Development of High Power ECH Systems for High and ELM-like Heat Flux in GAMMA 10 Tandem Mirror*)

Ryutaro MINAMI, Tsuyoshi IMAI, Tsuyoshi KARIYA, Tomoharu NUMAKURA, Hidetaka NAKABAYASHI, Taku EGUCHI, Ryo KAWARASAKI, Kazuhiro NAKAZAWA, Yoichi ENDO, Mafumi HIRATA, Makoto ICHIMURA, Ryuya IKEZOE, Isao KATANUMA, Junko KOHAGURA, Yousuke NAKASHIMA, Kensuke OKI, Mizuki SAKAMOTO, Masayuki YOSHIKAWA and GAMMA 10 Group

Plasma Research Center, University of Tsukuba, Tsukuba, Ibaraki 305-8577, Japan

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Development of high power gyrotrons and electron cyclotron heating (ECH) systems for the power modulation experiments in GAMMA 10 have been started in order to generate and control the high heat flux and to make the ELM (edge localized mode) like intermittent heat load pattern for divertor simulation studies. ECH for potential formation at the plug region (P-ECH) produces the electron flow with high energy along the magnetic filed line. From the power scaling of confining potential and electron flux in GAMMA 10, the higher ECH power generates the higher confinement potential and the higher electron flux. The peak heat-flux of more than 10 MW/m^2 has been obtained during the ECH injection within the available power of ECH. This value almost corresponds to the steady-state heat load of the divertor plate of ITER. However, we need substantial upgrade of the heating power to approach the ITER level ELM energy density. For this purpose, MW power gyrotrons at 28 GHz have been started and the development is undergoing efficiently in the ECH system upgrade program with the collaboration of Japan Atomic Energy Agency (JAEA).

Keywords: ECH power modulation, high heat flux, ELM, gyrotron, GAMMA 10 tandem mirror

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1. 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. Particularly, in the GAMMA 10 tandem mirror, ECH is recognized as a primary scheme to produce plasma-confining potentials.

In the GAMMA 10, fundamental ECH at the plug region (P-ECH) generates the axial ion confining potential ϕ_c. Experimental observation shows that ϕ_c increases with the P-ECH power, and no saturation has been observed as long as the electron density is kept at a certain level. The P-ECH drives a portion of the heated electrons into the loss cone and induces an intense axial flow of warm electrons. A portion of the axially flowing electrons is observed as end loss electrons.

The new program to simulate the divertor plasma which utilizes advantages of mirror plasma confinement device have been started, in addition to core confinement studies as the mainframe 6 year work plan [1]. Since the boundary plasma physics is the key to sustain the steady-state fusion reactor plasma, the divertor plasma control and plasma wall interaction are urgent issues for ITER and the fusion research. Making use of resources of GAMMA 10 device, we started the GAMMA 10/PDX project, where PDX denotes **P**otential control and **D**ivertor simulating e**X**periment. The divertor plasma simulator which makes use of high heat flux generated at the open end of the GAMMA 10 is called E-Divertor. It is relevant to the fusion reactor peripheral plasma. This is one of the uniqueness of the GAMMA 10 E-Divertor. The development of the high power 28 GHz gyrotron is major hardware efforts in GAMMA 10/PDX project.

In this paper, the empirical scaling of heat flux with P-ECH power is studied. In addition, the development of over-1 MW power gyrotron at 28 GHz for the new experiments to generate the high and ELM-like heat flux is reported under the assumption that the extension of scaling is valid.

2. Experimental Apparatus

The GAMMA 10 is the world largest tandem mirror device (full length of 27 m), featuring the MW level high power heating systems. The plasma confinement is achieved by a magnetic mirror configuration as well as

author's e-mail: minami@prc.tsukuba.ac.jp

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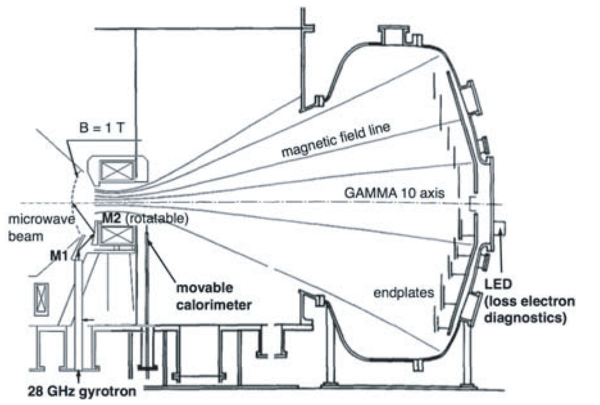

Fig. 1 Cross-section of the plug region and the end region. Microwave power is injected to the 1.0 T surface from the antenna. The LED is installed behind the innermost endplate.

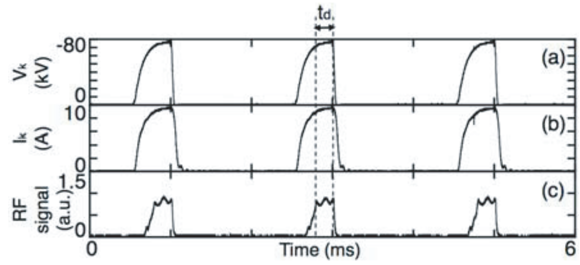

Fig. 2 The example waveform of the power modulation test. (a) V_k (b) I_k (c) RF signal refer to the acceleration voltage, the beam current and the diode signal corresponding to the output power, respectively.

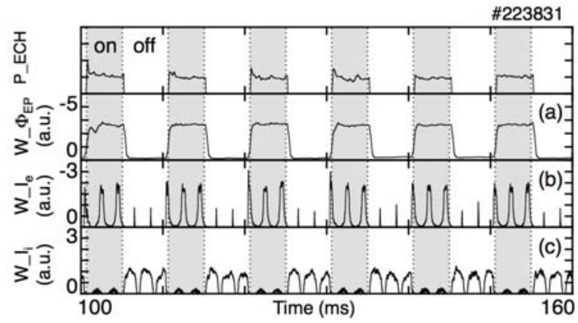

Fig. 3 Temporal evolution of (a) the end plate potential at the west end. The end loss (b) electron current and (c) ion current at the west end. The P-ECH power of about 300 kW is applied from t = 101 ms to 161 ms with 100%, 100 Hz square wave power modulation.

positive and negative potentials at the plug/barrier region formed by ECH. The main plasma confined in the central cell of GAMMA 10 is produced by ion cyclotron range of frequency (ICRF) wave. ECH systems (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 [2].

Figure 1 shows the P-ECH system and locations of the diagnostic systems used in the preliminary P-ECH modulation experiment to generate the high and ELM-like heat flux.

A gyrotron radiates a quasi-Gaussian beam from a output window. The radiated beam couples to the HE_{11} mode in the corrugated waveguide of 2.5 inch diameter through the Matching Optics Unit (MOU). The transmission line has two miter bends and it is connected to the GAMMA 10 vacuum vessel. In the vessel, a launcher composed of an open ended corrugated waveguide and two mirrors (M1 and M2) is installed. It radiated the microwave power to the resonance layer as shown in Fig. 1. The microwave beam is obliquely injected into the resonance surface at an angle of 54°. Power density profile on the resonance surface is well fitted to a Gaussian distribution with an e-folded radius of 62 mm. The mirror M2 can be rotated around the horizontal axis and can change the beam direction [3].

The heat flux is measured by the movable calorimeter. This diagnostics instrument is located at 30 cm downstream from the end-mirror coil and can be inserted from the bottom of the vacuum vessel up to the center axis of GAMMA 10.

The flux and the energy spectrum of the end loss electrons are measured by a multi-grid energy analyzer (loss electron diagnostics, LED). The LED is installed behind the end plate and it measures the end loss electrons through a small hole on the plate [4].

3. Experimental Results

In the ECH systems of the plug region, the present 500 kW gyrotrons adopt the diode gun to be able to put in on the existing main electric magnet with bore diameter ϕ82 mm. The Main Power Supply (MPS) provides a beam current of 50 A with a cathode voltage (V_k) of 80 kV. Because the Collector Potential Depression (CPD) operation is not used, only the MPS can be modulated for the power modulated ECH experiments. Figure 2 shows the example waveform of the power modulation test.

In this case, the output power is modulated with the short pulse duration (t_d) of about 0.2 ms, which corresponds to the pulse duration of the ITER Type I ELM (0.1 - 1 ms).

Next, the plasma experiment for the ECH power modulation is carried out by the use of a plasma discharge after the time of t = 101 ms (Fig. 3).

During P-ECH from t = 101 ms to 161 ms, the pulse of ECH power of about 300 kW is applied six times by 100%, 100 Hz square wave power modulation (gray region between dot-lines in Fig. 3). The end plate potential is increased during P-ECH injection (Fig. 3 (a)). The end loss electron current is increased during P-ECH injection (Fig. 3 (b)), which is measured with a multi-gridded electrostatic energy spectrometer (LED). The pulse train of the

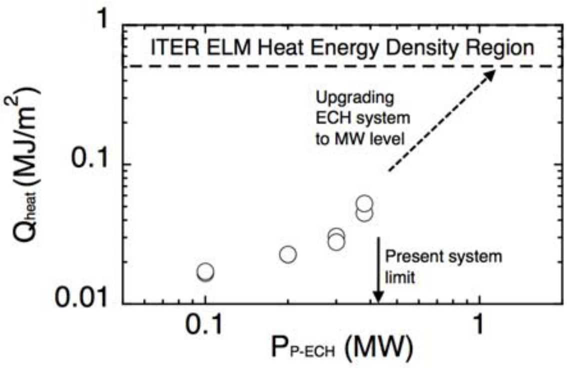

Fig. 4 The P-ECH power $P_{\text{P-ECH}}$ dependence of the energy density Q_{heat} at the axis position 30 cm from the mirror throat. The peak heat flux of 11.4 MW/m^2 is obtained.

electron current is due to sweep of the repeller voltage for energy analysis. Its envelope represents the electron current. Conversely, the end loss ion current is decreased during P-ECH injection (Fig. 3 (c)). Also its envelope represents the ion current.

The P-ECH has two functions on electrons by driving two types of velocity space diffusion. The first type of diffusion enhances mirror reflection beyond the plug position, which results in the plug potential. When ECH is applied to the plug region, the end loss ion current decreases owing to the potential reflection of low energy ions (Fig. 3 (c)). The second type of diffusion creates the electron flow (Figs. 3 (a) and 3 (b)). These data indicate that the P-ECH is able to control the end loss ion and electron fluxes by the use of power modulation, which can also produce the arbitrary heat load pattern like the various type of the ELM.

By modulating the ECH power, we can obtain arbitrary pulse heat load patterns. By changing the on/off timing, we can simulate the ELM intermittent heat pulses. The investigation of plasma flow from the end-mirror exit of GAMMA 10 is carried out to examine its performance relevant to the divertor simulation studies. A simultaneous measurement of heat and particle fluxes has been carried out by using a movable calorimeter installed at the west end-mirror exit.

The peak heat-flux of 11.4 MW/m^2 on the GAMMA 10 axis has been obtained during the P-ECH injection. It continues to increase with ECH power. This value almost corresponds to the heat load of the divertor plate of ITER. The energy density Q_{heat} per one pulse is plotted as function of the P-ECH power $P_{\text{P-ECH}}$ in Fig. 4.

These data indicate that the P-ECH is able to control the end loss ion and electron fluxes by the use of power modulation, which can also produce the arbitrary heat load pattern like the various type of the ELM. One pulse heat load energy density increases almost linearly with ECH power. The obtained maximum energy density is 0.05 MJ/m^2 with about 380 kW 5 ms pulse. This is still far lower than that of ITER ELM (0.5 - 1 MJ/m^2). We can expect the ITER level energy density by upgrading ECH to MW level.

As for the obtained preliminary scaling at the GAMMA 10 axis, it has been mainly aimed to estimate the required gyrotron power for heating system of GAMMA 10/PDX ELM-like simulation. It has been considered by the use of linear assumption, but it is sufficient to estimate the required gyrotron power roughly.

A major goal of ELM simulation experiments in GAMMA 10/PDX has been to study how ELM like intermittent heat load pattern has an effect on divertor plate. It is not able to simulate the energy distribution or charged species of ELM. It is only able to simulate the heat load produced by high energy electrons. However, it is able to obtain the experimental data of effects of target materials under the pulse heat load equivalent to ELM, which is produced by not electron beam but thermalized electrons. The target of ELM simulation experiments in GAMMA 10/PDX is to clarify the physical mechanism of effects on irradiated material under the pulse heat load equivalent to ELM, which including PWI studies.

4. Design Study of MW Gyrotron and ECH Antenna for High Energy ELM Simulation Experiments

Based on the scaling of Q_{heat} with $P_{\text{P-ECH}}$ as described in Fig. 4, it can be extrapolated to be more than 0.5 MJ/m^2 with 2 MW 10 ms pulse, assuming the linear power dependence. Therefore, we have started development of over-1.5 MW gyrotron at 28 GHz. The first tube of 1 MW, a few seconds, 28 GHz gyrotron for GAMMA 10 and other low B field device ECH source has been already fabricated and tested [5]. The obtained maximum output is 1.0 MW at 40 A. After successful results of the first 28 GHz 1 MW tube, we put the emphasis on the development of a multi-MW gyrotron, which has the performance of more than 1.5 MW a few seconds operation in 28 GHz which is required in GAMMA 10 high heat flux experiment. For the development of over-1.5 MW gyrotron, the new Magnetron Injection Gun (MIG) is now being installed in the above first tube.

Figure 5 shows the simulation result of beam current (I_k) dependence of output power (P_0) at the cavity without CPD in cases of pitch factor α (= $v_\perp/v_{//}$) = 1.3, 1.2 and 1.1, and the acceleration voltage V_{bk} = 80 kV. The output power increased with the beam current without saturation, and over 1.5 MW was obtained at I_k > 50 A, which suggest practicability of the ~2 MW power gyrotron output. Besides, an internal mode converter and mirrors are carefully optimized to minimize the electric field at the window edge and the diffraction loss. The total transmission efficiency from the mode converter to the output window is 94.7% and to the corrugated waveguide is 90.2% in the first tube. The improved designs that reduce the side lobe

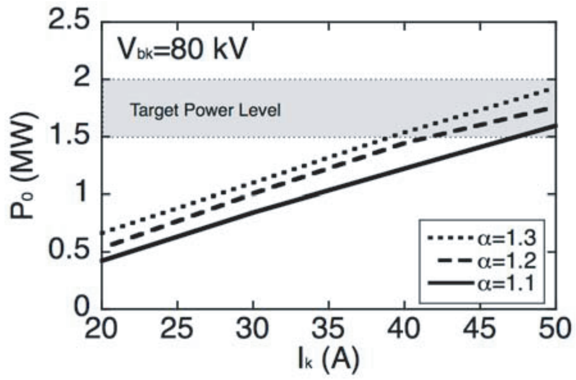

Fig. 5 Simulation result of the beam current dependence of the output power at the cavity in cases of the pitch factor α = 1.3 (dotted curves), α = 1.2 (dashed curves) and α = 1.1 (solid curves).

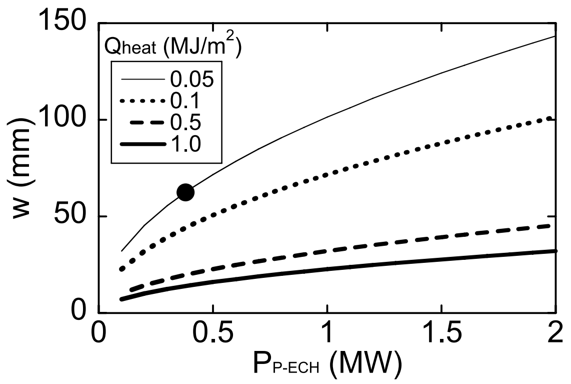

Fig. 6 Calculation result of the e-folding radius (w) dependence of the P-ECH power ($P_{\mathrm{P\text{-}ECH}}$), assuming the linear power scaling. Curves correspond to the energy density of Q_{heat} = 0.05 (thin-solid curves), Q_{heat} = 0.1 (dotted curves), Q_{heat} = 0.5 (dashed curves) and Q_{heat} = 1.0 (thick-solid curves), respectively. Filled plot is the experimental result of present systems.

of RF beam launched from the launcher and increase the transmission efficiency of the mirrors is being performed now with the target of total transmission efficiency over 95%. Calculated total output efficiency at the window is improved from 94.7% to 98.5%.

To achieve the generation of higher heat flux, it is necessary to design a high efficiency mirror antenna. Figure 6 shows the e-folding radius (w) of the power density of the radiation distribution on the resonance surface with P-ECH power. In the present ECH system, the e-folding radius of the power density is almost 62.5 mm. From Fig. 6, it is expected to approach the ITER level energy density is by the upgrade and combination of the multi-MW gyrotron and the new mirror antenna with narrower e-folding radius of the power density of radiation distribution.

5. Summary

Intermittent high heat pulse simulating the ELM pulse has been successfully generated. The maximum absolute value of the one pulse energy density on the GAMMA 10 axis is almost 0.05 MJ/m^2 with 380 kW 5 ms. It can be extrapolated to be more than 0.5 MJ/m^2 with 2 MW 10 ms pulse, assuming the linear power dependence. It remains a challenge for future research to study the detail electron flow dependence of the target plasma, the radial profiles of microwave power density and so on. According to the increasing and modulating ECH power, it is expected that the heat flux is enhanced and controlled, which enables the ELM resembling heat load pattern. It is expected to approach the ITER level energy density by the upgrade and the combination of the multi-MW gyrotron and the new mirror antenna with narrower e-folding radius of the power density of radiation distribution.

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