6. Radial Density Profile of Microwave Plasma for Wall Conditioning in a Purely Toroidal Magnetic Field

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(Received 25 October 2000)

Abstract

Microwave discharge plasma in a toroidal magnetic field is expected to be used for in-situ wall conditioning of steady-state fusion devices in future. This paper describes a basic study of plasma density profile along major radius for microwave discharge in a purely toroidal B-field. Fluid model analysis shows a significant influence of vertical electric field \(E\) induced by VB- and curvature drift. The density profile is determined mainly by the parameter \(P = (E/B)v_\parallel\) which is a ratio of \(E \times B\) drift time for minor radius \(a\) to the ionization frequency \(v_i\). For large values of \(P(> 1)\), the density distribution is relatively uniform. For smaller \(P\), however, the density dramatically increases along the major radius due to the \(E \times B\) outward drift. Such behavior was confirmed in the experiment of a simple magnetized torus, TOMAS. Relations between the measured density profile and the electron heating processes at electron cyclotron resonance or upper hybrid resonance are discussed.

Keywords: wall conditioning, simple magnetized torus, microwave discharge, electron cyclotron resonance, upper hybrid resonance, \(E \times B\) drift

6.1 Introduction

To date, dc glow discharges with no ambient magnetic field have widely been used in wall conditioning in order to remove impurities and control hydrogen recycling. In future fusion devices, however, the application of superconducting field coils forces one to maintain the B-field during wall conditioning where the conventional dc glow discharge does not work. Thus, new wall conditioning techniques compatible with the semi-permanent magnetic fields have been needed. Microwave discharge plasma is one of promising plasma sources and is maintained by electron heating at the Electron Cyclotron Resonance (ECR) frequency or at the Upper Hybrid Resonance (UHR) frequency. In case of tokamak devices, the wall conditioning has to be done in a purely toroidal magnetic field without toroidal plasma currents.

The feasibility of microwave discharges in such magnetic field configuration has been shown at different tokamak devices (e.g., TEXTOR \([1]\) or ALCATOR C-mod \([2]\)). However, actual fusion devices are not convenient for systematic studies with detailed diagnostics. Thus, a basic investigation using a simple magnetic torus, the TOMAS device, at the IPP FZ-Jülich has been started in collaboration among the IPP, Ruhr-Universität Bochum and Nagoya University. The

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results of thin film deposition by microwave discharge in this device have been already reported elsewhere [3,4]. This paper focuses on a problem of asymmetric radial distribution of plasma density: the shape of radial plasma profile shows, in most cases, increasing densities outward directed from the ECR position, with the density decrease in the opposite direction (inner wall). Such outward increasing density profiles have been also observed in detailed measurements of microwave plasma in a similar test device [5]. Understanding and control of the plasma density profile is inevitable to uniformly deposit thin boron layer on the torus wall.

First, we describe a model of discharge plasma in purely toroidal magnetic field and show two key parameters determining the plasma density profile. Then we compare the model with the experimental results and finally conclude.

6.2 Modelling of Discharge Plasma in Simple Toroidal Field

In a purely toroidal magnetic field \( B \), a particle of mass \( m \) and charge \( q \) moving with the speed \( v_b \) along \( B \) and \( v_i \) across \( B \) is subject to a curvature- and \( \nabla B \)-drift: the vertical drift velocity \( v_* \) is given by

\[
v_* = \frac{(m/q) (v_b^2 + v_i^2 / 2)}{R_B}
\]

(1)

for the curvature radius \( R_C \). Electrons and ions drift in opposite direction, and the charge separation (polarization) induces a vertical electric field \( E \), which eventually causes the \( E \times B \) outward drift of plasma.

Two fluid model gives the flux \( n u_\perp \) perpendicular to \( B \) as

\[
n u_\perp = n \mu_1 E - D_2 \nabla n + n (u_E + u_D) / (1 + v^2 / \Omega^2)
\]

(2)

where \( u_E = E \times B / B^2 \), \( u_D = -kTnqB^2 \nabla n \times B \), \( \mu_1 = ql / (1 + \Omega^2v^2) \), and \( D_2 = kTnqB^2 / (1 + \Omega^2v^2) \) for the cyclotron frequency \( \Omega \) and the collision frequency \( v \).

We consider a simple case of high magnetic field \( (\Omega >> v) \) and high drift velocity that \( |u_E| >> |u_D| \), which is equivalent to \( (E/B)v^2 \approx \rho v / a \), letting \( |\nabla n / n| \) be 1/a for the minor radius \( a \), the thermal velocity \( v_T \), and the Larmor radius \( \rho \). In order to examine the plasma density profile in a simple torus, we introduce Cartesian coordinate \((x, y, z)\) with the magnetic field \( B \) along the \( z \) axis (toroidal direction) and the electric field \( E \) along the \( y \) axis (vertical direction). We assume that the plasma density changes only in the \( x \) direction (major radius direction). Then the x-component of ion flux \((q = e)\) is obtained from Eq. (2) as

\[
n u_x = n(E/B) - D_2 \frac{dn}{dx}
\]

(3)

and the y-component as \( n u_y = n u_i E \). At first, we neglect the weak dependence of \( T_e \) and \( E \) on the position \( x \), and later we discuss about this assumption (see Fig. 1).

In general, ambipolar process governs the ion and electron transport. As observed in the experiment [5], the plasma potential is positive (\(-2T_e [eV]\)) against the wall potential in a simple toroidal magnetic field. This means that the electron loss flux (mainly along \( B \)) is larger than the ion loss flux (mainly across \( B \)). Since the slower loss process (ion diffusion across \( B \)) determines the overall ambipolar diffusion, we consider the ion diffusion hereafter.

Substituting the ion flux into the continuity equation, \( \partial n / \partial t + \nabla \cdot n u_\perp = v_i n \), one obtains the following differential equation for the plasma density \( n \) in steady state;

\[
D_2 \frac{d^2 n}{dx^2} - (E/B) \frac{dn}{dx} + v_i n = 0
\]

(4)

where \( v_i \) is the ionization frequency: \( v_i = n_e <\sigma_{i\nu}> \) for the gas density \( n_e \) and the ionization rate constant \( <\sigma_{i\nu}> \) which depends on the electron temperature \( T_e \).

![Fig. 1 Normalized density \( n(\xi)/n_0 \) vs. normalized position \( r/a \) for \( P_0 = (E_0/B_0)/\rho v_1 = 0.5 \) and \( Q_0 = D_2/\rho v_1 = 0.025 \). Dashed, thin solid, and thick solid lines indicate the uniform \( B \) solution, the non-uniform \( B \) approximate solution, and the non-uniform \( B \) exact solution, respectively.](image-url)
Two limiting cases are found from Eq. (4). One is the diffusion dominant case (the second term in eq. (4), $E/B \to 0$) whose solution is $n(\xi) \propto \cos(\sqrt{4Q/P} \xi)$ for $\xi = x/a$ and the diffusion time scale $\tau_0 = a^2/D_i$. The other is the $E \times B$ convection dominant case (the first term in Eq. (4), $D_i \to 0$) whose solution is $n(\xi) = \exp[(E/B)\xi]$ for the convection time scale $\tau_E = a/E/B$.

We examine the influence of $E \times B$ drift on the density profile, giving the boundary conditions, $n = n_0$ at $x = 0$ (the major radius position $R = R_0$) and $n = 0$ at $x = a$ (the outer wall at $R = R_0 + a$). Then Eq. (4) gives the following plasma density profile as a function of the normalized position $\xi = x/a$:

$$n(\xi)/n_0 = \exp \left( \beta_1 \xi \right) \cdot \left( 1 - \exp \left( \beta_2 \xi \right) \right)$$

where $\beta_1$ and $\beta_2 (> \beta_1)$ are the positive constants given by

$$\beta_1 = \frac{P}{2Q} \left( 1 - \sqrt{\frac{1 - 4Q}{P^2}} \right)$$
$$\beta_2 = \frac{P}{2Q} \left( 1 + \sqrt{\frac{1 - 4Q}{P^2}} \right)$$

and $\alpha = \exp(-\beta_1 + \beta_2)$, $P = 1/\tau_0 \nu_1$ and $Q = 1/\tau_0 \nu_1$ for the $E \times B$ drift velocity high enough to satisfy $P^2 > 4Q$.

The density profile expressed by Eq. (5) is determined by only two parameters, i.e., the convection parameter $P = (E/B)/a \nu_1$ and the diffusion parameter $Q = D_i/a^2 \nu_1$. In typical experimental conditions where $P^2 > 4Q$, we find $\beta_1 = 1/P$, $\beta_2 = P/Q (\gg \beta_1)$, $\alpha = \exp(-P/Q)$, and the density profile as

$$n(\xi)/n_0 = \exp \left( \xi/P \right) - \exp \left( (\xi - 1)P/Q \right).$$

The first term on the right hand side shows an exponential increase of density along the $E \times B$ plasma flow, and the second term provides a diffusion loss to the wall at $\xi = 1$. The dashed line in Fig. 1 shows an example of density profile calculated from Eq. (5) for $P = 0.5$ and $Q = 0.025$ ($P_0$ and $Q_0$ in the figure denote the values of $P$ and $Q$ at $\xi = 0$, respectively, in case of non-uniform magnetic field).

Eq. (5) was derived under the assumption of uniform $B$ and $E$. However, the toroidal magnetic field decreases as $B = B_0/(1 + x/R_0)$. The vertical drift velocity given by Eq. (1) is inversely proportional to $R_0 B = R_0 B_0/(1 + x/R_0) = R_0 B_0$, and hence the vertical electric field will be independent of $x$ ($E = E_0 = constant$) under the assumption of $E$ proportional to the vertical drift velocity. Thus, the $E \times B$ drift velocity $E/B$ will be expressed as $(E_0 B_0)(1 + x/R_0)$, and the diffusion constant $D_i$ as $D_{i0}(1 + x/R_0)^2$. As a consequence, $P$ and $Q$ depend on the position as $P = P_0(1 + x/R_0)$ and $Q = Q_{00}(1 + x/R_0)^2$ for $P_0 = (E_0 B_0)/a \nu_1$ and $Q_0 = D_{i0}/a^2 \nu_1$.

Substituting the ion flux into the continuity equation, one finds the additional terms containing the space derivatives, $dD_i/dx$ and $d(E/B)/dx$. However, those terms are negligible when $R_0/a \gg P_0 \gg (a/R_0)Q_0$. As the aspect ratio is $R_0/a = 3$ in the present experiment, the above condition will be satisfied for $3 \gg P_0 \gg Q_0/3$. Then Eq. (4) is still available with $D_i$ and $E/B$ depending on the position $x$. We directly solved this differential equation and plotted as the exact solution in Fig. 1 by the thick solid line. In addition, we give the approximate density profile from Eqs. (5) and (6) with $\beta_1$ and $\beta_2$ depending on the position $x$, as indicated by the thin solid line. For simplicity, we use the non-uniform $B$ approximate solution from now on, since the difference from the exact solution is small except the region near the wall.

The density increase along the $E \times B$ drift is explained as follows. When electron of density $n$ makes a drift of distance $dx = d\xi/a$ with the speed $E/B$, ionization during the time interval $dx/(E/B)$ gives rise to a density increase $dn = n \nu_1 (\xi/E/B)$, and hence $dn/dx \approx n \nu_1 (\xi/E/B)$. Thus, the convection parameter $P$ mainly determines the density profile. The influence of the diffusion parameter $Q_0$ is shown in Fig. 2 for $P_0 = 0.5$. As the value of $Q_0$ increases by two orders of magnitude, the plasma density near the wall ($\xi = 1$) decreases due to the large diffusion loss.

Figure 3 shows how the plasma density profile depends on the convection parameter $P_0$ for $Q_0 = 5 \times 10^{-4}$. Small change of $P_0$ dramatically modifies the density profile, especially for $P_0 < 0.2$. For smaller value of $P_0$, i.e., for smaller $E_0/B_0$ and/or larger $\nu_1$ (larger $T_e$), ionization takes place more frequently during the electron convection across the plasma column, so that the density increases more rapidly with the distance $\xi$. In contrast, the large values of $P_0 (> 1)$ gives the relatively uniform density profile.

6.3 Experimental Results

The experiment was done in the TOroidal MAgnetic field System (TOMAS) device at IPP FZJülch. The toroidal vessel of major radius $R_0 = 0.78$ m and minor radius $a = 0.26$ m is one half of the size of TEXTOR. The magnetic field generated by 16 toroidal
field coils is a purely toroidal magnetic field with neither poloidal nor vertical magnetic field. The variable toroidal B-field can reach a maximum of 0.12 T on the torus axis. Microwave at 2.45 GHz with maximum power of 6 kW is launched via a rectangular waveguide of TE_{01} mode and a cooled quartz window located at the top of the vessel above the torus axis. This antenna excites both O-mode and X-mode of waves in a plasma due to the wave polarization at the launcher exit, and partly due to multiple wall reflection of waves. Microwave plasma of density $n = 10^{16}$-10$^{17}$ m$^{-3}$ and electron temperature $T_e = 1.5$-15 eV is obtained in the condition of ECR and UHR in H$_2$, He, Ar or CH$_4$ gases at pressure $p = 0.025$-1 Pa. In the present paper, data of argon discharge will be shown unless otherwise stated.

Some examples of plasma density distribution along the minor radius are shown in Fig. 4(a) for different discharge powers, which were measured by a movable Langmuir probe at about 150° toroidal position from the microwave launcher. The radial profiles show increasing densities outward through the ECR position at $r = 0.1$ m. The dashed line in the figure indicates the local UHR density $n_{UH}$ calculated from the local value
of $B$. The measured local plasma density is close to $n_{\text{UH}}$ at the low power (330 W, 450 W) and considerably higher than $n_{\text{UH}}$ at the high power (750 W). These results suggest the following physical picture. Hot electrons produced at the ECR layer make the $E \times B$ outward drift, ionizing and increasing the plasma density. At the low powers, they may further undergo the UHR heating [4] during the drift.

The measured densities are normalized with the peak density for each discharge power and replotted in logarithmic scale in Fig. 4(b), normalizing the position with the minor radius $a = 0.26$ m. The solid curves in the figure indicate the density profiles calculated from Eq. (5) with the position dependence of $\beta_1$ and $\beta_2$ taken into account. Here the theoretical curves are not sensitive to the $Q_0$ value but the slope of density increase significantly changes with the $P_0$ value. Comparison of the measured points with the theoretical curves in Fig. 4(b) suggests the best fitting value to be $P_0 = 0.38$. Using this value and the definition of $P_0 = (E_0/B_0)\nu_1$, we can estimate the vertical electric field to be $E_0 = 57$ V/m where $B_0 = 0.0986$ T, $a = 0.26$ m, and the ionization frequency $\nu_1 = 5.8$ kHz given by the measured electron temperature ($T_e = 2.4$ eV) and argon pressure ($p = 0.59$ Pa). On the other hand, the selected value of $Q_0 = 5.5 \times 10^{-4}$ leads to $D_{\text{ion}} = 0.22$ m$^3$/s, which is reasonable in the present conditions of $B_0$ and the argon ion-neutral collision frequency $\nu = 71$ kHz.

An example of the plasma density profile for low pressure (0.025 Pa) and high discharge power (1,200 W) is shown in Fig. 5. The plasma density starts to increase from the ECR position ($r = 0.092$ m) and becomes the density slightly above the local UHR density. The solid line indicates the theoretical density profile fitted best for the measured points with $P_0 = 0.22$ and $Q_0 = 5.5 \times 10^{-4}$. The measured electron temperature is relatively high ($T_e \approx 3.5$ eV), and the argon ionization cross section gives $\nu_1 = 2.4$ kHz at $p = 0.025$ Pa. Thus, the best fit value of $P_0 = 0.22$ leads to the vertical electric field of $E_0 = 13$ V/m.

In most cases, as shown in Figs. 4 and 5, the plasma starts to grow near the ECR point and gets the peak density near the outer wall, thus filling only the outer half part of the toroidal vessel. In order to fill the entire vessel with plasma, the ECR position was shifted toward the inner wall ($r = -0.26$ m) by decreasing the magnetic field. Then, the plasma almost fully covered the torus volume as shown in Fig. 6(a), where the ECR position is $r = -0.2$ m with $B_0 = 0.0657$ T, $p = 0.59$ Pa and the discharge power of 600 W. For the same power and pressure, 1.5 times higher magnetic field of $B_0 = 0.0986$ T gives the outward increasing distribution of plasma density as shown in Fig. 6(b), in contrast to the
uniform distribution in Fig. 6(a).

Such drastic change in the shape of plasma density profile is qualitatively understood as follows. The UHR condition \((\omega^2 = \omega_p^2 + \Omega_e^2)\) requires the higher plasma density \((n_{UH})\) for the lower magnetic field: the distribution of \(n_{UH}\) (UHR density) is indicated by the dashed line in Fig. 6. It is seen in Fig. 6(a) that the UHR condition \((n - n_{UH})\) is satisfied only in a narrow region around \(r = -0.16\) m. On the contrary, the UHR heating occurs in a wide radial position from \(r = 0\) to \(r = 0.26\) m in Fig. 6(a) where \(n \geq n_{UH}\). This difference in the UHR heating efficiency gives rise to the difference in the electron temperature: the Langmuir probe measurement gives \(T_e = 1.9\) eV and 2.4 eV for the low B-field (Fig. 6(a)) and the high B-field (Fig. 6(b)), respectively. The measured electron temperatures give six times higher ionization frequency in the high B- than in the low B-field case. This means six times large value of \(P_0\) in the low B- than in the high B-field case. The solid lines in Fig. 6 indicate the calculated density profiles for the values of \(P_0\) and \(Q_0\) estimated from the measured \(T_e\) and pressure. Thus our model accounts for the rather flat profile measured in the low B-field.

The uniform distribution of plasma density was observed in case of low B-field in the present experiment. However, this does not mean that \(B_0\) is only one essential parameter for the density profile. Even in the low B-field, the outward increasing distribution will be observed if the discharge power is high enough for the plasma density to exceed \(n_{UH}\) in a wide region. In fact, the low-density uniform distribution for low powers and the high-density outward increasing distribution for high powers have been observed as shown in Fig. 6(b) of Ref. [5]. Thus, the key parameter governing the density profile is \(P_0 = (E_0/B_0)/a\nu_t\). Here \(\nu_t\) strongly depends on the electron temperature which is low in the off-resonance and high in the resonance condition of UHR or ECR. On the other hand, the high-density uniform distribution filling the half volume of the torus has been observed at high powers (see Fig. 1 of Ref. [4]) when the ECR zone is located slightly inward from the launcher window.

The model described in Sec. 6.2 assumes the uniform electron temperature. The local electron heating at the UHR or ECR layer may lead to the non-uniform \(T_e\) profile. However, the Langmuir probe measurements have not shown clear local heating in the present experiment and the previous reports [3-5], except observation of the UHR heating in the the port outside the torus geometry (see Fig. 1 in Ref. [4]). The rather flat \(T_e\) profiles can be explained as follows. As for the ECR heating, the power absorption occurs very sharply near the ECR point for relatively cold plasmas [7]. Hot electrons can not stay on the "resonant" magnetic field lines \((\Omega_e = \omega)\) for long time, but they are radially swept due to the \(E \times B\) drift, thus making the electron temperature profile flat. In case of the UHR heating [8], most of the low-power low-density experiments [3-5] show that the UHR condition is satisfied in a wide radial zone, and thus the heating is not localized.

6.4 Conclusion

The use of superconducting field coils in future fusion devices requires development of in-situ wall conditioning in a steady state magnetic field. As a promising alternative of dc glow discharge, microwave discharges can be applied to the wall conditioning in such environment. This paper presents the microwave plasma production in a purely toroidal magnetic field \(B\), focusing on the radial distribution of plasma density. Taking account of a vertical electric field \(E\) caused by VB- and curvature drift, the plasma density distribution is analyzed in two fluid model.

The analysis reveals that the radial profile of plasma density is determined by two parameters. One is \(P = (EB)/a\nu_t\) which is a ratio of the ionization time \((1/\nu_t)\) to the \(E \times B\) drift time for the minor radius \(a\). The other is \(Q = D/a^2\nu_t\) which is a ratio of the ionization time to the cross-field diffusion time. For large values of \(P (>= 1)\), the density distribution is relatively uniform. For smaller \(P\), however, the plasma density dramatically increases along the major radius due to the smaller \(E \times B\) drift toward the outer wall.

The basic experiments in a simple magnetized torus, TOMAS, support the radial density profile predicted in this model. Namely, two types of the radial density profiles were observed. One is a relatively uniform profile which is characterized with the lower \(T_e\) (smaller \(\nu_t\)), thus giving the large \(P\) \((>= 1)\). The other is the outward increasing profile which has the higher \(T_e\) (large \(\nu_t\)), and the small \(P\) \((<= 1)\). It is notable that the plasma density always starts to increase from the ECR point, owing to the efficient ECR heating. However, the electron temperature does not show the profile strongly localized around the ECR point, due to the outward \(E \times B\) drift. The local heating may take place in large fusion devices \((a >> \lambda_0; \text{free space wavelength})\) for superconducting high magnetic fields \((30-100\text{ GHz}, \lambda_0 < 10\text{ mm})\).

Finally, it should be pointed out that the essentially
same types of plasma density profile will be observed in ion cyclotron resonance heating discharges in a simple magnetized torus for the wall heating.

Acknowledgements

This work has been carried out under the TEXTOR-Japan Collaborative Research Program. The authors would like to thank those who have taken care of this program, especially Dr. N. Noda in the Japanese side and Dr. V. Philipp in the IPP FZ-Jülich side.

References

プロントトリデポジション（その場再付着）

Prompt Redeposition

磁気繊維型核融合装置において、スッパリングなどによりプラズマを対向壁から放出された粒子がその前面のプラズマで直ちにイオン化され、繊維によるラーモラ運動を介して放出点近傍に再付着する現象のことである。特に、イオン化距離が短く、ラーモラ半径の大きい高 Z (原子番号) 原子に対して観察され、対向壁から周辺プラズマに侵入する高 Z 原子が 1 桁程度少なくなる。ASDEX-U, TEXTOR, DIII-D トカマクなどの実験におけるこの現象の実証実験が、近年、タングステンなどの高融点金属材料をプラズマ対向材として見直すきっかけとなった。

単心プラズマへの不純物の侵入を抑制するだけでなく、高粒子数プラズマにさらされる対向壁（ダイバータ板やリミク）の実質的な損耗量を小さくする効果がある。このため、国際熱核融合実験炉 ITR の設計において、ダイバータ内の垂直ターゲットの部分をすべてタングステンで構成することが検討されている。原子番号が小さい炭素材料の物理スッパリングに対してはこの効果が小さいが、化学スッパリングにより放出された熱エネルギー鉄化素分子に対してもその影響が大きいと考えられ、最近、その詳細が実験と計算機シミュレーションにより調べられている。

ITR のデータケージダイバータの特性、特に垂直面のプラズマ温度が物理スッパリングの起こらない数 V 程度に押さえられる場合には、垂直ターゲット材として考えられている炭素材料 (CFC) の実質の寿命も、prompt redeposition よりかなり長くなることが期待される。（村島大工 大宅 薫）

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単純トーラス Simple Magnetized Torus

回転変換をもたない、純粋にトポロジーが原因であるような磁場をいえる。この磁場 B の大きさの半径方向に減少し、磁力線は主半径方向の曲率をもっている。そのため、磁力線に巻きついて回転する荷電粒子は、垂直上方方向に VB ドリフトと曲率ドリフトを起こす。このドリフトの向きは電荷の符号によって逆、例えばイオンが上方にドリフトすると、電子は下方にドリフトし、トポイダルプラズマの上部下部に電荷が分離して帯電する。その結果として垂直電場 E が発生し、半径方向 (外向き) に E × B ドリフトが起こる。このドリフトは電荷の符号によらないから、プラズマ全体として外向きに移動して容器壁に当たって消失してしまうが、それで、磁力線をポロイダル方向に分けて回転変換を与え、磁力線を磁気においてつなぎ合わせることにより、分離した電荷を磁力線に沿って移動し、垂直電界を消すことがトポイダルプラズマ保持の基本的な考え方である。

（名大工 庄司多津男）