A summary of "*Collective optical Thomson scattering in pulsed-power driven high energy density physics experiments*"

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Background: Thomson scattering (TS) is a diagnostic which analyzes the spectrum of light scattered by a plasma from a probing coherent radiation source such as a laser. In contrast to many line-integrated diagnostics, such as self-emission imaging, spectroscopy and interferometry, Thomson scattering provides localized measurements of the plasma properties within a volume defined by the intersection of the probing radiation and scattered light collection optics.

The spectrum of Thomson scattering contains two features: the electron feature, containing light scattered from free electrons; and the ion feature, with scattered light from the electrons which Debye-shield the ions. These features can either be in the collective or non-collective regime, depending on whether the wavelength of the scattering vector is larger (collective) or smaller (non-collective) than the Debye length of the plasma. In the non-collective regime, the electron motions are uncorrelated, and the scattered spectrum simply reproduces the Doppler shift expected from the underlying electron distribution function. In principle, the density, bulk velocity and temperature of the plasma can be recovered from taking moments of the measured distribution function. In the collective regime, the electron motions are correlated by modes within the plasma, such as the ion-acoustic waves (IAWs) and electron-plasma waves (EPWs). These modes are sensitive to plasma properties such as the temperature and density, and so can be used as local probes of the plasma conditions.

Diagnostic Summary:

This paper [1] uses collective Thomson scattering of the ion feature to make spatially and temporally localized measurements of plasmas generated by 1.4 MA peak current driven by the MAGPIE pulsed-power facility. These plasmas have $n_e \approx 10^{17} - 10^{19}\mathrm{cm}^{-3}$, $T \sim 100\,\mathrm{eV}$, $V_{fl} \approx 100\,\mathrm{km\,s^{-1}}$, $B \sim 5\,\mathrm{T}$ and spatial and temporal scales of $\sim 1\,\mathrm{cm}$ and $\sim 10 - 100\,\mathrm{ns}$. A 3 J, 8 ns long pulse of 532 nm laser light is generated from a Nd:YAG laser, and is cleaned up using a vacuum spatial filter prior to the chamber. The paper discusses the focusing and collection optics at length, and notes the important of having a tight focal spot to prevent stray light(reflected from metal surface) contaminating the TS spectra.

The probe beam is scattered in many directions, and the light is captured using two linear fiber-optic arrays on opposite sides of the vacuum chamber. The discrete fiber optics collect light from distinct volumes, giving the diagnostic its spatial resolution of $\sim 100\,\mu\mathrm{m}$ depending on the collection optics used. The temporal resolution of 4 ns is given by the gated iCCD on the spectrometer. The two fiber arrays are aligned to the same volume using a thin metal needle, which scatters light simultaneously into the fibers and into an interferometric imaging system, enabling the electron density at each volume to be determine post-shot from the interferometry data.

The spectra shown in Fig. 2 b,c and d can be fit with theoretical models which assume a Maxwellian distribution. The Thomson scattering here is in the collective regime, and the authors focus on the ion-acoustic waves, which provide information on the flow velocity (from the Doppler shift), the

Figure 1

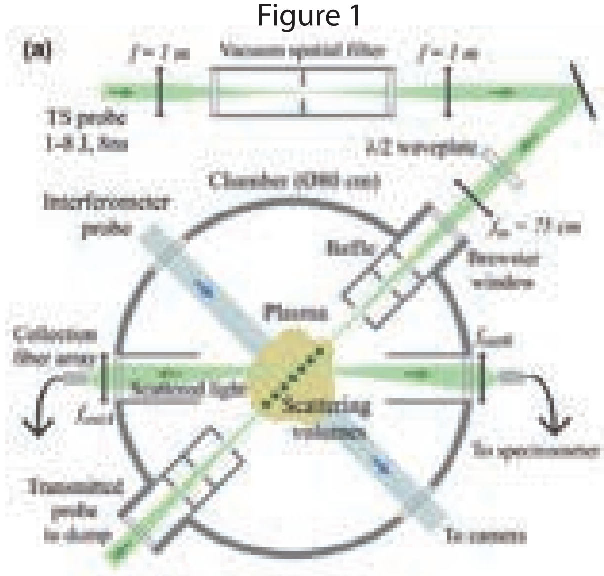

Figure 2

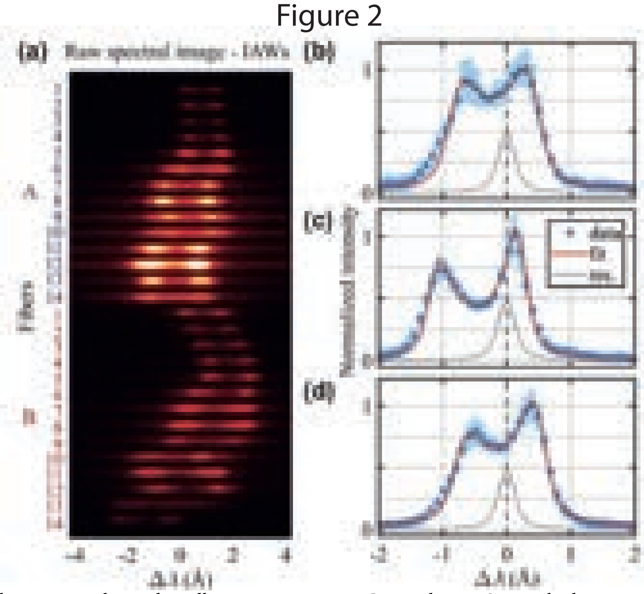

Figure 1: Figure 1: The diagnostic set up, showing the TS probe beam passing through a spatial filter to ensure the beam is tightly focused before entering the vacuum chamber through a polarizer and a Brewster window which set the polarization of the beam. The probes scatters from the plasma and is collected by lenses on opposite sides of the chamber, which focus it onto linear arrays of fibers which provide the spatial resolution.From [1]. Figure 2: Raw Thomson scattering spectra of the collective ion feature data from a jet-target interaction experiment. The spectra are Doppler shifted and exhibit double peaks due to scattering from forward and backward propagating ion acoustic waves (IAWs). Lineouts of spectra with theoretical fits are shown for three fibers, corresponding to three spatial locations.

electron thermal energy $\bar{Z}T_e$ from the separation of the ion-acoustic peaks, and the ion temperature T_i from the peak broadening, and the electron-ion drift velocity U_{drift} from the peak asymmetry. The authors use the electron density from an interferometry diagnostic to further constrain the fits.

This diagnostic is demonstrated on three plasma experiments. In the first, a jet collides with a target, though no analyzed data is shown for this experiment - the raw data is shown in Fig. 2. Fig. 3c shows analyzed data from the second experiment, a rotating disk. The authors resolve the radial and azimuthal velocity of the plasma flow, with velocities of up to 60 km/s. The error bars are around 10 km/s, suggesting that is significant uncertainty in these measurements.

The third experiment studies magnetic reconnection, and data is shown from two scattering geometries. In one geometry, the scattered light is collected in a horizontal plane, enabling the inflow and outflow velocities in the layer to be measured, as well as the strong electron heating, with $T_i \sim$ 600. The other geometry measures the scattered light in the vertical direction, with the scattering vector aligned with the electric current. This produces asymmetric ion-acoustic peaks, and by measuring this asymmetry the authors can determine the current inside the reconnection layer, which is agrees with other diagnostics. However, for this current measurements the uncertainties are more than 50%, which suggests that it is difficult to measure the local current accurately using this technique. This large uncertainty is not discussed.

Discussion:

In this diagnostic, the collection optics are separated by 180°, and so the scattering wave-vectors are orthogonal, allowing the velocity vector to be measured in the plane containing the collection optics. This is a significant advantage over systems at other HED facilities where the light is collected from only one direction [2], and so only the magnitude of the velocity can be measured. This capability is shown to good effect in Fig. 2a (shown in this summary) and Fig. 3c (not shown).

Although the density of the plasma can be measured directly from the intensity of the scattered light (with a suitable calibration, [3]), the authors opt to instead use line-integrated interferometry measurements along with symmetry arguments to determine the local electron density. The diagnostic would be more convincing if this cross-calibration has been performed, and the authors could demonstrate that their interferometric technique gives the same results as the calibrated intensity from the Thomson scattering diagnostic. An alternative would be simultaneously measuring the spectrum of the EPWs, as the separation of these peaks gives the electron density. This technique is discussed, along with the limitations due to high self-emission overwhelming the EPW signal.

This diagnostic uses a linear array of discrete fibers to image the scattered light from the plasma. Although this provides a simple setup, there are several key limitations - the presence of dead fibers within the linear array means that there are gaps in the spatial resolution, and the signal is integrated over the collection volume, such that shear flow within the collection volume can give the appearance of higher temperatures. To overcome this, several groups directly image the scattering volume formed by the probing laser onto the slit of spectrometer, producing a truly spatially resolved image [**Katz2021**], but the authors do not discuss this technique.

Summary:

The authors present a Thomson scattering diagnostic for studying pulsed-power driven plasmas. The key innovations are the fiber coupling to the spectrometer, which simplifies the optical configuration and enables precise selection of scattering angle to probe different regimes and flow velocity components. This system is demonstrated on a wide range of plasmas, with good results. The uncertainties associated with some measurements are quite large, and it is unclear what can be done to reduce these further.

References:

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