Thomson Scattering measurements on DIII-D using in-vessel laser mirrors to diagnose a new divertor location[a)]

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Translatable in-vessel mirrors have enabled the DIII-D Thomson Scattering system to diagnose the divertor plasma in high triangularity plasma shapes. Previous divertor Thomson scattering measurements in DIII-D were restricted to spatial locations along a Nd:YAG laser beam that was directed through a vertical port. This only allowed measurements to be made in low triangularity shaped plasmas. The new mirrors re-route the laser underneath floor tiles to a position of smaller major radius as necessary for high triangularity plasmas. New in-vessel collection optics transmit scattered light from regions inaccessible to external lenses. Damage to mirrors and high stray light levels are challenges that were overcome to successfully make these measurements. Through the careful use of baffles and light shields, stray light leakage into polychromator detector channels was reduced to negligible levels, allowing temperature measurements below 1 eV. The system is described and initial results presented.

I. INTRODUCTION

Thomson scattering measurements of electron temperature and density in the divertor region of the DIII-D tokamak have been done for the past 20 years[1,2]. The location of these measurements were restricted to the area above a vertical port near the center of the machine where the laser beam could be directly injected into the vacuum vessel. In addition, magnetically sweeping the divertor region across the laser beam enabled 2D measurements of this complex region. This system worked well for low triangularity shaped plasmas.

As the understanding of the advantages of highly shaped plasmas on stability and confinement improved[3], operation in high triangularity shaped plasmas became desirable. In 2006, the DIII-D divertor region was modified to accommodate high triangularity shaped plasmas by the introduction of a cryogenically pumped divertor shelf[4]. However, operation at high triangularity moved the divertor plasma away from the laser beam and precluded Thomson scattering measurements of this important region.

This paper, together with a previous paper[5], describes the design and initial results of a Thomson scattering system in which the laser beam is introduced into the vacuum vessel at one location and then moved to another location through a series of mirrors located underneath the protective wall tiles. Figure 1 shows the old location of the laser beam on the divertor shelf and the new location on the divertor floor. Also shown are locations of two other laser beams for the core[6] and tangential[7] Thomson scattering systems.

It had been thought that stray light from in-vessel mirrors would be so strong as to preclude the measurements, and laser beam intensities on the mirror so great that the mirrors would be immediately damaged. Through the use of advanced high-quality interference filters in the polychromators, high damage threshold laser mirrors, and careful design, these challenges have been overcome and successful Thomson scattering measurements have been made in high triangularly shaped, diverted plasmas in DIII-D.

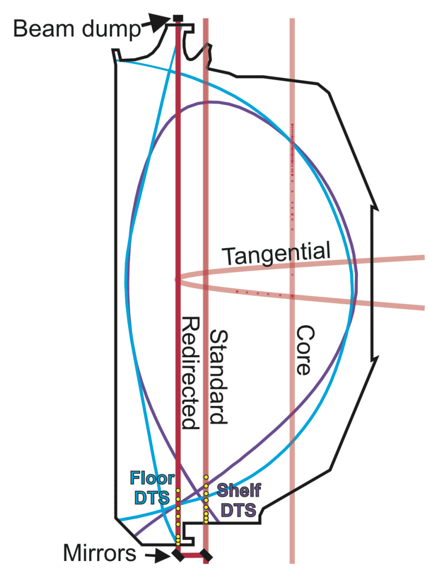

FIG. 1. Location of the laser beams for Thomson scattering measurements in DIII-D. Also shown are the standard shelf Divertor Thomson Scattering (DTS) measurement locations and the new floor DTS locations.

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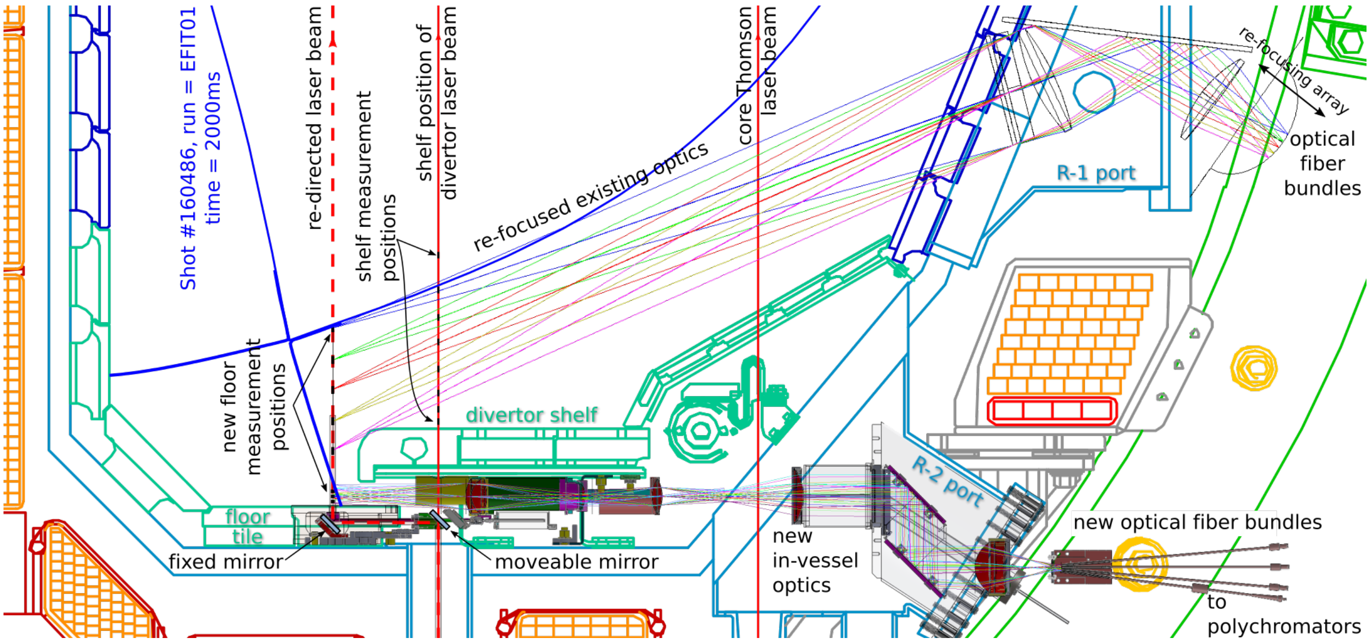

FIG. 2. Schematic of the lower divertor showing the re-directed laser beam to the floor region, in-vessel relay optical elements, and the existing optics of the current system with adjustable focus. The separatrix of a high-triangularity plasma discharge is overlain.

II. EXPERIMENTAL ARRANGEMENT

Thomson scattering measurements are available in both the shelf and floor configurations as shown Figure 2. A moveable mirror located below the shelf is either pneumatically retracted to allow the laser beam to continue to the shelf location at R=1.485 m, or it is inserted to redirect the laser beam inboard to a second mirror which directs it vertically up through a 1 cm hole in the floor tiles at R=1.335 m. External collection optics[1] look down from a port above the divertor region and image the laser beam on an array of fiber optic bundles which carries the light to 8 remotely located polychromators[8]. When the laser beam is moved to the floor configuration, the fiber bundles are moved along a precision track to keep the laser beam in focus. Details of the design can be found in reference 5.

The lower portion of the floor region is not visible to the external collection optics so an in-vessel lens system located under the shelf relays the image of the laser beam in this region through a window of another port where it is subsequently imaged on another fiber bundle array.

In the shelf configuration the laser beam exits the vessel through a symmetric port at the top of the machine and is absorbed by an external beam dump. In the floor configuration the laser beam exits through a 2 cm hole in a ceiling tile and is absorbed in a glass absorbing beam dump located behind the tile[5].

Both systems use the same polychromators optimized for low T_e measurements in the divertor region (0.5-500 eV) and the same 50Hz Nd:YAG laser, nominally 1 J and 10 ns pulses.

III. DESIGN ISSUES

The introduction of mirrors in the vessel so close to the scattering volume presented a number of challenges. Scattering of laser light from the mirrors, even at very low values, would create significant stray light that could easily overwhelm the Thomson signal. To minimize the collection of stray light, the laser path was completely baffled from the in-vessel optics. In addition, the hole through the shelf was sealed with a shutter that closes as the mirror is inserted. This prevents stray light from entering the vessel, except for the 1 cm hole in the tile where the laser enters. The in-vessel lenses are shrouded and baffled to limit their exposure to light from unwanted sources. Advanced hard-coated interference filters[9] were used in the polychromators, and these have an optical density greater than 5 (except for the 1061.9 nm filter which has an OD of 3) at the laser wavelength to further reject any collected stray light. The laser beam dump uses absorbing glass at Brewster's angle to minimize any reflected light. These techniques proved effective at eliminating stray light from the Thomson signals even at wavelength channels near the laser line (needed for low T_e measurements).

Polychromators for divertor region have an additional long wavelength side (1067 nm) filter channel to extend and improve their low T_e measurement capability. The change in the central wavelength of this filter from laser line ($\Delta\lambda$) is placed between $\Delta\lambda$s of the first two filters on short wavelength side of the laser line (Figure 3). This improves measurement of narrow, very low T_e (<0.5 eV) scattered spectra (Figure 4). In addition, an 800 nm (200 nm wide) filter was also added to extend the high T_e range to over 8 keV.

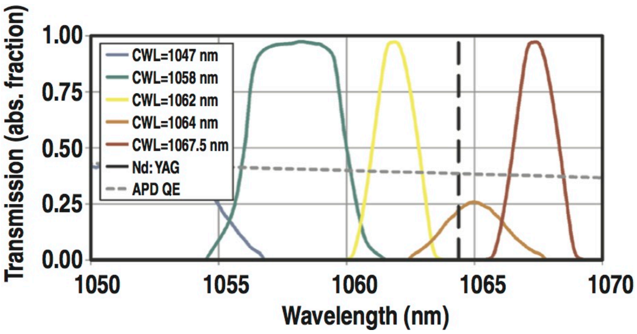

FIG. 3. Interference filter transmission of filters on both the long and short wavelength sides of the laser line (vertical dashed line).

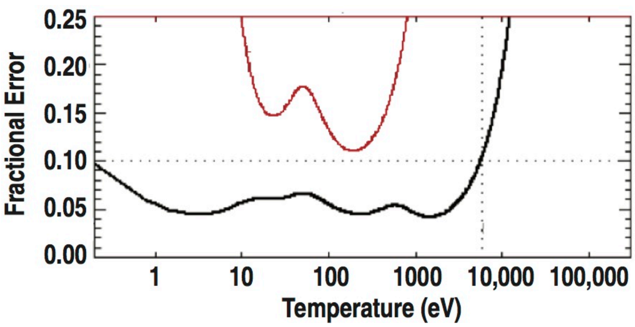

FIG. 4. Calculated expected fractional T_e measurement error from an 8 channel polychromator (black) compared to a previous 6 channel polychromator (red). The addition of the 1067 nm filter extends the range to less than 1 eV, and an 800 nm filter increases the range to over 8 keV.

Typically, in Thomson scattering systems the laser is focused at the scattering volume. Due to the presence of mirrors so close to the scattering volume, the laser beam was focused at the center of the vessel to allow the beam to expand somewhat at the entrance and exit where laser mirrors are located. This reduced the laser intensity from 11 J/cm^2 at the focus (3 mm diameter) to 3.3 J/cm^2 at the mirrors (5.5 mm diameter). High damage threshold, dielectric, ion beam sputtering coated mirrors (40 J/cm^2) that can tolerate 400 ^{o} C bake out temperatures were used[10]. In addition, the laser divergence is controlled by warming up the laser sufficiently before permitting it to enter into the system. An improperly warmed up laser could focus near one of the mirrors and damage it. To further minimize the fluence on the laser mirrors the Q-switch timing is adjusted to throttle the laser energy to the minimum required to obtain a useful signal. Typically, 0.2 joules are sufficient for high density divertor operation. Lastly, the input plasma facing mirror has a shutter linked to the moveable mirror which opens only when the system is in use. This protects the mirror from glow discharge cleaning, boronization operations, and general plasma exposure during experiments for which the system is not in use.

Initial alignment of the system is done by personnel in the vessel during vents. The moveable mirror is pushed against a stop where its front surface encounters three precision aligned small raised surfaces near the edge of the mirror that define a reproducible position. The second mirror is aligned in a kinematic mount and locked in place. The overall laser alignment is done at fiducials at the entrance and exit windows. Alignment is checked during operations using an in-situ alignment monitor consisting of an array of 5 fiber optics that span the laser beam and measure its position relative to the collection fibers[2].

IV. RESULTS

Raw data in digitizer counts of the scattered light for the lowest spatial channel is shown in Figure 5 for a shot in which the divertor is swept past the floor divertor system as shown in Figure 6. The scattered signal is the output of a 30 ns gated integrator centered on the laser pulse after a 30 ns delay line subtraction of the background light[11,12]. This channel, whose wavelength is centered at 1062 nm, shows no signal until plasma is present at about 2.5 seconds. This demonstrates the effectiveness of the filter in suppressing stray light and permits the measurement of low T_e plasmas. Unfortunately, the 1064 nm channel, used for Rayleigh scattering calibration of the system, is saturated and cannot be used for absolute density calibration. For the results reported here, the density calibration for the shelf system was extended to the floor system, taking into account the change in the optical magnification and collection solid angle between the two systems.

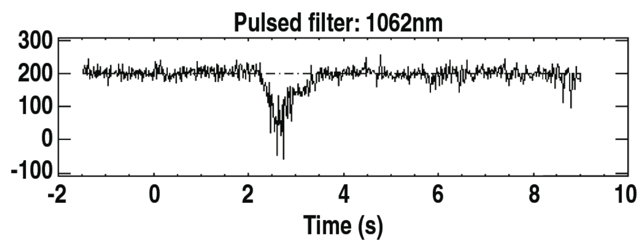

FIG. 5. Raw data in digitizer counts of the Thomson scattered signal from the lowest floor divertor channel for shot 173031. The signal is from the 1062 nm wavelength channel and light produces negative going signals. The dashed line represents the no-light signal level. The laser starts firing at -1.5 sec and the plasma discharge starts at 0.0 sec.

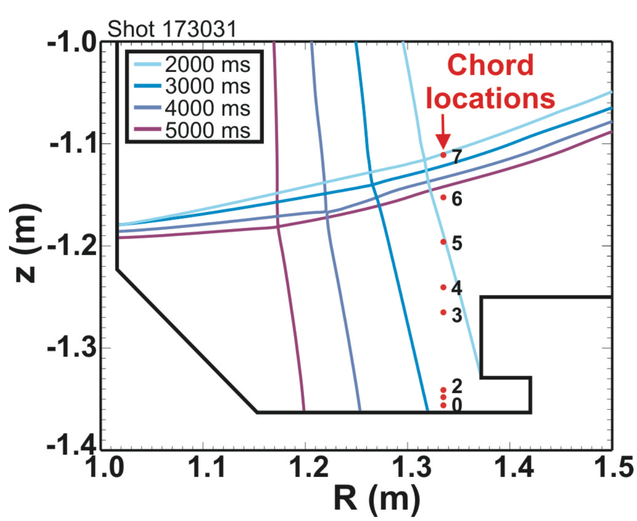

FIG. 6. Reconstructed separatrix locations relative to the floor divertor Thomson scattering (DTS) chord locations at various times during the x-point sweep of shot 173031.

Temporal evolution of T_e and n_e for three of the floor divertor channels are shown in Figure 7. Temperatures near 5 eV and densities of $1x10^{20}$ m^{-3} are measured near the floor as the outer strike point moves across the lowest spatial location. The large spikes in T_e are due to the effects of ELMs which periodically exhaust heat and particles from the main plasma to the divertor. The spatial profile of T_e and n_e measured at 2400 ms is shown in Figure 8. The error bars represent the 1-sigma uncertainty of the fit to the raw data. A composite 2D map of T_e, n_e, and p_e based on measurements as the divertor leg is swept past the laser beam for several plasma discharges is shown in Fig. 9. The data is mapped to magnetic flux surfaces and displayed at a fixed x-point location. Low T_e and p_e near the floor may indicate partial plasma detachment in this case.

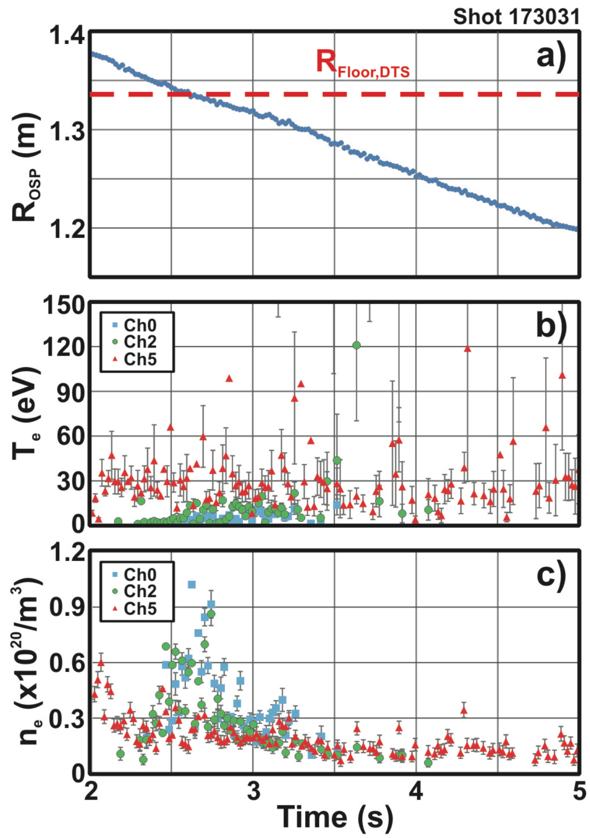

FIG. 7. Time evolution of (a) the variation of the outer strike point (R_{OSP}) and the floor DTS (R_{FLOOR_DTS}) location, (b) T_e and (c) n_e for three of the floor divertor channels

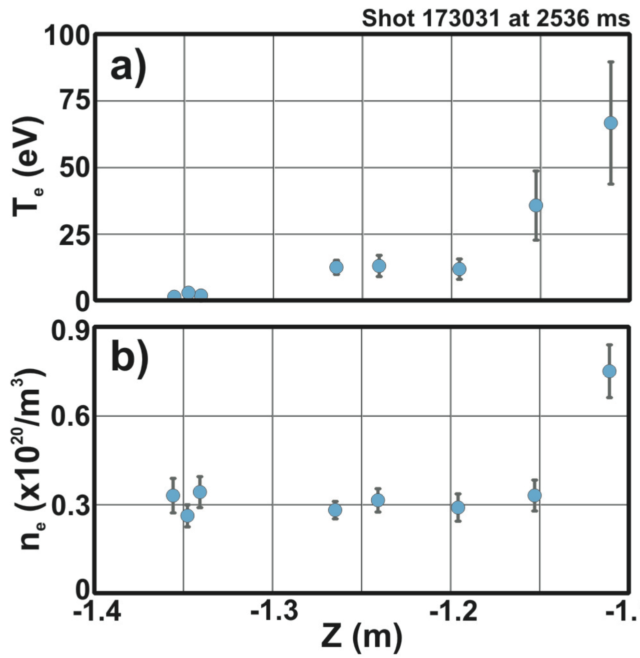

FIG. 8. Spatial profile of (a) T_e and (b) n_e at 2400 ms of shot 173031.

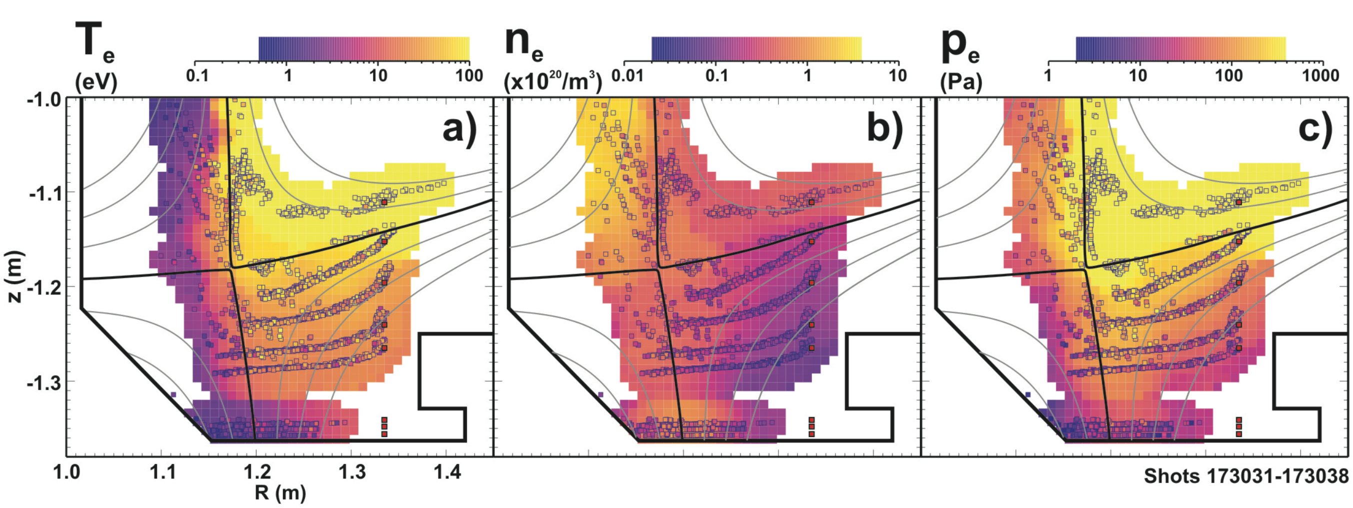

FIG. 9. Composite 2D constructions of (a) T_e, (b) n_e, and (c) p_e based on measurements as the divertor leg is swept past the measurement locations shown as red squares at R = 1.335 m. The data is then mapped to magnetic flux surfaces and displayed at a fixed x-point location.

V. FUTURE WORK

Because high stray light levels prevent calibration using Rayleigh scattering in argon, Raman scattering in nitrogen will be used to absolutely calibrate the density. Raman scattering produces signals in wavelength channels near the laser line which do not suffer from stray light pollution. This signal is much weaker than the Rayleigh signal and therefore requires higher pressures to obtain good signal-to-noise ratios. Typically, argon pressures of 4 torr are used for Rayleigh scattering calibration. Nitrogen pressures of 100 torr are expected for Raman calibration.

There are also plans to expand the system to include a scanning laser and optics system that can provide many vertical beams and produce 2D measurements of T_e and n_e in the entire divertor region without having to scan the plasma across the laser beam. It is envisaged to use an external fast-steering mirror to move the laser beam across a stationary multi-element mirror to direct the beam to different vertical chords on a pulse by pulse basis.

VI. ACKNOWLEDGMENTS

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VII. DISCLAIMER

VIII. REFERENCES

[1]T.N. Carlstrom, *et al*., Rev. Sci. Instrum. **66** (1995) 493.
[2]T.N. Carlstrom, *et al*., Rev. Sci. Instrum. **68** (1997) 1195.
[3]C. Holcomb, J. Ferron, T. Luce, T. Petrie, P. Politzer, C. Challis, J. DeBoo, E. Doyle, C. Greenfield, R. Groebner et al., Phys. Plasmas **16**, 056116 (2009).
[4]P. Anderson, Q. Hu, C. Murphy, E. Reis, Y. Song, and D. Yao, Fusion Eng. Des. **82**, 1756 (2007).
[5]F. Glass, *et al*., Rev. Sci. Instrum. **87**, (2016) 11E508.
[6]T.N. Carlstrom, *et al*., Rev. Sci. Instrum. **63** (1992) 4901.
[7]D.G. Nilson, *et al.,* General Atomics report GA-A23198 presented at LAPD (1999).
[8]T.N. Carlstrom, *et al*., Rev. Sci. Instrum. **61** (1990) 2858.
[9]Alluxa, 3660 North Laughlin Road, Santa Rosa, CA 95403; alluxa.com
[10]Advanced Thin Films, 5733 Central Avenue, Boulder, CO 80301; advancedthinfilms.com
[11]T. M. Deterly, B. D. Bray, C.-L. Hsieh, J. A. Kulchar, C. Liu, and D. M. Ponce, IEEE Trans. Plasma Sci. 38, 1699 (2010).