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# Electron density fluctuation measurements in the tandem mirror GAMMA 10

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1. INTRODUCTION. The tandem mirror GAMMA 10 utilizes an electron cyclotron resonance heating (ECRH) for forming a confinement potential [1-7]. A new record of the formation of highest ion-confining potential 3.0 kV is achieved in the hot-ion mode; that is 4 times progress as compared with that potential attained 1992-2002 [1-4]. Fluctuation in the plasma is important to be measured for studying the improvement of the plasma confinement by the formation of the plasma confinement potential. Density fluctuation is observed using microwaves, such as interferometer [8-13], reflectometry [8] and Fraunhofer diffraction (FD) method [9, 10], and electrostatic probes [11]. Ultrashort-pulse reflectometry has an advantage of detecting fluctuation locally. The wave number can be obtained by the FD method. In the edge plasma region electrostatic probes are used. We have constructed a new multi-channel microwave interferometer to measure the plasma density profile and density fluctuation profile in a single plasma shot. The fluctuation is excited in the hot-ion mode plasma [1-4]. When the ECRH is applied, electron density in the central cell increases gradually due to the improvement of the plasma potential confinement. When the good plasma confinement is achieved in the good plasma condition, the intensity of the density fluctuation is suppressed. At this point, radial potential distribution, i.e., electric field varies along with the formation of plug potential. From this behaviour, it is deduced that the fluctuation is closely related to the potential formation and improvement of the plasma confinement. This paper describes the initial results of density and line-integrated density-fluctuation measurements in the central cell of the tandem mirror GAMMA 10 by using the newly constructed multi-channel interferometer.

2. EXPERIMENTAL APPARATUS. GAMMA 10 is an effectively axisymmetrized minimum-B anchored tandem mirror with a thermal barrier at both end-mirrors [1-7]. The device consists of an axisymmetric central mirror cell, anchor cells with minimum-B configuration, and plug/barrier cells with axisymmetric mirrors. In the tandem mirror GAMMA 10, the plasma confinement is achieved by not only a magnetic mirror configuration but also high potentials at the both end regions. The main plasma confined in

GAMMA 10 is produced and heated by ion cyclotron range of frequency (ICRF) power deposition. The potentials are produced by means of ECRH at the plug/barrier region. Neutral beam injection (NBI) is also utilized at the plug/barrier cell to produce the sloshing ion. They cause the density increase in the central cell. The typical electron density, electron temperature and ion temperature are about $2 \times 10^{12}$ cm$^{-3}$, 80 eV and 5 keV, respectively. We have constructed a multi-channel microwave interferometer to observe the line-integrated density radial profile and the radial fluctuation profile in a single plasma shot.

A single channel microwave interferometer with movable horns has been installed and operational in the central cell of the GAMMA 10 tandem mirror. We have developed a multi-channel microwave interferometer and applied it to measure the central cell plasma. The schematic diagram of the multi-channel microwave interferometer system is shown in FIG. 1. It is designed using a Gaussian-beam propagation theory and a ray tracing code. The system is configured as a heterodyne interferometer consisting of a 70 GHz (1 W) Impatt oscillator (Quinstar Technol., QIO-7030CL) and a 150 MHz oscillator. The output of the Impatt oscillator is divided into two microwave beams. The first is a probe beam that goes through the plasma, and other is a reference beam that is combined with the output of the 150 MHz oscillator using an upconverter. The probe microwave beam is injected into the plasma without a lens system from the upper port of GAMMA 10. The probe beam extends and is received by 6 horns settled at the measuring position of y = 6 cm (ch. 1), 3 cm (ch. 2), 1 cm (ch. 3), -2 cm (ch. 4), -4 cm (ch. 5), and -7 cm (ch. 6) at the bottom outside the port of GAMMA 10. The spatial resolution of the system is approximately 3 cm. The received signals cos ($\omega t + \Delta\varphi$) in each channel, where $\Delta\varphi$ is the phase change due to the plasma density, and the combined reference signal cos ($\omega t + \omega' t$) are combined with a directional coupler and fed to a phase detection circuit (R&K, PSD-1G) through the detectors with low pass filters. The outputs of the phase detection circuits give the dc signal components of sin $\Delta\varphi$ and cos $\Delta\varphi$. The line-integrated electron density of each position is

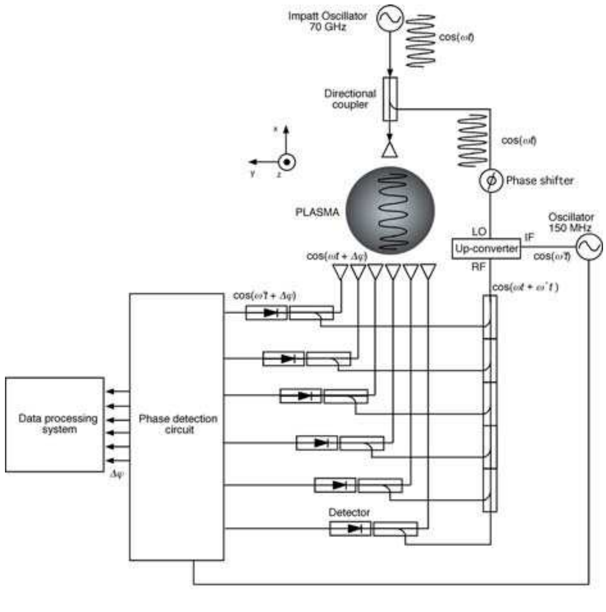


*Figure 1. The schematic diagram of the multi-channel microwave interferometer system.*

calculated numerically by taking arctan (sin $\Delta\varphi$ /cos $\Delta\varphi$). The phase change $\Delta\varphi$ is given by the electron density

$$\Delta\varphi = \frac{\pi}{\lambda n_c} \int_l n_e(r) dx. \qquad (1)$$

Here, $n_c$ is the cutoff density, given by $n_c = \varepsilon_0 m_e \omega^2/e^2$, and $n_e(r)$ is the electron density at plasma radius, $r$. Then the Abel inversion technique is used for obtaining the electron density radial profile

$$n_e(r) = -\frac{\lambda n_c}{\pi^2} \int_r^a \frac{d(\Delta\varphi)}{dy} \frac{dy}{\left(y^2 - r^2\right)^{1/2}}. \qquad (2)$$

We combined the data of the movable interferometer of the measured position of y = 15 cm and those of the multi-channel interferometer in order to obtain the plasma radial density profiles with a single plasma shot. When we use the movable interferometer, we have to use around 10 plasma shots to obtain the plasma radial density profile.

3. DENSITY PROFILE AND FLUCTUATION MEASUREMENTS. The plasma is produced at 50.5 ms and sustained by ICRF. Then barrier-ECRH is applied between 60 and 80 ms to create thermal barrier potential and plug-ECRH is applied between 68 to 80 ms to create confining potentials. NBI is injected between 68 and 72 ms. The density in the central cell is measured by the movable interferometer and the newly installed multi-channel microwave interferometer in a single plasma shot. Figure 2(a) and 2(b) show the electron density radial profiles before applying plug-ECRH at 67-68 ms, and that during applying plug-ECRH at 73-74 ms, respectively. The density on the plasma axis is $2.9 \times 10^{12}$ cm$^{-3}$ without the plug-ECRH and $4.5 \times 10^{12}$ cm$^{-3}$ with the plug-ECRH. The electron density peaked during the plug-ECRH due to the formation of the confining potential in the plug/barrier region. The radial density fluctuation is clearly observed in FIG 2(b). An error of approximately 20% is included in this measurement when compared with the results of shot-by-shot movable interferometer measurement method.

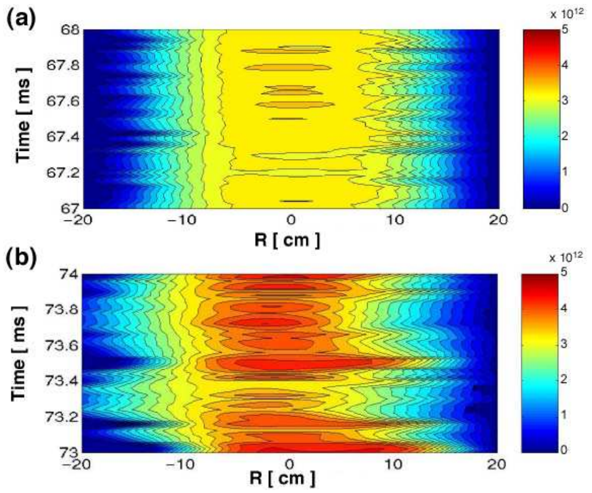


*Figure 2. The electron density radial profiles before applying plug-ECRH at 67-68 ms (a), and that during applying plug-ECRH at 73-74 ms (b), respectively.*

Figure 3 displays the Fast-Fourier-Transformed (FFT) frequency spectra of the line-integrated densities measured at each position using the multi-channel interferometer. Figure 3(a) and 3(b) show the FFT spectra before and during the plug-ECRH, respectively. In the spectrum on each channel before plug-ECRH, the strong peak is not observed. During the plug-ECRH, the spectrum of each channel shows that the increase in the fluctuation is around 2 times greater than that before the plug-ECRH, particularly at the higher frequency range. The coherent mode is near 4 kHz and its second order is observed. This coherent mode is due to E × B drift.

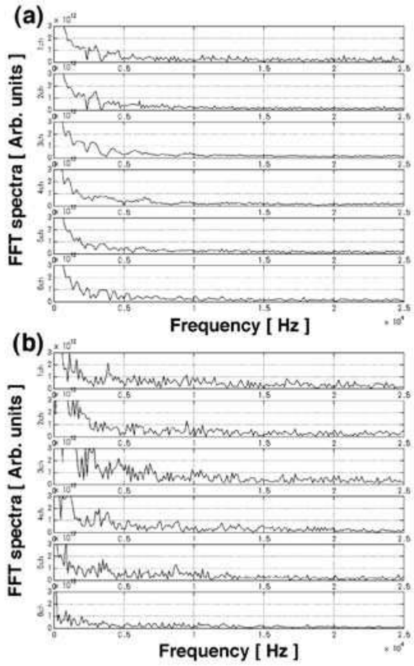


*Figure 3. The FFT spectra before plug-ECRH (a) and those during plug-ECRH (b), respectively.*

4. CONCLUSION. We have constructed a new multi-channel microwave interferometer to observe the radial plasma density and density fluctuation. We can successfully obtain the time dependent plasma density radial distribution using the Abel-transform technique for output signals of the multi-channel microwave interferometer and the movable interferometer. Moreover, we can obtain the radial line-integrated density fluctuation spectra after FFT signals for each channel. We prepared the one of the useful diagnostic tools for studying the improvement in the plasma confinement.

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