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Multichannel far-infrared polarimeter-interferometer system on the MST reversed field pinch

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The multichannel far-infrared (FIR) heterodyne polarimeter-interferometer system on the Madison Symmetric Torus (MST) is now operational. The combined system consists of 11 channels with variable radial and toroidal spacing. Poloidal magnetic field is determined by measuring the Faraday rotation of the FIR laser beam after propagation through the plasma by use of a phase technique. The polarimeter has 3 mrad rms noise level and 1 ms temporal resolution while the interferometer resolution is $n_e dl = 1 \times 10^{12}\,\mathrm{cm}^{-2}$ with time response of 1 μs. Absolute calibration of the polarimeter system is achieved by use of a rotating quartz half-wave plate. The first 11-channel polarimeter measurements from MST indicate a Faraday rotation profile in good agreement with expectations from the MSTFIT equilibrium code. Future plans to reduce the polarimeter time response from 1 ms to 10 μs will allow direct measurement of magnetic fluctuations associated with global resistive tearing modes on MST. The effect of these modes on density is already clearly resolved and provides insight into the dynamics of these structures. Improving the time response will also result in lower phase noise for both the polarimeter and interferometer. [DOI: 10.1063/1.1321744]

I. INTRODUCTION

Understanding reversed-field pinch (RFP) stability and confinement requires detailed information regarding the electron particle density, current density distribution, and poloidal magnetic field. The stability of the plasma to tearing modes and other magnetohydrodynamic (MHD) events such as the sawtooth perturbation or dynamo are closely related to the current density profile. In addition, more recently, advanced RFP discharge scenarios have been achieved through modification of the current density distribution, thereby attaining access to new stability regimes and improved confinement. Motivated by the need for improved information on the spatial distribution and temporal evolution of the current density and poloidal magnetic field, the multichannel interferometer system[1,2] on MST was reconfigured to include a simultaneous polarimeter capability. Here, in addition to measuring the phase change of the laser radiation transmitted through the plasma, information on the polarization rotation is also obtained. The new polarimeter-interferometer system is being used to investigate changes in the current density profile and poloidal magnetic field associated with standard and high-confinement discharges in MST.

II. POLARIMETER-INTERFEROMETER SYSTEM

The vertically viewing, multichannel, heterodyne FIR laser polarimeter-interferometer system on MST consists of 11 discrete chords divided between toroidal locations 250° (five chords positioned at $x = R - R_o = 36$, 21, 6, -9, and -24 cm) and 255° (six chords at $x = 43$, 28, 13, -2, -17, and -32 cm). The laser signal and local oscillator beams are subdivided into nominally equal portions for each chord and the reference channel through the use of Ni-plated wire-mesh beam splitters. The FIR laser system operates at frequency 694 GHz (432.5 μm) with intermediate frequency (IF) between the dual laser cavities typically set to 750 kHz. Phase detection techniques are employed for both the polarimetry and interferometry measurements. The polarimetry technique was developed based on a rotating polarization ellipse and successfully implemented on MTX[3] and TEXT Upgrade.[4,5] This approach eliminates the need for a second detector array and is insensitive to signal amplitude changes associated with refractive effects. Contamination to the polarimeter signal resulting from plasma birefrigence is also mitigated. GaAs Schottky diode mixers (one mixer per chord) are used as the detectors for the simultaneous polarimetry and interferometry measurement. The interferometry measurement, $\int n_e\, dl$, is made by determining phase changes on the 750 kHz IF signal with respect to a reference. The Faraday rotation signal, $\int n_e B_\theta\, dl$, is extracted from the amplitude-modulated waveform at 4 kHz resulting from the rotating polarization ellipse. A schematic of the polarimeter-interferometer system is shown in Ref. 6.

A. Interferometer

The interferometer system has fast time resolution and excellent phase resolution. The upper bound on the system bandwidth is limited by laser IF of 750 kHz. To reduce the

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data load, reference and signal waveforms are digitized at 1 MHz aliasing the IF to 250 kHz and thereby limiting the interferometer bandwidth. This time response has proven sufficient to see the high-frequency density fluctuations on MST which are typically below 150 kHz. The phase information is extracted through the use of software using a numerical demodulation algorithm.[2,7] The rms phase noise for each interferometer channel is approximately 0.03 rad or about 2°. This implies a minimum line-averaged density measurement capability of $n_e dl = 1\times 10^{12}\,\mathrm{cm}^{-2}$. For the central chord of MST, a line-integrated density of $1\times 10^{10}\,\mathrm{cm}^{-3}$, approximately 0.1% of the peak density, can be measured. Since the interferometer operates on the basis of a phase measurement, absolute calibration of the measured phase change due to the plasma density and its fluctuations is easily achieved. The system resolution is sufficient to investigate small-amplitude density fluctuations associated with resistive tearing modes in MST.

Due to the toroidal separation of the interferometer chords, toroidal mode number information can be obtained for wave numbers $k_{\max}\leqslant 0.8\,\mathrm{cm}^{-1}$. This is sufficient to see all the modes of interest in MST. Separation of the chords along the major radius can be used to extract information on the poloidal mode number. By computing the cross-phase and cross-coherence between various chords, the mode number information can be resolved and correlated with magnetic coil data. Details on the density and density fluctuation measurements made with the MST interferometer are provided in Refs. 2 and 8.

B. Polarimeter

The poloidal magnetic field is determined by measuring the Faraday rotation profile of the FIR laser beam polarization as it propagates through the plasma. The rotation angle in radians is given by

$$\Psi(x) = 2.62\times 10^{-13}\lambda^2 \int B_z(x,z)\, n_e(x,z)\, dz,$$

where B_z is the component of the poloidal magnetic field parallel to the vertically propagating FIR beam, n_e is the electron density, $x = R - R_o$, and λ is the FIR laser wavelength, all in mks units. Since $n_e(r)$ is known from the simultaneous interferometer measurement, the poloidal magnetic field can be determined from inversion of the above equation. The current density is then obtained from Amperes law where $\mathrm{J} = \boldsymbol{\nabla}\times\mathbf{B}/\mu_o$. The polarimeter has 3 mrad (0.18°) rms noise level and 1 ms time response. The polarimeter bandwidth is limited by the mechanical rotator used to generate the rotating polarization ellipse. Polarization rotation information from the polarimeter is evaluated by isolating the 4 kHz amplitude-modulated waveform for the signal and reference mixers and computing the phase change via use of the numerical demodulation algorithm mentioned earlier.

1. Polarimeter calibration

The polarimeter system was designed to be insensitive to amplitude changes in the beams. However, any deformation in the polarization state will appear as an additional change in the measured polarimetry phase. As mentioned earlier, to divide the laser power among the 11 chords, wire mesh beamsplitters are used. These meshes complicate the polarimetry measurement because their anisotropic reflection and transmission properties can distort the polarization state of the beam.[6] This distortion couples multiplicatively to the measured phase of each chord and requires that each channel of the polarimeter system, unlike the interferometer, be absolutely calibrated.

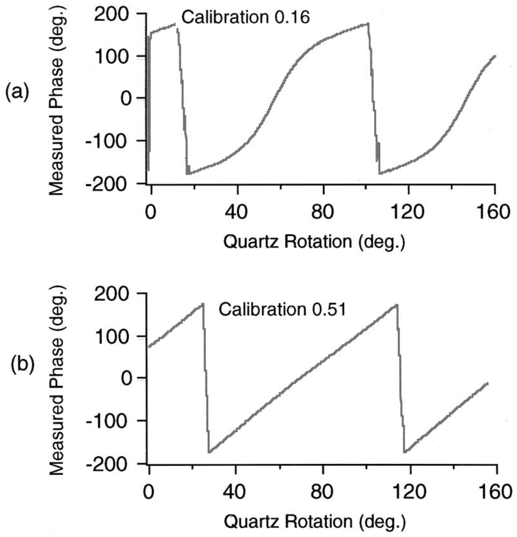

FIG. 1. Calibration traces for polarimeter channels (a) $x = -32$ cm and (b) $x = -2$ cm.

Calibration of the polarimeter system can be achieved by measuring the reflectivity and transmissivity of the mesh beamsplitters for the TE and TM polarization components. This must be done for each mesh in the system and computation of a correction factor must be made based upon the series of meshes a beam traverses for each channel. This approach was successfully accomplished for a five-channel system that was previously tested.[6] However, as the number of channels and therefore mesh beamsplitters increases, the process becomes more complex and errors in evaluating the correction factor increase. To simplify this process and minimize system errors, a new calibration procedure has been developed. In this approach, a crystal quartz $\lambda/2$-wave plate replaces the plasma and is placed in front of the signal beam for a specific chord. This wave plate, which is rotated at a few cycles/s, introduces a known rotation to the FIR beam polarization. By comparing the measured polarization rotation to the known rotation of the quartz, the calibration factor can be determined.

As an example, the calibration traces for two of the polarimeter channels are shown in Fig. 1. The horizontal axis corresponds to the quartz rotation angle while the vertical axis is the measured rotation. For chord $x = -32$ cm [Fig. 1(a)], the FIR beam is transmitted through six mesh beamsplitters of different wire densities before being directed into the vacuum vessel and plasma. The calibration trace indicates a nonlinear relation between the quartz rotation and the measured rotation. This is a direct consequence of the asymmetric reflection and transmission properties of the wire meshes. The calibration factor is evaluated by measuring the

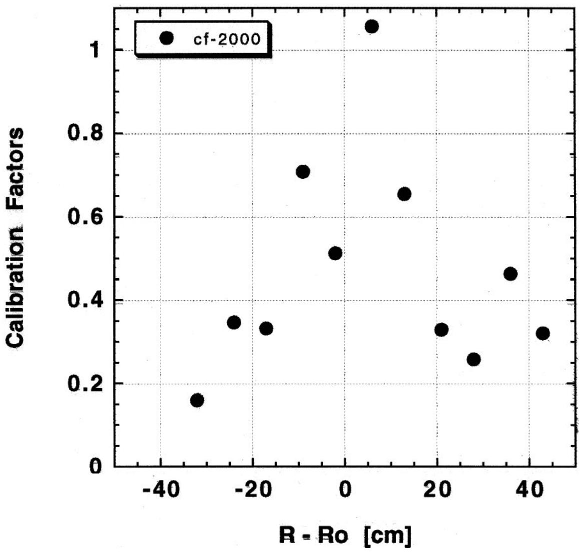

FIG. 2. Calibration factors for the 11-channel polarimeter system.

slope of the trace at the point of the channel dc offset. If the system were single channel using only mirrors, the trace would be linear, indicating a measured rotation of exactly two(four) times the actual polarization(quartz) rotation or a calibration factor of 0.5. The calibration trace for the chord at $x=-2$ cm is shown in Fig. 1(b). For this channel, the FIR beam is transmitted through four meshes and reflected from one mesh. The measured rotation varies linearly with quartz rotation and looks similar to the mirror-only case. A plot showing the calibration factors for each of the polarimeter channels is provided in Fig. 2. This factor is multiplied by the measured rotation to give the calibrated polarimeter output.

2. Initial polarimeter results

Calibrated time traces from each of the 11 chords for a 400 kA MST discharge with peak density $n_e=1\times10^{13}\,\mathrm{cm}^{-3}$ are shown in Fig. 3. This discharge represents a high-confinement MST discharge achieved through pulse-poloidal current drive (PPCD). The PPCD acts to modify the current density profile such that the gradient necessary to drive resistive tearing modes unstable is reduced. Improved confinement is obtained through stabilization of these global modes. The channel at $R-R_0=6$ cm shows zero rotation and corresponds to the MST magnetic axis. Chords on either side of the magnetic axis have opposite sign as expected from Faraday rotation due to the change in direction of the poloidal field. The Faraday rotation profile at time $t=16$ ms is shown in Fig. 4, for both the calibrated and uncalibrated data. For this shot, the measured rotation angles range from −6° on the low-field side to 7° on the high-field side of the plasma. This variation with major radius is expected due to the toroidal geometry.

To obtain the component of the poloidal magnetic field along the FIR beam path $B_z(x,z=0)$ as plotted in Fig. 5, the line-integrated density and calibrated Faraday rotation profiles are spline fit and inverted in a manner consistent with the Grad–Shafranov equilibrium to first order in the large aspect-ratio $[R_o/a]$ expansion. The toroidal current density is shown in Fig. 6, for both the standard Ohmic and improved confinement PPCD discharges at 400 kA. This represents the first measure of the toroidal current density profile in a reversed-field pinch. The polarimeter measurements indicate that the toroidal current density profile is strongly peaked for the improved confinement PPCD plasma. This is consistent with the measured peaking of the electron temperature profile.

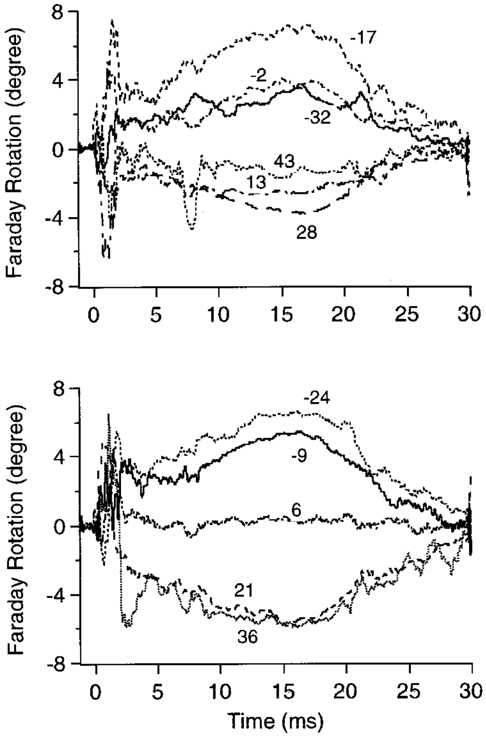

FIG. 3. Polarimeter time traces for a 400 kA MST discharge with PPCD. PPCD pulse on from 7–20 ms.

From these results it is clear that the preliminary profile measurements from the polarimeter system are encouraging. Comparison of the measured Faraday rotation profile to calculations from the equilibrium reconstruction code MSTFIT[9]

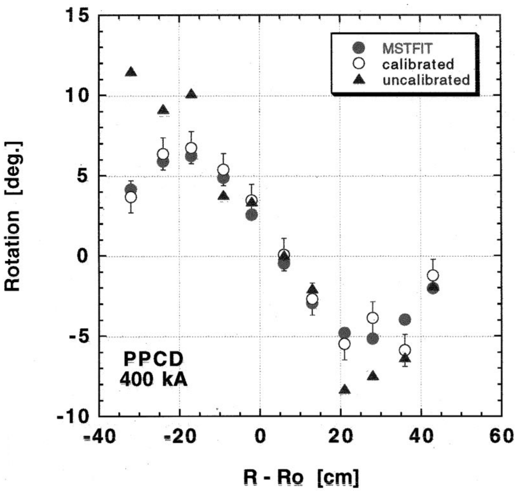

FIG. 4. Faraday rotation profile at $t=16$ ms (same discharge as Fig. 3).

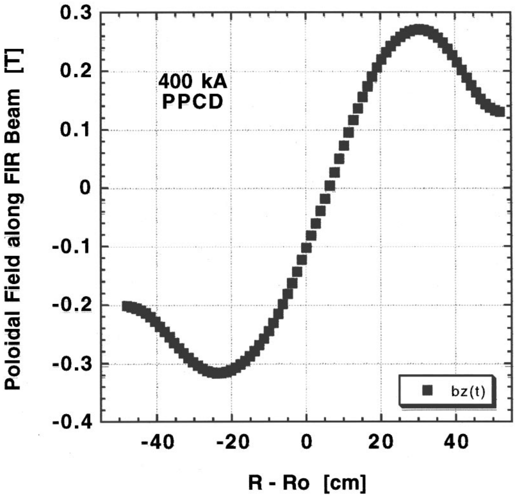

FIG. 5. Poloidal magnetic field profile at $t = 16$ ms (same discharge as Fig. 3).

are also encouraging. As shown in Fig. 4, agreement between code and measurement is quite good. The next step will be to use the polarimeter measurements as a constraint on the equilibrium reconstruction.

III. FUTURE SYSTEM UPGRADES

A problem associated with use of a mechanical rotator to spin the $\lambda/2$ wave plate is that it introduces phase noise into the interferometer signal.[10] Although this can be removed by appropriately filtering the interferometer signal, the time resolution is compromised. In addition, the mechanical rotator is a high-loss element in the optical system resulting in 50% signal reduction. A final consideration is the slow time response of the polarimeter system itself. Unlike the interferometer which has a time response up to 1 μs, the polarimeter system is limited to 1 ms by the mechanical rotator which is spinning at its upper bound. Hence, the polarimeter is unable to resolve fast profile changes or fluctuations like those seen by the interferometer. The phase noise limit for the polarimeter system is also determined by the mechanical rotator.

Reduction in polarimeter and interferometer phase noise, improved polarimeter time response, and increased signal level can all be achieved in the MST polarimeter-interferometer system by removing the $\lambda/2$ plate mechanical rotator and replacing it with a third FIR laser beam. This scheme employs three separate FIR laser beams to determine the plasma density and Faraday rotation. The method basically involves two separate phase measurements using orthogonally polarized waves. The interferometric phase and Faraday angle are obtained by combining these two measurements. Since no mechanical polarization modulation techniques are used, the modulation artifacts which contaminate the phase are absent. The achievable temporal resolution is, in principle, limited by signal-to-noise considerations and can be comparable to that of the interferometer. This would permit resolution of fast changes in the poloidal magnetic field profile and perhaps even magnetic fluctuations corresponding to the core-resonant global tearing modes (5–30 kHz) on MST.

In order to implement this system, a third laser cavity is required along with appropriate wave plates. The detection scheme remains completely unchanged from the existing setup used on MST. The proposed changes to the polarimeter-interferometer system have been tried recently on the RTP tokamak.[11] In this case, equilibrium profile information was obtained. However, the improved time response associated with the 3λ laser technique was never realized in plasma measurements. On MST, the improved time response will be utilized to investigate physics issues related to fast profile changes and magnetic fluctuations.

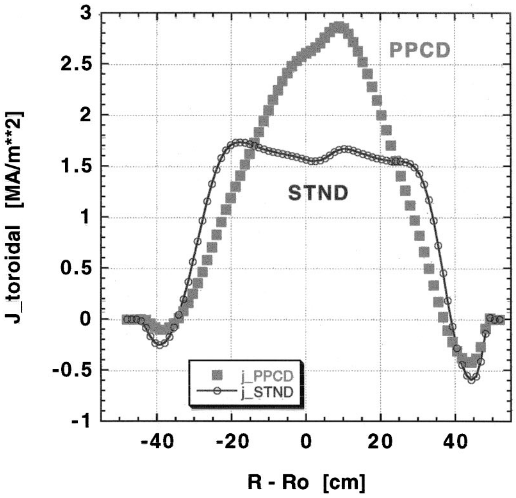

FIG. 6. Toroidal current density profiles for 400 kA standard and PPCD (same discharge as Fig. 3) MST plasmas.

ACKNOWLEDGMENT

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