Design of a millimeter-wave polarimeter for NSTX-Upgrade and initial test on DIII-D[a)]

J. Zhang,[b)] W. A. Peebles, T. A. Carter, N. A. Crocker, E. J. Doyle, S. Kubota, X. Nguyen, T. L. Rhodes, C. Wannberg, and L. Zeng
Department of Physics and Astronomy, UCLA, Los Angeles, California 90095-1547, USA

(Presented 8 May 2012; received 5 May 2012; accepted 18 June 2012; published online 13 July 2012)

Polarimetry is a powerful diagnostic technique to probe plasma equilibria and magnetic fluctuations in fusion plasmas. In a high beta plasma such as the National Spherical Torus eXperiment (NSTX), these measurements are important to understand plasma stability and anomalous transport. A 288 GHz polarimeter operating along a major radial chord in retroreflection geometry has been developed and is being tested on the DIII-D tokamak to prepare for future implementation on NSTX-Upgrade. The system launches a rotating linearly polarized beam and detects the phase shift directly related to the polarization change caused by the plasma. To accomplish this, a pair of orthogonal linearly polarized beams with a stable difference frequency is generated using a single sideband modulation technique, then combined and transformed to be counter-rotating circularly polarized. To improve phase resolution, quasi-optical isolation, using Faraday rotators and polarizers, is utilized to eliminate a multi-path feedback effect, which is found to be the primary source of phase error. The bench tests in the laboratory and DIII-D power supply test discharges indicate $\leq 1^\circ$ phase resolution.
 [http://dx.doi.org/10.1063/1.4733735]

I. INTRODUCTION

Polarimetry is a powerful diagnostic technique to probe plasma equilibria and magnetic fluctuations in fusion plasmas. In a high beta plasma such as the National Spherical Torus eXperiment (NSTX), these measurements can assist investigating the physics of plasma stability and anomalous transport. For example, alfvén eigenmodes (AEs), one category of fast-ion driven instability, can cause fast-ion transport or loss thereby modifying the heat absorption distribution, e.g., the distribution of fusion α-particles and neutral beams.[1] Neoclassical tearing modes (NTMs) are another important magnetic instability particularly at high beta.[2] NTMs are large scale instabilities driven by current or pressure gradients that can lead to plasma disruption in plasmas such as ITER. A monitor of the internal magnetic fluctuation level is important for both mode control and improved physics understanding.

The current manuscript describes the development of a 288 GHz polarimeter, which has been designed, fabricated, and bench-tested at UCLA. The system is currently installed on the DIII-D tokamak for experimental plasma tests prior to future implementation on NSTX-Upgrade. The system launches a rotating linearly polarized beam and detects the phase shifts directly related to the polarization changes caused by the plasma. The rotating linearly polarized beam is achieved by combining a pair of frequency-offset counter-rotating circularly polarized beams.[3] The single-side-band (SSB) modulation technique used in the source section assures a stable difference frequency. The beam combination and polarization transformation is performed in the following quasi-optical section. The primary source of phase error is found to be a multi-path feedback effect. This effect is mainly caused by reflection at the receiver, which has a typical VSWR of 2:1, i.e., the E-field reflection coefficient is $\sim$30%. Quasi-optical isolation using Faraday rotators and polarizers is introduced to significantly improve the phase resolution by suppressing this effect. Bench tests in the laboratory indicate $\leq 1^\circ$ phase error with the feedback effect suppressed. Phase resolution is also assessed using DIII-D power supply test discharges, suggesting that the system is sufficiently sensitive to be able to measure the magnetic fluctuations associated with AEs and NTMs. This paper is presented in the following order: Section II presents the design of the polarimeter and discusses the multi-path feedback effect and quasi-optical isolation; in Sec. III, tests in the laboratory and on DIII-D are presented; conclusions are given in Sec. IV.

II. POLARIMETER DESIGN

A. System geometry

The 288 GHz polarimeter is designed to operate along a major radial chord in retroreflection geometry. (Fig. 2) A rotating linearly polarized microwave beam is launched into the plasma from the outboard side. The beam retroreflects at a flat reflective graphite tile on the inboard wall, and is finally detected by a mixer, which generates a sinusoidal voltage output. The phase shift between this output voltage and a reference sine-wave directly relates to the plasma polarimetry effects. The system can be conceptually divided into the source, quasi-optical, and receiver sections.

[a)]Contributed paper, published as part of the Proceedings of the 19th Topical Conference on High-Temperature Plasma Diagnostics, Monterey, California, May 2012.

[b)]Electronic mail: xyzhangj@physics.ucla.edu.

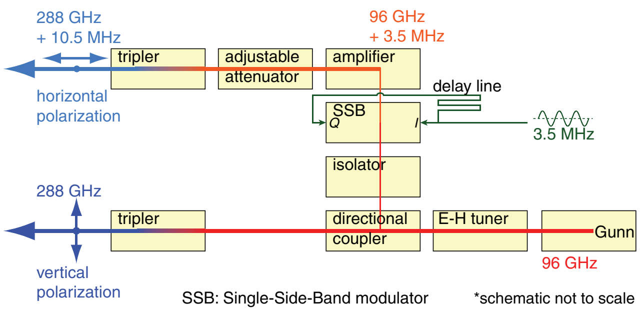

FIG. 1. Schematic of 288 GHz polarimeter source. Lines going through the microwave components indicate the microwave power flow.

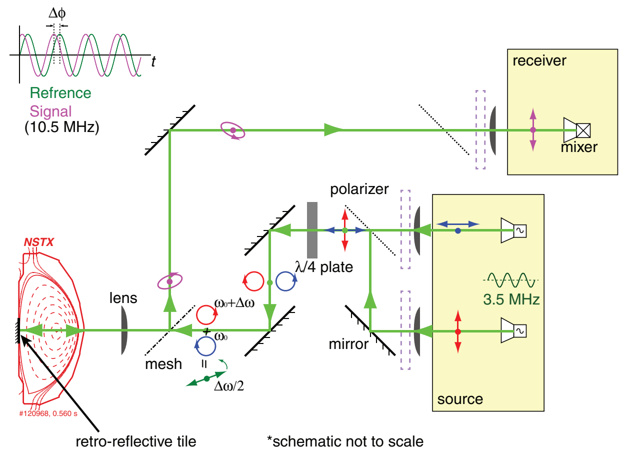

FIG. 2. Schematic of quasi-optical design of 288 GHz polarimeter. The green lines with arrows indicate beam propagation. Double-arrows, circles, and ellipses represent the polarization of mm-wave beam (in beam frame of reference) at the corresponding positions. The three dashed rectangles indicate where the quasi-optical isolators (discussed below) are inserted.

B. Source

The source employs a SSB modulation technique to generate a pair of orthogonal linearly polarized beams with a stable difference frequency (Fig. 1). A 96 GHz Gunn diode oscillator generates ~20 dBm of microwave power. A small fraction of the Gunn output power is coupled to the SSB modulator via a 10 dB directional coupler. In the SSB modulator, the 96 GHz frequency is upshifted using a stable 3.5 MHz crystal oscillator. The SSB modulator requires two separate 3.5 MHz inputs with 90° phase difference. This is achieved by splitting the crystal oscillator output and delaying one branch with an appropriate length of BNC cable. The output of the SSB modulator is then amplified using a high gain W-band amplifier. The remainder of the original 96 GHz and the amplified 96 GHz + 3.5 MHz microwave are fed into separate frequency triplers and then coupled to free space via dual-mode horns.[4] An E-H tuner is inserted between the Gunn and the input port of the directional coupler for impedance matching to achieve the optimum microwave power coupling. A W-band isolator is used in the coupled port of the directional coupler to eliminate reflection from the SSB that can disturb the frequency stability of the original transmitted 96 GHz microwave. This isolator is protected from the tokamak stray magnetic fields with a close-fitting, soft iron shield. An adjustable attenuator is inserted after the W-band amplifier to optimize the emerging power of the upshifted millimeter-wave (mm-wave). Necessary W-band waveguides are used to connect the above microwave components and also create the required orthogonal polarization between the two frequency-offset beams. The emerging 288 GHz and 288 GHz + 10.5 MHz mm-wave each have approximately 3 dBm power. A portion of the original 3.5 MHz crystal oscillator output is electronically tripled in frequency to provide a reference for the mm-wave phase shift measurements.

C. Quasi-optical and receiver sections

The aperture dimensions of the components used for beam manipulation are on the order of 10 cm (approximately 100 millimeter-wavelengths), which categorizes the design to the quasi-optical regime.[5] The schematic is shown in Fig. 2. The emerging mm-wave from the triplers is coupled to aspherical lenses made of high density polyethylene. These lenses convert the diverging mm-wave from the horns to collimated Gaussian beam propagation. A similar lens in front of the mixer focuses the returned beam into the dual-mode horn attached to the mixer. Another longer focal length lens is inserted between the mesh and the plasma to control beam propagation and place a beam waist on the retro-reflective tile. The orthogonal linearly polarized beams launched from the two triplers are combined using a polarizer and converted to a pair of counter-rotating circularly polarized beams via a birefringent crystal quartz λ/4 wave plate. The combined right- and left-hand circularly polarized beams are equivalent to a linearly polarized beam whose polarization direction rotates at half the difference frequency. As illustrated in Fig. 2, this combined beam transmits through a mesh (~90% reflection coefficient in E-field), propagates through the plasma from the outboard side, retroreflects at a flat reflective graphite tile on the inboard wall, which returns the beam through the plasma a second time. This returned beam then reflects from the mesh, and is directed towards the mm-wave receiver. During propagation through the magnetized plasma, the beam experiences polarization modifications related to the Faraday rotation and Cotton-Mouton effects. The vertical E-field component of the returned beam is selected by a polarizer and subsequently detected by a single-ended 288 GHz mixer. The mixer generates a sinusoidal voltage output at the original difference frequency, i.e., 10.5 MHz, corresponding to the rotating linearly polarized beam input. The phase shifts between the previously mentioned 10.5 MHz reference and sinusoidal mixer output voltage directly relate to the polarization changes caused by the plasma. For example, pure Faraday rotation would advance the linear polarization rotation, resulting in a measured phase shift between the two sine-waves.

D. Multi-path feedback and quasi-optical isolation

The primary source of phase error is found to be a result of multi-path feedback effect. These effects are created due to the cavities formed in the system by reflections at the triplers

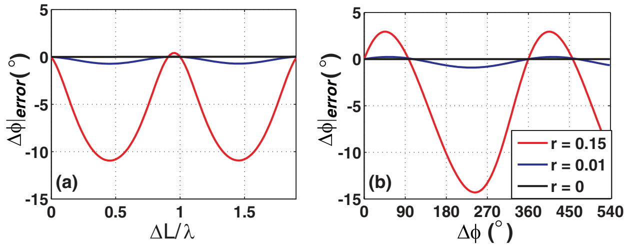

FIG. 3. Calculated error in polarimetry phase measurements caused by the feedback effects. (a) shows the dependence on path length (L); (b) shows the dependence on polarimetry phase ($\Delta\phi$) caused by a magnetized plasma. Red and blue curves show the phase error with effective E-field reflection coefficients at the cavity ends (r) of 0.15 and 0.01, respectively. The black horizontal curve shows zero phase error if there is no feedback effect, i.e., $r = 0$.

and also the 288 GHz mixer. The highly reflective mesh (illustrated in Fig. 2) helps to isolate the effects of reflection from the triplers. The cavity formed between the tile and the mixer was therefore found to be dominant. A beam can propagate multiple times in such a high-Q cavity before its power is attenuated to a negligible level. At the mixer, the E-field of this feedback beam interferes with the E-field of desired main return beam. As a result, the amplitude and phase of the 10.5 MHz beat wave detected at the mixer become functions of the path length (L) and the polarimetry phase shift ($\Delta\phi$) caused by the plasma. Quantitive phase error dependences on L and $\Delta\phi$ using realistic parameters are calculated and displayed in Fig. 3. The effective E-field reflection coefficient at the cavity ends (r) is estimated to be 0.15. During a typical plasma operation cycle, L can vary a few tens of wavelengths due to plasma interferometry effects, and $\Delta\phi$ can vary tens of degrees due to plasma polarimetry effects. Mechanical vibration can also cause changes in L on the order of a few hundred microns. Due to these variations, as shown in Fig. 3, the resultant 10.5 MHz phase error can easily be at the level of 10°, if the feedback effect is left unsuppressed. Figure 3 also shows that the phase error can be decreased to $<1°$ by reducing $r < 0.01$. One approach to achieve this is to introduce quasi-optical isolation to degrade the cavity Q. Inserting a +45° polarizer, a +45° Faraday quasi-optical rotator plate and a vertical polarizer in series creates a one-way passage for the main beam (Fig. 4). The different components of the feedback beam are selectively isolated at the polarizers. Such isolators are inserted in the receiver path and also in both source branches, where linearly polarized beams are propagating.

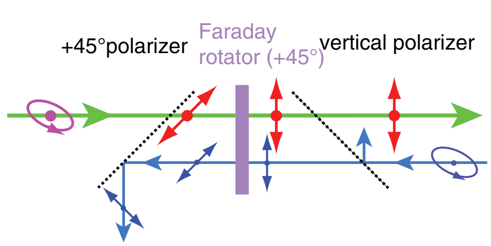

FIG. 4. Principle of quasi-optical isolation. Green line indicates the desired main beam. Cyan line indicates the feedback beam. Polarizations in the frame of reference of the beam are marked along the propagation.

III. TESTS IN LABORATORY AND ON DIII-D

The polarimeter without the presence of multi-path feedback should be insensitive to small changes in the path length change. Therefore, any phase variations while changing the path length is a good indicator that feedback effects are active and important. In the bench tests in the laboratory, the phase variations were measured while translating the tile by a few millimeters. It was found that, with quasi-optical isolation included, phase resolution improved from tens of degrees without isolation to $\leq 1°$.

The 288 GHz polarimeter was installed on the DIII-D tokamak in 2011 for experimental demonstration prior to future implementation on NSTX-Upgrade. A DIII-D power supply test discharge, i.e., a vacuum shot (shot no. 147 714), was analyzed to assess the phase resolution with the presence of decaying toroidal magnetic field. The phase resolution, i.e., the rms of the phase variations, over a wide frequency range of 500 Hz–1 MHz is approximately 0.3°. This resolution is sufficient to satisfy the measurement capability required to study magnetic fluctuations associated with AEs or NTMs, whose magnitude ≥ 10 G ranging from a few to hundreds of kHz. In order to assess the feedback effects induced by mechanical vibration, the extraneous noise, such as 60 Hz harmonics (noise from power line) were removed from the low frequency phase variations (<500 Hz). The rms of these low frequency variations is $\sim 0.2°$.

IV. CONCLUSION

The development of a 288 GHz polarimeter for NSTX-Upgrade has been presented. The system launches a rotating linearly polarized beam and detects the phase shifts directly related to the polarization changes caused by the plasma. This is accomplished by combining a pair of frequency-offset equal power counter-rotating circularly polarized beams. A SSB modulation technique is used to generate a pair of orthogonal linearly polarized beams with a stable difference frequency, which is subsequently combined and transformed to be counter-rotating circularly polarized. A multi-path feedback effect has been identified as the primary source of phase error. This effect can be suppressed using quasi-optical isolation, which significantly improves the phase resolution. The tests in the laboratory and on DIII-D indicate $\leq 1°$ phase resolution. Further fundamental tests and calibrations of the polarimeter are being planned before commissioning.

ACKNOWLEDGMENTS

This work is supported by the U.S. Department of Energy under Grant Nos. DE-FG02-99ER54527, DE-AC02-09CH11466, SC4500027285, and DE-FC02-04ER54698. The authors are grateful for the contributions of the DIII-D research team.

[1]K. L Wong, Plasma Phys. Controlled Fusion **41**, R1 (1999).
[2]R. J. La Haye, Phys. Plasmas **13**, 055501 (2006).
[3]G. Dodel and W. Kunz, Infrared Phys. **18**, 773 (1976).
[4]H. M. Pickett, J. C. Hardy, and J. Farhoom, IEEE Trans Microwave Theory Tech. **32**, 936 (1984).
[5]P. F. Goldsmith, Proc.-IEEE **80**, 1729 (1992).