Microwave polarimetry system in the CDX-U tokamak

Y. S. Hwang, Å. Fredriksen,[a] H. Qin, C. B. Forest,[b] and M. Ono
Plasma Physics Laboratory, Princeton University Princeton, New Jersey 08543

(Presented on 9 May 1994)

An existing microwave interferometer system is modified to add the capability of polarimetry in the CDX-U tokamak. Though this interferometer system can scan vertically and radially, only the vertical view channel is modified to accomodate Faraday rotation measurements, with its radial scanning capability preserved. For our relatively long microwave wavelength, the signal amplitude variation due to refraction is more important than effects due to vibration. An amplitude independent design of Faraday rotation diagnostics has been developed. By using a linearly polarized beam as input and putting a rotating polarizer in the beam after the plasma, birefringency effects are minimized. A digital phase detection technique has been developed for better resolution of the Faraday rotation angle. © *1995 American Institute of Physics.*

I. INTRODUCTION

The Current Drive Experiment-Upgrade (CDX-U) device is a low-aspect-ratio tokamak facility to investigate tokamak improvement concepts such as novel noninductive current drive techniques and confinement improvements.[1,2] Measurement of the plasma current profiles is very important for the study of these physics issues. Taking advantage of low-temperature plasmas, internal magnetic probes as well as external magnetic pickup coils were used to obtain plasma current-density profiles.[3] Recently, the CDX-U tokamak has been upgraded with a new ohmic heating (OH) system. With the new OH system, plasmas with higher densities and currents in a low-aspect geometry are achievable. This new operating regime opens up the possibility of microwave polarimetric measurement of current-density profiles by modifying the existing microwave interferometer system.[4]

Since the Faraday rotation method was proposed as a tool for measurement of tokamak plasma current distribution by Marco and Segre,[5] several variations of the technique have been developed. Starting with the experimental demonstration on TFR,[6] Faraday rotation measurements were adopted as a current profile diagnostic in several devices.[7,8] Conventional amplitude dependent designs have progressed toward a phase-sensitive detection technique to remove possible errors such as refraction and ellipticity effects.

Present-day tokamaks use wavelengths in the far-infrared range both for interferometry and for polarimetry. On CDX-U, the relatively low plasma density allows the use of a 2 mm wave for interferometry and polarimetry. A longer wavelength is favorable for the Faraday rotation signal, which is proportional to the square of wavelength. However, refraction and birefringency effects, proportional to the square and the cube of wavelength, respectively, also become large with wavelength. In view of this, phase-sensitive detection is more advantageous for the 2 mm polarimeter system than an amplitude sensitive method.

In Sec. II, polarization changes are calculated for different probing beam polarizations. Looking at linear birefringency effects and Faraday rotation separately, qualitative and quantitative changes of the probing beam polarization are estimated for the polarimetry system design. Also, expected signal levels from Faraday rotation in CDX-U plasmas are presented. Section III describes the present microwave interferometer system and the proposed polarimetry modification. With radial scanning capability preserved, the present interferometer system can operate as a polarimeter system by adding a rotating linear polarizer and an additional amplitude-modulation detection circuit.

II. POLARIMETRY THEORY

To calculate the polarization rotation ($\Delta\psi$) and ellipticity change ($\Delta\chi$) experienced by the probing beam as it propagates through the plasma, we have followed the formalism given by Marco and Segre.[5] When the initial polarization is linear, $\Delta\psi$ is equivalent to the pure Faraday rotation, given in SI units as

$$\Delta\psi_c = 2.6\times10^{-13}\lambda^2\int_{-z0}^{z0} n(z)B_z(z)dz, \tag{1}$$

where B_z is the component of the magnetic field along the beam. In the more general case of elliptical polarization, the rotation of the polarization angle will also be a function of the optical activity, or linear birefringence, of the plasma. The total rotation can now be written as

$$\Delta\psi = \Delta\psi_c - \tan 2\chi_0 \cos 2\psi_0 \Delta\chi_b \tag{2}$$

for small values of $\Delta\psi$ and $\delta\chi$. The quantity $\Delta\chi_b$ is given by

$$\Delta\chi_b = 1.2\times10^{-18}\lambda^3\int_{-z0}^{z0} n(z)B_\perp^2(z)dz \tag{3}$$

which also defines the change (caused by the plasma) in the ellipticity of the beam. Here, $B_\perp$ is the component of the magnetic field perpendicular to the beam. Since the toroidal field B_T is by far the largest component of $B_\perp$, the birefringency depends in practice on the toroidal field.

We see that the Faraday rotation increases with λ^2, and therefore a longer wavelength will be favorable below the density cutoff value. On the other hand, birefringency in-

[a]University of Tromsø, Norway.
[b]General Atomics, San Diego, CA.

Downloaded 20 Sep 2007 to 198.35.1.65. Redistribution subject to AIP license or copyright, see http://rsi.aip.org/rsi/copyright.jsp

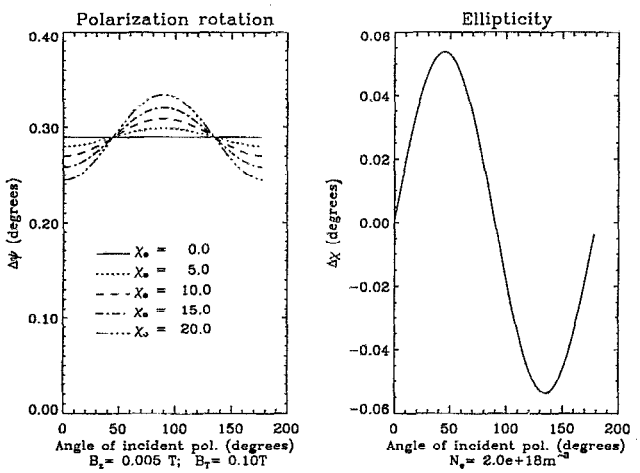

FIG. 1. The effects from elliptical polarization on $\Delta\psi$ and $\Delta\chi$ as a function of initial polarization angle ψ_0 for various probing beam ellipticities. The solid lines refer to the case of linear polarization.

creases as λ^3. It is therefore important to investigate this effect more closely in the case of longer wavelengths like that in the present experiment.

In Fig. 1 an example is shown of how the birefringence effect in the case of an elliptically polarized wave affects $\Delta\psi$ and $\Delta\chi$ as a function of the incident polarization angle ψ_0 and for different values of χ_0. In the case of linear polarization, the polarization change is due only to Faraday rotation, as discussed above. For elliptically polarized waves, the birefringency effects induce a periodical variation in the difference between the pure Faraday rotation and $\Delta\psi$ as shown in Eq. (2). The deviation from pure Faraday rotation at $\chi_0=20°$ is up to $\pm 15\%$. From the above description we see that the birefringence effects in a phase-sensitive experiment (rotating initial polarization) may be avoided by either transmitting a linearly polarized beam through the plasma or by taking out the birefringence effects from the signal of a rotating elliptically polarized beam with a bandpass filter centered at the rotating frequency of the beam. For small to moderate angles of χ_0, we see from Fig. 1 that the change in ellipticity is less than $\pm 0.06°$ and hence of little importance for experimental considerations.

Theoretical calculations for the parameters of the CDX-U tokamak were carried out in order to assess the expected values of $\Delta\psi$ and $\Delta\chi$, giving a basis for the experimental method to be chosen. Simple parabolic models of the electron density n_e and toroidal current density j_p were used, with $n_e=n_0\,[1-(r/a)^2]$ and $j_p=j_0\,[1-(r/a)^2]$, n_0 and j_0 being, respectively, the electron density and current density at the center and a the radius of the plasma cross section. The toroidal magnetic field is given as $B_T=B_{T0}/(1+d/R_m)$, where d is the distance from the plasma center to the beam chord, R_m the major radius of the plasma center, and B_{T0} the central toroidal field. The results from these calculations, with a total current of 50 kA and line integrated density of 1×10^{18} m^{-2}, indicate that we may expect the maximum Faraday rotation to be approximately 1.5°. This value is very small, and therefore a phase resolution better than 0.1° is needed to resolve the current profile.

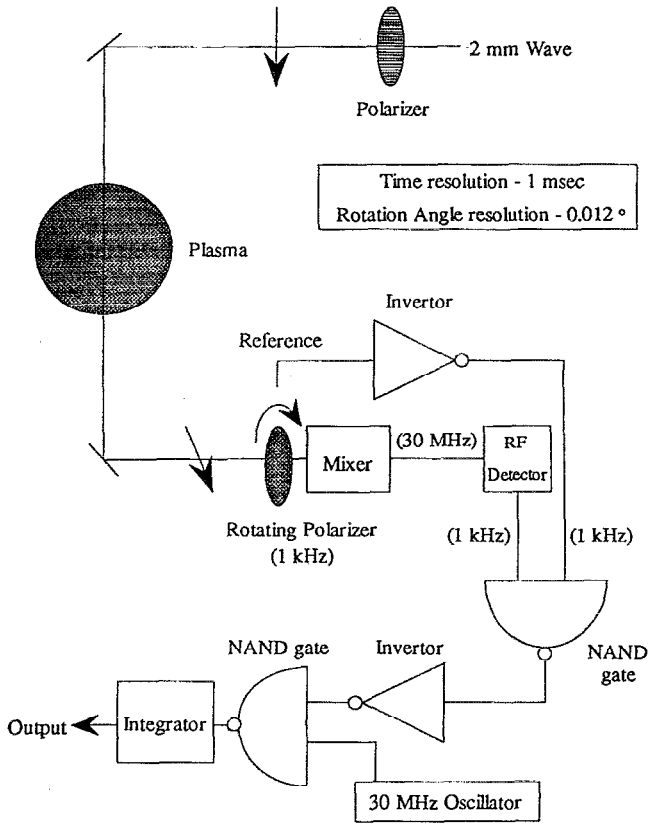

FIG. 2. A schematic of the CDX-U polarimetry system.

III. INTERFEROMETER/POLARIMETER SYSTEM

A. Microwave interferometer system

A 140 GHz microwave interferometer system[4] was built to measure electron-density profiles in CDX-U. Using top and bottom rectangular ports, a vertical view from $R=26$ to 58 cm is provided. Also, the horizontal view has a scanning capability from $Z=-22$ to 22 cm through the rectangular side port by reflecting off the mirror at the centerpost. One cm thick, fused-quartz windows are used to transmit microwaves through the vacuum ports. The whole table containing optical elements and electronics moves radially, and horizontal view optics mounted on this table move vertically. For complete two-dimensional density data, scanning is performed by taking one position measurement per shot.

To measure the phase shift, a heterodyne detection technique is used. Two Gunn diode oscillators with a small frequency difference are used as transmitter and local oscillator (LO) to do the heterodyne detection. The drifting frequency difference between the transmitter and the LO is removed by a forward-tracking circuit.[9] The mixed signal is down-shifted to an intermediate frequency of 30 MHz for phase detection.

Downloaded 20 Sep 2007 to 198.35.1.65. Redistribution subject to AIP license or copyright, see http://rsi.aip.org/rsi/copyright.jsp

B. Polarimeter system design

The existing microwave interferometer system can be modified to have the capability of polarimetry. The conventional way is to put a polarizer in front of the detector and measure the amplitudes of two orthogonal polarizations. However, these amplitude measurements can be complicated by the effects of refraction and beam ellipticity. Refraction effects in a region with a strong density gradient can reduce amplitudes significantly by beam deflection. Several different methods are introduced to remove these complexities, mainly via phase-sensitive techniques. Among them, the rotating polarization ellipse technique[8] has been most popular due to its simplicity and amplitude independency.

If we assume that the plasma properties are reproduced from shot to shot, simultaneous polarimetric and interferometric measurements are no longer required. Therefore linear instead of elliptical polarization can be used in the probing beam, and an additional narrow-bandpass filtering to get rid of birefringence effects can be avoided. Any induced ellipticity of a linearly polarized probing beam along its transmission path can be maintained infinitessimally small by fixing input polarizations either parallel or perpendicular to the toroidal magnetic field. In this arrangement, the amplitude modulation can be done by putting a rotating linear polarizer and a receiving antenna behind the plasma.

The modulated signal can be downconverted to 30 MHz with the same circuits used in the interferometer, and the modulated envelope wave form can be detected by a rf amplitude detector. Reference pulses can be generated by the rotator itself instead of another reference beam pass. The resolution of Faraday rotation angle can be improved significantly by using a digital phase detection technique as shown in Fig. 2. The inverse of the reference signal from the rotating polarizer is combined with the detected signal via an AND logic gate. The short pulse due to phase difference can be measured by passing through another AND gate with high-frequency local oscillator signals, and integrating these very short pulses. In this scheme, a rotation angle of 0.012° can be measured with a 30 MHz oscillator and a 1 kHz rotating polarizer.

Time resolution depends on the modulation frequency, i.e., rotation speed of the polarizer. By putting a slow rotator (rotating speed of only up to 100 Hz), the amplitude modulation and detection has been tested. At this slow speed, time resolution is not small enough for ohmic discharges in the CDX-U tokamak. However, the present technology of mechanical rotators allow them to reach around 1 kHz with an air bearing spindle, allowing a time resolution of 1 ms.

IV. SUMMARY AND FUTURE PLANS

The microwave interferometer system on CDX-U is modified to add the capability of polarimetry. Accounting for relatively large birefringency effects on longer wavelengths, probing beam polarizations are constrained to be linear and either parallel or perpendicular to the toroidal magnetic field. Also, using polarization modulation after passing through the plasma and detecting phase change, amplitude variations due to refraction are eliminated. A slowly rotating polarizer and a receiving antenna have been installed to test a newly designed microwave polarimeter system. Since the time resolution of this slow modulation system is not fast enough for the CDX-U ohmic discharges, a high-speed rotator is under construction for better time resolution. For accurate measurements of rotation angles, a digital phase detection technique has been developed. These Faraday rotation measurements will be combined with data from CDX-U magnetic diagnostics and interferometry in order to reconstruct current-density profiles.

ACKNOWLEDGMENTS

The authors are grateful to Dr. H. K. Park for fruitful discussions. This work was supported by Department of Energy Contract No. DE-AC02-76-CHO-3073. One of the authors (Å. Fredriksen) was supported by The Research Council of Norway.

[1] M. Ono, G. J. Greene, D. Darrow, C. Forest, H. Park, and T. H. Stix, Phys. Rev. Lett. **59**, 2165 (1987).
[2] C. B. Forest, Y. S. Hwang, M. Ono, and D. S. Darrow, Phys. Rev. Lett. **68**, 3559 (1992).
[3] Y. S. Hwang, C. B. Forest, D. S. Darrow, G. Greene, and M. Ono, Rev. Sci. Instrum. **63**, 4747 (1992).
[4] C. B. Forest, G. Greene, and M. Ono, Rev. Sci. Instrum. **61**, 2888 (1990).
[5] F. De Marco and S. E. Serge, Plasma Phys. **14**, 245 (1972).
[6] H. Soltwisch and T. F. R. Equipe, Infrared Phys. **21**, 287 (1981).
[7] H. Soltwisch, Rev. Sci. Instrum. **57**, 1939 (1986).
[8] B. W. Rice, Rev. Sci. Instrum. **63**, 5002 (1992).
[9] J. L. Doane, Rev. Sci. Instrum. **51**, 317 (1980).

Downloaded 20 Sep 2007 to 198.35.1.65. Redistribution subject to AIP license or copyright, see http://rsi.aip.org/rsi/copyright.jsp