REVIEW OF SCIENTIFIC INSTRUMENTS **87**, 11E104 (2016)

Polarimeter for the General Fusion SPECTOR machine

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(Presented 7 June 2016; received 6 June 2016; accepted 27 June 2016;
published online 1 August 2016; publisher error corrected 4 August 2016)

A polarimeter has been designed to measure Faraday rotation and help to understand the profile of its safety factor, q, on the recently built SPECTOR magnetized target fusion machine at General Fusion. The polarimeter uses two counter-rotating, circularly polarized, 118.8 μm beams to probe the plasma. Grad-Shafranov simulations have been used to investigate the effect of measurement error and chord geometry. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4959797]

I. INTRODUCTION

General Fusion, Inc. is developing a magnetized target fusion (MTF) power plant (see Figure 1). The concept is to drive a liquid lithium-lead liner with an array of pistons to compress a magnetized plasma to fusion conditions.[1] The SPECTOR machine is designed to create spheromak[2] and spherical tokamak[3] plasma configurations and explore confinement and other properties relevant to an MTF system. Characterization of the plasma performance will be done in both laboratory situated experiments without compression, and in remotely situated tests where a featureless flux conserver is compressed on a time scale of ~140 μs.

Plasma stability is strongly affected by its q-profile (safety factor),[4] how the average magnetic pitch angle of each flux surface varies across the minor radius of the plasma. A multi-chord polarimeter is being built to measure the q-profile in laboratory SPECTOR experiments. The measured q-profile is used in plasma simulations to verify and predict stability. It is also possible to modify the q-profile in SPECTOR to optimize plasma stability.

The polarimeter measures Faraday rotation, ϕ_F, along four toroidal chords (see Figure 1(b)). Faraday rotation is the rotation of linearly polarized light's polarization plane in a magnetized plasma,

$$\phi_F[\text{rad}] = 2.63 \times 10^{-13} \lambda^2 \int n_e B_{\parallel} dl, \qquad (1)$$

where λ[m] is the light's wavelength, n_e[m^{-3}] is the electron density, and $B_{\parallel}$[T] is the component of the magnetic field parallel to the light's direction of propagation.[5]

II. POLARIMETER DESIGN

A 150 W CO_2 laser pumps two cavities filled with 0.2 mbar of methanol gas to generate the polarimeter's two 118.8 μm, 200 mW far infrared (FIR) beams. Faraday rotation is measured with a heterodyning method[6–10] where combined left- and right-circularly polarized beams are sent along each plasma chord. The two beams are offset by 2 MHz, obtained by detuning the lengths of the FIR cavities. After passing through a polarizer, the beams' interference at the Schottky diode mixer is a sinusoidal signal oscillating at the beams' difference frequency. Faraday rotation is measured by comparing the phase of each chord's signal with a reference signal.[11] The polarimeter's optical layout is shown in Figure 2.

Typically, a third frequency-offset FIR beam is used to obtain a density measurement with the same mixer.[7] SPECTOR currently uses a 1.31 μm–1.55 μm fiber-based interferometer array, which is low cost and easy to align. However, its short wavelength makes it sensitive to mechanical shock from the machine firing. It is a priority to reduce mechanical coupling down to a level equivalent to 10^{13} cm^{-3}. If this cannot be achieved, a non-fiber system must be developed with a longer-wavelength laser such as a 10.6 μm CO_2 or an additional 118.8 μm beam.

The size of the FIR beam has been simulated assuming Gaussian beam propagation as shown in Figure 3. In the far field, the EH_{11} mode launched from the FIR cavity, an oversized hollow dielectric waveguide, can be approximated as a Gaussian beam with 1/e waist diameter $0.416D$, where D is the inner diameter of the waveguide.[12] The inner diameter of the FIR cavity is 38 mm, and the output coupler exit aperture is 13 mm. The beam's waist at the exit of the laser has been calculated with the assumption that $D = 13$ mm. This must be tested once the laser is operational.

Moisture in the air can rapidly absorb the 118.8 μm beam. Therefore, an acrylic waveguide with 1 in. inner diameter and filled with dry nitrogen is used to transport the beam from the laser table to SPECTOR (see Figure 2(b)). To efficiently couple the beam into the waveguide, the beam must be focused such that its waist is located at the waveguide entrance. The waist 1/e diameter must also be about 0.4 times the waveguide inner diameter.[13] The beam is focused down to the appropriate size with a TPX plastic lens with 1m focal length.

III. SOURCES OF ERROR

Error can be introduced into the Faraday rotation measurement if the counter-rotating beams pass through the plasma in a

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Note: Contributed paper, published as part of the Proceedings of the 21st Topical Conference on High-Temperature Plasma Diagnostics, Madison, Wisconsin, USA, June 2016.

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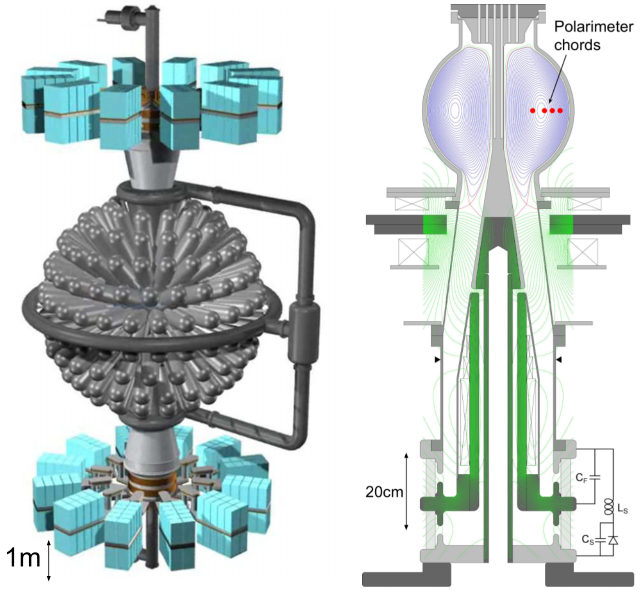


(a) (b)

FIG. 1. (a) Concept General Fusion power plant. (b) SPECTOR plasma generator.

non-circularly polarized state. A number of measures are taken to ensure beams maintain circular-polarization: Z-cut quartz windows are used to avoid birefringence effects, reflector surfaces are unprotected gold, and the quarter-waveplates are placed near the machine after the wire mesh beam splitters. A rotating half-waveplate can be used to mimic Faraday rotation in a plasma and measure this error.[14]

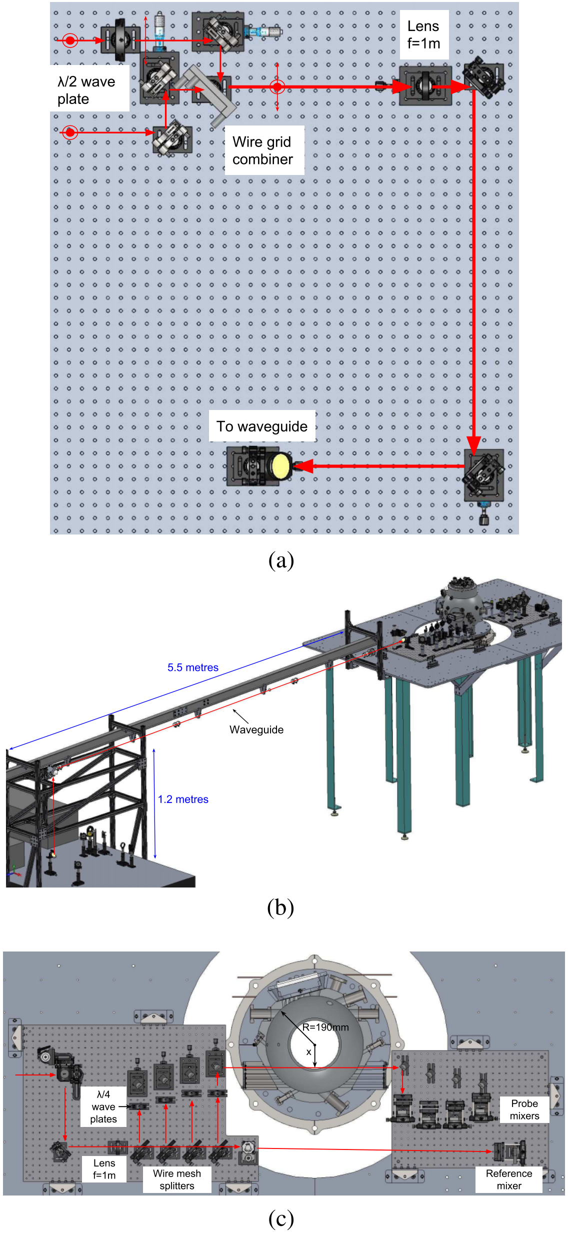
The Cotton-Mouton (CM) effect is the change in the ellipticity of a beam passing through a magnetized plasma.[5,15] This is a potential source of error, but is expected to be small.

It is important to ensure the two counter-rotating beams are collinear.[16] Non-collinear beams take slightly different paths through the plasma, and so encounter different densities. This leads to a phase difference between the beams indistinguishable from Faraday rotation. An Ophir Pyrocam-IV pyroelectric camera has been acquired to help with alignment and improve beam collinearity. A polarizer can be placed in the path of the plasma-probing beams before entering the plasma to measure the magnitude of the collinearity error.

To further investigate these errors, a Grad-Shafranov equilibrium solver was used to calculate magnetic fields from typical shot data. A parabolic density profile was assumed and scaled to observed average densities. Refraction of the beam in the plasma was also considered.

SPECTOR generates plasmas with magnetic field $B \approx 1$ T, average electron density $\bar{n}_e \approx 3 \times 10^{14}$ cm^{-3}, and magnetic lifetime $\tau = 1$ ms. A typical shot is shown in Figure 4. Polarimeter chords are 20–34 cm long and located on the midplane. The beam's wavelength is 118.8 μm.

Given these parameters, the simulation calculates Faraday rotation to be in the range of 30° to 5° from the longest to the shortest chord. The Cotton-Mouton effect is found to be small. Collinearity error due to density gradients ranges from 0.2° to 1° from the longest to shortest chord for 0.1 mm separation between the beams.



(a)

(b)

(c)

FIG. 2. Polarimeter optical layout. Chord offset from the geometric axis is $x = 90$, 120, 140, 160 mm. Wall is at $R = 190$ mm. (a) Laser table where the two beams are combined. (b) Waveguide filled with dry nitrogen to send beam to SPECTOR. (c) Beam splitting and detection optics on SPECTOR platform.

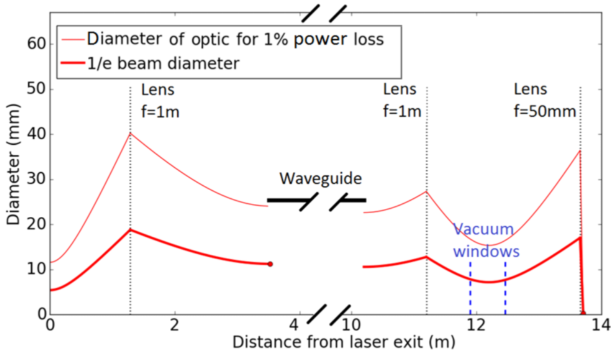


FIG. 3. Simulation of beam size from FIR cavity to mixer.

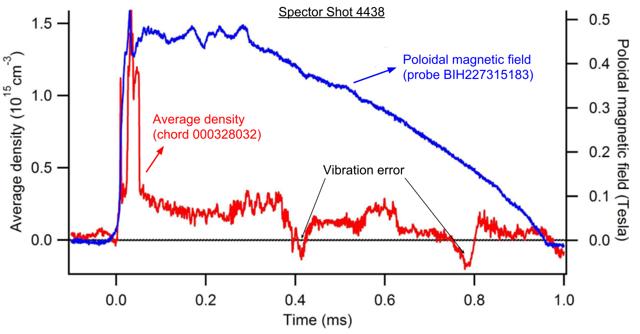


FIG. 4. SPECTOR poloidal magnetic wall probe and 1.31 μm-1.55 μm dual wavelength interferometer data.

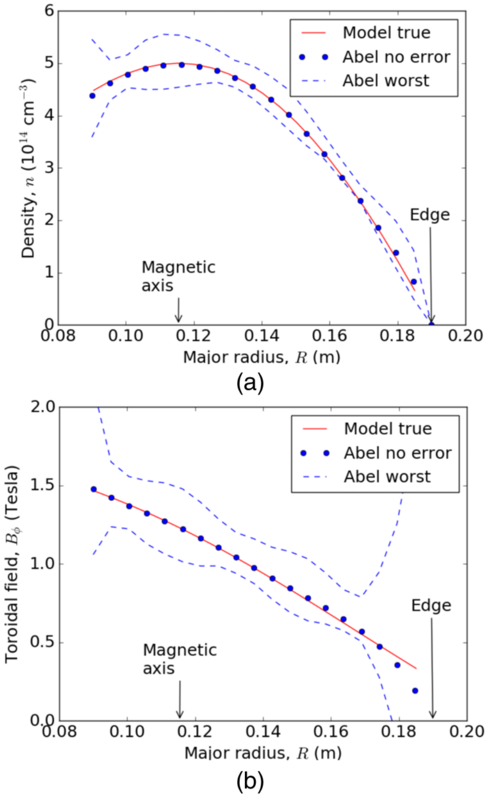


FIG. 5. Abel inversion profiles from simulated polarimeter measurements. “Abel no error” is the result for no measurement error. “Abel worst” is the envelope of the worst profile estimates in 1000 runs with simulated measurement error. (a) Density profile and (b) toroidal field profile.

Simulated polarimeter/interferometer measurements were Abel inverted to obtain the axisymmetric radial profiles of density, $n_e(R)$, and toroidal field, $B_\phi(R)$. The inversion of ϕ_F to obtain $B_\phi(R)$ is given by[17]

$$B_\phi(R) = -\frac{R}{\pi n_e(R)} \int_R^{R_{wall}} \frac{(dG/dx)}{\sqrt{x^2 - R^2}} dx, \tag{2}$$

$$G(x) = 3.8 \times 10^{12} \lambda^2 \frac{\phi_F(x)}{x}, \tag{3}$$

where R_{wall} is the major radius at the wall, and x is the chord position offset from the geometric axis. Assuming no measurement error, the estimated and true profiles match well, as shown in Figure 5.

To investigate the effect of measurement error, the polarimeter simulation was repeated 1000 times with random error added to each density and Faraday rotation measurement. The error was sampled from a uniform distribution with a range of $\pm 10^{13}$ cm^{-3} and ±1° for density and Faraday rotation, respectively. At these levels of added error, density and Faraday rotation measurements contributed roughly equally to the error in $B_\phi(R)$.

IV. FUTURE WORK

Progress is being made to commission the FIR laser. The interferometer system is being developed to measure density with an accuracy better than $\pm 10^{13}$ cm^{-3}. Once the polarimeter system is operational, its measurements will be integrated into the Grad-Shafranov solver to constrain q-profile equilibrium reconstructions.

ACKNOWLEDGMENTS

Special thanks to Eli Parke, Weixing Ding, David Brower, and Jim Irby for their help answering polarimetry questions. Funding was provided in part by the Natural Sciences and Engineering Research Council of Canada.

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