AIP | Review of Scientific Instruments

Far-infrared tangential interferometer/polarimeter design and installation for NSTX-U

E. R. Scott, R. Barchfeld, P. Riemenschneider, C. W. Domier, C. M. Muscatello, M. Sohrabi, R. Kaita, Y. Ren, and N. C. Luhmann Jr.

Citation: Review of Scientific Instruments **87**, 11E114 (2016); doi: 10.1063/1.4960415
View online: http://dx.doi.org/10.1063/1.4960415
View Table of Contents: http://scitation.aip.org/content/aip/journal/rsi/87/11?ver=pdfcov
Published by the AIP Publishing

REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 11E114 (2016)

Far-infrared tangential interferometer/polarimeter design and installation for NSTX-U

E. R. Scott,[1,a)] R. Barchfeld,[2] P. Riemenschneider,[3] C. W. Domier,[3] C. M. Muscatello,[4] M. Sohrabi,[3] R. Kaita,[5] Y. Ren,[5] and N. C. Luhmann, Jr.[3]
[1]*Department of Mechanical and Aerospace Engineering, University of California, Davis, California 95616, USA*
[2]*Department of Applied Science, University of California, Davis, California 95616, USA*
[3]*Department of Electrical and Computer Engineering, University of California, Davis, California 95616, USA*
[4]*General Atomics, San Diego, California 92121, USA*
[5]*Princeton Plasma Physics Laboratory, Princeton, New Jersey 08540, USA*

(Presented 7 June 2016; received 6 June 2016; accepted 13 July 2016; published online 9 August 2016)

The Far-infrared Tangential Interferometer/Polarimeter (FIReTIP) system has been refurbished and is being reinstalled on the National Spherical Torus Experiment—Upgrade (NSTX-U) to supply real-time line-integrated core electron density measurements for use in the NSTX-U plasma control system (PCS) to facilitate real-time density feedback control of the NSTX-U plasma. Inclusion of a visible light heterodyne interferometer in the FIReTIP system allows for real-time vibration compensation due to movement of an internally mounted retroreflector and the FIReTIP front-end optics. Real-time signal correction is achieved through use of a National Instruments CompactRIO field-programmable gate array. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4960415]

I. INTRODUCTION

The FIReTIP system is a laser-based plasma diagnostic used for measuring line-integrated electron density.[1–3] The core of the FIReTIP system consists of four lasers: three optically pumped 118.8 μm methanol lasers, one of which utilizes Stark-effect tuning to vary the output frequency by ±5 MHz and provides LO power, and a 100 W CO_2 laser to provide pump power. The FIReTIP system, previously installed on NSTX (National Spherical Torus Experiment), has been refurbished and upgraded for installation on NSTX Upgrade (NSTX-U). Removal of the original system was required due to space limitations set by the second neutral beam injection (NBI) system included in the NSTX upgrade, which doubles the plasma current and achievable magnetic field of NSTX.[4] FIReTIP has been moved to a fenced-off location, or cage, in the corridor (“gallery area”) immediately outside the NSTX-U test cell. A hollow, dielectric-coated aluminum overmoded waveguide was designed and fabricated to allow for low-loss transport of the FIR beam from the gallery area to the vacuum vessel and FIReTIP mixers, a distance of >20 m.

Due to space limitations, the retroreflector which facilitates FIReTIP’s double-pass measurements could not be mounted on a mechanical vibration isolation stand external to the vacuum vessel; instead, the retroreflector is mounted directly to the interior of the vacuum vessel in a spool piece at Bay B, where “bay” refers to one of the spaces between the twelve toroidal field coils on NSTX-U. Because the FIReTIP system is sensitive to vibrations, a visible light interferometer system is being implemented as part of the FIReTIP upgrade to measure and subtract the effects of vibrations from the FIReTIP signal, thus reducing system noise.

II. DESIGN AND SYSTEM DETAILS

Though much of the previous FIReTIP system is being reused, new locations and space limitations near the vacuum vessel and the test cell have required adjustment and redesign of the FIReTIP system. Three FIReTIP channels are planned for NSTX-U.

The first channel, between Bays G and B, is used for core electron density measurements. The launching optics for the G-B channel are located at Bay G, and the retroreflector inside the vacuum vessel at Bay B. The beam travels through the Bay G optics to the retroreflector, where the beam is reversed, sending it back along the same path. The beam again passes through the Bay G optics before re-entering the waveguide.

The second channel, between Bays L and I, and the third channel, between Bays B and L, will measure core and edge plasma fluctuations, respectively. The L-I channel will enter the vacuum vessel from Bay L and have a retroreflector located at Bay I. The B-L channel will enter the vacuum vessel from Bay B and have a retroreflector at Bay L. The FIReTIP beam paths are shown in Fig. 1.

A. FIReTIP lasers

Two standard optically pumped methanol lasers output 150 mW of CW power at 118.8 μm. A third optically pumped methanol laser utilizes Stark-broadening to shift the emission

Note: Contributed paper, published as part of the Proceedings of the 21st Topical Conference on High-Temperature Plasma Diagnostics, Madison, Wisconsin, USA, June 2016.
[a)]Author to whom correspondence should be addressed. Electronic mail: evrscott@ucdavis.edu.

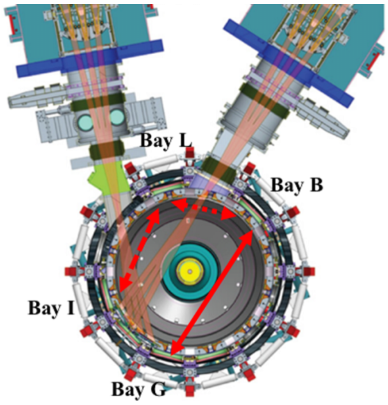

FIG. 1. Top-down view of NSTX-U with FIReTIP channels overlaid. Channel 1 (G to B, solid line) will supply the core density measurement for density feedback control and Thomson scattering calibration. Channels 2 (L to I, dashed line) and 3 (B to L, dotted line) will observe plasma fluctuations. The semi-transparent lines represent the NBI beam paths. Reproduced with permission from J. E. Menard *et al.*, Nucl. Fusion **52**, 083015 (2012). Copyright 2012 International Atomic Energy Agency.

spectra, making it possible to tune the laser frequency by ±5 MHz. One 100+ W grating-tunable CO_2 laser provides pumping power for the 3 methanol lasers. For methanol to lase at 118.8 μm, the CO_2 laser line 9P36 (9.69 μm) is used. For the FIReTIP polarimeter system, the two standard methanol lasers are given right and left circular polarization and are detuned from one another by 2 MHz, making signals from the right and left circularly polarized beams easily distinguishable from one another in the FIReTIP electronics.

The FIReTIP lasers and those of another UCD diagnostic, the high-k scattering system, share space in the corridor outside the NSTX-U test cell. Space limitations would not allow a horizontal laser table orientation. Therefore, a vertical table allows for a total of 6 lasers (4 FIReTIP, 2 high-k scattering) to occupy the same floor space as would 2 lasers otherwise.

B. Waveguide

The previous FIReTIP system was located in the NSTX test cell directly beneath the input window. For NSTX-U, however, this location is used for the second neutral beam injector (NBI). Space limitations have forced the new FIReTIP system out of the test cell and into a neighboring gallery area. Though only separated from the test cell by one 4-ft thick concrete wall, the distance to the FIReTIP entrance window and receiver table (Section II D) has grown to >20 m. Therefore, a means of low-loss transmission is required for FIReTIP to function. An overmoded dielectric-coated aluminum waveguide has been designed, fabricated, and tested by UCD. Attenuation of the FIR beam within the waveguide has been measured at −0.15 dB/m with the Gaussian beam profile preserved upon exiting the waveguide. Due to the ready absorbance of FIR light by water vapor (approx. −3 dB/m in air at 118.8 μm), the waveguide is filled with dry nitrogen to displace any water vapor. A mesh beam splitter located within the waveguide splits the FIR beam into reference and signal beams, with the former going directly to the receiver enclosure and the latter going to the front-end optics at Bay G.

C. Front-end optics

After the beam has reached Bay G via the waveguide run, it passes through an optics box designed to place the FIR beam waist on the internally mounted retroreflector in the Bay B spool piece. This allows the beam to couple back to the waveguide with minimal losses after reflecting off of the retroreflector. The beam splitter located within the waveguide then redirects the signal beam to the receiver enclosure. Additionally, the front end optics must allow the visible light interferometer beam and the FIR beam to share a beam path through the optics and the plasma. A 0.5 mm thick high-resistivity silicon wafer coated with alternating layers of ZnSe and ThF_4 transmits 90% of the FIR beam at 18.8° incidence while reflecting >99% of the HeNe beam, allowing for collinear propagation of the two wavelengths.

D. Receiver table

The FIReTIP mixers as well as the vibration compensation system's hardware are located in an enclosure (receiver table) below bay G. The receiver table consists of three levels: the lower two levels each house 2 corner-cube mixers, and the upper level houses the visible light interferometer optics. A shelf is suspended from the lower level to house power supplies for the HeNe laser, the acousto-optic modulator, and two HeNe diode detectors, all part of the vibration compensation system. Two corner cube mixers will be utilized as reference and core plasma density channels, while the remaining two are for upgrades to the FIReTIP system, allowing for detection of core and edge plasma fluctuations with the addition of two FIReTIP chords.

III. VIBRATION COMPENSATION SYSTEM

The previous FIReTIP system employed external retroreflectors mounted on mechanical vibration isolation mounts. These isolators reduced movement of the retroreflectors, thus reducing vibrational noise in the collected density data. However, due to space limitations, the new FIReTIP system employs an internally mounted retroreflector located in a Bay B spool piece. Because the retroreflector is hard-mounted to the interior of the inner vacuum vessel, noise due to vibrations and retroreflector movement causes significant noise issues if not compensated. To alleviate this issue, the FIReTIP system has been upgraded to a two-color interferometer through the inclusion of a heterodyne 632.8 nm HeNe laser-based interferometer. A schematic is shown in Fig. 2. Due to the short wavelength, phase in the plasma leg of the interferometer is minimally affected by the plasma density and only reflects movement of the retroreflector and of the front-end optics. This induced phase change by movement can be subtracted from the FIR signal, resulting in a density measurement free of noise due to mechanical vibrations of much of the system's optics.

One of the main goals of the FIReTIP system is to provide a real-time density signal to the NSTX-U plasma control

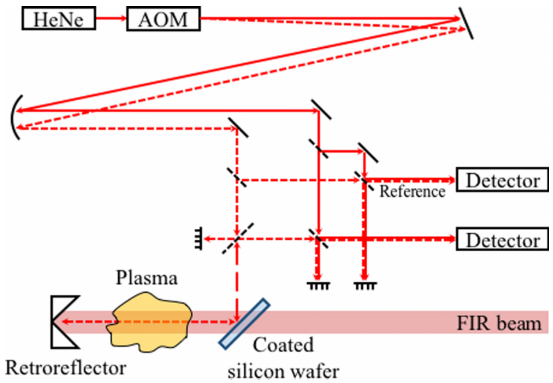

FIG. 2. Schematic of the visible light heterodyne interferometer with the zeroth-order beam (solid) and the first-order diffracted beam (dotted) from the acousto-optic modulator (AOM). Beam splitters are shown here as in a fully optical system for clarity; fiber optics are used in the physical set-up.

system (PCS) for real-time density feedback control. For a robust density signal to be supplied to the PCS, the FIReTIP measurement must be corrected for the effects of vibrations in real-time. The HeNe heterodyne-type interferometer is used for unambiguous determination of the sign of the phase change due to vibrations. To provide the frequency offset required for heterodyne interferometry, the beam is passed through an acousto-optic modulator (AOM), giving ±40 MHz to the first-order diffracted beam. Signal and reference detectors send their respective information to an I/Q demodulator which extracts phase information from the two 40 MHz signals. This information is passed to an NI CompactRIO FPGA where the output from the I/Q demodulator is translated to physical displacement before being subtracted from the FIReTIP density measurement. An analog signal from the FPGA directly related to the line-integrated plasma density by a predetermined factor is then sent to a PCS input. A control system will be designed that will open and close actuators to increase or decrease the plasma density.

IV. INSTALLATION AND GOALS

The FIReTIP system is being installed on NSTX-U to collect preliminary data for the end of the 2016 run period. The fenced area in the NSTX-U gallery has been expanded to meet safety and egress requirements set by PPPL for system operation. In addition to the graphite-backed Lexan paneling on the laser table, 250 W Kentek FLEX-GUARD™ laser curtains are installed immediately inside the cage; they provide protection against scattered CO_2 laser light when the paneling is removed for alignment purposes.

The main goal of the FIReTIP system on NSTX-U is to provide robust, real-time core electron density measurements for incorporation into the PCS for real-time density feedback control. A real-time analog density signal from the VCS FPGA is expected by the end of the 2017 run period. Additionally, the FIReTIP system will supply calibration for the Thomson scattering system and be used for MHD analysis due to its high time resolution (up to 4 MHz[5]). After a robust core density signal is demonstrated, the FIReTIP polarimeter functions can be brought online for magnetic field measurements. Two additional FIReTIP chord channels have also been proposed to measure core and edge fluctuations, but will not be implemented until at least the 2018 run period.

ACKNOWLEDGMENTS

This work is supported by the United States Department of Energy under Contract Nos. DE-FG02-99ER54518 and DE-AC02-09CH11466. The digital data for this paper can be found at http://arks.princeton.edu/ark:/88435/dsp011v53k0334.

[1]H. K. Park *et al.*, Rev. Sci. Instrum. **70**, 710 (1999).
[2]K. C. Lee *et al.*, Rev. Sci. Instrum. **74**, 1621 (2003).
[3]K. C. Lee *et al.*, Rev. Sci. Instrum. **75**, 3433 (2004).
[4]J. E. Menard *et al.*, Nucl. Fusion **52**, 083015 (2012).
[5]W. C. Tsai, C. W. Domier, K. C. Lee, N. C. Luhmann, Jr., R. Kaita, and H. K. Park, Rev. Sci. Instrum. **81**, 10D526 (2010).