Use of the Far Infrared Tangential Interferometer/Polarimeter diagnostic for the study of rf driven plasma waves on NSTX[a)]

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A rf detection system for waves in the 30 MHz range has been constructed for the Far Infrared Tangential Interferometer/Polarimeter on National Spherical Torus Experiment (NSTX). It is aimed at monitoring high frequency density fluctuations driven by 30 MHz high harmonic fast wave fields. The levels of density fluctuations at various radial chords and antenna phase angles can be estimated using the electric field calculated by TORIC code and linearized continuity equation for the electron density. In this paper, the experimental arrangement for the detection of rf signal and preliminary results of simulation will be discussed. © *2010 American Institute of Physics.* [doi:10.1063/1.3499506]

I. INTRODUCTION

A spherical torus (ST) can confine a high β plasma, which may be required for optimal fusion power plant applications. However, there is insufficient space in the center stack of a ST for an Ohmic heating system, compared to a conventional tokamak, so another means of generating the confining plasma current may be needed. Because the plasma dielectric constant in a spherical torus is large, $(\omega_{pe}/\omega_{ce})^2 \sim 10-100$, conventional wave heating and current drive techniques, such as electron cyclotron heating and lower hybrid current drive, cannot be used because of the accessibility problem. Ono predicted that high harmonic fast waves (HHFWs) are able to access high dielectric plasmas and heat electrons efficiently via transit time magnetic pumping and electron Landau damping.[1] In the National Spherical Torus Experiment (NSTX), a HHFW system operating at 30 MHz (corresponding to $\sim 8\ \omega_{cH}$ near the magnetic axis) with $\sim$6 MW rf power is being used to assist plasma ramp-up and sustain the plasma.

The HHFW antenna consists of 12 large strap-antenna array, which covers 90° in toroidal direction. The 12 straps are fed by six decoupled sources. The mth and $(m+6)$th elements of the array are driven by one transmitter and connected, forming a half-wave resonant loop, which results in 180° out-of-phase currents on the pair of straps. Active phasing control between the transmitters and the consequent phase difference between adjacent antenna elements can improve the launched wave spectrum and drive current as the plasma β increases.[2]

Depending on the antenna phase angle, heating efficiencies and current drive efficiencies in the good confinement region can vary significantly because of the rf power losses in the edge of the plasma. In order to understand the mechanisms controlling the wave dynamics, it is important to obtain the information on the rf electric field distribution in the plasma. It is possible to predict the field distribution using wave simulation codes such as TORIC and AORSA, but it is crucial to verify the accuracy of the theoretical simulations with experimental measurement.

Many attempts have been made to detect the rf waves using reflectometry, such as in the DIII-D (Ref. 3) and NSTX,[4] and phase contrast imaging in Alcator C-mod.[5] rf waves in the plasma induce an electric field that subsequently drives density fluctuations, which may be detectable using an interferometer to measure the phase oscillation of the probe beam caused by the fluctuating density. Interferometry using a far infrared (FIR) laser is a widely used plasma diagnostic method for electron density measurements in tokamaks that could be utilized to measure the rf-induced density fluctuations.

The Far-Infrared Tangential Interferometer/Polarimeter (FIReTIP) was intended to provide the temporal measurement of the plasma electron density (n_e) profile and B_T profiles for the NSTX.[6] This paper describes the novel use of FIReTIP to study rf-induced density perturbations with the use of a heterodyne detection system with a wide bandwidth for wave studies. FIReTIP can measure the density information at six different radial positions. This multichord measurement can be used for reconstructing the radial profile of rf density fluctuations and fields. A prototype circuit for rf measurement was constructed and installed at the chord that was expected to give the strongest signal. In order to determine the best location for the chord, the full-wave TORIC

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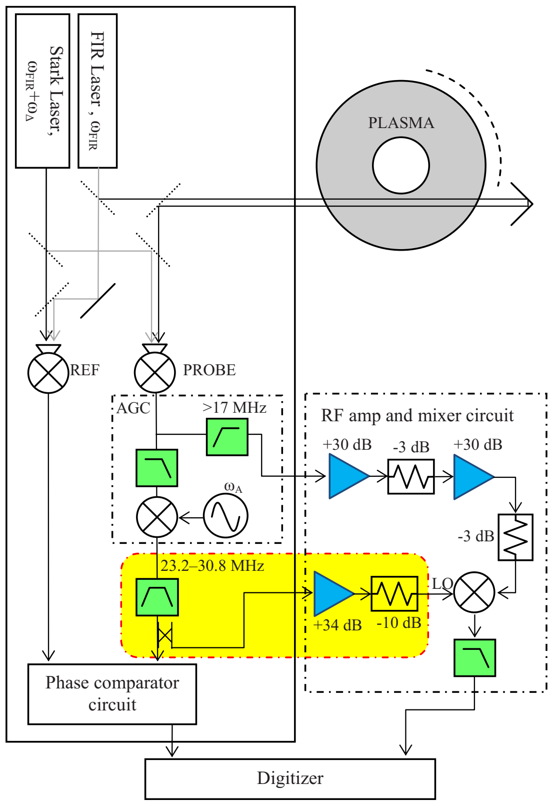

FIG. 1. (Color online) The schematic diagram of the FIReTIP heterodyne detection circuit with second stage rf mixer circuit. AGC stands for the automatic gain controller circuit.

code was used to calculate the spatial distribution of rf electric field, which is directly proportional to the HHFW-driven density fluctuations.

II. FIRETIP SYSTEM

There are two possible diagnostic systems that may be able to measure the rf density fluctuations in NSTX: the high-k scattering system and the FIReTIP system. The high-k scattering system with a 280-GHz carcinotron can measure the frequency spectra of density fluctuations for five discrete wave numbers with a minimum detectable $\delta n_e(\mathbf{k},\omega)/n_e \sim 10^{-6}$ at a local position.[7] Though the FIReTIP system measures line-integrated densities with a minimum detectable $\delta n_e(\omega)\mathrm{L} \sim 10^{12}\ \mathrm{cm}^{-2}$, where L is the length of the FIReTIP chord, the multichord capability of FIReTIP has the advantage of potentially providing a radial profile measurement for a single discharge.

FIReTIP is equipped with a 119-μm methanol laser with $\sim$60 mW power pumped by CO_2 laser. The FIR beam is split into seven, with one used as reference beam and the other six beams used as probe beams passing through the plasma tangentially with different tangency radii as described in Sec. III. Seven beams are mixed with the local oscillator (LO) by a Schottky diode as shown in Fig. 1. The LO is a Stark tuned laser, which operates at a frequency of 5 MHz away from that of the other FIR laser.

FIR beams passing through the plasma experience a phase advancement, $\Delta\Phi_e$, which is proportional to the product of the line-averaged plasma density, n_e and path length, L. Suppose that the rf waves induce density fluctuations, $\tilde{n}_e$, oscillating with small amplitude $\tilde{n}_{eo} \ll \bar{n}_e$ at the same frequency as the rf waves, ω_{rf}. Here, $\bar{n}_e$ is the equilibrium density, which varies slowly compared to ω_{rf},

$$n_e(t) = \bar{n}_e + \tilde{n}_{eo}\cos\omega_{\mathrm{rf}}t. \tag{1}$$

Thus, the resulting the phase change is given by $\Delta\Phi_e = \Delta\bar{\Phi}_e + \Delta\tilde{\Phi}_{eo}\cos\omega_{\mathrm{rf}}t$. The perturbed electric field of the FIR laser can be described as

$$E_{\mathrm{FIR}}(t) = E_o \exp i(\omega_{\mathrm{FIR}}t + \Delta\Phi_e). \tag{2}$$

This laser beam is then down-mixed with the Stark laser with a frequency, $\omega_{\mathrm{FIR}}+\omega_\Delta$ $(\omega_\Delta/2\pi \sim \pm 5\ \mathrm{MHz})$ at the Schottky mixer. $\Delta\bar{\Phi}_e$ can be considered as a constant because $(\partial/\partial t)(\Delta\bar{\Phi}_e) \ll \omega_{\mathrm{rf}} \ll \omega_{\mathrm{FIR}}$. Hence, the IF signal from Schottky mixer is, using the Jacobi–Anger identity,

$$S_{\mathrm{SM}}(t) = S_o \exp i(\Delta\bar{\Phi}_e - \omega_\Delta t) \times \sum_{n=-\infty}^{\infty} i^n J_n(\Delta\tilde{\Phi}_{eo})\exp i(n\omega_{\mathrm{rf}}t). \tag{3}$$

In order to detect the high frequency density fluctuation, the second stage rf amp and mixer circuit was added to the FIReTIP heterodyne circuit. rf-related signals are extracted from the output of the preamplifier following the Schottky diode in an automatic gain controller (AGC) circuit. As shown in Fig. 1, the signals are amplified and mixed with the AGC output.

The output from the Schottky diode is split into two components. One is the n=0 term in Eq. (3), which contributes to the $\bar{n}_e$ calculation, and all the other terms except for $n=\pm 1$ will be filtered out at the rf mixing circuit. Thus, taking the real part of the $n=\pm 1$ terms, which are detectable by the rf amp and mixer circuits, and applying the asymptotic approximation to the Bessel function, $J_1(x) \sim x/2$ where $0 < x \ll 1$, the rf input signal to the mixer can be described as

$$S(t) = S_o \cos\Delta\bar{\Phi}_e \times \Delta\tilde{\Phi}_{eo} \times [\sin(\omega_\Delta + \omega_{\mathrm{rf}})t + \sin(\omega_\Delta - \omega_{\mathrm{rf}})t] \tag{4}$$

where the corresponding frequencies are 25 and 35 MHz. As shown in Eq. (4), the signal is modulated with $\cos\Delta\bar{\Phi}_e$. By mixing the coupled low frequency signal from AGC output with the high frequency signal from AGC at the mixer in the rf circuit, both down-mixing and demodulation of $\cos\Delta\bar{\Phi}_e$ can be accomplished. In other words,

$$S(t) = S_o\Delta\tilde{\Phi}_{eo}[\sin(\omega_{\mathrm{rf}} - \omega_A)t + \cos(2\Delta\bar{\Phi}_e) \times \sin(2\omega_\Delta + \omega_A - \omega_{\mathrm{rf}})t]. \tag{5}$$

To find the most efficient chord for rf signal observation using this circuit, the TORIC code was used to predict the distribution of the rf electric field that drives the electron fluctuation.

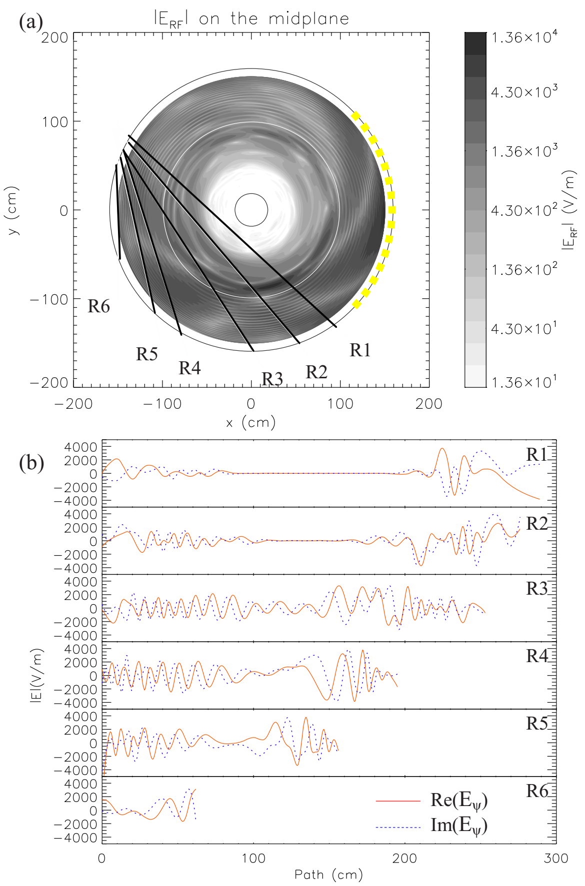

FIG. 2. (Color online) (a) rf electric field amplitude on the NSTX midplane calculated by TORIC with equilibrium data of shot number 130608 at 0.335 s and antenna phase angle=180°. The lines R1–R6 on the midplane represent the FIReTIP chords with tangency radii of 32, 57, 85, 118, 132, and 150 cm. (b) E_ψ component along the each FIReTIP chord.

III. DENSITY FLUCTUATION AMPLITUDE PREDICTION WITH TORIC

The rf electric fields can be evaluated by the TORIC full wave code, which solves the Maxwell equations in toroidal axisymmetric plasmas for a fixed rf frequency assuming a linear quasilocal hot plasma dielectric response of plasma.[8,9] One execution of TORIC gives the two-dimensional distribution of the sum of the poloidal components of rf electric field on the poloidal cross section for a given toroidal mode, n_φ. The three-dimensional structure of the rf electric field is then constructed from a weighted sum of multiple TORIC results with different n_φ (from 22 to 31), where the weighting factor, $w(n_\varphi)$, is calculated from the power spectrum of HHFW antenna. Figure 2(a) shows the contour plot of the rf electric field amplitude on the NSTX midplane with six FIReTIP chords at different tangency radii; Fig. 2(b) shows the electric fields along the FIReTIP chords.

Assuming that the measured density fluctuations are dominated by the rf field driven oscillations rather than by local turbulence, the rf electric field calculated by TORIC can then be related to the electron density fluctuations through the linearized electron continuity equation,

$$\tilde{n}_{eo} = \frac{i}{\omega_{\rm rf} e} \nabla \cdot \tilde{\mathbf{J}}_{eo}, \tag{6}$$

where $\tilde{n}_e(t)=\tilde{n}_{eo}\exp(-i\omega_{\rm rf}t)$ and $\tilde{\mathbf{J}}_e=\tilde{\mathbf{J}}_{eo}\exp(-i\omega_{\rm rf}t)$

In a hot, inhomogeneous plasma, the high frequency electron current density is related to rf electric field by a constitutive relation, which is a complicated integral equation. Here, for simplicity, the local uniform and cold plasma approximation can be used for the constitutive relation in order to estimate the magnitude of the expected HHFW-driven density perturbation. Hence, $\tilde{\mathbf{J}}_e=\bar{\bar{\boldsymbol{\sigma}}}_{e,\rm cold}\cdot\tilde{\mathbf{E}}$, where $\bar{\bar{\boldsymbol{\sigma}}}_{e,\rm cold}=-i\omega\varepsilon_o\bar{\bar{\boldsymbol{\chi}}}_{e,\rm cold}$ and where $\bar{\bar{\boldsymbol{\chi}}}_{e,\rm cold}$ is the cold plasma electron susceptibility tensor calculated from the equilibrium reconstruction code EFIT for the magnetic field and the multipoint Thomson scattering diagnostic for the electron density for NSTX. Thus, the amplitude of the density fluctuation detected by FIReTIP can be predicted from the line integral of the following equation along the FIReTIP chords:

$$\tilde{n}_{eo} = \frac{\varepsilon_o}{e} \nabla \cdot (\bar{\bar{\boldsymbol{\chi}}}_e \cdot \tilde{\mathbf{E}}). \tag{7}$$

Assuming in the HHFW regime that $E_z \ll E_\perp$, $\omega \sim k_\perp V_A$, and using conservation of Poynting flux to estimate the magnitude of the HHFW electric field in the core region for 1 MW of input power, the HHFW can be expected to drive a density fluctuation on the order of $\delta n_e \sim 9\times 10^{10}$ cm^{-3}. This is about an order of magnitude above the minimum density fluctuation detectable by the FIReTIP system, as mentioned in Sec. II. In the future, the actual hot plasma dielectric response used in the TORIC simulations will be used to calculate the actual density perturbation expected in a given NSTX discharge. However, since the HHFW-driven density perturbation is proportional to the magnitude of the wave electric field, it is likely that for the plasma parameters used in Fig. 2, the density perturbation would have been largest along the chord R3. Detailed comparisons between the experiments and the simulations will be completed when HHFW-driven density fluctuation measurements from the FIReTIP system are available.

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