_m) with the background gas (pressure~mbar) obtained from simulation is 4.25×10^6 Hz which is three times smaller than the effective collision frequency.The effective collision frequency makes the E-field smooth over ECR surface thus keeping the total absorbed power intact.

E-FIELD DISTRIBUTION WITHOUT PLASMA

Microwave E-field is optimized using four-step ridge waveguide at an input port power of 500W. At 2.45GHz microwave frequency, E-field is maximum at the centre having value 1.29×10^5 V/m. The WR 284 ridge waveguide at the mouth of the plasma chamber injection side has a width of 48mm and height of 9.8 mm.The length of the total waveguide is 220 mm. Ridge lengths are 35.1 mm, 37.4 mm, 45.1 mm and 102.4 mm respectively, as shown in Fig.3.

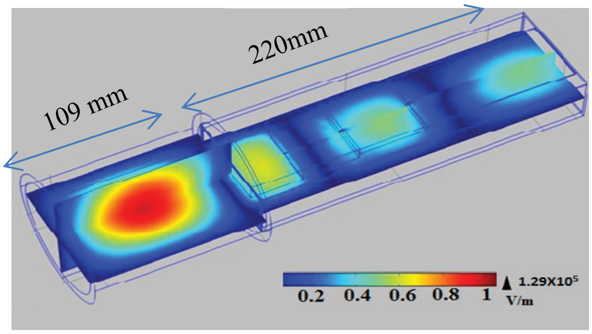

Figure 3: E-field under empty plasma chamber cavity of dimension 109 mm.

E-FIELD DISTRIBUTION IN PLASMA

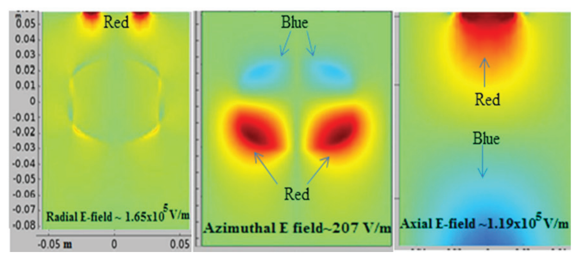

Figure 4: E-field distribution in plasma for 50W total absorbed power and 10^{-2}mbar pressure.

Peak values are shown on the graphs. Scales are linear. Axial field ranges from -0.4×10^5 V/m to 1.19×10^5V/m, azimuthal field ranges from -597 V/m to 207 V/m and radial field from -1.55×10^5 V/m to 1.65×10^5 V/m are shown. Blue colour denotes positive maximum and red colour negative maximum (colour online). Axial and radial e-field is discontinuous on ECR surface due to high microwave conduction current (high plasma conductivity).

RESULTS AND DISCUSSIONS

For 2.45 GHz microwave frequency, critical density of plasma is 7.4×10^{16}/m^3, beyond which MW power is not absorbed and gets reflected Figure 4 and 5 shows the results simulated in 2D-axis-symmetric domain under three different low gas pressure conditions and at a fixed plasma absorbed power of 50 W. Microwave is launched through coaxial port to the plasma chamber in TEM mode.

Two axial and radial electric fields are mainly responsible for the plasma generation. The azimuthal electric field is two orders less than the axial and radial electric field. Electrons absorb microwave power mainly

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on ECR surface area. Fig. 6 shows power absorption is peaked along the resonant surface. Peak electron temperature is ~3 eV which is almost constant along the magnetic flux density lines. Plasma potential of 18.7 V has almost flat profile from the ionization region to the pre-sheath region which is five times more than the peak electron temperature.

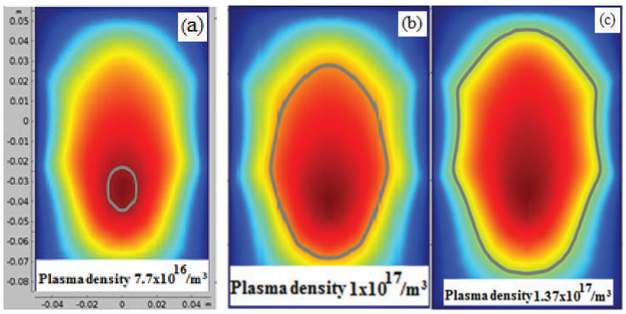

Figure 5: Plasma density contours at different pressures (a) 2×10^{-3} mbar, (b) 3×10^{-3}mbar, (c) 5×10^{-3} mbar. Thick grey line represents critical plasma density of 7.4×10^{16} /m^3. Total plasma absorbed power is fixed at 50 W.

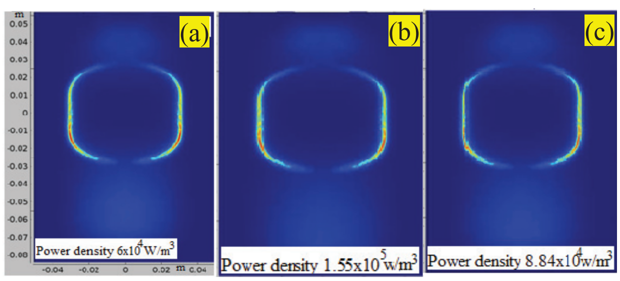

Figure.6: Spatial distribution of Power density at various pressures (a) 2×10^{-3} mbar**,** **(**b) 3×10^{-3} mbar and (c) 5×10^{-3} mbar and at constant absorbed power of 50 W.

At low pressure, magnetized electrons have high axial mobility and very low radial component across the magnetic field line. So, electrons gyrating around the pre-sheath region, assumed to be isolated from the ionization region. Argon ions have mobility, which is almost equally distributed along the radial and axial direction, so that quasi-neutrality is lost around the sheath region. To attenuate the radial ion velocity, potential becomes nearly flat profile.

From Fig. 5, it is observed that plasma density increases from 7.7×10^{16}/m^3 to 1×10^{17}/m^3 for increase in pressure from 2×10^{-3} mbar to 3×10^{-3} mbar. From Fig. 5 and Fig. 6, it is visible that an increase of the plasma density from 7.7×10^{16}/m^3 to 1×10^{17}/m^3 is observed as power density is increased from 6×10^4W/m^3 to 1.55×10^5W/m^3. From these data, we can deduce a significant increase in plasma density with increasing the power density. Increase in the microwave power density actually increases the gas temperature also.

It is noted that plasma density increases with pressure and reaches beyond a critical density. Power density profile coincides with the critical density contour shown (grey colour). Similar trends happen while increasing absorbed power at constant pressure also.

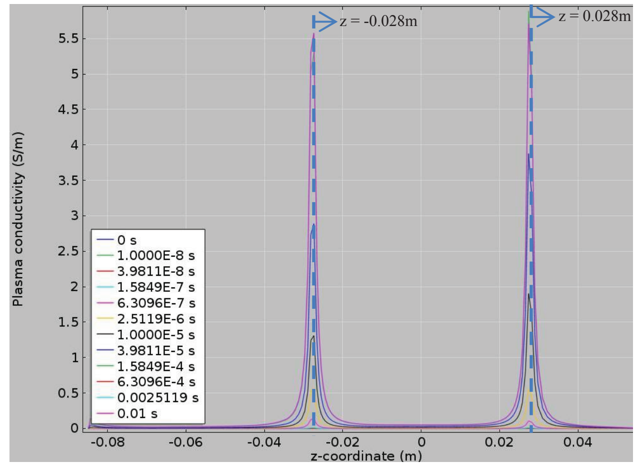

Figure 7: Plasma conductivity near resonant surface locations due to the permanent magnet.

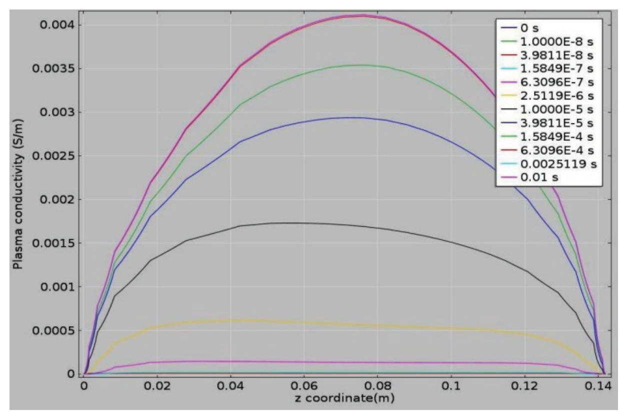

Figure 8: Variation of plasma conductivity with axial distance for different time, without magnets.

At the resonant flux density (0.0875T) the plasma conductivity is 2×10^3 times higher than the case where no static magnetic field is present, as shown in Fig. 7 and Fig. 8.

TIME EVOLUTION OF PLASMA WITH POWER DEPOSITION

Microwave can't penetrate the critical density into the plasma. In Fig. 9, it is clear that microwave imparts very less amount of energy to the electrons from time = 2.5 μS onwards on the ECR surface zone, because during that time plasma started evolving. As a result, Microwave power deposition is shifted from ECR zone to the plasma edge (from ns to μs).

Initially, during 1550 microwave periods electrons are gaining energy continuously on resonant surface at an ionization rate ~ 2.66×10^{22}/m^{3}sec (From simulation results).

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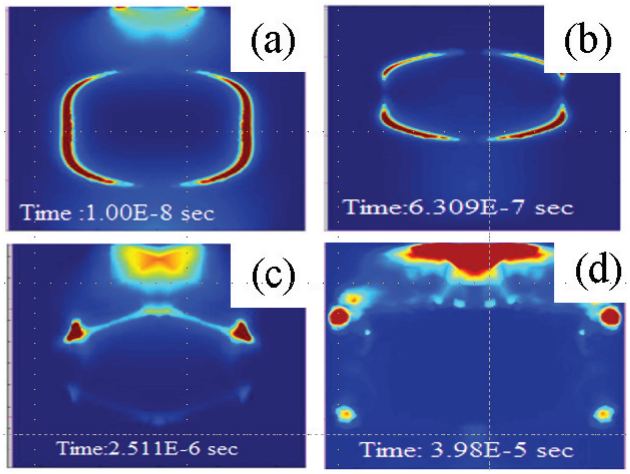

Figure 9: Maximum Power density at different time instants. (a) 6.6×10^4 W/m^3, (b) 1.43×10^7 W/m^3, (c) 3.12×10^6 W/m^3 and (d)1.67×10^7 W/m^3 at pressure 10^{-2} mbar, 50 W power.

Up to time 6.31×10^{-7}-s density is increased by 1.17×10^{15}/m^3.At instant 2.511×10^{-6}s, density becomes 6.65×10^{16}/m^3 which is close to critical density and correspondingly resonant power deposition area is least. At 0.01s power deposition no longer takes place on ECR surface but shifted towards wall because of the peak density~1.16×10^{18}/m^3 near resonant zone which is beyond critical density. This plasma creation near the edge replenishes the plasma loss in the core and maintains steady state. The power density variation on the resonance surfaces during the microwave discharge process gives an estimation of the total time required for the plasma come to steady state. The results shows plasma obtains steady state condition within 100-200μs which is in good agreement with the experimental data given in Ref.10.

SUMMARY

The purpose of this paper is to describe the effects of gas pressures and power density on the microwave argon plasma characteristics under low pressure. A FEM model in a cylindrical 2D axis-symmetric environment is simulated. Comparatively at higher pressure, more molecules are available to collide with electrons and generate electron-ion pair. So, with increasing pressure plasma density increases but collisional mean free path of electron decreases. If electrons get less time before collision, it will gain less energy. Hence, electron impact ionization will be less and there will be decrease in electron-ion pair. So these two effects are contradictory to each other. Power density is decreased from 1.55×10^5 W/m^3 to 8.84×10^4 W/m^3 for pressure from 3×10^{-3} mbar to 5×10^{-3} mbar. Analytically it can be deduced that at this higher pressure (5×10^{-3}mbar) collision frequency becomes more than the resonant frequency, so the power density in the resonance zone decreases.

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