Density Fluctuation Measurements Using FIR Interferometer on HL-2A Tokamak *

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Density fluctuations were first measured in the core region of HL-2A tokamak plasma using a newly developed multi-channel FIR interferometer system. In divertor ohmic discharges, we measured the radial density fluctuation levels of 5%, which increase to 10–20% during the appearance of MHD activity. Most of the power density in the density fluctuation spectrum is directly associated with $m = 2$ tearing modes. The fluctuation levels reduce to 1/3 and plasma confinement is improved during off-axis electron-cyclotron-resonance heating (ECRH).

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The effects of MHD activities on plasma confinement and the disruption-free operation of a tokamak reactor remain hot issue in fusion research. It is important to measure equilibrium and fluctuating profiles to gain insight into the physics underlying these instabilities and their effect on the energy and particle confinement. Many new experimental tools have been developed to measure and to characterize the fluctuations of plasma parameters and in particular the electron density. For example, CO_2 laser scattering diagnostic[1] can give the relative profile of density fluctuations, Doppler reflectometry[2] and beam emission spectroscopy[3] have a rather good spatial resolution of the order of 1 cm, whereas they need repeated discharges to scan the profile using several identical shots. From these techniques, it appears difficult to provide the absolute value of the density fluctuation with good time scale of the order of a few milliseconds. Density fluctuation measurement by interferometer can measure the absolute value of the fluctuations from the refractive index integrated along the probing laser beam. This method has been used in reversed-field pinch (RFP[4] and MST[5,6]), but only few experimental results are reported in tokamak.[7]

In this Letter, we present the capability of the FIR interferometer to measure density fluctuation profile and give the first experimental results on HL-2A tokamak. The phase measurement allows absolute calibration of the fluctuation amplitude while multichords generate information on the spatial distribution. Low frequency density fluctuations are observed during ohmic and wave heating discharges.

HL-2A[8] is a middle size tokamak (major radius $R = 1.65$ m, minor radius $a = 0.4$ m) with a closed divertor, whose experimental programme includes a focus on basic physics studies of fluctuations and transports. It can be operated with plasma current up to 500 kA, toroidal field 2.8 T , average line electron densities of $5 \times 10^{13}\,\mathrm{cm}^{-3}$ and discharge duration of 5 s with single-null divertor or limit configuration.

Recently, a new multi-channel, horizontal viewing, heterodyne FIR laser interferometer[9] has been constructed and applied on HL-2A tokamak. The laser source operated at 337 μm and the cavity length of 6 metres. The interferometer phase shift Φ is given by

$$\Phi = A \int n_e dl, \tag{1}$$

where n_e is electron density, the integral is taken along the path length of a chord, and A has the value of 3.31×10^{14} (note that the interferometer is a double-pass through the plasma). In order to obtain density information from the phase shift directly, a rotation grating (diameter 176 mm, number of grooves 1320) is used to produce 10–50 kHz Doppler shift. The eight interferometer chords with spaced 7 cm each other are arranged at r = 24.5, 17.5, 10.5, 3.5, −3.5, −10.5, −17.5 and −24.5 cm. The eight probing beams enter the vacuum chamber through eight Φ50 mm windows. The 13 mm probing beam waists are fixed in the centre of plasma. The eight chords interferometer data are routinely sampled at 1 MHz. A minimum measurable phase shift of 1/33 fringe (density sensitivity of $1.7 \times 10^{11}\,\mathrm{cm}^{-3}$) has been obtained by implementation of high power source of radiation (up to 300 mW), high response detector and digital phase comparator. As a consequence of using this new diagnostics system, the density fluctuation and density sawtooth (the details have been previously described[9]) can be first resolved on HL-2A tokamak.

To identify the plasma fluctuation mode, a 10-position toroidal pick-up coil array and an 18-position

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coil poloidal array[8] are available to monitor the equilibrium and fluctuating magnetic fields. The multi-coil array permits the magnetic fluctuation to be decomposed into their Fourier harmonics, allowing the poloidal (m) and toroidal (n) mode number spectra to be determined.

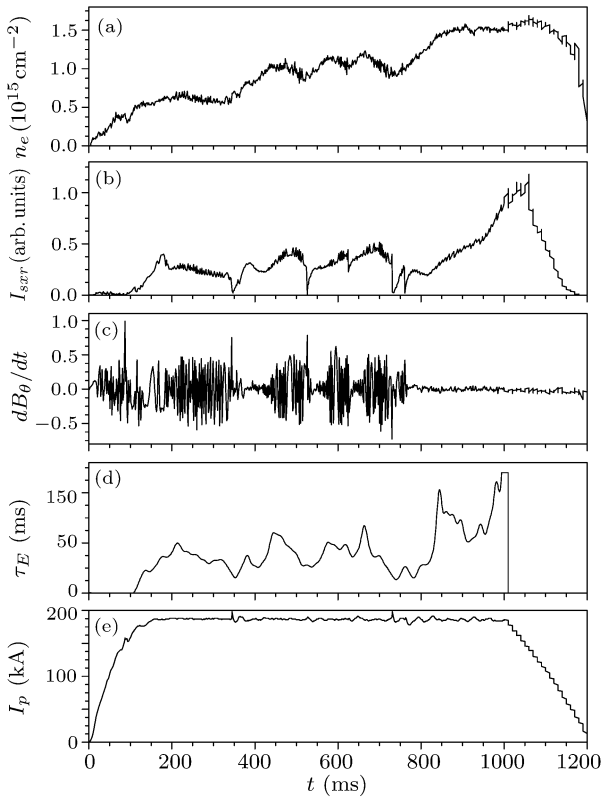

Fig. 1. Divertor discharge signals of shot No 8660: (a) plasma line density, (b) soft x-ray intensity, (c) Mirnov signal, (d) plasma energy confinement time, (e) plasma current.

In Fig. 1, the shot 8660 divertor discharge waveform on the HL-2A device is shown for an ohmic deuterium plasma with $I_p = 187\,\mathrm{kA}$, $B_t = 1.5\,\mathrm{T}$, and $\bar{n}_e = 2\times10^{13}\,\mathrm{cm}^{-3}$. One can see that the energy confinement has been limited by turbulence of plasma: during plasma current rises up high MHD fluctuation appear on density, soft x ray and Mirnov signals. As is expected, the plasma energy confinement time τ_E (Fig. 1(d)) is lower when plasma fluctuated. After discharge time $t = 800\,\mathrm{ms}$, the MHD fluctuation disappears, then the energy confinement time increases obviously. To examine the fluctuations in the interferometer signals, the density fluctuation time traces from 612 to 620 ms are shown in Fig. 2. The low-frequency oscillations with period roughly 1ms are presented at all the chords signals. A phase delay within each channel location is revealed from line (d) ($r = 3.5\,\mathrm{cm}$) to line (e) ($r = 24.5\,\mathrm{cm}$). We observe a minimum line density fluctuation appeared in the plasma centre (the magnetic axis), and a π-phase change observed on the chord of $r = 24.5\,\mathrm{cm}$ ($0.61a$). By computing the delay phase between two adjoining chords, one can estimate the mode poloidal rotation speed which is about 1100 m/s, and the direction of rotation is in the election diamagnetic direction.

Using the FFT technique, the frequency power spectrum, averaged over 100 ms, for typical chord-averaged data is analysed in Fig. 3. Correlation between different FIR chords demonstrate that these fluctuations are highly coherent and in phase across the entire plasma column (Fig. 3(b)). The spectrum is peaked strongly at $f = 1.09\,\mathrm{kHz}$ (see Fig. 3(a)). In the low frequency range ($< 10\,\mathrm{kHz}$), density and magnetic fluctuations are also very coherent. By correlating individual interferometer chord with individual poloidal harmonics, which is obtained from a magnetic pick-up coil array, we can extract the density fluctuation associated with the $m = 2$ magnetic tearing modes.

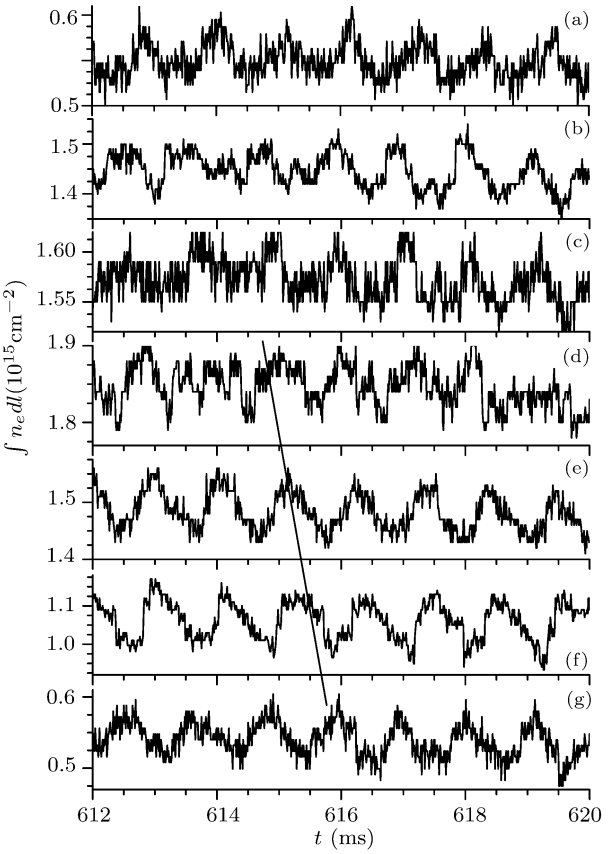

Fig. 2. Interferometer signals for shot 8660 by time windows of 8ms, on which the MHD oscillation was developed clearly, for interferometer chords $r = 17.5$, 10.5, 3.5, -3.5, -10.5, -17.5 and $-24.5\,\mathrm{cm}$ [(a)–(g)], respectively. The line connects maxima showing a time delay from chord to chord.

An accurate knowledge of the amplitude profiles is important for the identification of mode and in comparison with the theoretical models. The multi-channel interferometer can provide line-integrated

measurements of $\int n_e dl$, where $n_e = n_{\rm equi} + \tilde{n}_e$, the equilibrium and fluctuating quantities. The spectrum is peaked strongly at a dominated frequency, so the fluctuations is determined by signals at frequencies above 0.1 kHz, the equilibrium density can be regarded

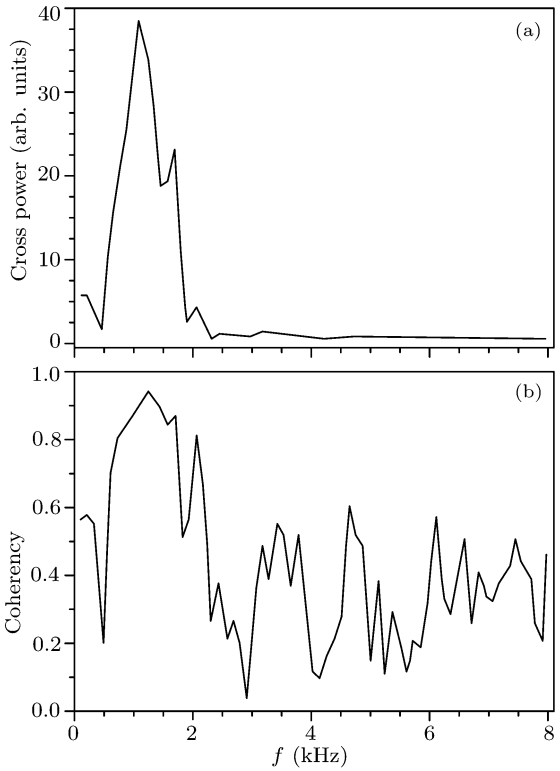

Fig. 3. Shot 8660 power spectra and coherency curves for interferometer chords ($r = 17.5$ cm and 24.5 cm).

as the average density. Upon Abel inversion we obtain radial profiles of the local density and density fluctuation amplitude. Figure 4 shows the density fluctuation spatial distribution of shot 8660. We observe that the $m = 2$ MHD instability region enters the interferometer line of sight at the radial, where a striking density depression is observed in the central area. The density fluctuation profiles are generally hollow. The region of space where the fluctuation amplitude peaks ($r \sim 0.65a$) also corresponds to the steep density gradient region of the plasma density profile. This implies that the large equilibrium density gradient in the edge is deformed in space by the perturbed magnetic field lines. In Figs. 4(i) and 4(ii), we can see that the width of density fluctuation in space is about $0.4a$(16 cm), which is somewhat larger than the measured results of pick-up coils. This implies that we are limited by the spatial resolution, especially at the edge. However, despite this limitation, these data provide a good indication of what one might expect the density fluctuation distribution to look like. In order to estimate the fluctuation level quotient one can make the fluctuating line integral dividing the line density as seen in Fig. 4(iii). It is shown that the fluctuation in the centre is lower with a line-integrated fluctuation level of 5%, and the fluctuation in the confinement area ($r \sim 0.65a$) is peak with a line-integrated fluctuation level of 20%. The local fractional fluctuation level is obtained by $\tilde{n}_e$ divided into local density $n_e(r)$ as shown in Fig. 4(iv). We find that in the peak point the absolute calibration of the fluctuation amplitude is about 5×10^{12} cm^{-3} and the local fractional fluctuation level is about 30%.

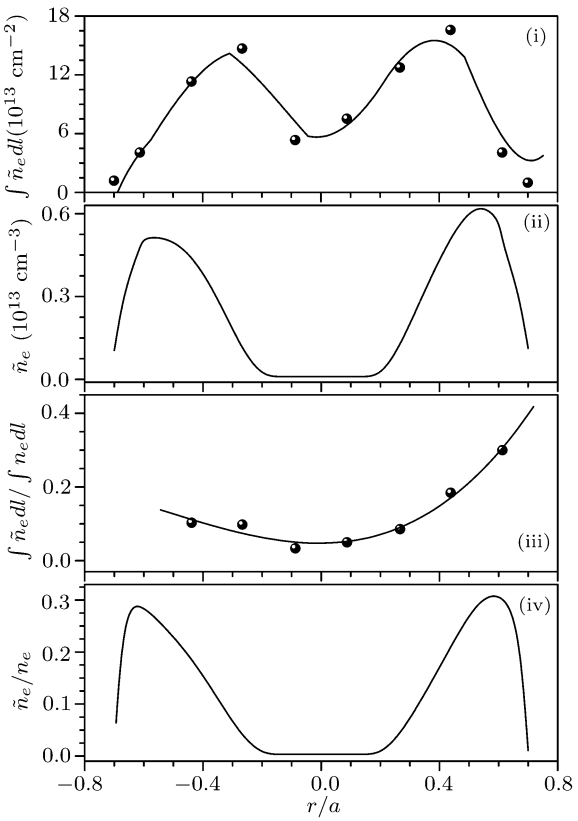

Fig. 4. Density fluctuation spatial distribution of shot 8660: (i) line-integrated $\int \tilde{n}_e dl$, (ii) inverted $\tilde{n}_e$, (iii) line-integrated fractional fluctuation level $\int \tilde{n}_e dl / \int n_{\rm equi} dl$, and (iv) local fractional fluctuation level $\tilde{n}_e / n_e$.

It has been experimentally demonstrated on many devices that with localized electron cyclotron resonance heating, the $m = 2$ MHD oscillations could be suppressed, and the energy confinement should be enhanced. During off-axis ECRH discharges on HL-2A, a dramatic reduction in the chord-integrated density fluctuations is observed, and particle confinement is enhanced. Figure 5 shows the typical density fluctuation amplitude profile with and without ECRH. The density perturbation for $m = 2$ mode is approximately $\int \tilde{n}_e dl / \int n_{\rm equi} dl \sim 12\%$ in the absence of the ECRH. During ECRH the density fluctuation amplitude drops most significant in all the radial directions, especially in plasma edge where reductions of threefold have been observed. This indicates that the off-

axis electron-cyclotron-resonance wave should deposit close to the $m = 2$ magnetic field surface, which also corresponds to the simulation result by EFIT code and the measured result by SX ray. Reduction of core density fluctuations strongly correlates with $m = 2$ mode suppression and improved energy and particle confinement.

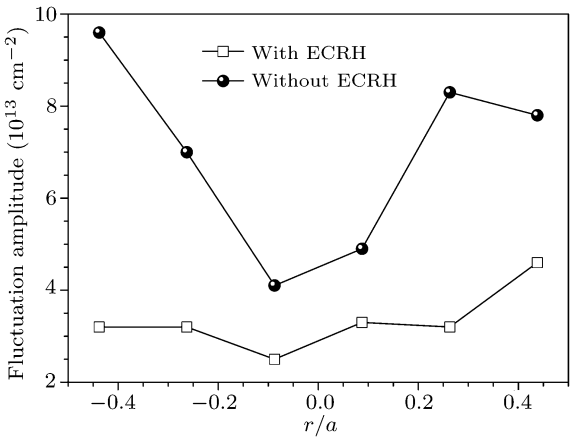

Fig. 5. Line density fluctuation amplitude of shot 7844 before and during ECRH launch into plasma vs unitary minor radius r/a.

In summary, electron density fluctuations have been first measured in the HL-2A divertor tokamak using a newly developed high-signal-to-noise-ratio multichannel HCN laser interferometer. The fluctuation absolute amplitude is obtained while multi-chords generate information of the spatial distribution. Density fluctuations associated with magnetic islands are measured to have $\tilde{n}_e/n_e \sim 5$–20%. The fluctuation level is reduced of threefold in the edge and plasma particle confinement is improved during off-axis ECRH.

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