Density fluctuation measurements by using the Fraunhofer diffraction method in GAMMA10

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ABSTRACT: We applied Fraunhofer diffraction (FD) method to GAMMA10 plasma. The FD method can measure the density fluctuation in detail and the wave number of the fluctuation. We successfully obtained the density fluctuation spectra in GAMMA 10. Analyzing the FD method signals of radial fluctuation intensity profile, we can successfully obtain the wave number and the phase velocity of the low frequency density fluctuation.

KEYWORDS: Plasma diagnostics - interferometry, spectroscopy and imaging; Plasma diagnostics - charged-particle spectroscopy; Optics
1 Introduction

Measurements of spatially and temporally resolved frequency and wave number spectra of the fluctuations are important. A measurement of spatially and temporally resolved frequency ($\omega$) and wave number ($k$) spectra is essential for the waves. Microwave to infrared laser scattering techniques have been used for the purpose. There are two types of instabilities which are a rotationally driven mode with the lowest azimuthal mode number and a drift-wave mode with high azimuthal mode numbers. In tandem mirrors the rotational mode is driven by $E_r \times B$ rotation energy at the lowest azimuthal mode number, $m = 1$. Higher modes with $m > 2$ will be stabilized by finite Larmor radius effects. On the other hand, the drift-wave mode arises because of the existence of a density gradient. The radial electric field $E_r$ arising from the potential causes the $E_r \times B$ plasma rotation in the direction of the ion diamagnetic drift velocity, which may enhance instabilities, such as rotational flute and drift-wave modes, and degrade radial confinement. However, present study shows that the suppression of drift type fluctuation in the potential and density fluctuations with producing axial confining potential in GAMMA 10 [1]. GAMMA10 is a minimum-B anchored tandem mirror with thermal barrier. The confinement in the central cell is improved by means of creating electrostatic potentials with application of electron cyclotron heating (ECH). Typical plasma parameter of the electron and ion temperatures, electron density, and the plasma potential are about 40 eV, 5 keV, $2 \times 10^{12}$ cm$^{-3}$, and 200 V, respectively. The electron and ion temperatures are measured by using an yttrium-aluminium-garnet Thomson scattering system [2] and a charge exchange neutral particle analyzer, respectively. The electron density and the potential are measured by using the microwave interferometer system and the gold neutral beam probe (GNBP) system, respectively. In GAMMA10, there are several fluctuation measurement systems, such as the electrostatic probes, magnetic probes, GNBP system, microwave interferometer systems, reflectometry systems, a Fraunhofer diffraction (FD) method, and end plate systems [1]. FD method is one of the forward scattering methods. FD method system can measure the radial profile of the density fluctuations in plasma in detail. With comparing the probe beam and the scattered beam by the fluctuation in the plasma, we can obtain the wave number of the fluctuation. In GAMMA 10 FD method system, we can obtain the 8 channel signals to obtain the radial fluctuation profile in a single plasma shot. In the former system of FD method, we could measure only the 20 ms in
the plasma duration in a single plasma shot. Then we have to use several plasma shots in order to obtain total FD signals of the total plasma duration. We changed the analogue to digital converter (ADC) system for improving the long time signal acquisition. In this study, we applied FD method to measure density fluctuations in the central cell of the GAMMA10 plasma.

2 Experimental apparatus

GAMMA10 is an effectively axisymmetrized minimum-B anchored tandem mirror with thermal barrier at both end-mirrors (figure 1). The x-axis and y-axis are perpendicular to the magnetic field in the vertical and horizontal directions, respectively. The z-axis is parallel to the magnetic field. In the tandem mirror GAMMA10, the lengths of central, anchor and plug/barrier cells are 6.0 m, 4.8 m and 2.5 m, respectively. The hydrogen plasma is created by plasma guns, and heated and sustained using ion cyclotron heating (ICH) systems. When fundamental ECH is applied in the plug region, an ion confining potential is created owing to the formation of a potential depression in the thermal barrier. The P-ECH produces warm electrons at the end mirror cells. A fraction of heated electrons is driven out of the end mirror through loss cone along the magnetic field lines. The plug potential increases owing to the existence of warm electrons, while the potential of the floating end plates decreases.

FD method system is installed in the central cell of GAMMA 10 at \( z = 2.4 \) m. In FD method system, a heterodyne detection is applied to the scattered and incident beams to detect them within the undeviated incident beam, i.e. within the divergence of the probing beam. The scattering angle has to be larger than the divergence angle of the incident beam in order to avoid stray light. This technique makes it possible to investigate long wavelength waves, which are considered to be relevant to anomalous transport. The long wavelength means low-frequency. In the GAMMA 10 central cell, there are low-frequency fluctuations. We show a schematic diagram of FD method system in figure 2 and the optical system in figure 3. The spot-size of the beam waist \( (w_0) \) at the plasma center and that at the front focal plane \( (w_f) \) are 39.8 mm and 13.5 mm, respectively. The lengths from the horn to the lens, from the lens to the central of the plasma, and from the lens to detector are 423 mm, 600 mm, and 480 mm, respectively.

![Figure 1. The detector of the FD method.](image-url)

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The detector of the FD method.
A beam of 70 GHz frequency is focused on the plasma center by a fused quartz lens ($f = 400 \text{ mm}, \phi = 105 \text{ mm}$). The frequency-shifted FD signal and the unshifted transmitted wave are focused via another lens ($f = 400 \text{ mm}, \phi = 125 \text{ mm}$) onto GaAs Schottky barrier diode mixers bonded to gold bow-tie antennas which form a monolith with a fused quartz substrate. The probe beam is shown as

$$E_f = E_0\Psi_i(x,y,z) \exp \left( j \omega_i t - k_i \cdot r \right)$$  \hspace{1cm} (2.1)

where $E_f$ is the Electric field of the undeviated incident beam, $\Psi_i$ is the normalized spatial distribution function of the incident beam. The scattered beam is shown as

$$E_r = E_0 r_0 \int \frac{1}{R} \Psi_t(x,y,z) \tilde{n}_e \times \exp \left( j \omega t' - k_i \cdot r \right) dV_i$$  \hspace{1cm} (2.2)

where $t'$ is the rerated time, $r_0$ is the classical electron radius, $R$ is the distance between a diffraction point and the observing point, and $V$ is the diffracting volume. The signal intensity of the FD method ($I$) is shown as

$$I = \frac{|E_f^* E_r + E_r^* E_f|^2}{2}$$  \hspace{1cm} (2.3)

Eight channel antenna array detector is used in FD method system. The distance between the channels is 5.2 mm in the detector. The aperture of the antenna is selected to be smaller than the
beam width Rectangular waveguide antennas in the $TE_{10}$ mode are installed on the reverse side of the diode detectors. The aperture of the waveguide antenna operates as a spectrometric slit in the plane of the observation. The signals of intermediate frequency from the mixers are amplified by low noise amplifiers and fed to ADC system. The sampling rate of the former ADC was 1 MS/s and the maximum measuring duration is 20 ms. We applied new ADC system with the sampling rate of 100 kS/s and the maximum measuring duration is 200 ms. The eight channel detector is used in the FD method system. The detector position can be moved in the y-axis direction in order to study the FD signal profiles in detail. The wave number of the density fluctuation can be obtained by the radial profile of FD signal analysis.

3 Experimental results

The plasma is maintained and heated with applying ICH from $t = 51$ ms to 250 ms and the confinement potential is produced by applying P-ECH with power of 200 kW from $t = 141$ ms to 170 ms. The left figure of the figure 4 shows the time evolution of the electron density (red line) and diamagnetism (blue dotted line) at the central cell. In this plasma, the electron density and diamagnetism increase between $t = 141$ ms and $t = 171$ ms during P-ECH periods. The strong fluctuation in the line density is observed between $t = 90$ ms and $t = 130$ ms. The time evolution of the FD raw signal and the fast Fourier transform (FFT) analyzed spectrogram of channel 6 are shown in the right figure of figure 4 (a) and figure 4 (b), respectively. We can obtain the FFT spectrograms of all channels in the plasma periods, except for channel 2. Unfortunately, we could not obtain the signal of channel 2.

It is found that there are strong fluctuations from $t = 90$ ms to $t = 140$ ms. The strong fluctuation with frequency of about 3.2 kHz is observed without P-ECH. It is the diamagnetic drift type fluctuation which is determined by using electrostatic probes.
In figure 5, the FFT-analyzed spectrum of each channel between 118 ms and 123 ms is shown. We can successfully obtain the FD signals of seven channels in a single plasma shot. In figure 6, the fluctuation intensity radial profile at frequency of about 3.2 kHz is shown.

Here $u$ is the normalized radius ($u = x/w_f$). The wave number of the density fluctuation can be calculated using fluctuation intensity radial profile in figure 6 [6]. We can obtain the phase velocity. The wave number ($k$) is $42.9 \pm 7.8 \text{ m}^{-1}$. The value of phase velocity ($v_p = \omega/k$) obtained from the results of the FD method is $0.47 \pm 0.12 \text{ [km/s]}$. The rotation velocity of $E_r \times B$ drift ($v_\theta$) and diamagnetic drift ($v_d$) are given by

$$v_\theta = E_r / B, \quad v_d = \frac{kT_e}{eB \rho_m^2} \frac{1}{1 + k^2 \rho^2}$$

respectively, where $E_r = -\partial \Phi_e(r) / \partial r$ ($\Phi_e$ is the plasma potential in the central.), $\kappa$ is the Boltzmann constant, $e$ is the charge of an electron, $T_e$ is the electron temperature, $B$ is the magnetic field,
\( L_n \) is the density scale length, \( \rho = (m_i \kappa T_e/e^2 B^2)^{1/2} \), and \( m_i \) is the ion mass. The phase velocity \( (v_p) \) can be calculated by
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v_p = |v_d - v_\theta|.
\] (3.2)

Calculated value of \( v_p \), using the plasma parameters measured by other diagnostics, such as YAG-TS, GNBP, and the microwave interferometer system, is 0.51 ± 0.13 [km/s]. The phase velocities of fluctuations with frequency of about 3.2 kHz obtained by using FD method and calculated value obtained by using plasma parameters are comparable. We can successfully obtain the wave number and phase velocity of the low frequency density fluctuation by using FD method.

4 Summary

The FD method was applied to the GAMMA10 plasma in order to measure the low frequency density fluctuations in detail. We could successfully obtain the wave number and phase velocity of the low frequency fluctuation. The every FD signals are obtained between 50 ms and 250 ms with sampling rate of 100 kS/s in the single plasma shot. We can study fluctuations in plasmas in detail by using the FD method system with changing the plasma heating sequences.

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