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Electron cyclotron resonance negative ion source

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Production and control of electron cyclotron resonance (ECR) plasmas for negative ion sources have been studied. A new production method using permanent magnets is proposed as one possibility for a large diameter high density uniform microwave plasma. The microwave power is launched by an annular slot antenna into the circumference of a chamber with a line-cusp or a ring-cusp type permanent magnets, where magnetic field can be applied in a local region and plasmas can be efficiently produced if the ECR condition is satisfied. In this article, we report the structure of the ECR negative ion source, the characteristics of the ECR plasmas, and comparison of the ECR plasmas with dc discharge plasmas from the viewpoint of a negative ion source for neutral beam injector. H^- volume production is confirmed in ECR plasmas although the effect of the magnetic filter for controlling plasma parameters is different from that in dc discharge plasmas. © *2000 American Institute of Physics.* [S0034-6748(00)63102-7]

I. INTRODUCTION

In the design of a neutral beam injection (NBI) system for future large experimental fusion devices, such as the International Thermonuclear Experimental Reactor (ITER), the use of a deuterium negative ion source with an energy of 1 MeV is proposed. In the present negative ion sources of NBI systems, the source plasma is generated by dc arc discharge where hot filaments act as a cathode. The lifetime of the ion source is limited to several hundred hours due to erosion and fatigue of the cathode filaments and damage to the filaments by anomalous arc discharge. In future fusion reactors, the device materials will become radioactive due to irradiation of neutrons yielded by the fusion reaction, and accessibility of the device will be extremely limited. In addition contamination of the plasma source by evaporated filament materials could also be a problem in cesium-seeded operation of the negative ion source. Thus, a long-lifetime ion source is required for future NBI systems. A microwave-discharge ion source[1,2] and an rf-driven ion source[3,4] are promising as long-lifetime ion sources because they have no filaments.

In the present work, a new production method using permanent magnets is proposed as one possibility for generating a large-diameter high-density uniform microwave plasma.[5,6] The microwave power is launched into the circumference of a chamber by an annular slot antenna and the magnetic field of both a ring-cusp-type and a line-cusp-type permanent magnets. The advantages of using permanent magnets are that the magnetic field can be applied in a local region, where plasmas can be efficiently generated if the electron cyclotron resonance (ECR) condition is satisfied, and that an almost magnetic-field-free condition can be achieved on the extraction grid.[2]

In this article, we report the structure of the ECR discharge negative ion source, the characteristics of the ECR plasmas,[6–8] and the results of negative ion extraction.[6] Comparison of two type ECR plasmas with dc discharge plasmas, from the viewpoint of the magnetic filter effect, is also briefly discussed.

II. CONCEPT OF THE ECR PLASMA SOURCE

A schematic diagram of the ECR hydrogen negative ion source is shown in Fig. 1. The plasma source chamber (210 mm in diameter and 300 mm in length) made of stainless steel is a conventional multicusp volume source equipped with both a magnetic filter (set at $z=20\,\mathrm{cm}$) and a plasma grid (set at $z=22\,\mathrm{cm}$).

We test the two types of magnetic field structure for the ECR field.

Case I. The microwave power (2.45 GHz, 100–600 W) is transferred to the annular slot antenna[5] through a coaxial waveguide, and launched from the antenna into the circumference of the cylindrical vacuum source chamber (210 mm in diameter and 300 mm in length) through a fused silica plate window (30 mm in thickness). The width of the annular slot is 20 mm (the outer and the inner diameters are 200 and 160 mm, respectively). Namely, the microwave power is launched directly into the source chamber through the fused silica plate window, as shown in Fig. 1. Twelve columns of samarium–cobalt permanent magnets are located just outside the source chamber. In this case, the line cusp of permanent magnets provides both the resonance magnetic flux density of 875 G for 2.45 GHz inside the chamber (i.e., the annular region 10–15 mm from the chamber wall) and confinement of the produced plasmas.

Case II. The microwave circuit system is the same as that in Case I. The ring-cusp samarium–cobalt permanent magnets are located[5] just outside the chamber with facing same polarities at a separation of 4 mm, as shown in Fig. 2. These permanent magnets provide the resonance magnetic

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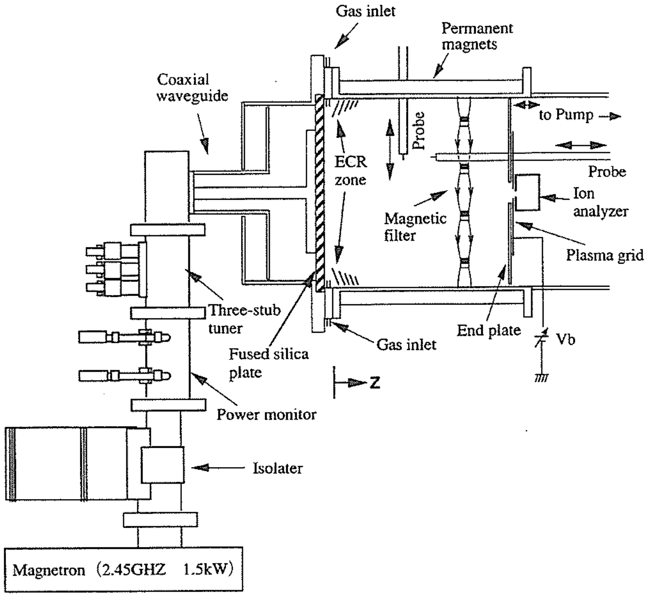

FIG. 1. Schematic diagram of the ECR negative ion source with the line-cusp resonance magnet.

flux density of 875 G for 2.45 GHz inside the chamber, i.e., the annular region 15–20 mm from the chamber wall.

In both cases, plasma parameters are measured using two Langmuir probes movable in axial and radial directions. The right end plate, i.e., the plasma grid, has a single hole (5 mm diameter) through which negative ions are extracted from the source. A Faraday cup with a separation magnet is used for measurement of the extracted H^- current.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. dc plasmas

To show the characteristics of the source plasma produced by dc discharge, instead of the microwave launcher and the silica window shown in Fig. 1, a filament flange is set in the source chamber.

H^- ions are generated by the dissociative attachment of slow plasma electrons ($T_e \sim 1$ eV) to highly vibrationally excited hydrogen molecules, $H_2(v'' \geqq 5-6)$. These $H_2(v'')$ are primarily produced by collisional excitation of fast electrons with energies in excess of 20–30 eV.[9,10] Usually, the H^- production like this is called the two-step volume production. With the use of a magnetic filter, the electron energy distribution function in dc discharge plasmas is well controlled for the two-step process of H^- formation. With increasing discharge power, the extracted H^- current increases linearly[6] as shown in Fig. 4.

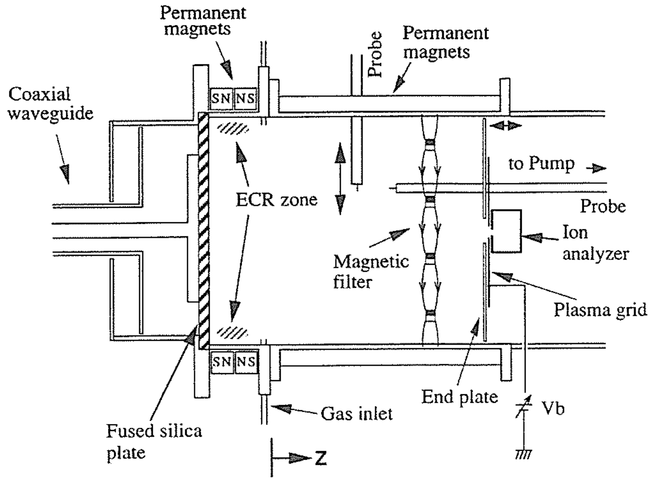

FIG. 2. Schematic diagram of the ECR negative ion source with the ring-cusp resonance magnet.

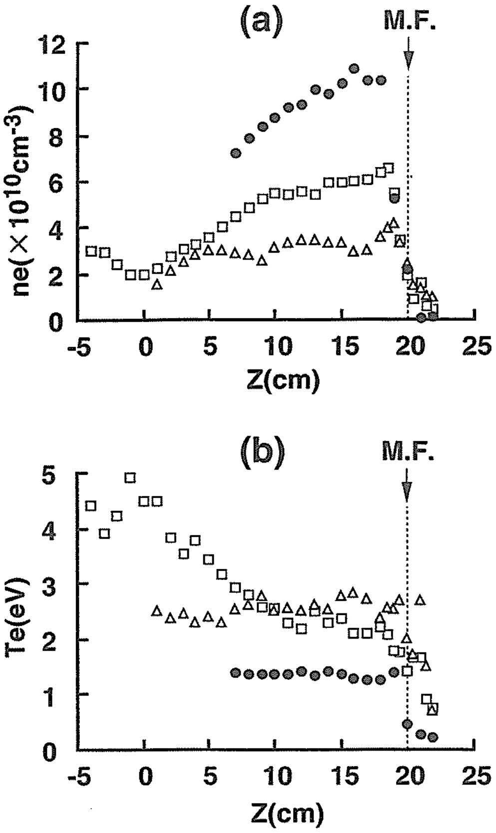

FIG. 3. Axial distribution of plasma parameters in dc discharge plasma and ECR discharge plasmas: (a) electron density n_e, (b) electron temperature T_e. Experimental conditions of dc plasmas are discharge voltage $V_d = 80$ V, discharge current $I_d = 3$ A (●), and hydrogen gas pressure $p(H_2) = 2$ mTorr. For ECR plasmas, microwave power $P\mu = 450$ W and $p(H_2) = 3$ mTorr in the line-cusp case (△). In the ring-cusp case (□), $P\mu = 600$ W and $p(H_2) = 2$ mTorr M.F. indicates the position of the magnetic filter. End plate is set at $z = 22$ cm.

B. ECR plasmas

On production of ECR plasmas, we reported some results elsewhere.[7,8] With increasing microwave power P_μ, both n_e and T_e increase. P_μ is estimated as $(P_f - P_r)$, where P_f is the power of the forward-moving wave and P_r is the power of the reflected wave. With increasing hydrogen gas pressure $p(H_2)$,n_e increases and T_e decreases. These features of plasma parameters are nearly the same as those in dc plasmas, except that n_e in ECR plasmas is lower than that in dc plasmas.

Next, we discuss the axial distribution of plasma parameters (n_e and T_e), i.e., the effect of the magnetic filter. Figure 3 shows a typical example of axial distributions of n_e and T_e. For reference, n_e and T_e in dc plasmas are also plotted by closed circles. As a whole, n_e in ECR plasmas are lower

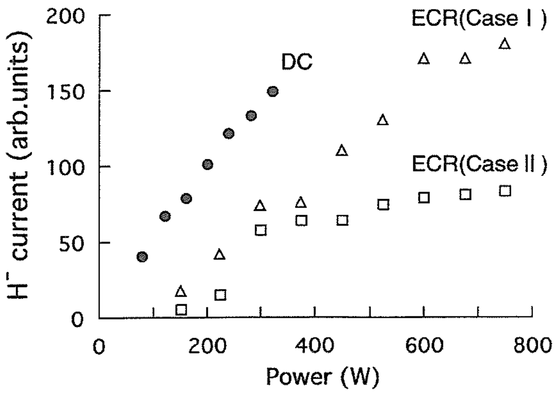

FIG. 4. Extracted H$^-$ currents, corresponding to the plasma parameters in Figs. 5 and 6, vs $P\mu$. Extraction voltage $V_{ex}=600$ V. For reference, extracted H$^-$ current in dc plasmas is also plotted as a function of discharge power. Experimental conditions in dc discharge are $V_d=80$ V, $p(H_2)=2$ mTorr and I_d is varied from 1 to 4 A. In the line-cusp case (△), $p(H_2)=3$ mTorr and in the ring-cusp case (□), $p(H_2)=1.2$ mTorr. In dc plasma experiment, the plasma grid has a single hole with 10 mm diameter, different from the experiment with ECR plasma (5 mm diameter).

than n_e in dc plasmas. Concerning T_e, in the source region ($z=0-20$ cm), T_e is a nearly constant value although, in the resonance region of the ring-cusp case (case II) (i.e., permanent magnets for ECR is set at $z=-4.5$ cm and $z=-2$ cm), T_e is high and decreases markedly along the axial direction. As clearly shown, however, T_e in both ECR cases does not decrease or change markedly across the magnetic filter, unlike T_e in dc plasmas. Namely, T_e in the extraction region is rather high. Therefore, the dissociative attachment process (H$^-$ formation) is not controlled well compared with dc plasmas, and thus the extracted H$^-$ current may also become small.

Now, we discuss H$^-$ production in the present ECR plasmas.

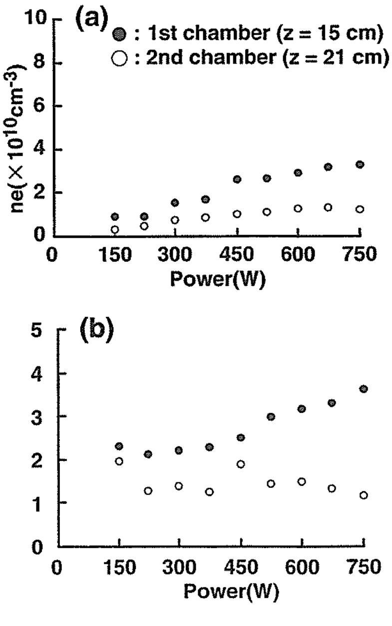

FIG. 5. Parameters of ECR plasmas (case I) as a function of microwave power $P\mu$: (a) n_e, (b) T_e. Parameters in the source region (filled symbols) and those in the extraction region (open symbols) were measured at $z=15$ and 21 cm, respectively. $p(H_2)=3$ mTorr.

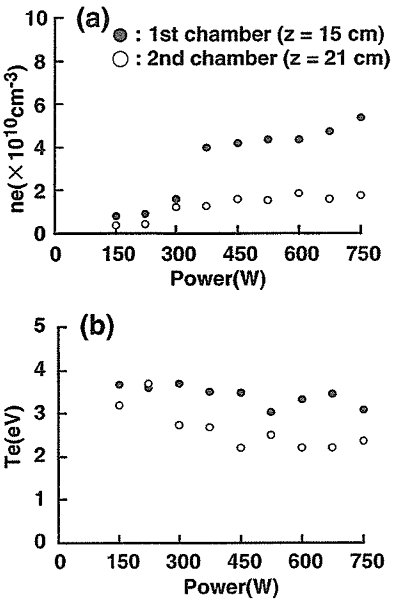

FIG. 6. Parameters of ECR plasmas (case II) as a function of $P\mu$: (a) n_e, (b) T_e. Experimental conditions are the same as the ones in Fig. 5 except that $p(H_2)=1.2$ mTorr.

Figure 4 shows the dependence of extracted H$^-$ currents on $P\mu$, where extraction voltage $V_{ex}=600$ V. For reference, the H$^-$ current in dc plasma is also plotted. The H$^-$ currents in dc plasma is higher than those in ECR plasmas. According to the results shown in Fig. 3, for H$^-$ production, T_e and n_e of ECR plasmas in the second chamber are not controlled well by the magnetic filter. In addition, plasma production efficiency, and also production of fast electrons, are not necessarily high compared with dc plasma production. Therefore, the optimization of plasma parameters for the H$^-$ production is under study.

In Fig. 4, with increasing $P\mu$, the H$^-$ current in the line-cusp case (case I) is becoming higher than that in the ring-cusp case (case II). Figures 5 and 6 show the plasma parameters (n_e and T_e) in the first chamber (the source region) and the second chamber (the extraction region), corresponding to the H$^-$ currents in Fig. 4, as a function of $P\mu$. They are measured at $z=15$ cm in the source region and $z=21$ cm in the extraction region, where the plasma grid is set at $z=22$ cm. According to the plasma parameters shown in Figs. 3, 5 and 6, n_e in case I is lower than n_e in case II, and there is no clear difference in T between the two cases. Namely, concerning plasma production (i.e., values of n_e and T_e, pressure and $P\mu$ dependencies of n_e and T_e), case II has nearly the same characteristics as case I. However, for the H$^-$ production, plasma parameters in case I are more optimized. Key parameters for the H$^-$ production are the number of fast electrons, $H_2(v'')$ and T_e. Therefore, to optimize the production of fast electrons, and thus $H_2(v'')$, permanent magnet arrangements and antenna locations are important.[6]

The role of the magnetic filter (i.e., preferential reflection of high-energy electrons) is not well clarified although it is widely used to reduce T_e. In the proposed model,[11,12] the fluctuating field **E** plays an important role, and **E** in dc plasmas should be different from that in ECR plasmas. Thus, our model can account for the difference in the magnetic filter effect in controlling plasma parameters between dc plasmas and ECR plasmas. This point is now under study.

IV. CONCLUSIONS

We have designed a new ECR plasma source for NBI systems. ECR hydrogen plasmas are well produced, although n_e is lower than that in dc plasmas. We have confirmed that the H^- volume production in ECR plasmas is obtained, and that the effect of the magnetic filter is different from that in dc plasmas. In the future, the production of high-density ECR plasma, the optimization of plasma parameters for the H^- volume production, the effect of a magnetic filter, and the extraction of H^- ions will be studied.

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