HIGH POWER ECH EXPERIMENTS FOR DIRECT BULK ELECTRON HEATING IN CENTRAL-CELL REGION PLASMAS ON GAMMA 10 TANDEM MIRROR

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High power electron cyclotron heating (ECH) experiment for the central-cell region in GAMMA 10 has been started in the hot ion mode operation (T_i=several keV). Transmission system for the central-cell ECH, including a taper, mirrors and polarizers, has been designed and installed for efficient direct bulk electron heating. ECH system with a twister and a circular polarizer for central-cell region has the advantages for controllable polarization of incident wave. Recently, a high power gyrotron of ~500 kW at 28 GHz has been developed in collaboration with Japan Atomic Energy Agency (JAEA) and this high power gyrotron was installed in central-cell region of GAMMA 10. This high power and efficient ECH system was applied to central-cell electron heating and significant increment of soft X-ray and diamagnetism signals during a pulse of ECH operation was obtained. In this paper, central ECH experimental results in the hot ion mode operation are reported.

I. INTRODUCTION

Electron cyclotron heating (ECH) is a promising way to heat magnetically confined plasmas. Besides the plasma heating, ECH has been recognized as a useful tool for plasma production, current drive, plasma profile modification, magnetohydrodynamics control, and transport study[1]. Particularly, in the GAMMA 10 tandem mirror, ECH is recognized as a primary scheme to produce plasma-confining potentials.

In the central cell region of GAMMA 10, ion cyclotron range of frequency (ICRF) heating effectively operates and the ion temperature, T_i, increases up to several keV in the hot ion mode and several hundred eV in the high potential mode. The bulk electron temperature, T_e, in the central cell is less than 100 eV in both modes. Thus, T_i is much larger than T_e and heated ions are cooled down through collisions with cold electrons, which is called electron drag. Therefore, increasing T_e in the central cell is very important task in the GAMMA 10 experiments. With this objective, direct heating of bulk electrons with central-cell electron cyclotron heating (C-ECH) has started.

In the present ECH system in the central cell region, the resonance surface locates far from the antenna and the microwave beam is launched obliquely. Oblique launch of the electromagnetic wave to magnetized plasma demands specified elliptical polarization for high mode purity of ordinary or extraordinary waves.

In this paper, the characteristics properties of ECH system in the central cell region and C-ECH experimental results in the hot ion mode operation are reported.

II. EXPRIMENTAL APPARATUS

The C-ECH system with a 500 kW gyrotron is shown in Fig. 1.

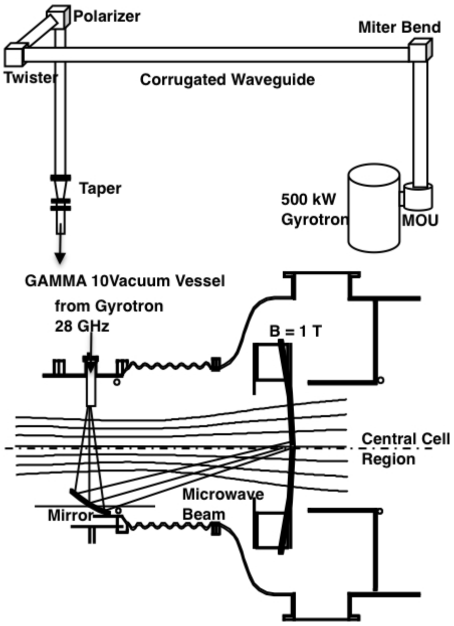

Fig.1 A schematic view of the C-ECH system composed of the outside transmission line (up) and the inside launcher (down).

The 500 kW gyrotron[2] has the diode gun to be able to put it on the previous main electric magnet with bore diameter of ϕ82 mm. The cavity mode is $TE_{4.2}$. The transmission line is composed of 2.5 inch corrugated waveguides, a miter bends, a twister, a polarizer, a taper and a vacuum window as shown in Fig.1.

Two mirror polarizers can generate all polarization in principle. One grooved mirror (polarizer) produces the elliptical polarization from the linear polarization using the phase difference of 90 degrees, the other mirror (twister) rotates the axis of polarization ellipse using the phase difference of 180 degrees. The groove depth of a polarizer and a twister are 2.90 mm and 1.98 mm. The linearly polarized incident wave which is outputted from a gyrotron window can be changed into the elliptically polarized reflected wave by the grating polarizer.

The mirror is set at the bottom of the vacuum vessel. It reflects and focuses the beam onto the resonance layer as show in Fig. 1. The shape of mirror is an ellipsoid to converge the beam onto the axis of the resonance surface with an axi-symmetrical profile. The design of mirror is optimized by the use of our electromagnetic (EM) code.

The transmission efficiency from the MOU to the antenna port is about 82%, which is measured by the water dummy load. The transmission efficiency of the taper is about 98% and that of the vacuum window is about 97%, which are evaluated by the low power test. The transmission efficiency of the microwave radiated from the open-end of the 45 mm waveguide to the resonance surface is about 88%, which is evaluated by the low power test.

Plasma experiments have been carried out in GAMMA 10, which is a minimum-B anchored tandem mirror with outboard axi-symmetric plug and barrier cells. GAMMA 10 has an axial length of 27 m, and the total volume of the vacuum vessel is 150 m^3. The central cell has a length of 6 m and a limiter with a diameter of 0.36 m, and the magnetic field intensity at the midplane is 0.405 T with mirror ratio of 5.2. Ion cyclotron heating system (ICH; 6.3 MHz, 200 kW) is employed for producing hot ions in the temperature range of 1-10 keV. Electron cyclotron heating systems (ECH; 28 GHz, 200 kW at barrier cells and 500 kW at plug and central cells) are prepared for producing plasma-confining potentials in the plug and barrier regions, and also for direct electron heating in the central cell[3,4].

III. EXPERIMENTAL RESULTS

Experiments for high power ECH in the central cell region are carried out by the use of a plasma discharge after the time of t=110 ms (Fig. 2).

During ECH in the central cell [between two dot-lines in Fig. 2], a increase of the diamagnetism DM_c appears in Fig. 2(a) accompanied by a increase of the soft x-ray intensity $I_{sx}l$ at the central-chord in central cell [Fig. 2(c)]. Also, the line density signal is gradually decreased during ECH injection [Fig. 2(b)]. The end loss electron current is increased during ECH injection [Fig. 2(d)], which is measured with a multi-gridded electrostatic energy spectrometer (LED). The pulse train of the electron current is due to sweep of the repeller voltage for energy analysis. Its envelope represents the electron current.

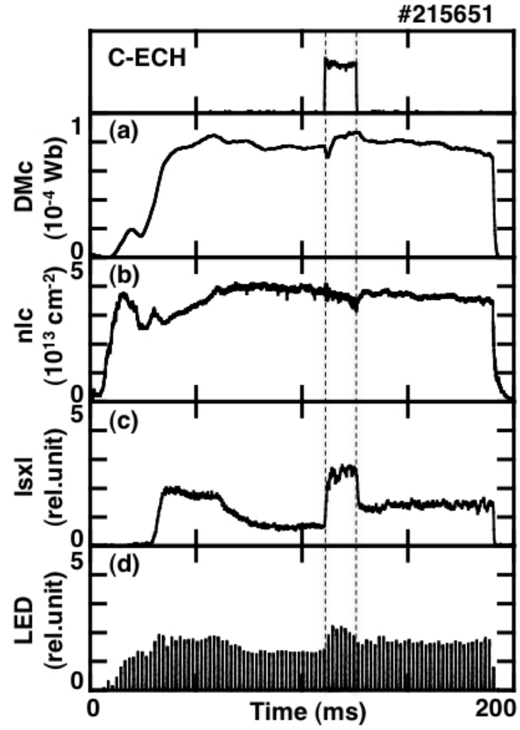

Fig.2 Temporal evolution of (a) diamagnetisms, (b) line density at the central-chord, (c) soft x-ray intensity at the central-chord and (d) end loss electron current at the west end. The output power of gyrotron is 150 kW.

In Fig. 2, the line density is not increased during C-ECH, thus it is considered that the electron density n_c is not increased in C-ECH. The diamagnetisms ($\propto n_c T_i$) is increased in C-ECH (about 10%) and soft x-ray intensity at the central-chord is also increased. Thus, these data indicate increases of not only the electron temperature but also the ion temperature due to the reduction of the electron drag.

Figure 3(a) shows the radial profiles of the soft x-ray intensity before (closed circles) and during (open circles) C-ECH injection, respectively. One can see a significant increase in the soft x-ray intensity due to the direct ECH in the central cell. The electron is strongly heated on the axis.

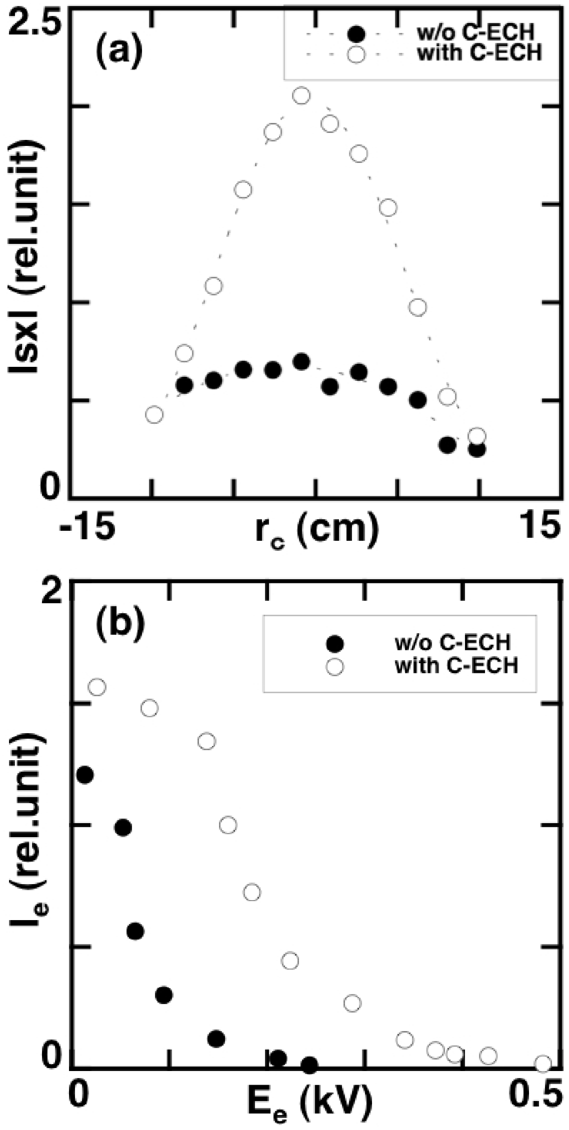

Fig.3 (a) Radial profiles of soft x-ray intensity and (b) end loss electron energy spectrum. In both data, closed circles and open circles correspond to before and during C-ECH injection.

Figure 3(b) shows the end loss electron energy spectrum measured by LED before (closed circles) and during (open circles) C-ECH injection, respectively.

The end loss electron energy is increased during C-ECH. Besides, one can see the electron current is increased overall energy region. These data indicate that the electrons in the central cell (which are the source of the end loss electrons) are effectively heated by the fundamental ECH.

Here, it is important to note the effects of polarization control of the incident wave in C-ECH. Above these results, the polarization of incident wave is X-mode dominant case. In this case, incident wave is enough absorbed in core plasma, so the absorption of the power of incident wave at the edge plasma is decreased. Thus, the core plasma is heated efficiently by ECH in central cell. On the other hand, in O-mode dominant case, most of plasma shots collapse during C-ECH. In this case, the incident wave is not enough absorbed in core plasma, so the absorption of the power of incident wave at the edge plasma is large. Thus, this non-axi-symmetric power deposit distribution induces radial transport of plasma and eventually leads to plasma disruption.

IV. CONCLUSIONS

High power electron cyclotron heating experiment for the central-cell region in GAMMA 10 has been started in the hot ion mode operation. The transmission system for the central-cell ECH has been designed and installed for efficient direct bulk electron heating. This high power and efficient ECH system was applied to central-cell electron heating and significant increment of soft x-ray and diamagnetism signals during a pulse of ECH operation has been obtained. These data indicate increases of not only the electron temperature but also the ion temperature due to the reduction of the electron drag.

ACKNOWLEDGMENTS

The authors would like to appreciate Prof. K. Sakamoto in the Japan Atomic Energy Agency, Prof. T. Saito and Y. Tatematsu in the University of Fukui, as well as the members of the GAMMA 10 group for their collaboration and valuable discussion. This work is partially supported by National Institute for Fusion Science (NIFS) Collaborative program (NIFS04KUGM009 and NIFS09KUGM032).

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