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Core density gradient fluctuation measurement by differential interferometry in the helically symmetric experiment stellarator[a)]

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The interferometer system on the Helically Symmetric eXperiment (HSX) stellarator uses an expanded beam and linear detector array to realize a multichord measurement. Unlike conventional interferometry which determines the plasma phase shift with respect to a reference, directly evaluating the phase between two adjacent chords can be employed to measure the change in plasma phase with impact parameter. This approach provides a measure of the equilibrium density gradient or the density gradient fluctuations and is referred to as differential interferometry. For central chords, measurements are spatially localized due to a geometrical weighting factor and can provide information on core density gradient fluctuations. The measurement requires finite coherence between fluctuations in the two spatially offset chords. This technique is applied on the HSX stellarator to measure both broadband turbulence and coherent modes. Spatial localization is exploited to isolate core turbulence changes associated with change in magnetic configuration or heating location. [http://dx.doi.org/10.1063/1.4730999]

I. INTRODUCTION

Multichannel interferometry has been successfully utilized to measure equilibrium electron density spatial distribution and its fluctuations on the Helically Symmetric eXperiment (HSX) (Refs. 1 and 2). HSX is a new concept stellarator in which the symmetry of magnetic field strength is restored along the helical direction.[3] Experimental results demonstrated success in reducing neoclassical transport in the low collisionality regime through this optimization concept.[4] Anomalous transport induced by plasma instabilities and turbulence will likely play an important role in plasma confinement in the quasihelically symmetric stellarator. A limitation of the conventional interferometric measurement is that the results are line-integrated, whereas spatially localized information from the plasma core is highly desired for physics studies. Differential interferometry has been shown to measure the electron density and its gradient fluctuations successfully in Madison Symmetric Torus (MST) reversed-field pinch.[5] This approach, which determines the phase difference between closely spaced chords, provides a localized measurement of core fluctuations and is complementary to density fluctuations measurements by interferometry and far-forward scattering previously applied on HSX.

II. DIFFERENTIAL INTERFEROMETER SYSTEM

Conventional interferometry determines the plasma induced phase of probe beam with respect to an external reference, providing a measure of $\phi(x,t) = r_e\lambda \int n_e(r,t)\,dz$, where $r_e = 2.82 \times 10^{-15}$ m is the classical electron radius, $x = R - R_o$ is the chord impact parameter, λ the probe wavelength, n_e the electron density, and dz the path through the plasma (all in units of meter). However, this measurement is line-integrated and the local density is obtained by performing an Abel inversion. For simplicity, the formula for cylindrical geometry is given by

$$n(r) = -\frac{1}{\pi r_e \lambda} \int_r^a \frac{\partial \phi(x)}{\partial x} \frac{dx}{\sqrt{x^2 - r^2}}. \tag{1}$$

From Eq. (1), one can see that the spatial derivative of ϕ (x) is required to determine local density. This derivative can be written as

$$\frac{\partial \phi(x)}{\partial x} = r_e\lambda \int \frac{\partial n(r)}{\partial r}\frac{\partial r}{\partial x} dz = r_e\lambda \int \frac{\partial n(r)}{\partial r}\frac{x}{r} dz$$
$$= r_e\lambda \int \frac{\partial n(r)}{\partial r} \cos(\theta) dz, \tag{2}$$

where $\cos(\theta) = x/r$ is a geometrical weighting factor.

A detailed description of the multichannel interferometer system on HSX can be found in Refs. 1 and 2. The electromagnetic wave source is a bias-tuned Gunn diode oscillator of frequency 96 GHz with passive solid-state tripler providing output at 288 GHz with power of ~5 mW. Heterodyne interferometry measurement is accomplished by frequency sweeping source (~120 MHz in 1 μs) and maintaining a 4 m path difference between the probe and reference legs leading to a 0.750 MHz intermediate frequency signal. All signals are digitized at 2 MHz sampling. Both the probe and reference beams are expanded in one dimension using parabolic beam expansion optics so that the beam covers the available port view of 2.5 cm × 13.5 cm. A linear detector array is used to realize a multi-chord measurement. The detector array

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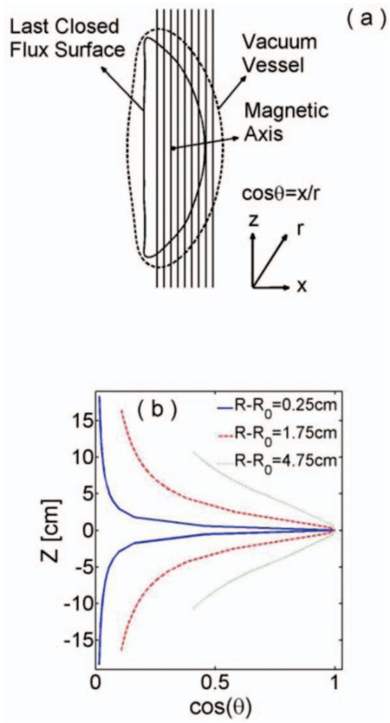

FIG. 1. (a) Schematic of differential interferometer system and (b) geometrical weighting factors for HSX QHS configuration.

consists of nine Schottky-diode corner-cube mixers with 1.5 cm spacing. An array of nine HDPE lens with $\Delta x = 1.5$ cm width is positioned in front of the mixer array and focuses a portion of the probe beam on each detector. The phase between signal from each mixer and a reference is the standard interferometry scheme. However, simultaneously a direct measurement of the phase between two adjacent chords can be used to provide a differential interferometry diagnostic as shown in Fig. 1(a). The geometrical weighting factor described earlier varies strongly with chord position and is calculated for central and edge chord pairs for quasi-helically symmetric (QHS) configurations as shown in Fig. 1(b). One can see that when impact parameter is close to zero (near the magnetic axis), the geometrical weighting factor becomes very narrow, approaching a delta function. This leads to a spatially localized measurement of the density gradient and its fluctuations, i.e., $\partial\phi/\partial x \approx \partial n/\partial r$. In this configuration of the interferometer system, density fluctuations and density gradient fluctuations can be measured simultaneously.

The interferometer system on HSX has been successfully used to measure the equilibrium density profile and density fluctuations.[6,7] Since the density fluctuation measurement is line-integrated, information on core localized effects can only be inferred by comparing edge and central chords. As an example, three chord data for a quasi-helically symmetric HSX discharge are shown in Fig. 2(a), where fluctuations for the central chords ($x = 1$ and -0.5 cm) are larger than for the edge chord ($x = 4$ cm). In Fig. 2(b), we see time histories of the density gradient fluctuations from the differential interferometer for chords at $x = 0.25$, 1.75, and 4.75 cm. As an example, for differential interferometer position x = 0.25, the system measures the phase difference between chords located at $x = -0.5$ and 1.0 cm. The ability of differential interferometry to measure core-localized density gradient fluctuations requires finite coherence between the signals from two adjacent chords. This has been experimentally established and is shown in Fig. 2(c), for chord pairs at $x = -0.5$ and 1.0 cm. The coherence is calculated from the phases of the two adjacent chord signals relative to reference signal, the data are taken from time window (830–849) ms of 28 similar shots. Finite coherence is evident for the frequency ranges f < 15 kHz and 35 < f < 100 kHz. These data are for the quasi-helically symmetric magnetic configuration in HSX, with 50 kW electron cyclotron resonance heating [ECRH] applied off-axis inboard at r/a ~0.2. Differential interferometry measurements clearly establish the existence of large fluctuations in the plasma core that could only be inferred from the standard interferometry data. Combining the two interferometers schemes can be used to measure the density and its gradient fluctuations simultaneously.

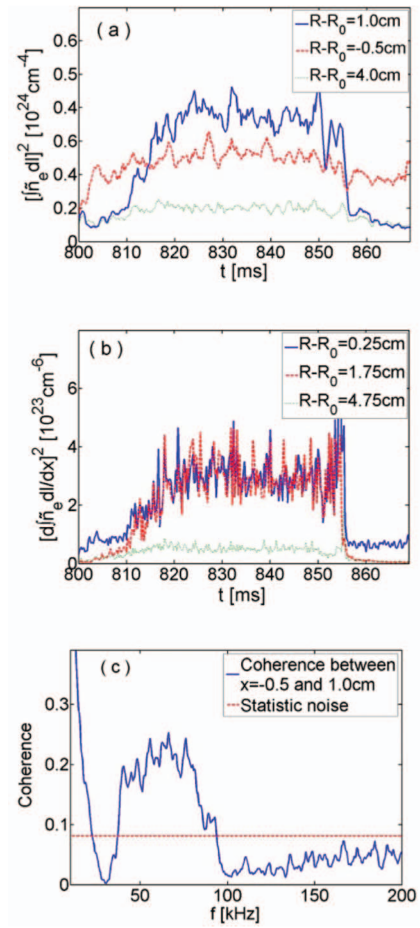

FIG. 2. Time histories of (a) line-integrated density and (b) density gradient fluctuations for different viewing chords. Plasmas have inboard ECRH at r/a = 0.2; (c) coherence between two central chords at $x = -0.5$ cm and 1.0 cm. Plasma onset occurs at $t = 800$ ms.

The time series data can also be used to do frequency spectral analysis. FFTs are done by taking multiple 2 ms time windows averaged over total 25 ms. Figure 3(a) shows power spectra for two interferometer chords located at the plasma core ($x = 1$ cm) and near edge ($x = 4$ cm). The dashed lines are for a QHS plasma with 50 kW ECRH at the magnetic axis; the solid lines are for a similar shot except the heating location is moved to inboard at r/a ~0.2. The dotted line is the

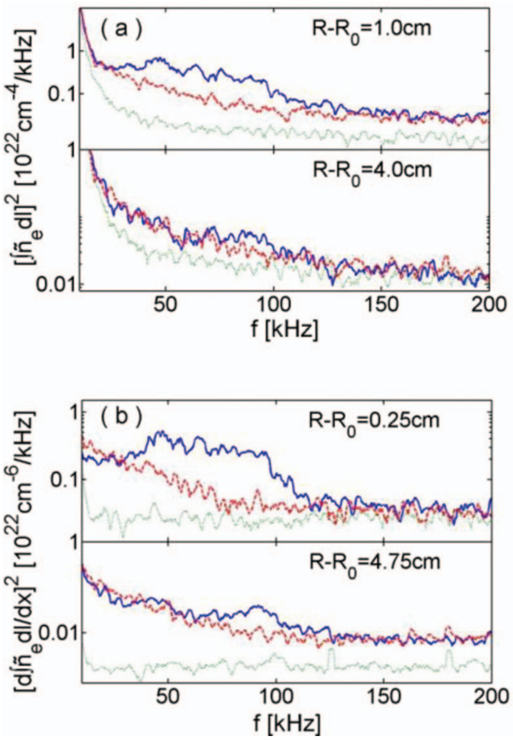

FIG. 3. Density fluctuation frequency spectra for same shot comparing measurements by (a) standard interferometer; (b) differential interferometer. Solid lines are for plasma ECRH inboard at r/a ∼ 0.2; dashed lines are for plasma with ECRH at magnetic axis, and dotted lines are noise.

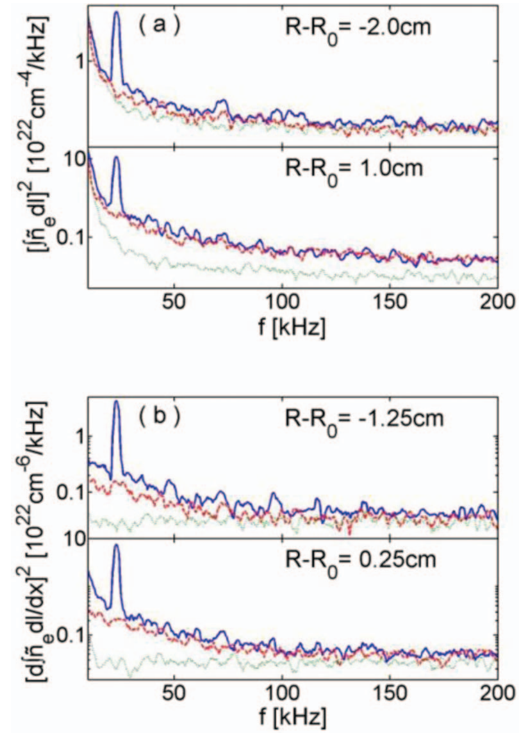

FIG. 4. Density fluctuation frequency spectra for plasmas with QHS and non-axisymmetric (Mirror) magnetic configurations. (a) Standard interferometer; (b) differential interferometer. Solid lines are for plasma without symmetry (Mirror); dashed lines are for plasma with symmetry (QHS), and dotted lines show measurement noise.

phase noise. One can see that with plasma heating off-axis, the fluctuations are larger for the central chord compared to the edge chord implying a change in the core density fluctuation level. Measurement of density gradient fluctuations are shown in Fig. 3(b), where a significant increase is noted for the core differential interferometry location. Only a minor increase is observed for the differential measurement nearer the edge. This confirms that the core density fluctuations are indeed increasing when the ECRH is moved inboard from the magnetic axis. Also note that the noise levels are reduced for the differential measurement as both probe beams use common optics and travel a largely common path which leads to vibration cancellation and reduced phase noise. On HSX, the magnetic configuration can be manipulated by changing the current in the auxiliary coils. In Fig. 4, we see the density fluctuation frequency spectra for shots with and without quasi-helical symmetry. These plasmas are heated with 100 kW ECRH on the magnetic axis. Plasma toroidal magnetic field $B_t = 1$ T and electron density, $n_e \sim 4.2 \times 10^{12}$ cm^{-3}. One can see that a coherent mode is excited for the non-axisymmetric configuration while the differences in broadband density fluctuations remain minimal. While this coherent mode is observed by both interferometry techniques, differential interferometry measurements [shown in Fig. 4(b)] confirm this mode exists in the plasma core.

III. CONCLUSION

Application of the differential interferometry technique on HSX has been successfully demonstrated by measurement of fluctuation activity originating in the plasma core. Using this approach, both density fluctuations and density gradient fluctuations can be measured simultaneously. In the future, these measurements along with those of plasma flow and kinetic profiles will be used to compare with output of 3D Gyrokinetic code simulation. The goal is to identify the origins of the density fluctuations and transport in the quasi-helical stellarator configuration. By comparing results from various magnetic configurations, including axisymmetric and non-axisymmetric, information will be obtained to assist in optimizing the design of future stellarators

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