Thomson scattering on the Large Plasma Device

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We have developed a non-collective Thomson scattering diagnostic for measurements of electron density and temperature on the Large Plasma Device. A triple grating spectrometer with a tunable notch filter is used to discriminate the faint scattering signal from the stray light. In this paper, we describe the diagnostic and its calibration via Raman scattering, and present the first measurements performed with the fully-commissioned system. Depending on the discharge conditions, the measured densities and temperatures range from $4.0 \times 10^{12} \text{ cm}^{-3}$ to $2.8 \times 10^{13} \text{ cm}^{-3}$, and from $1.2 \text{ eV}$ to $6.8 \text{ eV}$, respectively. The variation of the measurement error with plasma parameters and discharges averaged is also discussed.

I. INTRODUCTION

Thomson scattering (TS) is a powerful, first-principles, and non-invasive plasma diagnostic that derives electron density and temperature from the Doppler shift imparted to photons scattered by plasma electrons. In the non-collective regime encountered in tenuous basic plasmas, the temperature can be derived from the width of the broadened line, and the density from the scattering signal intensity, after an absolute irradiance calibration. TS measurements in this regime are challenging since the faint scattering signal must be discriminated from a much brighter background laser light. However, TS spectra from such plasmas can be resolved by using a suitable notch filter for stray light suppression.

We have developed a TS system on the Large Plasma Device (LAPD), a 22 m long magnetized linear plasma device at the University of California Los Angeles. The instrument allows model-independent measurements of the density and temperature in experiments involving fast laser-driven flows at ion-scales, that cannot be diagnosed with swept electrostatic probes. Scattering spectra can be obtained by accumulating the signal from as little as ten discharges.

II. EXPERIMENTAL SETUP

A schematic of the setup is shown in Fig. 1a. Large plasmas (19 m length and 50 cm diameter) are created by accelerating electrons emitted from a heated cathode into a gas by an electrostatic field. In this experiment, the plasmas are magnetized by a straight axial magnetic field of 1.0 kG, and pulsed on for 15 ms at 1/3 Hz repetition rate. Helium gas is injected near the plasma source by two fast Piezo valves pulsed on 5 ms prior to and for the duration of the discharge (80 V gate voltage, 450 SCCM, 33 PSI backing pressure). The TS diagnostic is installed in port 32, about 13 m from the plasma source.

A frequency-doubled Nd:YAG laser produces 4 ns long pulses of 460 mJ energy at a wavelength of $\lambda = 532 \text{ nm}$, at a repetition rate of 20 Hz. The laser output is collimated to a 15 mm diameter beam using a Galilean telescope and is focused by a 1.5 m focal-length lens into the center of the plasma column. This small-solid angle f/67 lens produces a cylindrical beam around the focus with an 0.8 mm full-width at half-maximum (FWHM) over a length of several centimeters. The beam enters and exits the chamber from top to bottom through Brewster windows and a series of baffles, that minimize stray light entering the detector. A half-waveplate linearly polarizes the incident beam along the longitudinal axis. The laser energy was monitored on each shot using a pyroelectric sensor and was found to be stable within $\pm 2.5\%$.

Scattered light is collected perpendicularly to the injection path ($\Theta = 90^\circ$) by a 50 mm diameter and 20 cm focal-length lens, located at a distance of 94 cm from the beam focus. This lens projects a 3.7× demagnified image of the beam onto a linear fiber bundle. Using relatively slow focusing and collection lenses outside the vacuum chamber allows the diagnostic to move from port to port and minimizes alignment sensitivity, and yet results in high light-collection efficiency with an effective optical extent of $0.9 \times G_{\text{max}}$, where $G_{\text{max}}$ is the spectrometer extent. The fiber array consists of 40 linearly arranged 200 μm diameter core optical fibers with a numerical aperture of 0.22, mapped end-to-end with combined slit dimensions of 8.8 mm x 0.22 mm. The intersection of the beam and fiber array projection defines the scattering volume (Fig. 1b). Integrating light from all 40 fibers results in a 33 mm long x 0.74 mm wide vertical scattering volume, while the spatial resolution of a single fiber is sub-millimeter. The 25 m fibers are coupled directly to the input of the spectrometer.

A custom triple grating f/4 Czerny-Turner imaging spectrometer is used to resolve the scattering signal (Fig. 1c). Light from the fibers passes through three monochromator stages before reaching the detector. The first stage images the spectrum onto a mask, where a 0.75 mm wide stainless steel notch blocks a 1.5 nm range around $\lambda_e$. Dispersion caused by the first stage is canceled by the second stage. This allows the double-subtractive system to operate as a tunable notch filter. The final stage disperses the stray light subtracted spectrum onto the detector. Holographic gratings, in combination with baffles, and an intermediate slit between the second and third stages are used to minimize stray light. The three 110 mm x 110 mm aluminium-coated, 1200 grooves/mm gratings are blazed at 500 nm, for an efficiency around 60% at 532 nm. All other reflectors are silver-coated to maximize throughput. The

\[ \text{460 mJ energy at a wavelength of } \lambda = 532 \text{ nm, at a repetition rate of 20 Hz.} \]
FIG. 1. (a) Schematic of the setup on the LAPD. The laser beam is focused into the scattering volume (SV) by a focusing lens (FL) and enters and exits the chamber top to bottom through Brewster windows (BW) and a series of baffles (B). The scattering volume is imaged onto the fiber array (FA) by the collection lens (CL). The chamber and pink magnets have been cut to provide a view on the inside. Also shown are the Langmuir probe (LP), and the quartz crystal (QC) used for alignment and calibration. (b) Scattering volume showing light collected by the top, center, and bottom fiber at an angle $\Theta = 90^\circ$. (c) Schematic of the light path through the spectrometer showing the three diffraction gratings (DG), notch mask, intermediate slit, and the spherical (SM) and toroidal (TM) mirrors.

measured transmission without the notch is around 20% at $\lambda_i$. Input and output focal lengths of each stage are 50 cm and 55 cm, respectively. Using an asymmetric system with two different focal lengths permits high throughput and spectral resolution, while maintaining off-axis angles large enough to avoid vignetting. Toroidal mirrors provide compensation for inherent astigmatism introduced by off-axis spherical reflectors. The system was designed with this tunable notch instead of a volume Bragg grating to be compatible with 527 nm and experiments that require higher laser energies.

Spectra are recorded on an image intensified charge coupled device (ICCD) equipped with a generation III photocathode and a quantum efficiency of around 50% at 532 nm. The micro-channel plate is gated at 10 ns and at maximum gain. Despite using $2 \times 2$ hardware binning the average pixel count is only a small fraction of the 16-bit maximum and well within the linear response range. For all data presented here, the spectra were also software binned over 512 vertical pixels (all 40 fibers) and over two pixels horizontally into 256 total bins with 0.0776 nm/bin. A background image recorded without the plasma is subtracted from each TS spectrum.

Figure 2a shows the stray light spectrum measured without the notch and represents the instrument function. The instrument profile is the convolution of the Gaussian contribution due to the aberrated slit width, and the Lorentzian profile caused by diffraction off of the three gratings. Both the input and intermediate slits were fully open (4 mm) to maximize light throughput, and so the fiber array itself serves as 0.20 mm wide slit. This configuration provides a spectral resolution of 0.28 nm (FWHM) over a spectral range of 19.8 nm. A calculated TS spectrum for 4.7 eV and $1.2 \times 10^{13}$ cm$^{-3}$ is shown for comparison (from section III). Without the notch, the stray light at $\lambda_i$ exceeds the TS signal by more than three orders of magnitude, and the broad wings drown out the signal even far from $\lambda_i$. While stray light can be subtracted using background spectra, its shot noise cannot. The notch filter reduces the stray light to well below the faint TS signal throughout the entire spectrum (red line) and makes its detection pos-

FIG. 2. (a) Laser stray light is used to measure the instrument function (black). The profile shows a Gaussian peak with 0.28 nm FWHM and the broad Lorentzian wings caused by diffraction off of the gratings. A simulated TS spectrum for 1.1 $\times 10^{13}$ cm$^{-3}$ and 4.7 eV is shown for comparison (green). The notch reduces the stray light to well below the TS signal across the entire spectral range (red). (b) Measured Raman scattering spectrum from nitrogen at 10 torr (black) and theoretical fit for T=298 K (orange) used for the irradiance calibration. The fine structure (blue) due to the rovibrational lines is mostly washed out by the broad instrument function.
sible. The notch reduces the intensity of the wings outside the 1.5 nm blocking range, since it removes stray-light before it can diffract and scatter off of the final two gratings.

Raman scattering off of gas was used for an absolute irradiance calibration. For this purpose, the chamber was filled with nitrogen at (10.0 ± 0.1) torr. This pressure results in a Raman signal comparable to TS in amplitude and width, which minimizes potential inaccuracies related to a non-linear detector response. Figure 3(a) shows the measured Raman signal obtained by averaging the scattered light from 5,000 laser shots. The spectrum consists of dozens of peaks on either side of $\lambda_i$. Each line corresponds to a different rovibrational transition from one rotational state to another, induced by the inelastic scattering process. The fine structure (blue) is mostly washed out by the instrument function, which allows only to resolve the brightest lines. A theoretical fit for a gas temperature of 298 K obtained as described in detail elsewhere[14] and convoluted with the instrument function reproduces the measured spectrum well (orange), including the difference in brightness of the red-shifted Stokes and the blue-shifted anti-Stokes lines[15]. Although the notch blocks most of the elastic Rayleigh scattering line that has an amplitude about 2,000 times that of the Raman signal, a small fraction leaks through the edge of the notch and contributes to the measured spectrum close to $\lambda_i$. Therefore, the calibration factor is determined from the area under the fit (shaded orange), which is slightly smaller than the integrated measured Raman signal. For nitrogen, the ratio between the TS signal (counts) and the Raman signal is $N_T/N_R = 1.23 \times 10^4 \cdot (n_e/n_{gas})$, where $n_e$ is the electron density responsible for TS, and $n_{gas} = 3.24 \times 10^{17}$ cm$^{-3}$ is the gas density responsible for the Raman signal[15]. In this experiment the electron density can, therefore, be determined from the measured TS signal $N_T$ as

$$n_e = (2.98 \pm 0.20) \times 10^8 \text{ cm}^{-3} \cdot N_T.$$  

This factor agrees within 10% with a redundant calibration obtained from Raman scattering off of a quartz crystal, that can be inserted into the scattering volume in lieu of the gas[15].

III. RESULTS AND DISCUSSION

When the scattering is non-collective, as it is in this experiment, the scale length of the electron density fluctuation sampled by TS ($\sim 1/k$) is small compared to the electron screening length $\lambda_D$. Here $k = 4\pi \cdot \sin(\Theta/2)/\lambda_i$ is the scattering vector, and $\lambda_D = \sqrt{k_0n_BT_e/n_e^2}$ is the Debye length. The scattering parameter is then $\alpha = 1/k\lambda_D \ll 1$. If the energy distribution is Maxwellian, the TS spectrum has a Gaussian shape, and the temperature can be determined from its width

$$T_e = \frac{m_ec^2}{8k_B^2}\left(\frac{\Delta\lambda_1/e}{\lambda_i}\right)^2.$$  

Here $m_e$ is the electron mass, $c$ is the speed of light, $k_B$ is the Boltzmann constant, and $\Delta\lambda_1/e$ is the spectral (e$^{-1}$) half-width. For $\Theta = 90^\circ$ and $\lambda_i = 532$ nm the formula can be simplified to $T_e$ (in eV) = 0.4513·($\Delta\lambda_1/e$)$^2$.

![Graph](image)

**FIG. 3.** (a) The TS spectrum at t=10 ms after breakdown, obtained by integrating the signal from 2,000 discharges. (b) Evolution of the TS spectrum during the 15 ms long discharge. The streak-plot combines 77 individual spectra recorded in steps of 0.25 ms.

Figure 4 shows a TS spectrum from a plasma discharge in helium, recorded at 10 ms after the breakdown. The spectra from 2,000 discharges were averaged to increase the signal-to-noise ratio (SNR). The profile has a Gaussian shape, with the central 1.5 nm section suppressed by the notch. The Gauss-fit is consistent with $T_e = (4.7 \pm 0.1)$ eV and $n_e = (1.2 \pm 0.1) \times 10^{13}$ cm$^{-3}$. The scattering parameter is $\alpha = 1.3 \times 10^{-2} \ll 1$. Figure 5 shows the evolution of the TS spectrum in time. This streak-plot is constructed from individual spectra obtained in steps of 0.25 ms, with 200 shots averaged per time step. During these discharges, the spectral width slowly increases with time, while the intensity decreases. When the discharge ends at t=15 ms the width quickly decreases. The evolution of $T_e$ and $n_e$ can be derived from this data and is compiled in figure 6 along with other discharge and plasma parameters. A capacitor bank voltage of 140 V results in an average discharge current of 6.3 kA and a power of 0.58 MW at this gas pressure. The time that the plasma current crosses a threshold value of about 1 kA defines t=0. Within the error bars, the measured $T_e$ initially decreases from 5.5 eV after the breakdown to 4 eV around t=3 ms, before gradually increasing up to 5.2 eV. The measured density remains constant at $1.2 \times 10^{13}$ cm$^{-3}$ throughout the discharge until t=15 ms, and then decreases approximately exponentially. TS measurements of $T_e$ agree well with data derived from the current-voltage (I-V) trace measured by a swept Langmuir probe[12] that show a similar temporal evolution of $T_e$ but 20% higher temperatures. This discrepancy could be due to the fact that the probe was located 32 cm from the scattering volume and closer to the plasma source. The Langmuir probe is also sen-
FIG. 4. Evolution of select measured discharge and plasma-parameters as a function of time: (a) Discharge current, voltage, and power. (b) and (c) Electron temperature and density measured by TS and by a Langmuir probe (LP). (d) Ion saturation current from the Langmuir probe and comparison to $n_e \sqrt{T_e}$ from the TS data, scaled to fit the current. (e) Photodiode measurements of the plasma visible light self-emission at different distances from the source.

Sensitive to electrons in the tail of the distribution, while TS is less so. TS measurements of $n_e$ also agree within 20% with Langmuir probe data. Relative probe measurements of the electron density profile $n_e(x)$, are absolutely calibrated with the line-integrated density measured by a 100 GHz microwave interferometer, although in a port two meters closer to the source. Figure 4d shows the ion-saturation current measured with the Langmuir probe and comparison to $n_e \sqrt{T_e}$ from the TS data, scaled to fit the current. Plasma self-emission measurements performed with a silicon photodiode, integrating all wavelengths between 200 nm and 1100 nm (Fig. 4e), show a strong axial dependence of the intensity and temporal evolution on the distance from the source. This suggests an axial variation of $T_e$, consistent with Langmuir probe measurements in other experiments, that have observed much higher temperatures ($T_e > 10$ eV) near the source.

Scattering spectra for different capacitor bank voltages and gas pressures measured at $t=10$ ms are shown in Fig. 5. The temperature increases with the bank voltage and as the gas pressure is lowered, resulting in broader and smaller amplitudes. The temperature increases with discharge power $P$. For the LAPD operating mode described here and for a constant inlet pressure, the trend is $T_e \sim P^2$ (Fig. 5b). A lower gas pressure and plasma density result in a higher temperature for a given bank voltage, in accordance with a simple discharge model. Maximizing the gas pressure by pulsing the Piezo valves at maximum voltage ($\approx 1500$ SCCM total flow) raises the plasma density to $2.8 \times 10^{13}$ cm$^{-3}$ but leads to a much lower temperature $T_e = 1.2$ eV. Near the plasma source the temperatures are likely much higher, with a large axial gradient in electron temperature in this particular operation (modest input power and a high feedstock gas fill rate).

The accuracy of the temperature measurement depends on the SNR. Shot noise due to plasma self emission is negligible with the short exposure time. The 20 e$^-$ / pixel readout noise of the cooled ICCD (-20°C) is also negligible when binning and averaging multiple images, and so the total noise is determined solely by the shot noise of the TS signal. Based on Poisson statistics, the SNR increases with the number $N$ of spectra averaged as $\text{SNR} \sim \sqrt{N}$. Figure 6 shows the error $\Delta T_e$ measured for different temperatures as a function of $N$. This error is directly determined by the nonlinear least squares fit (NLSF) used to fit the Gaussian spectrum. This NLSF error agrees with the shot-to-shot variation calculated as the root-mean square deviation (RMSD) of 10 spectra, each produced by averaging $N$ different shots. Only the RMSD for the 4.7 eV data is shown to declutter the graph. The data is described well by $\Delta T_e \sim 1/\sqrt{N}$ and so the error scales inversely proportional to the SNR as expected. An empirical formula based on scaling relations is derived from this data: equation...
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IV. CONCLUSION

We have commissioned a TS system on the recently upgraded LAPD, and have performed the first measurements of electron density and temperature using the fully operational diagnostic. Measured densities and temperatures range from $4.0 \times 10^{12}$ cm$^{-3}$ to $2.8 \times 10^{13}$ cm$^{-3}$, and from 1.2 eV to 6.8 eV, depending on discharge parameters and in good agreement with Langmuir probe data. For a given pressure, the plasma temperature increases with the square of the discharge power. The measured error $\Delta T_e$ is described well by an empirical formula derived from data. In relatively colder plasma (1-2 eV) $T_e$ can be determined accurately by averaging as little as 10 discharges.