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RECENT PROGRESS IN THE PILOT GAMMA PDX-SC SUPERCONDUCTING MIRROR

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Abstract

A superconducting mirror Pilot GAMMA PDX-SC was constructed to contribute to the DEMO divertor study. Ion cyclotron heating (ICH) and electron cyclotron heating (ECH) systems have been developed. The plasma heating experiments were carried out in a DC arc discharge plasma using these heating systems. The electron density decreased due to ICH, and it increased due to ECH. The electron temperature increased significantly during ICH but remained almost unchanged during ECH. An ion-sensitive probe indicated that the ICRF power produced high-energy ions when an ICRF wave with a frequency of 1.8 MHz and a power of 160 kW was applied to plasma sustained by a DC arc plasma source. The spectral fluctuation intensity in the frequency band around 0.75 MHz decreased as the voltage applied to the outer bias plate at the east end of the main chamber increased.

1. INTRODUCTION

Power and particle handling in the divertor is one of the most critical issues for DEMO [1, 2]. Even though most of the fusion power is dissipated as radiation, the heat flux to the divertor is still significantly large. Plasma detachment is necessary to reduce the heat flux below the allowable level and understanding the atomic and molecular processes that lead to plasma detachment is crucial. It is essential to simulate the DEMO divertor accurately. The following parameters seem to be necessary for DEMO divertor simulation: the plasma density is $\sim 10^{20}$ m^{-3}, ion and electron temperatures are ~100 eV, and the magnetic field is a few T. Linear plasma devices can contribute to DEMO divertor simulation and PWI issues for their high flexibility of experiments. In the GAMMA 10/PDX tandem mirror device, divertor simulation studies have been extensively done using end-loss plasma, whose temperature is comparable to that of the SOL plasma of DEMO [3-5]. At the Plasma Research Center at University of Tsukuba, moreover, the superconducting (SC) mirror Pilot GAMMA PDX-SC (PGX-SC) was constructed for the DEMO divertor study. The target plasma parameters are as follows: plasma density 10^{19} m^{-3}, electron and ion temperatures several tens of eV, and discharge duration 10 − 100 s. We have been developing ICH and ECH systems and diagnostics. The paper describes recent results from PGX-SC experiments.

2. EXPERIMENTAL DEVICE

Figure 1 shows a schematic drawing of PGX-SC. The inner diameter of the main chamber is ~ 1.15 m. A pair of NbTi SC coils with a bore diameter of 0.9 m is installed on both sides of the main chamber to produce a simple mirror configuration. The distance between the SC coils is 4.3 m. A pair of Cu coils with a bore diameter of ~1.5 m is installed near the midplane. The maximum magnetic field B_{max} is 1.5 T, and the mirror ratio is 30 without the Cu coils and ~20 with them. The main chamber and differential pumping chamber are pumped by turbomolecular pumps with the pumping speeds of 5,400 L/s and 2,700 L/s for hydrogen gas, respectively.

One of the features of PGX-SC is that steady-state plasma is supplied from a plasma source installed at the east end region to the main chamber, and it is heated by ICH and ECH. A DC arc plasma source and a helicon plasma source have been developed for high-density and large-diameter plasma production. For the DC arc plasma source, a large-diameter LaB_6 cathode (ϕ = 150 mm) is used and is being developed to increase the cathode temperature and discharge current. The electron density of more than 1 x 10^{19} m^{-3} was obtained at the mirror throat under the conditions: the discharge voltage of 300 V and the discharge current of 40A. As for the helicon plasma source, 13.56 MHz waves generated by a two-turn flat loop antenna with outer and inner loop diameters of 10 cm and 5.5 cm are injected through a quartz window into the differential pumping chamber to produce high-density plasma [6]. The electron density of 3 x 10^{18} m^{-3} was obtained at RF power of 18 kW at the mirror throat. The neutral gas used for the plasma source is primarily pumped through a differential pumping chamber located between the plasma source and the main chamber.

Regarding the electron cyclotron heating (ECH), a 28 GHz gyrotron is used for second harmonic heating. The 28 GHz microwaves are transferred from the gyrotron through corrugated waveguides, miter bends, and a vacuum window to the main chamber. Microwaves emitted from an open-ended corrugated waveguide are reflected by an antenna mirror and reach the position of second harmonic resonance at Z = 1.54 m (B = 0.5 T). The vacuum window (ECH port) is located at the west end of the main chamber as shown in Fig. 1. The ECH duration is restricted due to the influence of the magnetic field leaking from the superconducting coil of PGX-SC on the gyrotron tube. Improvements have been achieved through the use of magnetic shielding around the gyrotron tube, enabling longer ECH heating.

A double half-turn antenna is installed at Z = 1.1 m for the ion cyclotron heating (ICH). A Faraday shield is installed around the antenna. Plasma-facing surfaces of the Faraday shield and the antenna are tapered along the magnetic field lines. ICRF differential-frequency (DF) wave heating [7, 8] is planned to heat the high-density plasma. The beach heating with a slow wave is popular in the mirror device, but it cannot be applied to high-density plasma. So, a DF wave between two fast waves, which can propagate into a high-density core plasma, is a good candidate for high-density heating. We plan to install three antennas for the DF heating eventually.

Three concentric plates are installed at the east end of the main chamber. The inner radii of the inner, middle, and outer plates are ϕ70 mm, ϕ100 mm, and ϕ130 mm, respectively. The width of each plate is 15 mm. The step difference in the Z-direction between each plate is 20 mm. Each plate is biased, grounded, or floating.

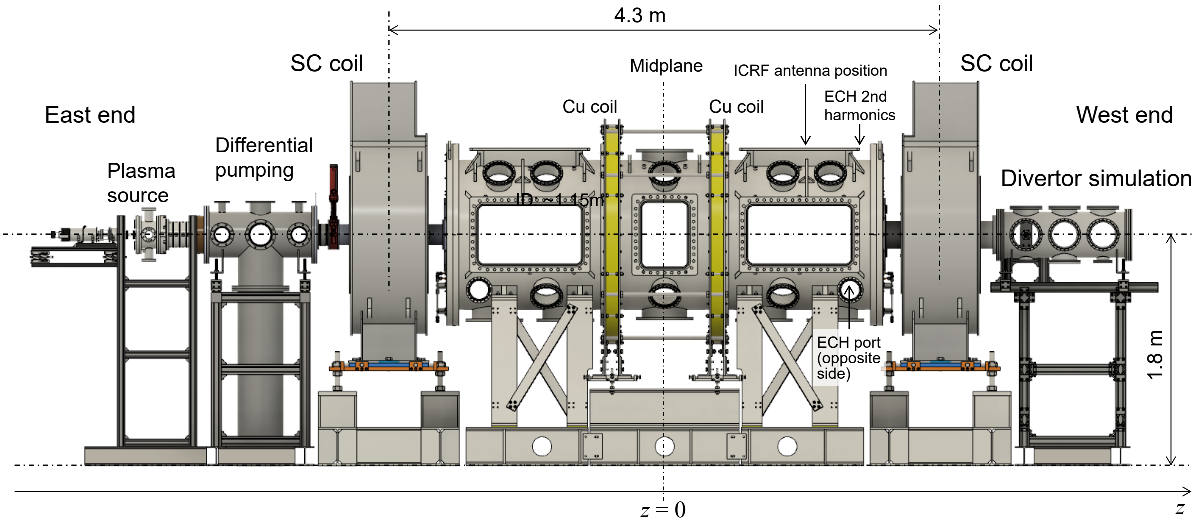

FIG. 1. Schematic drawing of Pilot GAMMA PDX-SC (PGX-SC).

3. EXPERIMENTAL RESULTS

Figure 2 shows the time evolution of the line electron density of the hydrogen plasma that was produced by a DC arc discharge and heated by ICH and ECH. The discharge current was 16 A. The frequency and power of ICH were 1.8 MHz and ~180 kW. The resonance position of the ion cyclotron frequency of 1.8 MHz is Z = 0.904 m. The ECH power was ~240 kW at the MOU outlet. The neutral pressure inside the main chamber was ~4 x 10^{-2} Pa, and it was relatively high due to the supply of hydrogen gas (600 sccm) for the DC arc discharge. The density decreased by about 30 % due to ICH, and it recovered to the original level due to ECH as shown in Fig. 2(a). On the other hand, the density increased by about 70 % due to ECH, and it decreased to the original level as shown in Fig. 2(b).

Figure 3 shows the spatial distributions of H_α intensity during the DC arc discharge plasma (DC), ICH (DC+ICH), ICH following ECH (DC+ICH+ECH), shown in Fig. 2(a), and ECH (DC+ECH), ECH following ICH (DC+ECH+ICH), shown in Fig. 2(b). Regarding the DC arc discharge plasma without heating, it flowed into the main chamber from the east end region and expanded toward the Faraday shield position due to the radial diffusion. On the other hand, the plasma was present in the shadow region of the Faraday shield during ICH and ECH, indicating that plasma was produced there by ICH and ECH. It is important to note that despite the plasma appearing to be thicker in Fig. 3, the line electron density decreased due to ICH as shown in Fig. 2(a). Identifying the cause remains a subject for future research.

As shown in Fig.4, a single-probe measurement shows that the electron density decreased during ICH, consistent with the results shown in Fig. 2. The electron temperature increased significantly during ICH. On the other hand, ECH did not increase the electron temperature, but the electron density increased during ECH.

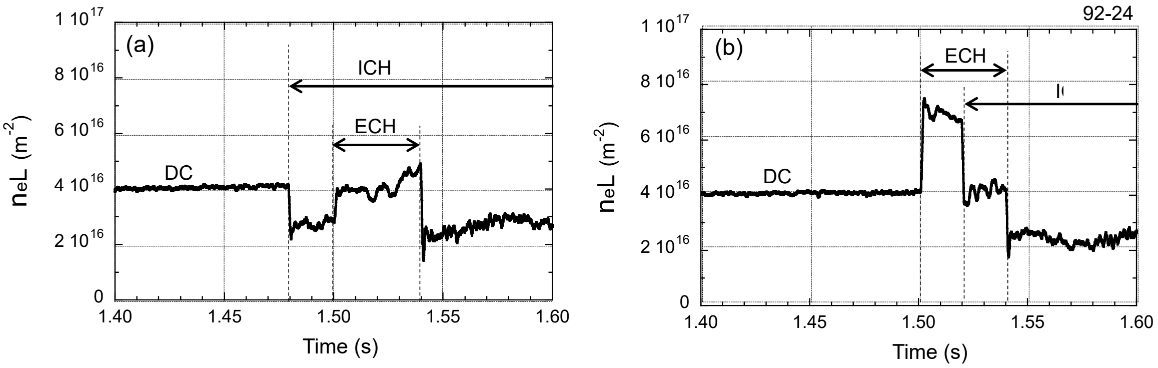

FIG.2 Time evolution of line density of (a) ICH to plasma sustained by DC arc discharge following ECH and (b) ECH to plasma sustained by DC arc discharge following ICH. The measurement position is Z = -0.92 m.

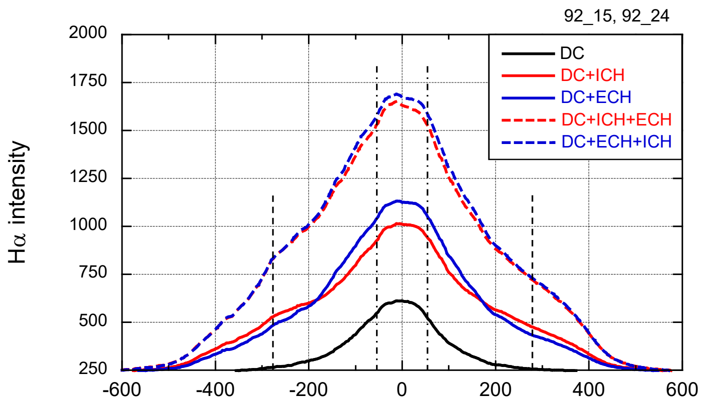

FIG.3 Spatial distributions of the H_α intensity at Z = 0.12 m. The horizontal axis indicates the radius projected onto the midplane at Z = 0. The dash-dotted lines indicate the position corresponding to the outer periphery of the cathode of the DC plasma source. The dashed lines indicate the position corresponding to the Faraday shield.

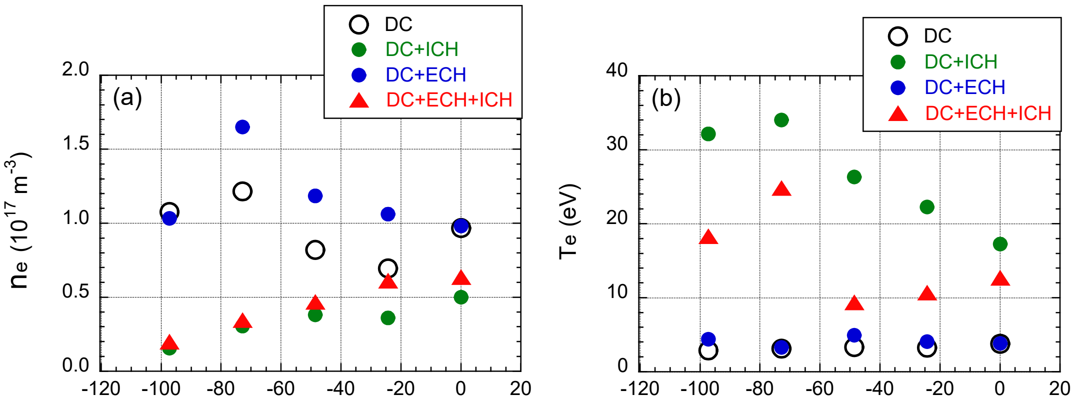

FIG.4 Radial distributions of (a) electron density and (b) electron temperature measured at Z = 1.9 m by a single probe. The horizontal axis indicates the radius projected onto the midplane at Z = 0.

Figure 5 shows results obtained with an ion-sensitive probe (ISP) installed at Z = 1.9 m. An ICRF wave with a frequency of 1.8 MHz and a power of 160 kW was applied to plasma sustained by a DC arc discharge. The plasma density at Z = 0.92 m was 3.4 x 10^{17} m^{-3}. The guard current (i.e., electron current) and the collector current (i.e., ion current) were increased by the ICH power. As shown in Fig. 5(d), collector current-voltage characteristics indicate that the ICH power produces high-energy ions. Preliminary analysis shows the ion temperatures before and during ICRF heating are 9 eV and 21 eV, respectively. Although the electron density was low in this experiment, the effect of beach heating may be confirmed. The next step is to work on increasing the density.

To cope with MHD instability, three concentric electrodes are installed at the east end of the main chamber to apply a method of vortex confinement aiming to suppress the growth of flute instability [9]. In this experiment, a voltage of 50 V was applied to the inner plate, while the middle plate was grounded. The voltage applied to the outer plate was varied from 0 to 100 V. Figure 5 (d) shows the spectral fluctuation intensity in the frequency band around 0.75 MHz. It decreased as the bias voltage of the outer plate increased. In another experiment, when 250 V was applied to the outer electrode and the middle and inner electrodes were grounded and floating, respectively, the fluctuation during ICH was reduced.

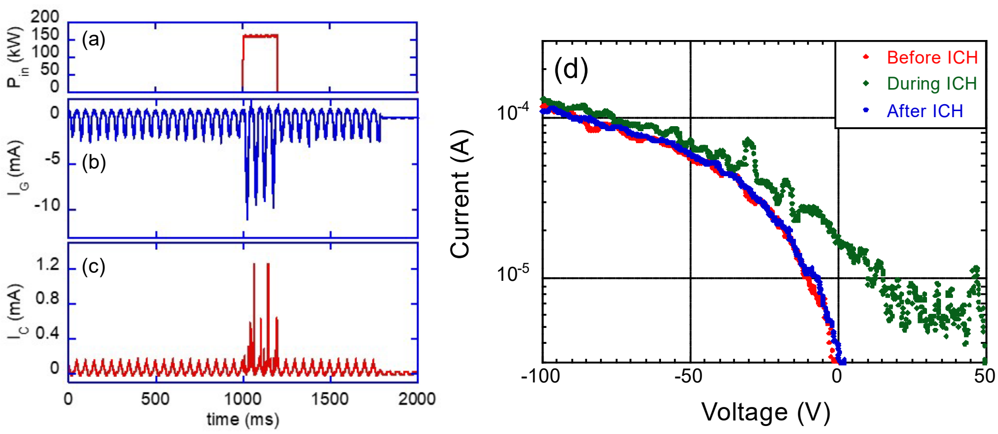

FIG. 5 Time evolution of (a) ICRF power, (b) guard current, and (c) collector current of ISP. (d) collector current as a function of applied voltage.

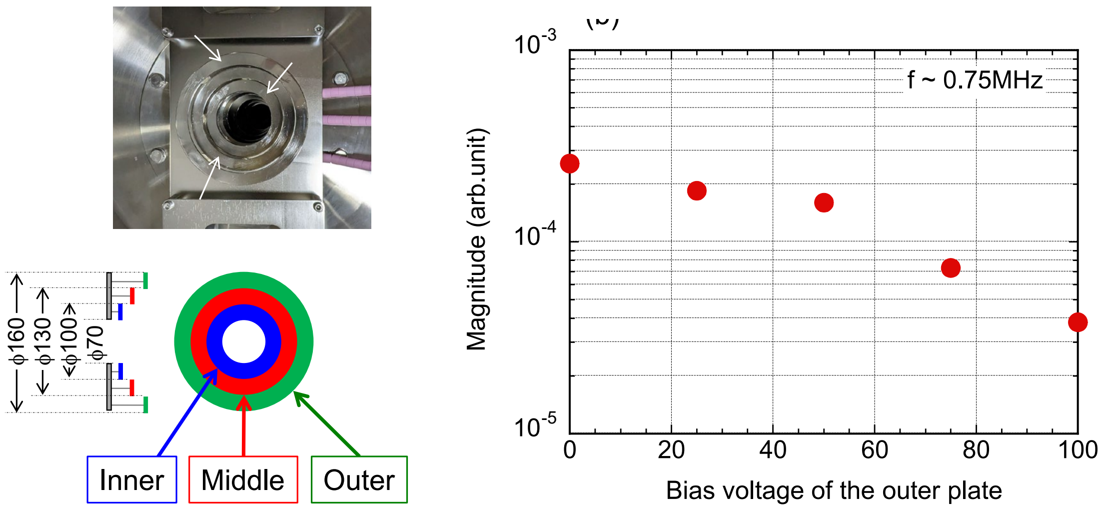

FIG. 6 (a) Arrangement of three concentric biasing plates that are installed at the east end of the main chamber. (b) Spectral fluctuation intensity in the frequency band around 0.75 MHz.

4. SUMMARY

The superconducting mirror PGX-SC has been developed to study divertor simulation for DEMO. One of the features of PGX-SC is that steady-state plasma is supplied from a plasma source to the main chamber. A DC arc plasma source and a helicon plasma source have been developed, and the electron densities of more than 1 x 10^{19} m^{-3} and 3 x 10^{18} m^{-3} were obtained at the mirror throat, respectively. Plasma heating experiments were carried out using ICH and ECH systems. The electron density decreased by approximately 30% due to ICH and recovered to the original level due to ECH when ICH and ECH powers were ~180 kW and ~240 kW, respectively. The electron temperature increased significantly during ICH but remained almost unchanged during ECH. An ion-sensitive probe indicated that the ICRF power produced high-energy ions when an ICRF wave with a power of 160 kW was applied to plasma sustained by a DC arc plasma source. The plasma that flowed from the plasma source to the main chamber expanded toward the Faraday shield position due to the radial diffusion. Besides, the plasma was present in the shadow region of the Faraday shield during ICH and ECH, indicating that plasma was produced there by ICH and ECH. The spectral fluctuation intensity in the frequency band around 0.75 MHz decreased as the voltage applied to the outer bias plate at the east end of the main chamber increased.

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