Resonance surface, microwave power absorption, and plasma density distribution in an electron cyclotron resonance ion source

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Resonance surfaces for a 2.45 GHz electron cyclotron resonance ion source are investigated. In addition to the typical flat-B and minimum-B profiles, we have investigated on two new magnetic field structures, namely the torus zone and the double zone configurations. The impacts of such surfaces on the microwave power absorption are discussed. Furthermore, the uniformity of the ion emissive surfaces in connection with the resonance surfaces is examined. Different configurations for absorbing microwave power and simultaneously for producing uniform ion density distribution near the extraction wall of the source are discussed.

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I. INTRODUCTION

The generation of intense beams of highly charged ions has been facilitated by development of the electron cyclotron resonance ion sources (ECRISs) [1,2]. In an ECRIS, the ions are extracted from a dense plasma excited by a microwave inside a cylindrical metallic chamber. The ECR is indeed a mechanism for microwave power absorption by plasma electrons. High charge state ions are produced due to successive collisions of hot electrons with ions. To achieve longer lifetimes for high charged state ions, plasmas are confined within a special magnetic field trap known as the minimum-B configuration. This configuration is commonly set by a system of solenoids to generate an axial magnetic trap and a transversal magnetic hexapole to confine the plasma radially [3]. This configuration is believed to be the best plasma confinement structure for the optimum operation of the source. Most of the microwave power absorption occurs in the vicinity of the ECR zone characterized by a closed constant-B surface. The ECR zone is defined by the condition of $\omega = \frac{eB}{m}$, where ω , e , m and B are the angular frequency of the microwave, the electron charge, the electron mass and the magnetic flux density, respectively.

Simulations have played a pivotal role in understanding many features of ECRISs over the past few decades. In 1995, Gopinath and Grotjohn developed a three-dimensional (3D) electromagnetic particle-in-cell (PIC)

code to model a compact ECR plasma source [4]. They presented the microwave power absorption, plasma potential, and microwave electric fields. Lampe *et al.* performed a quasineutral particle simulation of magnetized plasma discharges by developing an electrostatic particle-in-cell/Monte Carlo (PIC/MC) code in 1998 [5]. They used the code for an axisymmetric simulation of an ECR discharge in low-pressure argon and showed that the discharge is strongly affected by the cross-field ion flows. In 2002, Dougar-Jabon *et al.* simulated the electromagnetic fields in a cylindrical cavity of an ECRIS [6]. They solved the Maxwell equations through the Yee's method and used the Biot-Savart law. Later in 2009, Mironov and Beijers modeled the ion production in an ECRIS using a PIC/MC code in a 3D geometry [7]. In their code, only the heavy particles (ions and atoms) are tracked. Electrons are represented using a Maxwell-Boltzmann energy distribution with the electron density determined from the requirement of quasineutrality. They reproduced some features of ECRIS plasma including the charge-state distributions of extracted ion beams and sputtering patterns inside the source. In 2010, Bodendorfer *et al.* simulated the charge state distribution inside a specific type of the ECR plasma and in the extracted ion beam [8]. They used a self-consistent ECR plasma ionization model to compute the ion confinement time for every ion species and in every time step. The idea was based on the actual plasma potential rather than using a prescribed constant ion confinement time. They found good agreement between simulation results and the measured data of the ion beam charge state distribution. Biri *et al.* used a code to simulate the spatial and energy structure of the lost and nonlost electrons in the ECR plasma, the multicusp, and other ion source plasmas in 2011 [9]. Neri *et al.* developed a 3D MC code for the modeling of plasma dynamics and beam formation mechanism in the ECRIS in 2012 [10].

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They explained effects such as the hollow beam formation and the main plasma deconfinement mechanism. In 2015, Mascali *et al.* provided a numerical solution of the Vlasov equation via kinetic codes coupled to the finite element (FE) solvers, based on a PIC strategy to simulate ECRIS [11]. They presented some results about wave-plasma interaction and electron-ion confinement. Also in 2015, Mironov *et al.* used a PIC code to model the dynamics of ions in ECRIS plasma [12]. They showed that a gas dynamical ion confinement mechanism is sufficient to provide the ion production rates in an ECRIS close to the experimentally observed values. They also studied the empirical scaling laws for ECRISs design and discussed the underlying physical effects. Later in 2017, they simulated the gas mixing effect in ECRIS by a PIC/MC code [13]. Winklehner *et al.* provided an upgrade to a PIC ion beam simulation code to run highly realistic simulations of the spiral inflector system of a compact cyclotron in 2017 [14]. They compared the simulated injection efficiencies and beam shape with the measured values after injection. In 2018, Torrisi *et al.* described 3D numerical simulations and radio frequency measurements of wave propagation in microwave-heated magnetized plasmas of ion sources [15]. They investigated the full-wave solution of Maxwell's equations through the FE method by taking into account the inhomogeneity and anisotropy of magnetized plasma. Their simulations reproduced the main features of the wave-plasma interaction of a special plasma trap named the flexible plasma trap (FPT). The characteristics of the FPT was described by Gammino *et al.* [16]. In this device, the flexible magnetic field is generated by means of three coils while the microwaves in the range 4–7 GHz can be injected with a variable tilt angle with respect to the magnetic field. The measurements of plasma electron density and rf electric field, performed for different magnetic field configurations of the FPT, allowed a direct comparison with the simulation model.

In most of the aforementioned works, one fixed magnetic field configuration (commonly, the minimum-B structure) has been used for simulating the ECR plasma. In practice, however, a tunable magnetic field profile could be more advantageous as it allows the study of the plasma properties for different states of the field profiles. In fact, a tunable magnetic field configuration can be used as a test bench for preliminary optimization of an ECRIS.

In the present work, we have attempted to systematically study some of the main concepts of an ECR plasma using simulations based on the FE method. To this end, 3D geometries of the resonance surfaces for different magnetic field configurations are illustrated and discussed. These 3D resonance surfaces have been rarely addressed in the literature. They are, however, instrumental in understating the wave-plasma interaction in an ECRIS. Our investigation on the resonance surfaces has been conducted via changes in the currents of the solenoids as the most convenient technique to tune the profile of the magnetic fields. We note

that the variation in the geometry of the resonance zone changes the microwave power absorption, which projects the characteristic feature of an ECRIS. We have also provided a detailed study about the dependence of the distribution of the absorbed power on the magnetic field configuration. Moreover, various magnetic field profiles give rise to different plasma confining conditions and consequently a change in the plasma density is also observed. The impact of the plasma density on the source operation is more pronounced in the vicinity of the extraction wall of the source. The ion density distribution in this region determines the transverse beam profile and plays an important role in the initial emittance of the beam [17]. We have, therefore, studied the influence of the magnetic field configurations on the ion density distribution with particular attention on its uniformity at the extraction region.

It should be noted that some magnetic field profiles have been introduced for the FPT device [15,16]. The simulation and experimental results presented in these works, however, are restricted to the flat-B profile and the simple mirror configurations with various mirror ratios. In these works, no investigation was performed on the 3D structure of the resonance surfaces associated with the considered configurations and their effects on the ion density distribution.

The remainder of this paper is divided into five sections. The description of the simulation model is given in Sec. II. The 3D resonance surfaces and the magnetic field profiles of the various configurations are illustrated in Sec. III. The microwave power absorption and the plasma behavior are studied in Secs. IV and V. Finally, a brief summary of results and conclusions is contained in Sec. VI.

II. MODEL

We consider a cylindrical plasma chamber [18]. The diameter and height of the plasma chamber are chosen to be 9 and 10 cm, respectively. The TE_{10} mode of a 2.45 GHz microwave is applied to the plasma in the chamber through a WR284 rectangular waveguide. The axial confinement of the plasma is provided by a set of three solenoids supported by iron yokes. A Halbach-type sextupole permanent magnet system is used for the radial confinement of the plasma. A 3D view and a cut view in the Y-Z plane of the simulation model are presented in Fig. 1.

The ECR plasma is treated in two stages. The profile of the magnetic field is independent of the presence of the plasma and the microwave. Therefore, in the first stage we could separately compute the static magnetic field produced by all the solenoids and the magnets. A fixed structure for all mechanical components of the model is considered. Our investigation on the resonance surfaces has been conducted via changes in the currents of the solenoids. This is the most convenient technique to vary the profile of the magnetic fields. Variations in the spatial profile of the magnetic fields would have considerable impacts on the

FIG. 1. A 3D view of the simulation model of the ECR plasma source (a), and its cut view in the Y-Z plane with the names of the components (b).

properties of the resonance surfaces and in turn the power absorption and also the plasma density. Armed with the calculated profile of the external magnetic fields, we will be in a position to apply the field profiles to the microwave heated plasma. In fact, in the second stage, the anisotropic conductivity tensor of the microwave plasma in the presence of the external magnetic field should be calculated. We consider an argon (Ar) plasma that is heated by absorption of 10 watts of microwave power at a background gas pressure of 1 Pa. It should be noted that in an ECRIS, a part of the microwave power will be reflected back to the microwave source due to the plasma impedance mismatch. The electric field energy stored in the plasma-loaded cavity would depend on the balance of the reflected and the absorbed powers. In the simulation, however, it is not necessary to determine or compute the forward and reflected powers separately. This is due to the renormalization procedure accomplished in the simulation for the transferred power from the microwave fields to the plasma electrons. As a result, it is sufficient to determine the total absorbed power as an input parameter for the simulation.

The possible reactions for the argon plasma chemistry are listed in the Table I. Further details about possible

reactions are given in Ref. [19]. We take interest on resonance surfaces and, therefore, we have not considered multiply charged argon ions. Moreover, for a low absorbed microwave power in our model, the electron temperature is not very high and the likelihood of generation of the multiply charged ions is low. Therefore, it is reasonable to assume that the electron energy distribution function has a very little deviation from the Maxwell-Boltzmann distribution.

III. FIELD PROFILES

In practice, changes in the current values of the solenoids act as a reliable knob to control the profile of the magnetic fields in ECRISs. In our simulation, we have scanned a wide range of values for the electric current of the solenoids. We have finally focused on four magnetic field configurations with the ampere-turns per solenoid as given in Table II. For comparison purposes, we have also considered a flat-B configuration of an off-resonance microwave discharge ion source (MDIS). The other configurations in Table II correspond to three different magnetic field profiles of an on-resonance ECRIS.

In Figs. 2(a)–2(d), we have plotted the variations of the magnetic flux density along the axis (Z-coordinate) of the model for the four magnetic field configurations. In these figures, two vertical solid black lines show the injection and extraction walls of the chamber. A horizontal solid red line also shows the resonance magnetic field.

Figure 2(a) shows a flat profile of an off-resonance MDIS. The magnetic flux density is higher than the resonance value at all points along the Z axis inside the chamber. This can be understood from the field profile of Fig. 2(a) as it does not intersect the ECR line at any point between the two vertical lines. In fact, there is not any point in the chamber for which the resonance condition is met. This is a result of implementing the same directions for the currents of three solenoids, as can be seen from Table II.

On the other hand, the necessary and sufficient condition for an on-resonance ECRIS is that the magnetic flux

TABLE I. List of collisions and reactions for the argon plasma. The excited argon atoms and the singly charged argon ions in the reactions are shown by Ar^* and Ar^+ , respectively.

Formula	Type
Volume reactions:	
$e + \text{Ar} \rightarrow e + \text{Ar}$	Elastic
$e + \text{Ar} \rightarrow e + \text{Ar}^*$	Excitation
$e + \text{Ar}^* \rightarrow e + \text{Ar}$	Superelastic
$e + \text{Ar} \rightarrow 2e + \text{Ar}^+$	Ionization
$e + \text{Ar}^* \rightarrow 2e + \text{Ar}^+$	Ionization
$\text{Ar}^* + \text{Ar}^* \rightarrow e + \text{Ar} + \text{Ar}^+$	Penning ionization
$\text{Ar}^* + \text{Ar} \rightarrow \text{Ar} + \text{Ar}$	Metastable quenching
Surface reactions:	
$\text{Ar}^+ \rightarrow \text{Ar}$	Neutralization
$\text{Ar}^* \rightarrow \text{Ar}$	Neutralization

TABLE II. The ampere-turns of three solenoids for four magnetic field configurations.

Source type	Configuration name	Ampere-turns		
		Solenoid 1	Solenoid 2	Solenoid 3
Off-resonance	Flat-B	7020	7020	3510
On-resonance	Minimum-B	24570	24570	−24570
	Torus Zone	24570	24570	−15210
	Double Zone	17550	17550	−14040

density should meet the resonance value at certain points. The configurations of Figs. 2(b)–2(d) are generated using a reversed direction for the current of the middle solenoid. Figure 2(b) shows a minimum-B structure of an on-resonance ECRIS. It is clear that the magnetic flux density meets the ECR line at two points between the two vertical lines.

Figure 2(c) shows deviations from the standard profile of an ECRIS. In Fig. 2(c), the minimum value of the magnetic flux density at the chamber axis is a little greater than the resonance value. This configuration also shows an on-resonance magnetic field profile. This is of course understandable as the resonance condition is met for other points out of the axis, inside the chamber. We will further explain this point and illustrate that there is an ECR zone placed inside the chamber for the case of Fig. 2(c). We have named this case as the torus zone configuration because, as will be more clearly shown in Fig. 3(c), a hole is generated at the center of the resonance surface. The hole is located around the axis so it is expected that there is no point on the axis to satisfy the resonance condition.

The resonance condition is clearly met for Fig. 2(d) at four points along the ECR line between the two vertical lines. This configuration significantly differs from the standard profile of an ECRIS and obviously represents a double zone configuration.

We now attempt to illustrate the resonance magnetic field isosurfaces inside the plasma chamber in Figs. 3(a)–3(d) corresponding to the foregoing four configurations. Due to the Doppler shift effect, one expects a broadening of the resonance zone. Therefore, we have chosen a range of 860 to 890 G around the target value of 875 G for the magnetic flux density. Obviously, there does not exist any resonance surface for the case of MDIS in Fig. 3(a). For the other cases in Fig. 3, the resonance conditions are met at all of the points on the isosurfaces.

The resonance surface for the minimum-B type of the ECRIS is shown in Fig. 3(b). A general comment may be appropriate here. For a system of two solenoids, with no transverse magnets, one could observe a simple ellipsoidal resonance surface. The effect of the magnetic field of the third solenoid would be a compression in the middle of the

FIG. 2. Variations of the magnetic flux density (in Gauss unit) along the Z axis for various magnetic field configurations of Table II: (a) flat-B, (b) minimum-B, (c) torus zone and (d) double zone. Two vertical solid black lines show the injection and extraction walls of the chamber. A horizontal solid red line also indicates the resonance magnetic field.

FIG. 3. 3D view of ECR isosurfaces (in Gauss unit) for various magnetic field configurations of Table II: (a) off-resonance or flat-B, (b) minimum-B, (c) torus zone and (d) double zone.

geometry toward a dumbbell shape. The azimuthal symmetry of the surface is still preserved. Such a configuration, in fact, indicates the famous minimum-B structure. If the effects of the transverse magnets are also accounted for, the azimuthal symmetry would no longer hold and a threefold symmetry would be seen at both ends of the surface. One end looks as if 60 degrees rotated with respect to the other end. This is shown in Fig. 3(b). The resonance surfaces emerge as more complex 3D entities for the rest of the configurations in Figs. 3(c) and 3(d). The isosurfaces of Figs. 3(b)–3(d) indicate a strong dependence of the resonance zones on the currents of solenoids. With a reduction in the current of the middle solenoid, the minimum-B structure of Fig. 2(b) changes to the profile shown in Fig. 2(c) where the lowest value of the B along the Z axis inside the chamber is located above the 875 G. The ECR surface corresponding to Fig. 2(c) is shown in Fig. 3(c). The ECR zone is similar to a toroidal region around the Z axis as expected. Therefore, we named this the torus zone configuration.

In Fig. 2(d), the currents in solenoids 1 and 2 are also decreased so that the field profile along the Z axis crosses the 875 G line 4 times. The corresponding 3D surface is shown in Fig. 3(d). This case does not show a toroidal region around the Z axis for its resonance surface. For this

case, however, the resonance surface splits into two separate closed surfaces. This is because of the high compression effect of the field from the middle solenoid. As a result of such a splitting, one deals with a couple of ECR zones. Therefore, we named this the double zone configuration.

It should be noted that the use of a reversed current in a middle coil in the ECRISs is a common technique for lowering the field intensity in the center of the source to achieve the famous minimum-B structure [2]. This technique is also used in a special ECRIS machine described in [20] to increase the ionization efficiency. The resultant magnetic field profile along the chamber axis presented in [20] is close to the field profile of the double zone configuration shown in Fig. 2(d). There is, however, no information about the 3D geometry of the resonance surfaces in [20] to ensure that a double zone configuration is generated in that device. In the present work, on the other hand, we have illustrated a well-defined 3D object for the double zone configuration with two separated closed ECR zones that are exclusively located inside the plasma chamber.

In Fig. 4, we have shown the contour plots of the magnetic flux densities inside the plasma chamber by defining three cut planes. The planes namely p_1 :

FIG. 4. Magnetic flux density distribution (in Gauss unit) on three cut planes, p_1 , p_2 and p_3 , inside the plasma chamber for various magnetic field configurations. Parts (a), (b), (c): the flat-B configuration; parts (d), (e), (f): the minimum-B configuration; parts (g), (h), (i): the torus zone configuration; parts (j), (k), (l): the double zone configuration. In all parts, the black stream lines and the white contours represent the magnetic field lines and the ECR zones, respectively.

$Y = X/\tan(\pi/6)$, p_2 : $Y = X/\tan(\pi/3)$ and p_3 : $Y = X/\tan(\pi/2)$, all include the Z axis. The plane p_1 (p_3) is -30 ($+30$) degrees rotated with respect to the plane p_2 . In Fig. 4, the magnetic field lines are also shown by black stream lines. Furthermore, the ECR contours, corresponding to the resonance surfaces of Fig. 3 are highlighted with a white color in Fig. 4. Obviously, the MDIS lacks the ECR contour. Different orientation of the ECR contours from one cut plane to another is a result of the change in the polarities of the transverse magnets.

The asymmetric field profiles in the planes p_1 and p_3 can be understood by considering the superposition of the magnetic fields due to the solenoids and the hexapole magnets. The effect of transversal hexapole magnets can be further seen by introducing cut planes perpendicular to the Z axis. Here in Fig. 5, we have shown the contour plot of the azimuthal component of the magnetic flux density together with the magnetic field lines for three cut planes p_4 , p_5 and p_6 . These planes are placed at $z = -25$ mm, $z = 0$, and $z = 25$ mm. Again, the white color represents

FIG. 5. Distribution of the azimuthal component of the magnetic flux density (in Gauss unit) on three cut planes, p_4 , p_5 and p_6 , inside the plasma chamber for various magnetic field configurations. Parts (a), (b), (c): the flat-B configuration; parts (d), (e), (f): the minimum-B configuration; parts (g), (h), (i): the torus zone configuration; parts (j), (k), (l): the double zone configuration. In all parts, the black stream lines and the white contours represent the magnetic field lines and the ECR zones, respectively.

the ECR contours inside the plasma chamber. While we move from a lower to a higher z value, the ECR contours rotate about 60 degrees as mentioned earlier.

In addition to the magnetic field distribution, the electric field profile also plays an important role in determining the behavior of plasma. Before the plasma ignition, the chamber with the foregoing dimensions behaves as a monomode cavity with the microwave's electric field profile shown in Fig. 6(a). The presence of plasma as an electrically conducting medium, however, disturbs the electric field profile. The contour plots of the self-consistent electric field

profiles in the Y - Z plane inside the chamber have been demonstrated for various configurations in Figs. 6(d)–6(e). In Fig. 6, the closed black contours show the critical plasma density of $7.4 \times 10^{16} \text{ m}^{-3}$ related to the microwave frequency of 2.45 GHz. In Figs. 6(b)–6(e), the electric field intensity is significantly reduced near the contour of the critical electron density and has its lowest magnitude inside the contour. This shows the shielding effect of the plasma on the microwave electric field.

Figure 7 provides an improved comparison for the electric field profiles for the various configurations.

FIG. 6. Distribution of the microwave electric field (in V/m) in the absence of the plasma (a) and the self-consistent electric field (in V/m) in the presence of plasma for various configurations: (b) flat-B, (c) minimum-B, (d) torus zone and (e) double zone. The closed black contour represents the location of the critical plasma density. All the plots are related to the Y-Z plane inside the plasma chamber.

The variations of the self-consistent electric field on the model axis (Z coordinate) and an arbitrary line along a diameter of the cylinder at the middle of the chamber (X coordinate) have been shown in Figs. 7(a) and 7(b), respectively. It is clear from Fig. 7 that the magnitude of the self-consistent electric field in microwave-heated plasma is significantly smaller than its unperturbed values in the absence of the plasma.

IV. MICROWAVE ABSORPTION

In Fig. 8, we have shown the dissipated microwave power in the Y-Z plane inside the plasma chamber for various configurations.

The power absorption in the off-resonance configuration of Fig. 8(a) is rather uniformly distributed within the plasma chamber compared to the other configurations.

FIG. 7. Variation of the electric field (in V/m) along the model axis (Z coordinate) (a); and on an arbitrary line along a diameter of the cylinder at the middle of the chamber (X coordinate) (b). The black line is related to the microwave electric field without the plasma. The self-consistent electric field at the presence of plasma are shown by the red, magenta, blue and green lines, respectively for the flat-B, the minimum-B, the torus zone and the double zone configurations.

FIG. 8. Distribution of microwave power absorption (in W/m^3 unit) in the Y-Z plane inside the plasma chamber for various magnetic field configurations: (a) flat-B, (b) minimum-B, (c) torus zone and (d) double zone. In all parts, the white contours represent the ECR zones.

An explanation is in order here. In microwave-heated plasma, the collisional Ohmic heating is the main microwave power absorption mechanism by the plasma electrons. So, the electric field patterns of the dominant

microwave mode play the key role in determining the power absorption distribution inside the plasma resonant chamber. When the external magnetic field meets the ECR condition somewhere within the plasma chamber, the

FIG. 9. Variation of the microwave power absorption (in W/m^3 unit) along the model axis (Z coordinate) (a); and on an arbitrary line along a diameter of the cylinder at the middle of the chamber (X coordinate) (b). The red, magenta, blue and green lines, respectively related to the flat-B, the minimum-B, the torus zone and the double zone configurations.

gyrating electrons rotate in phase with the microwave electric field and see a steady electric field over many gyro-orbits. The net result is to intensify the energy gain of the electrons in a narrow region of resonance surface. In the off-resonance configuration, the shape of the magnetic field profile is a quasiflat profile everywhere above the resonance value. Therefore, the relatively uniform distribution is seen because the power absorption mechanism lacks a resonant scheme in the microwave discharge plasma.

The localized ECR heating in the other configurations of Figs. 8(b)–8(d) results in a more nonuniform distribution for the power absorption. Generally speaking, power absorption occurs predominantly around the resonance contours. In addition, in all configurations, more power absorption takes place in the injection side of the chamber where the wave meets the plasma first. The wave deposits its energy to the plasma and hence less portion of the power remains to be absorbed at the extraction side. In the double zone configuration of Fig. 8(d), however, there is a chance again for the remaining power to be absorbed in the second zone. Therefore, the double zone configuration enhances the power absorption near the extraction side of the chamber.

Figure 9 provides an improved comparison of the microwave power absorption in the various configurations. The variations of the power absorption on the model axis (Z coordinate) and an arbitrary line along a diameter of the cylinder at the middle of the chamber (X coordinate) have been shown in Figs. 9(a) and 9(b), respectively.

V. PLASMA PROPERTIES

A nonuniform plasma density profile stems from the complex magnetic field configurations and the sophisticated power distributions. It is worthwhile to know how the plasma density profile varies when the magnetic field configuration changes. In Fig. 10, we have plotted the variation of the

electron number density distribution along the Z axis inside the plasma chamber for various configurations. From Fig. 10, it is clear that the peak plasma density for a minimum-B configuration is lower than those of the off-resonance and other on-resonance configurations. The plasma density uniformity in the Z direction, however, is better in the minimum-B configuration.

The properties of ions in the vicinity of the extraction wall of the chamber plays an important role in determining the extractable current and the emittance of the ion beam. In Fig. 11, we have plotted the argon ion number density distributions in a plane parallel to the X - Y plane of the model for various configurations. The plane is located at 5 mm from the extraction wall inside the chamber. In the ECRISs, ion beam is extracted from an ion emissive surface located inside the plasma. This surface is just behind an aperture which is usually embedded at the center of the extraction wall. All of the ion density distributions in Fig. 11 show a very smooth variation of the Ar^+ density at the central regions. Therefore, it is necessary to look at the

FIG. 10. Variation of electron number density (in m^{-3} unit) along the Z axis inside the plasma chamber for various magnetic field configurations: off-resonance (solid black), minimum-B (dashed red), torus zone (dotted blue) and double zone (dot-dashed green).

FIG. 11. Distribution of argon ion number density (in m^{-3} unit) in a plane parallel to the X-Y plane inside the plasma chamber (at a distance of 5 mm from the extraction wall) for various magnetic field configurations: (a) flat-B, (b) minimum-B, (c) torus zone and (d) double zone.

uniformity of the ion density distribution in a narrower region. An insight into the uniformity of the ion density distribution can be gained by introducing the flatness of density profile. The flatness is defined by the ratio of the average to the maximum Ar^+ density. We have considered a circular disk with a radius of 10 mm at the center of the cut plane used in Fig. 11 as the emissive surface. We have calculated the flatness of density profile on this disk. The average and maximum values of Ar^+ density and the flatness of density profile in the disk are listed in Table III for various configurations. From Table III, it is clear that in all configurations, ions are rather uniformly distributed near the extraction wall by a flatness value greater than 92%. A more uniform emissive surface is, however, observed in the flat-B configuration of the off-resonance MDIS. This is primarily due to a more homogeneous magnetic field distribution which in turn leads to a more uniform confining force of the plasma particles. Furthermore, in this configuration, there is no resonance heating as a significant source of the nonuniformity in the power absorption and consequently in the plasma properties. In the torus zone configuration, although the highest ion density could be

produced, the flatness value is a minimum. In the double zone configuration on the other hand, a uniform distribution similar to the flat-B configuration is observed. Among three different on-resonance configurations, a more uniform ion density distribution and consequently a lower beam emittance could be produced by the double zone configuration.

One important issue related to our simulation model is the adequacies of the meshing used to model the ECR plasma. In the FE method, a greater number of meshes

TABLE III. Properties of argon ion number density distribution in the vicinity of extraction wall for four magnetic field configurations.

Configuration name	Average density $\times 10^{16} \text{ m}^{-3}$	Maximum density $\times 10^{16} \text{ m}^{-3}$	Flatness (%)
Flat-B	3.0716	3.2400	94.8025
Minimum-B	2.9729	3.1896	93.2060
Torus zone	3.6296	3.9104	92.8191
Double zone	3.5316	3.7564	94.0155

FIG. 12. Variations of the xx component of the plasma conductivity tensor in S/m unit (right axis—red solid line) and the corresponding element size in mm unit (left axis—blue dotted line) along the Z axis for various configurations: (a) flat-B, (b) minimum-B, (c) torus zone and (d) double zone.

results in the more reliable results. For modeling the ECR plasma, however, a further refinement of meshing should be used around the resonance surfaces. This is required to accurately resolve the resonance zone for capturing the ECR heating. In order to evaluate the adequacies of the meshing used in the simulation, we have investigated the

behavior of the plasma conductivity tensor. This is because the resonance power absorption is associated with a significant increase in the plasma electrical conductivity. This sharp variation takes place in a narrow region in proximity of the resonance surfaces. If the distribution of the dimensions of elements follows the variations of plasma

FIG. 13. Variations of the xx component of the plasma conductivity tensor in S/m unit (right axis—red solid line) and the corresponding element size in mm unit (left axis—blue dotted line) along the X axis for various configurations: (a) flat-B, (b) minimum-B, (c) torus zone and (d) double zone.

electrical conductivity, a more reliable result is guaranteed. We have used the adaptive meshing procedure introduced in [19] for constructing an appropriate FE model of the ECR plasma. To achieve this, we have first used a rather uniform extra fine meshing and calculated the magnetic field distribution. We then used the functional-based mesh adaptation to make an extremely fine mesh on the resonance surfaces. In this functional evaluation, the initially calculated magnetic field distribution is used to modify the meshing structure. As a result of doing such a meshing procedure, the mesh distribution is refined so that its resolution at the proximity of the resonance surfaces is higher than those at the other places in the model. This adapted mesh is used in the next simulation step as a reference for further necessary refinements such as those required for the boundary layers near the plasma chamber walls.

In Figs. 12 and 13, we have plotted the variations of the xx component of the plasma electrical conductivity tensor and the corresponding element size for various configurations, respectively along the Z and X axes. In Figs. 12 and 13, the mesh size distribution has been carefully refined around the resonance regions. The minimum values of the mesh size occur in the places around which the plasma conductivity tensor has some significant peaks. Therefore, the mesh size distribution is matched with the plasma conductivity tensor variation.

VI. SUMMARY AND CONCLUSION

In summary, we have simulated a microwave heated magnetized plasma through the FE method. We have considered four magnetic field configurations and investigated some of the main concepts of the ECR plasma. The configurations include a flat-B profile for the off-resonance MDIS and the minimum-B, the torus zone and the double zone profiles for the on-resonance ECRIS. We have tuned the flexible magnetic field profiles via changes in the currents of the solenoids. The resonance surfaces and their impacts on the microwave power absorption and the plasma density distribution have been addressed in detail. It is shown that the typical closed resonance surface in the minimum-B configuration converts to a donut-shape entity in the torus zone configuration. Furthermore, it divides into two separate closed surfaces in the double zone configuration. We have provided better views of the 3D resonance surfaces with the aid of projection of the magnetic field profiles on 2D cut planes. We have investigated the behavior of the microwave electric field inside the plasma chamber. It is shown that the magnitude of the self-consistent electric fields is significantly reduced due to the shielding effect of the plasma on the microwave electric field. It is also shown that the resonance surfaces strongly affect the microwave power absorption. The microwave power is rather uniformly absorbed in the flat-B configuration of the off-resonance MDIS. The presence of the resonance surface in an ECRIS,

however, results in the concentration of the power absorption around the ECR zone. We have found that the power absorption at the vicinity of the extraction wall of the chamber is more significant in the double zone configuration. The effects of the resonance surfaces on the plasma density profiles have been also investigated. In view of the plasma density variations inside the chamber, we identified a more uniform profile for the minimum-B configuration among others. We have however found a completely different behavior for the variations of the ion density in the vicinity of the extraction wall of the source. We have introduced the flatness parameter for characterizing the uniformity of the argon ion density distribution. We found the flatness of the order of 93%–95% for the ion density distribution at the ion emissive surface in various configurations. We have finally evaluated the adequacies of the meshing used in the simulation by investigating the behavior of the plasma conductivity tensor. It is shown that the mesh refinements near the resonance surfaces are sufficient to follow the variations of the plasma conductivity tensor.

A question may be raised about the pressure regime at which simulations for the ECR plasma were conducted. An ECRIS should be operated at a low pressure regime to be compatible with the high or ultrahigh vacuum environment of an accelerator machine. At high pressures, the ECR mechanism cannot occur as the mean-free path of the electron would be very small. The gas pressure in our simulation model is higher than the usual values in the operational ECRISs for the accelerators. We have simulated the argon plasma at pressure of 1 Pa at which the mean-free path of electrons is larger than the size of the plasma chamber. Therefore, we still deal with a noncollisional plasma at this pressure regime. The operational gas pressure of the ion sources might change the physics behind the ECR plasmas. For example, the plasma chemistry would be modified at the lower pressures. The gas pressure, however, does not have any significant impact on the resonance condition at the lower pressures. The resonance condition is almost completely determined by the external magnetic field in the low pressure regime. The change in the operational pressure of the source indeed does not alter the shape of the resonance surface nor its position. The Doppler shift broadening of the ECR zone is the only pressure-dependent physical phenomena affecting the ECR heating. This broadening which does not undergo significant changes for different pressures is already considered in our simulation model. In other words, the gas pressure may slightly alter the thickness of the resonance surface, but does not perturb its position or profile. Therefore, the effects of the resonance surfaces on the power absorption distribution and the consequent ion density profile are almost independent from the gas pressure. Therefore, the validity of our finding could be extended to the low pressure ECRISs, with almost high degrees of certainty.

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