Electron Density Measurement by Using a Multi-Channel Interferometer System in the Tandem Mirror GAMMA 10

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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, reflectometry and Fraunhofer diffraction method. We have constructed a new multi-channel microwave interferometer for measuring the plasma density and fluctuation radial profiles in a single plasma shot. In order to study higher density plasma operation, we have started sub-millimeter hydrogen ice pellet injection experiments into the potential confined plasma. We successfully measured the time dependent density and line-integrated density fluctuation radial profiles in the pellet injection experiments using the multi-channel microwave interferometer.

Keywords: multi-channel microwave interferometer, GAMMA 10, density profile, fluctuation, pellet injection

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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 four 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 [8–12], 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 [12]. On the basis of the physics understanding of E_r shear importance, preliminary central ECRH (c-ECRH) is applied in a standard tandem-mirror operation with plug ECRH, which plays an essential role in both E_z plugging for an axial confinement improvement and automatically associated strong E_r shear flow for a radial confinement improvement simultaneously. 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. Moreover we have started pellet injection experiments for studying the plasma confinement improvement in the high plasma density condition. In order to study pellet plasma interaction in detail, we have to observe the plasma density radial profile in a quick response. Pipe gun type pellet injector was installed in GAMMA 10 tandem mirror [13,14]. Sub-millimeter hydrogen ice pellet is injected into the potential confined plasma with applying c-ECRH. We successfully obtained the radial density profiles in the pellet injection experiments for the first time. We achieved the higher plasma density of 5.1×10^{12} cm^{-3} in the potential confined plasma.

This paper describes the initial results of density and line-integrated density-fluctuation measurements in the pellet injection experiments on the tandem mirror GAMMA 10 by using the newly constructed multi-channel interferometer.

2. Experimental Apparatus

GAMMA 10 (Fig. 1) 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 ax-

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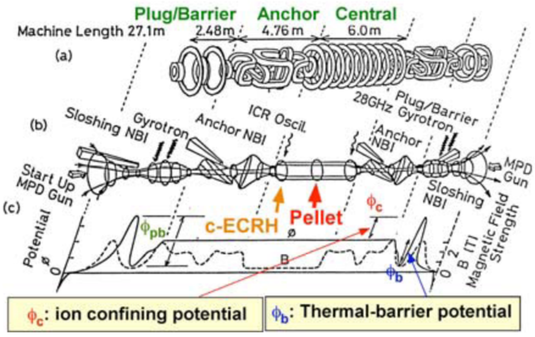

Fig. 1 The schematic view of the tandem mirror GAMMA 10.

isymmetric 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 300-380 kW ECRH at the plug/barrier region. Neutral beam injection (NBI) is also utilized at the plug/barrier cell to produce the sloshing ion. Moreover, the electron heating is achieved by the 150-250 kW c-ECRH at central region. The typical electron density, electron temperature and ion temperature before applying c-ECRH are about 2×10^{12} cm^{-3}, 80 eV and 5 keV, respectively. During applying 250 kW c-ECRH, the electron temperature raises from 80 eV to 0.75 keV. 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.

In order to study plasma confinement in the higher plasma density condition, we prepared a sub-millimeter hydrogen pellet injection system in the GAMMA 10 tandem mirror [13,14]. The pellet injector has eight barrels for forming the pellet sizes of 0.33, 0.58, 0.79 and 0.99 mm in diameter. The 0.79 mm barrel is used in these experiments. The pellet is cylindrical and its aspect ratio is from 0.5 to 2. The injected fueling pellet speed is the velocity range of 500-1000 m/s. We use a 6.4-m long Teflon guiding tube with 1/4 inch outer diameter in order to transfer the pellet from the injector to an injection port of GAMMA 10. We set the final stage pellet diagnostic system just before the plasma injection in order to measure the pellet speed, mass, and pellet shape by using light gate system, microwave mass measurement system, and pellet shadow graph system, respectively [14].

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. 2. It is designed using a Gaussian-

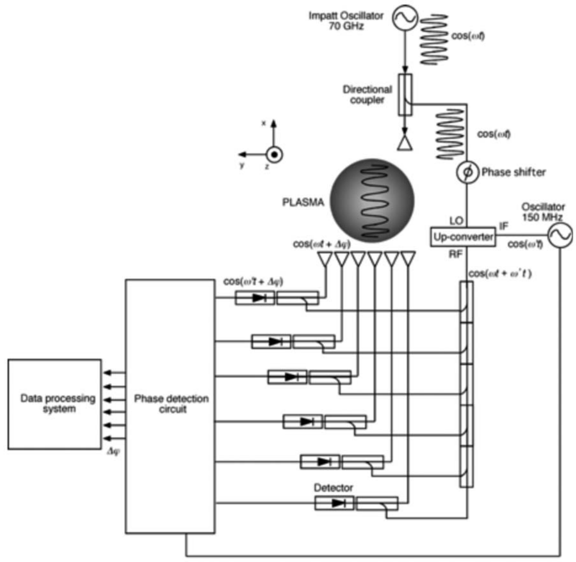

Fig. 2 The schematic diagram of the multi-channel microwave interferometer system.

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. We set the upper horn position at $y = 0$ cm in ref. 12. In that case, we observed the plasma line density between -6 cm $< y <$ 6 cm. However, the density of the edge region has to be observed. Then we set the upper horn position at $y = -16$ cm in these experiments. The probe beam extends and is received by 6 horns settled at the measuring position of $y = -1.7$ cm (ch. 1), -3.7 cm (ch. 2), -6.3 cm (ch. 3), -9.3 cm (ch. 4), -11.4 cm (ch. 5), and -14.4 cm (ch. 6) at the bottom outside the port of GAMMA 10. The distance between the probing horn and receiving horns is about 135 cm. The spatial resolution of the system is approximately 3 cm. The probing beam size at the receiving horns is about 36 cm in diameter. 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 output signals are led into the CAMAC system with sampling rate of 50 kSa/s. The line-integrated electron density of each position is calculated numerically by taking arctan (sin $\Delta\varphi$/ cos $\Delta\varphi$). The phase change $\Delta\varphi$ is given by the electron density

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

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. The Abel inversion technique is used for obtaining the electron density radial profile

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

We combined the data of the movable interferometer of the measured position of y = 6 cm and those of the multi-channel interferometer in order to obtain the plasma radial density profiles with a single plasma shot.

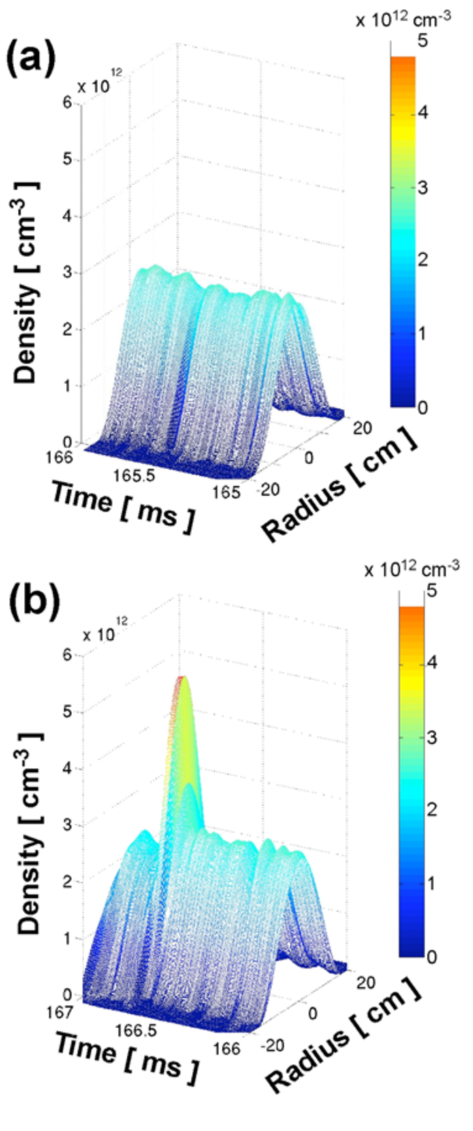

Fig. 3 The electron density radial profiles before pellet injection at 165-166 ms (a), and that during pellet injection at 166-167 ms (b), respectively.

3. Density Profile and Fluctuation Measurements in Pellet Experiments

The plasma is produced at 50.5 ms and sustained by ICRF. Then barrier-ECRH is applied between 155 and 175 ms to create thermal barrier potential and plug-ECRH is applied between 160 to 170 ms to create confining potentials. C-ECRH is applied between 161 to 169.5 ms to increase electron temperature. NBI is injected between 159 and 163 ms. The electron density in the central cell is measured by the movable interferometer and the newly installed multi-channel microwave interferometer in a single plasma shot. Pellet is injected at 166.6 ms. During early pellet injecting period, the plasma density increase is probably localized in the lower part of the plasma. However there is no measurement system for x direction plasma density profile. While the rapid line density signal increases are observed at the same time in all channels of the multi-channel interferometer by the pellet injection. Then we assume the plasma is axisymmetry. Figure 3(a) and 3(b) show the electron density radial profiles before pellet injection at 165-166 ms, and that during pellet injection at 166-167 ms, respectively. The density on the plasma axis is 2.9×10^{12} cm^{-3} before pellet injection and 5.1×10^{12} cm^{-3} with the pellet fueling. The electron density peaked during the pellet injection with the formation of the confining potential and electron heating by ECRH. An error of approximately 20 % is included in the measurements, because of the error of reproducibility of the measurements on the same plasma shots and the reconstruction by using Abel inversion technique.

Figure 4 displays the Fast-Fourier-Transformed (FFT) frequency spectra of the line-integrated densities measured at each position using the multi-channel interferometer. Figure 4(a) and 4(b) show the FFT spectra before and during the pellet injection, respectively. In the spectrum on each channel before pellet injection, the strong peak is not observed. During the pellet injection, the spectrum of each channel shows that the increase in the fluctuation is around 4 times greater than that before the pellet injection, particularly at the lower frequency range. This shows that the pellet injection made a low frequency density fluctuation in the plasma. It is thought that this fluctuation is come from the E×B drift. However this fluctuation mechanism has not been clear in detail. Then we have to study more detail of this fluctuation.

4. Summary

We have constructed a new multi-channel microwave interferometer to observe the radial plasma density and density fluctuation in a single plasma shot. We can successfully obtain the time dependent plasma density radial distribution in the pellet fueling experiments for higher plasma density experiments. Moreover, we can obtain the radial line-integrated density fluctuation spectra after FFT

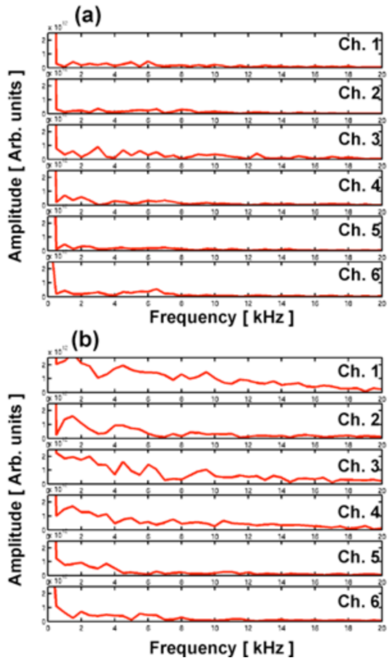

Fig. 4 FFT spectra before pellet injection (a) and those during pellet injection (b), respectively.

signals for each channel. We prepared the useful diagnostic tool for studying the pellet plasma interaction in detail.

Acknowledgments

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