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The Thomson scattering system on the Lithium Tokamak eXperiment (LTX)*

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Abstract. The Lithium Tokamak eXperiment (LTX) is a spherical tokamak with $R_0 = 0.4$m, a = 0.26m, B_{TF} ~ 3.4kG, I_P ~ 400kA, and pulse length ~ 0.25s. The goal of LTX is to investigate tokamak plasmas that are almost entirely surrounded by a lithium-coated plasma-facing shell conformal to the last closed magnetic flux surface. Based on previous experimental results and simulation, it is expected that the low-recycling liquid lithium surfaces will result in higher temperatures at the plasma edge, flatter overall temperature profiles, centrally-peaked density profiles, and an increased confinement time. To test these predictions, the electron temperature and density profiles in LTX will be measured by a multi-point Thomson scattering system (TVTS). Initially, TS measurements will be made at up to 12 simultaneous points between the plasma center and plasma edge. Later, high resolution edge measurements will be deployed to study the lithium edge physics in greater detail. Technical challenges to implementing the TS system included limited "line of sight" access to the plasma due to the plasma-facing shell and problems associated with the presence of liquid lithium.

I. Introduction

The Lithium Tokamak eXperiment (LTX)[1] is a spherical torus with $R_0 = 0.4$ m, $a = 0.26$ m, toroidal B-field ~ 3.4kG, I_P ~ 400kA, and pulse length ~ 0.25s. LTX is scheduled to begin operations at Princeton Plasma Physics Laboratory in 2008 and will be the first fusion device in which the plasma is almost entirely surrounded by a low-recycling, lithium-coated surface (in this case, a plasma-facing shell conformal to the last closed magnetic flux surface). ASTRA[2] modeling predicts that the low recycling lithium walls in LTX will result in higher temperatures at the plasma edge, flatter overall temperature profiles, centrally-peaked density profiles, and an increased confinement time. On CDX-U, the predecessor to LTX, lithium-coated limiter surfaces were already shown to reduce global recycling and improve confinement.[3]

Electron temperature (T_e) and density (n_e) profiles in LTX will be measured by a multi-point Thomson scattering system of the TVTS[4,5] design. The system will employ a 4-stage ruby laser (beam energy=15J) launched horizontally into the LTX plasma. Initially, the scattered light will be collected from up to 12 simultaneous spatial points between minor radius r=0 and r=0.23 m. Later, an edge view will be implemented to measure n_e and T_e near the last closed flux surface.

This paper provides a description of the Thomson scattering system on LTX. Many aspects of the LTX Thomson scattering system are typical for the diagnostic; however, the compact, shell-enclosed geometry of LTX and the presence of highly reflective and reactive lithium surfaces added additional technical challenges to the design. In section II, the components of the TVTS system are described, along with a discussion of how the system meets specific design challenges posed by LTX. Section III discusses issues related to calibration of the system. Section IV describes simulated predictions of the TVTS system performance.

II. System Components and Design Challenges

A. Laser and Beam Path.

Figures 1a and 1b show the layout of LTX and the Thomson scattering system. The TVTS system employs a 4-stage, single pulse Quantel ruby laser (beam energy=15J, pulse length ~20-40 ns) mounted on a 122 cm x 274 cm optical bench (Fig. 2). The laser beam is linearly polarized with the electric field component in the horizontal direction. The laser system is enclosed in a custom-built enclosure with removable panels. The 0.63 cm thick paneling of the enclosure is comprised of corrugated polyethylene sandwiched between sheet aluminum. The enclosure, in addition to protecting the laser from dust and offering laser safety protection to personnel, provides some degree of thermal insulation to mitigate fluctuating thermal gradients on the optical table that can cause misalignment of laser components.

The laser beam is collimated to a diameter of approximately 35 mm before being focused by a converging doublet toward the target position inside LTX, at about minor radius r = 0.11 m (between 250-300 cm away from the lens), with a target spot size of 1 mm or less. The beam crosses the vacuum interface through an anti-reflection coated BK7 glass window mounted at the end of a long flight tube (>2m). At the entrance window, the beam will still be larger than 21 mm, which places a maximum of 300 MW/cm^2 on the window (still below the threshold for damage).

The laser beam will enter the LTX vacuum vessel horizontally at the midplane of the experiment at an angle of 12 degrees with respect to the face of the rectangular entrance flange, and then will follow a path that just misses the toroidal centerstack (by about 5 mm from the beam edge), as shown in Fig. 1a. This beam path was chosen based on the line-of-sight limitations due to the near total enclosure of the plasma by the conformal plasma facing shell. The shell is divided into four quarters, so that there is a 'break' at the midplane (Fig. 1b), as well as two azimuthal 'breaks' where vertical lines of sight are possible. Since the TVTS system requires a line of sight for both laser beam propagation and light collection, the laser must pass through both the midplane and a vertical break in the shell, but still traverse a plasma cross-section that is useful for diagnostics. Also, the laser path had to be located so that razor blade viewing dumps could cover the background of all views of the beam (Fig. 1b). The laser exits the vacuum vessel at the end of another flight tube, and terminates in an absorbing beam dump.

Both the entrance and exit windows are placed at a 7 degree angle with respect to the beam path to prevent the excitation of resonant cavity modes that could damage the windows. To reduce stray light, a series of "baffles" with small, circular, knife-edged apertures are placed in each flight tube to block any stray laser light that can contaminate the scattered light signal.

B. Primary Light Collection

The primary TVTS light collection view will measure T_e and n_e profiles between minor radii r=0 and r=0.23 m. Light collection will be through a downward looking viewport on top of the machine, 90 degrees from the direction of laser beam propagation. This viewport is constructed from a 15 cm diameter BK7 glass window that seals with an o-ring directly to a 9 inch O.D. ASA gate valve (5 inch I.D.). Outside the window, the light is collected by a lens and imaged onto optical fibers that pipe the light to a spectrometer and intensified CCD camera detector.

During LTX operation, lithium will be evaporated onto plasma-facing components, which may also lead to unwanted lithium deposition onto the viewing window. To mitigate window deposition during operation, a mechanical shutter actuated by a pneumatic rotary vacuum feedthrough will be used to protect the window between shots. If over time the optical transmission of the window is reduced by lithium that migrates around the shutter, the gate valve between the window and the vessel will be used to isolate the window for removal and cleaning.

The primary light collecting lens is similar to that used in the Thomson scattering system on CDX-U.[6] The lens is comprised of 5 off-the-shelf commercial lens elements held in an aluminum lens holder designed and built at PPPL. Each element is anti-reflection coated, and the holder is black anodized to reduce reflectivity. The lens (f/3.8) is 59 cm from the beam line. The lens collects light over a solid angle of 0.012 sr at the center of view (minor radius r=0.11 m), down to about 0.01 sr at the edge of view (minor radius 0 and 0.23 m). The lens images the beam line onto a curved image surface (radius=103 cm, concave toward the objective) at an image distance of 5.1 cm from the last lens surface. The lateral magnification of this lens setup is -0.17.

After being imaged by the lens, the scattered light is collected at the image plane by a series of 1 mm diameter quartz-core optical fibers (0.8/0.9 mm core/cladding dia.) held in place by a custom fiber holder. Each fiber collects light from about 0.5 cm of the axial length of the laser beam. (Note that the beam diameter should not be greater than 3 mm in the imaged region, so the full beam width is easily imaged within the diameter of a single fiber.) If scattered light intensities from a single fiber are sufficient to give good photon statistics, then each spatial channel will consist of one fiber, giving a resolution of 0.5 cm. However, if two neighboring fibers need to be doubled up to increase the signal, the effective resolution will be 1 cm. On CDX-U, plastic rectangular fibers were used to increase the packing fraction and maximize the amount of collected light, but experience in those experiments proved that the plastic fibers had lower transmission than quartz fibers, despite stated technical specifications. Hence, round quartz fibers were chosen for LTX.

The fibers rest in triangular notches on the fiber holder and are held tight by clamps and soft rubber padding. The present design of the fiber holder holds two rows of 1 mm quartz fibers over a 22 degree arc of the image surface, corresponding to an image of 0.23 m of the laser beam. One row of fibers receives light imaged directly from the laser beam, and the other row is sparsely populated by 2-3 fibers to collect samples of background light. The height of the spectrometer entrance slit only permits about 15 fibers to be used as individual channels at any given time, so, with 3 background light channels, the number of spatial channels for T_e and N_e profile measurements is at most 12 (assuming one fiber per channel).

The fibers carry the light to the entrance slit of a fast (f/1.8) HoloSpec spectrometer attached to a Princeton Instruments Intensified CCD camera detector (GaAs photocathode, 512x512 pixels, 12.35 mm x 12.35 mm effective image area). The HoloSpec spectrometer employs a fixed position, volume phase holographic transmission grating, the dispersive properties of which are described thoroughly elsewhere.[6] Because electron temperatures in LTX are expected to range from about a hundred eV (without lithium) up to as much as 1 keV (with lithium), two spectrometer gratings will be available in order to cover this range. For the lower temperature regime, the high dispersion grating used in the CDX-U Thomson scattering system[5] will be used. This grating is designed to look at the broadened scattering spectrum between 703 nm and 732 nm on the 'red' side of the ruby laser line at 694.3 nm. For the higher temperature plasmas (above several hundred eV), a low dispersion grating (550-750 nm) will be used, which is centered at 650 nm on the 'blue' side of the scattering spectrum.

Because the H- and D-alpha emission lines around 656.3 nm are present on the blue side of the Thomson scattering spectrum, it is possible that these lines may saturate the detector around that wavelength. To avoid saturation, a notch filter will be placed just after the entrance slit of the spectrometer to block this line. A notch filter is also available to block the laser light at 694.3 nm, but this filter may not be used if Rayleigh scattering is chosen as the method to calibrate Thomson scattering for density measurements. (See III).

The CCD detector will be electronically shuttered with a 50 ns gate, just long enough to collect the entire laser pulse but also as short as possible to reduce stray light contamination of the signal. The shutter will be triggered by a sample of the laser beam carried via optical fiber to a photodiode switch. The overall effective quantum efficiency of the camera system was measured to be about 15% at 700 nm.[5]

C. Edge Viewing Geometry

The edge viewing TS system will image the laser beam at the edge of the plasma near last closed flux surface. The diagnostic viewport for the edge view is shown in Fig. 1b. This viewport gives a view over a 4-6 cm radial range near the plasma edge. In order that this viewport 'sees' the razor blade viewing dumps in the background (see II.B), as opposed to the reflective lithium-coated plasma-facing shell, the viewport is directed at the beam from an angle of about 82 degrees with respect to the horizontal E-field vector of the beam, giving an effective beam polarization angle of 82 degrees. Given that the scattered light intensity depends on the polarization angle φ and scattering angle θ as $1-\cos^2(\varphi)\sin^2(\theta)$, this view is non-optimal. However, the 82 degree angle in this case leads to a reduction of intensity of no more than 2%, which is acceptable.

III. Calibration for Density Measurements

Thomson scattering-based density measurement requires calibration of the fine details of the alignment between the laser beam and the collection optics. This is best accomplished by laser scattering in gas: Rayleigh scattering occurs at the laser wavelength and is easy to detect, but the presence of stray laser light can limit its usefulness; rotational Raman scattering, which occurs in series of lines shifted above and below the laser line, is immune to stray laser light, but has a much lower cross section than Rayleigh. In either case, an absolute calibration becomes possible if the gas pressure can be measured precisely. Simple molecular gas like N_2 or H_2 can be used for Rayleigh and Raman scattering, and a noble gas like argon provides a non-chemically active alternative although limited to Rayleigh scattering. Argon and nitrogen have comparable

Rayleigh cross section, making it easy to switch from one to the other. The LTX lithium research plan makes it necessary to proceed to a N_2 based calibration prior to evaporation in order to avoid lithium pacification. Doing Raman scattering in H_2 poses its own problems with a high energy ruby laser: care most be taken not to damage the input window in order to prevent oxygen from reaching in. Because of its low mass H_2 will have a wider Raman spectral coverage than N_2, but its low cross section may require, depending on the system sensitivity, to fill the vessel with gas at high pressure bringing about the possibility of laser induced breakdown. Relying on Rayleigh scattering will require a serious effort to mitigate the stray laser light, which in a small device like LTX could be a challenge.

IV. System Performance

To estimate system performance, simulated ray traces through the spectrometer were performed based on the spectrometer equations in Bell[6] and the Thomson scattering equations in Bretz, et. al.[7] The contribution to the intensity I_{ij} at pixel ij (at the jth row and ith column on the CCD chip) from the scattered photons in a single fiber is an integral function of the signal from a finite slit width (effectively the diameter of a fiber core) and height, given by

$$I_{ij} = \frac{4}{\pi a^2} \int_{x_1} \int_{y_{1,j}} \int_{x_{2,i}} N_{pe}\left(\lambda(x_1, y_1, x_2)\right)\left(\frac{\partial \lambda(x_1, y_1, x_2)}{\partial x_2}\right) dx_2 dy_1 dx_1 \qquad (1)$$

where a is the fiber core diameter, λ is spectral wavelength, x_1, y_1 are the horizontal and vertical coordinates at the slit, x_2 is the horizontal coordinate on the pixel screen, $\partial\lambda / \partial x_2$ describes the change of coordinates of λ to x_2 given by the mapping of wavelength through the spectrometer,[6] and N_{pe} is the number of photoelectrons produced from light in $d\lambda$ at λ. In Eq. (1), the integral over x_2 is over the width of a single pixel, and the integral in y_1 is over a region of the fiber core that maps to the height of a single pixel. The integral over x_1 is over the full slit width. Note that the y_2 dependence is not shown because y_1 maps independently onto y_2. N_{pe} is given by[7]

$$N_{pe} = \frac{N_i \eta T n_e {r_o}^2 L(\Delta\Omega)}{\lambda_i \delta \sqrt{\pi}} \exp\left(-\frac{(\lambda_s - \lambda_i)^2}{{\lambda_i}^2 \delta^2}\right) \qquad (2)$$

where N_i is the number of photons in the laser beam, η is the effective detector quantum efficiency (~15%), T is the optical transmittance (assumed 30% for the present simulations), n_e is the electron density, r_o is the classical electron radius, L is the axial beam length imaged into the fiber, $\Delta\Omega$ is the solid angle collected by the fiber, and $\lambda_{i,s}$ are the incident and scattered wavelengths, respectively. The parameter δ is given by $2(\sqrt{2kT_e/m_e}/c)\sin(\theta/2)$, where θ is the scattering angle with respect to the beam axis and c is the speed of light. The effect of the finite slit in Eq. (1) is to introduce instrument broadening to the measured signal (which for low temperatures could be significant), and slightly increases the effective bandwidth of the detector at the expense of spectral resolution.

To simulate the actual system, realistic photon noise was introduced to the calculated signals. The noise was calculated by first working backward from the "ideal" noise-free light signal at each CCD pixel within each small, resolution-limited wavelength band to get the "ideal" number of photons being scattered in the plasma in that wavelength band that would ideally arrive at the given pixel. That number of scattered photons is then varied randomly according to a Poisson distribution (this introduces a small variance at this early stage). Then for each of those photons (still within the small wavelength band going to a pixel *ij*), a random number is generated to determine if the photon survives to reach the CCD screen, (according to the combined transmission and quantum efficiency probability, ηT).

After generating the noisy signals, a two-parameter, non-linear least squares minimization routine was then applied to extract values for T_e and n_e, assuming a maxwellian plasma. The variances for T_e and n_e were calculated from standard least squares formulas[8] applied to the nonlinear case. The simulations demonstrated that with the high dispersion grating, using one fiber per channel, T_e=100 eV and n_e=2×10^{19} m^{-3} could be measured with 8% and 9% uncertainty, respectively. With the low dispersion grating, T_e=800 eV and n_e=0.6×10^{19} m^{-3} could be measured with 8% and 11% uncertainty, and Te=1000 eV and n_e=1.6×10^{19} m^{-3} could be measured with 6% and 8.5% uncertainty, respectively. Examples of the simulated noisy signals along with the ideal spectra are shown in Fig. 3.

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FIG. 1. (a) Overhead layout of LTX showing the TVTS laser system and laser path, microwave interferometer, and neutral beam (planned). (b) Side view LTX cross-section showing the TVTS collection optics and ray trace of scattered light from the laser beam through the primary collection optics. The edge viewport is also shown.

FIG 2. The LTX TVTS ruby laser with 3 amplification stages.

FIG. 3. (a) Simulated spectra with photon noise for the case of the high dispersion grating alongside the ideal spectrum (T_e=100 eV, n_e=2×10^{19} m^{-19}), and (b) the simulation of the low dispersion case (T_e=1000 eV, n_e=1.6×10^{19} m^{-19}).

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