Observation of the Effects of Radially Sheared Electric Fields by the Use of a Gold Neutral Beam Probe

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Intermittent turbulent potential fluctuations in ion-cyclotron wave heated plasmas and effects of their suppression due to strongly sheared plasma rotation with electron-cyclotron heating (ECH) for potential formation are observed in GAMMA 10. Such a shear effect on *the central-cell potential data* is demonstrated by the use of a heavy ion beam probe (HIBP) for the first time in GAMMA 10. The HIBP system with a gold neutral beam is employed for measuring profiles of radially formed potential as well as the associated radially sheared E_r in the central cell. During the application of ECH, the produced stronger E_r shear results in reduction of the turbulent fluctuations. The results are consistent with reported X-ray tomography data on the effect of E_r shear on turbulence suppression.

Keywords: gold neutral beam probe, E_r shear, potential fluctuation, x-ray tomography, electron-cyclotron heating

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1. Introduction

Considerable interests have been focused on the study of turbulent fluctuations, since various plasma confinement theories predict such turbulent fluctuations lead to anomalous transverse transport and energy loss in magnetic confinement systems. In fact, low frequency plasma turbulence and the resultant anomalous transport observed in various devices for magnetic plasma confinement exhibit rather common features. Recently, intermittent low-frequency turbulent vortex structures and effects of their suppression by strongly sheared plasma rotation are observed in GAMMA 10 [1, 2].

GAMMA 10 is a minimum-B anchored tandem mirror with outboard axisymmetric plug and barrier cells. The central cell has a length of 6 m and a limiter with a diameter of 36 cm. Electrostatic potentials have originally been produced in the plug and barrier regions so as to improve the confinement of central-cell ions and electrons (Fig. 1). Recently, high power gyrotrons (28 GHz, 0.5 MW) significantly enhance the potential heights [1, 2]. The advance in the potential formation gives bases for a finding of the remarkable effects of radially produced shear of electric field dE_r/dr, or non-uniform sheared plasma rotation on the suppression of intermittent vortex-like turbulent fluctuations. Such a shear effect is visually highlighted by X-ray tomography diagnostics [1–11]. During the application of electron cyclotron heating in the plug region (hereafter referred to as plug ECH), the produced stronger E_r shear results in disappearance of such intermittent turbulent vortices with plasma confinement improvement [1, 2].

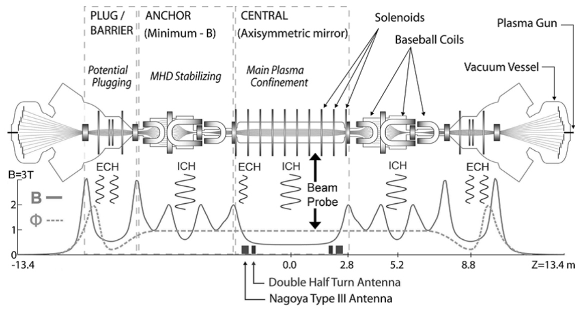

Fig. 1 Schematic view of the GAMMA 10 tandem mirror. Magnetic coil set and magnetic flux tube with heating systems, as well as the axial profiles of magnetic field (solid curve) and potential (dashed curve) are illustrated.

In this paper, we present the results obtained by means of the remarkable effects of radially produced sheared electric field on *turbulent potential fluctuations* directly in GAMMA 10 for the first time. We focus our discussions on the data from a gold neutral heavy-ion beam probe system (HIBP, and particularly referred to as GNBP) in the central cell. The system is employed for measuring profiles of radially formed potential as well as the associated radially sheared E_r in the central cell. By the use of capability of time and energy resolutions of the GNBP system, potential fluctuations are investigated from the view point of finding the relation between E_r shear and the *potential fluctuation* suppression.

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2. Principle of Beam Probe Measurements

A beam probe is a useful tool on the basis of the energy conservation of a heavy ion beam for the plasma potential measurement. The beam probe system consists of two parts. One is a beam source which produces a high energy ion beam, and the other is a beam detector by use of an electrostatic energy analyzer. The incident beam and the ionized ion beam in a plasma are referred to as primary and secondary beams, respectively. The basic principle of the potential measurement is a conservation law between the beam energy and the plasma potential. When the energy of the secondary beam is measured, the plasma potential is estimated from the change of the beam energy as follows:

$$\phi = \frac{1}{Ze}\left(E_{\mathrm{secondary}} - E_{\mathrm{primary}}\right) \quad (1)$$

where E_{primary} and $E_{\mathrm{secondary}}$ are the energy of the primary and secondary beams, respectively. Also, Z is the change of the ion charge number at ionization point, and ϕ is the plasma potential at the ionization point. The ionization point of the detected secondary beam is limited to the small volume due to the beam slit in front of the analyzer. Therefore, the electrostatic potential at the ionization point is measured with the beam probe. The secondary beam has the information on not only a plasma potential but also an electron density and a magnetic field, since the secondary beam current and the shift of the detected position depend on the electron density and the magnetic field. Therefore, it is possible to carry out the simultaneous measurements of the density, potential and magnetic field by the use of a beam probes.

3. A Gold Neutral Beam Probe System at the Central Cell

The GNBP system at the central cell is shown in Fig. 2. The system consists of a gold negative ion source of a spattering type, a beam transport region of the gold negative ion, a neutralizing gas box, a beam transport region of the primary gold neutral beam, a microchannel plate (MCP) ion detector and sweeping circuits of beam injection angle [12–14]. As the trajectories of the negative ion beam are influenced by leakage magnetic fields of the anchor coil to the central cell fields, the trajectories are adjusted by the electric field of a steerer. The accelerated energy is 11.783 keV. The electron affinity of the gold atom is about 2.7 eV. The negative ions are neutralize easily by collisions with hydrogen gas in a neutralizing gas box to which hydrogen gas is introduced from a gas reservoir through a Piezo electric valve. Hydrogen gas for the probe beam formation is employed, since the plasma is produced by hydrogen. Inflow of the neutralizing hydrogen gas to the plasma is almost negligible because of the use of a differential vacuum pumping system. A MCP detector is employed as the gold ion-beam detector, which amplifies the beam signals. Two types of MCP ion detectors

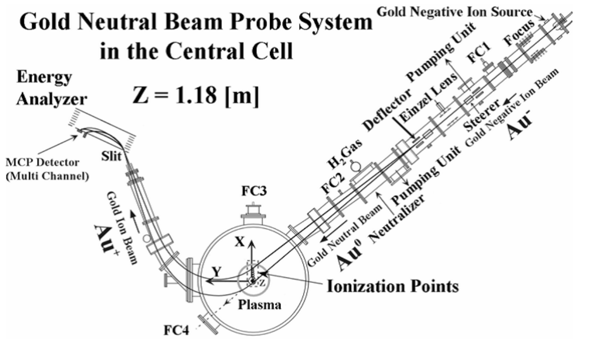

Fig. 2 The gold neutral beam probe system in the central cell of the GAMMA 10 tandem mirror. In the case of a vertically (z) directed beam sweep for radial potential profile observations in a single discharge, ionization points move in the vertical direction due to the injection angle changes. (Here, the z-axis is in the perpendicular direction to the plane).

are prepared; one is used mainly for the potential measurement, and the other is for magnetic fluctuation measurement. The system gives information on two dimensional potential profiles in the cross section of the plasma column, electrostatic potential fluctuations, and electromagnetic ones by sweeping and adjusting the energy and the injection angle of the primary beam

4. Experiment Result and Discussion

For the experimental investigations of the effects of radially produced sheared electric fields, fluctuations are measured with the GNBP in the GAMMA 10 experiments. The plasma is initiated with plasma guns installed in both end regions of GAMMA 10. Ion-cyclotron heatings (ICH) is used for the plasma production in the central cell as well as ion heating in the anchor cells for the MHD stabilization. Electrostatic potentials are originally produced in the plug and barrier regions due to ECH so as to improve the axial confinement of central-cell ions and electrons, respectively [1, 2].

Figure 3 shows radial potential profiles in the central cell during the application of ECH. Ion confining potentials are created in both plug regions. The central-cell potential is also raised due to plug potential formation because of electron flow effect between the central cell and the plug regions [1, 2]. The progress of high confinement potential formation up to 3 kV in turn gives bases for the formation of a strong central cell $\mathrm{d}E_{\mathrm{r}}/\mathrm{d}r$ [1, 2]. An ion temperature T_{i} is raised from 6 to 7 keV due to the ECH application.

Figure 4 provides the produced stronger E_{r} shear profile, which is observed with GNBP. The solid and dotted curves in Fig. 4 correspond to the cases plotted with the solid and dotted curves in Fig. 3, respectively. In the absence of ECH, a weaker E_{r} shear is formed as seen with the dotted curve.

Figure 5 shows the intensity integral of the fluctuation level of turbulence. During the application of ECH,

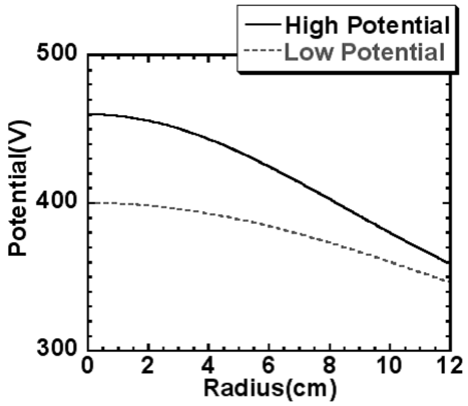

Fig. 3 The radial potential profiles in the central cell. The solid and dotted curves are obtained in the cases with and without ECH, respectively. The central cell has a length of 6 m and a limiter with a diameter of 36 cm.

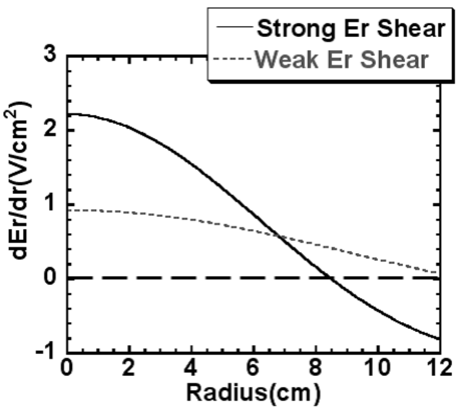

Fig. 4 The radially observed shear profile of electric fields dE_r/dr in the central cell. The solid and the dotted curves are obtained in the cases with and without ECH, respectively.

the potential fluctuations are found to be significantly reduced. Such *potential* behavior is consistent with that in the previously reported X-ray data [1, 2], which show the fluctuations of plasma parameters of *densities* and *electron temperatures*.

Figure 6 shows the contour of the *potential fluctuation levels* for the first time in the turbulence stabilization experiments of GAMMA 10 due to the E_r shear formation [1, 2]. The data in Fig. 6 directly show that a stronger E_r shear formation during the ECH application period suppresses *the turbulent potential fluctuations in mirrors for the first time* temporally and spatially.

5. Summary

Potential fluctuation data in the E_r shear formation experiments in GAMMA 10 [1, 2] are directly reported for the first time. The GNBP system is applied to characterize the turbulent *potential fluctuations* in the central-cell plasmas. The potential fluctuation level is observed to be significantly reduced due to the radially produced shear of

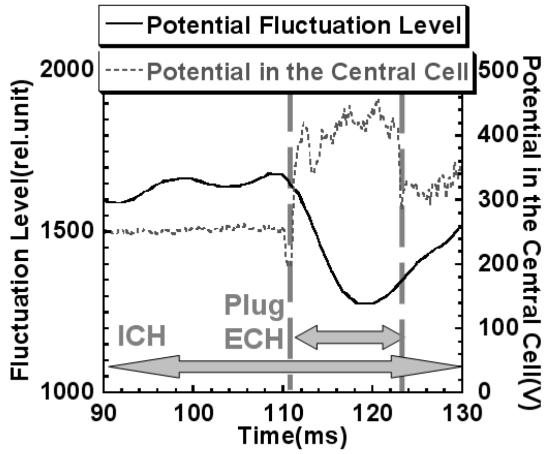

Fig. 5 The integrated fluctuation levels of turbulence.

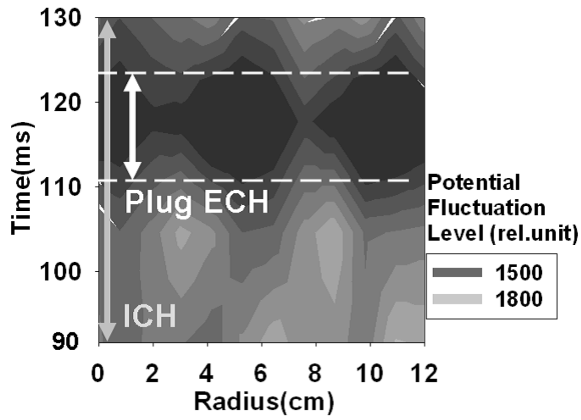

Fig. 6 The contour of potential fluctuation levels.

electric fields dE_r/dr. The GNBP data are consistent with the X-ray tomography data on the effect of E_r shear on turbulence suppression with transverse energy confinement improvement [1, 2].

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