Mitigation of Self-Focusing in Thomson-Scattering Experiments

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Accurately diagnosing plasma conditions is vital to the success of a wide variety of high-energy-density physics experiments. Optical Thomson scattering from collective ion-acoustic and electron wave features offers a method of measuring plasma parameters with spatial and temporal resolution. Analysis of Thomson-scattered spectra reveals an abundance of useful data including electron density, electron temperature, ion temperature, ionization state, ion species composition, bulk flow velocity, and heat flux.

A challenge associated with Thomson-scattering measurements arises from the small scattering cross section. To overcome this challenge, a high-energy probe laser beam is required to measure single-shot Thomson-scattering spectra with acceptable signal-to-noise ratio (SNR), but in order for the laser beam to propagate through the plasma, its power must remain below the self-focusing threshold,

$$P_{\mathrm{c}}\left(W\right) = 3 \times 10^{7} \frac{T_{\mathrm{e}}\left(\mathrm{keV}\right)}{n_{\mathrm{e}}/n_{\mathrm{c}}}, \tag{1}$$

where T_{e} is the electron temperature and $n_{\mathrm{e}}/n_{\mathrm{c}}$ is the electron density normalized to the critical plasma density for the wavelength of the Thomson-scattering laser.

Figure 1 shows the limitations of the Thomson-scattering SNR introduced by limiting the incident probe laser power to the threshold for self-focusing. The region below the curves has a reduced SNR because of the lower-than-optimum incident laser power. Increasing the laser power to raise the SNR above the curves results in self-focusing. The small SNR demonstrates the challenges

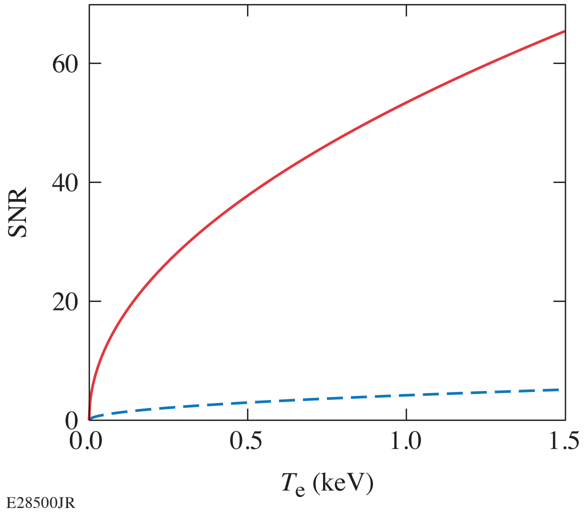

Figure 1
The curves represent the maximum measurable signal-to-noise ratio achievable in a Thomson-scattering experiment as a function of electron temperature assuming a Thomson-scattering probe beam with a power equal to the critical power for self-focusing for a beam with (dashed) and without (solid) a phase plate.

of obtaining high-fidelity Thomson-scattering spectra. The SNR can be improved by a factor of 10 by using a distributed phase plate (DPP). A DPP increases the filamentation threshold by distributing the laser's power across many lower power speckles.

Two-dimensional Thomson-scattering measurements (Fig. 2) show the limits of probe-beam propagation that are consistent with the limitations of self-focusing [Eq. (1)]. For experiments above the self-focusing threshold [Fig. 2(a)], the Thomson-scattering beam was observed to self-focus and no Thomson-scattering signals were observed from the Thomson-scattering volume located at the center (0, 0). By introducing a phase plate to the Thomson-scattering beam [Fig. 2(c)], excellent laser beam propagation was observed along with high-SNR Thomson-scattering spectra. The electron plasma and ion-acoustic wave features were measured, and these spectra were used to determine the electron density, temperature, and flow velocity as a function of time and space in a gas-jet plasma heated by a total of 1.8 kJ of laser energy on the OMEGA laser. The results show very uniform 1.5-mm density and temperature plateaus, which are ideally suited for future laser–plasma interaction experiments.

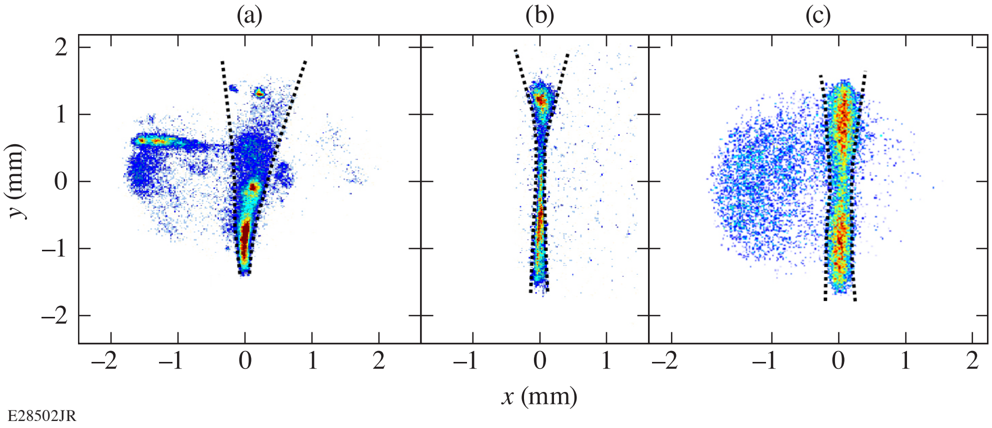

Figure 2
Two-dimensional images of Thomson-scattered light from a 2ω probe beam propagating through a gas-jet plasma (propagates from bottom to top). (a) No DPP, $P/P_c = 100$, $n_e = 4 \times 10^{20}$ cm^{-3}, $P = 45$ GW; (b) no DPP, $P/P_c = 4$, $n_e = 4 \times 10^{19}$ cm^{-3}, $P = 15$ GW; and (c) with DPP, $P/P_{c;\mathrm{DPP}} = 0.1$, $n_e = 2 \times 10^{20}$ cm^{-3}, $P = 40$ GW.

This material is based upon work supported by the Department of Energy National Nuclear Security Administration under Award Number DE-NA0003856, the University of Rochester, and the New York State Energy Research and Development Authority.