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Expansion of Scaling Law of Field-Aligned Potential Difference with Increased Plug ECRH Power in GAMMA 10

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The high power operation of gyrotrons exceeding their nominal powers has been carried out for ECRH at the plug region in the GAMMA 10 tandem mirror device. The highest recorded value of the axial ion confining potential for a hot ion mode plasma has been obtained. The mean energy $T_{\rm eff}$ of the axially flowing electrons driven by the plug ECRH increases to 3 keV according to the increase in the heating power up to 260 kW. The maximum field-aligned potential difference $\Delta\Phi$ has reached 5.5 kV and the scaling law between $\Delta\Phi$ and $T_{\rm eff}$ has expanded.

Keywords:

potential generation, ECRH, tandem mirror, GAMMA 10, gyrotron

In a current tandem mirror, it has been shown that the axial potential structure is predominantly generated by fundamental ECRH at the plug region (B = 1 T, plug ECRH) [1-4]. The axial ion confining potential φ_c increases with the plug ECRH power $P_{\rm plug}$ and no saturation has so far been observed in GAMMA 10. Thus, electron heating with a higher power is strongly desired and, as the first step, the high power operation of the existing 28 GHz gyrotrons for the plug ECRH exceeding their nominal power of 200 kW has been carried out by modifying the power supply and improving the high power handling capability of the wave guides. The highest recorded value of φ_c for a hot ion mode plasma is 1.4 kV at $P_{\rm plug}$ = 240 kW [5].

The plug ECRH generates an intense axial flow of warm electrons. A part of these electrons reaches an electrically floating end plate on the end wall of the vacuum vessel and appears as end loss electrons. The electron flow is a main component in the formation of the axial potential structure. In fact, the effective temperature $T_{\rm eff}$ as the mean energy of the end loss electrons is a good scaling factor of the axial potential difference $\Phi_P - \Phi_{EP}$ between the plug potential Φ_P and the potential Φ_{EP} of the end plate [6,7]. The value of $\Phi_P - \Phi_{EP}$ is a very important factor for understanding the axial potential structure [8]. The high power heating experiment described in the present study has expanded this relation. This paper presents the expanded scaling law between $\Phi_P - \Phi_{EP}$ and $T_{\rm eff}$.

Figure 1 denotes the central cell potential Φ_C and the barrier potential Φ_B in addition to Φ_P and Φ_{EP} for three different cases: (a) without plug ECRH injection (open triangles), (b) with $P_{\rm plug}$ of 130 kW (open circles), and (c) with $P_{\rm plug}$ of 240 kW (closed circles). The data points plotted in Fig. 1 are obtained from hot ion mode plasmas [9]. Each value is measured in reference to the vacuum vessel. The plug potential increases with $P_{\rm plug}$, while the central cell potential Φ_C remains at a nearly constant value. Thus, the ion confining potential $\varphi_c = \Phi_P - \Phi_C$ increases with $P_{\rm plug}$. At the same time, Φ_{EP} decreases to a deeply negative value and $\Phi_P - \Phi_{EP}$ becomes as large as 4.6 kV.

The large potential difference is generated by the axial flow of warm electrons. The end-loss electrons provide a good window into the characteristic feature of the electron flow. We use a multi-grid-type electrostatic energy analyzer for measurement of end loss electrons. The analyzer is located behind a small mesh-covered hole on the end plate.

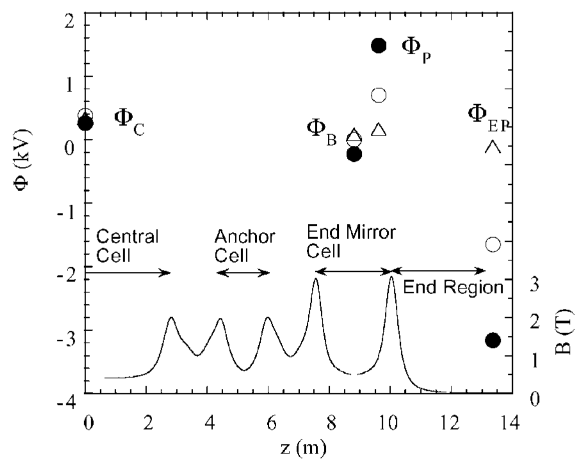

Fig. 1 Variation of the potentials at cardinal positions for three ECRH powers, 0 kW (triangles), 130 kW (open circles) and 240 kW (closed circles). The solid line shows the axial distribution of the magnetic field.

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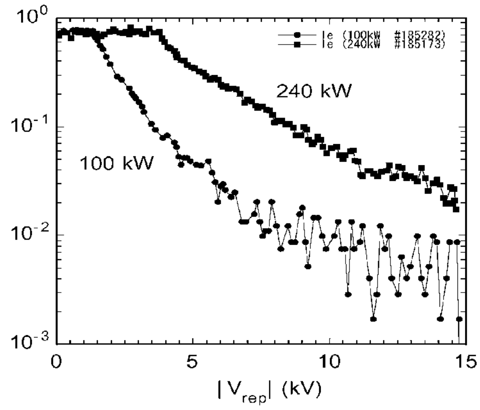

Fig. 2 Current-voltage characteristics of end loss electrons for middle and high power ECRH.

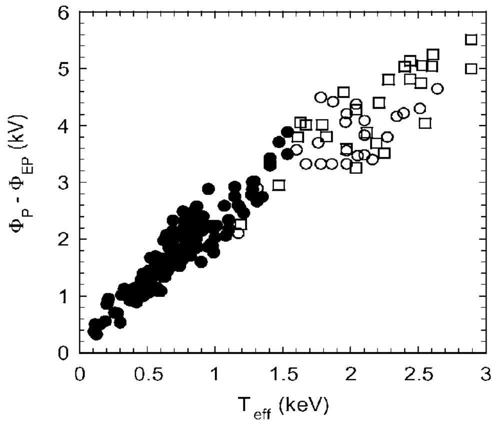

Fig. 3 Scaling law between the axial potential difference and the effective temperature of end loss electrons. Open symbols stand for recent high power ECEH experiment (hot ion mode indicated by open circles and high potential mode denoted by open squares).

Figure 2 shows the current voltage characteristics of the end-loss electrons for medium and high P_{plug}. Ions are reflected by a positively biased grid. The abscissa stands for the absolute value of the electron repeller voltage V_{rep}. The measured electron flux is constant while $|V_{rep}|$ is smaller than the magnitude of the end plate potential $|\Phi_{EP}|$ because the end plate in front of the analyzer works as an effective electron repeller grid. While the V-I characteristics have a multi-component feature, they are well fitted to a two-component Maxwellian with a lower temperature T_L and a higher temperature T_H. The effective temperature defined as $T_{eff} = (1-\beta)T_L + \beta T_H$ represents the mean energy of the end-loss electrons. Here, β is the flux fraction of the T_H component evaluated at $V_{rep} = \Phi_{EP}$. The flux of higher energy electrons significantly increases with P_{plug}, and T_{eff} linearly increases with P_{plug} as long as the electron density is kept nearly constant. A maximum value of 3 keV has been attained at P_{plug} = 260 kW.

The axial flow of high energy electrons generates a large field-aligned potential difference. The ECRH-generated axial potential structure is characterized by $\Phi_P - \Phi_{EP}$. Figure 3 plots the expanded scaling law between $\Phi_P - \Phi_{EP}$ and T_{eff}. The closed circles indicate data obtained with P_{plug} below the nominal power. The open symbols denote recent data obtained from high P_{plug} experiments. The value of $\Phi_P - \Phi_{EP}$ increases with T_{eff}. The range of $\Phi_P - \Phi_{EP}$ has significantly expanded. The data points obey the same scaling independent of operation modes, i.e., the hot ion mode and the high potential mode [10].

The plug ECRH performs two functions. It perpendicularly heats cold electrons emanating from the central cell and enhances mirror reflection of the heated electrons. This is the main function of the plug ECRH and leads to generation of a plug potential that maintains the charge neutrality with the ions [11,12]. The heated electrons form a group of warm electrons. These electrons exist in different locations in velocity space than do the cold electrons. The plug ECRH then drives those electrons into the loss cone [13,14]. This is the second effect. The electrons driven out of the plug region are confined by the potential difference $\Phi_P - \Phi_{EP}$. These electrons travel back and forth between the end plates on both ends. Thus, $\Phi_P - \Phi_{EP}$ is largely determined by T_{eff} and reflects the dynamics of the heated electrons.

The observed scaling indicates that the picture of the functions of the plug ECRH on electrons holds for high power heating. Use of 500 kW gyrotrons is planned in the next experimental campaign. Examination of the validity of the above picture at higher power is our next task.

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