Impact of the Langdon Effect on Cross-Beam Energy Transfer

D. Turnbull,[1] A. Colaïtis,[1,2] A. M. Hansen,[1] A. L. Milder,[1,2] J. P. Palastro,[1] J. Katz,[1] C. Dorrer,[1] B. E. Kruschwitz,[1] D. J. Strozzi,[3] and D. H. Froula[1]

[1]Laboratory for Laser Energetics, University of Rochester
[2]Centre National da la Recherche Scientifique
[3]Lawrence Livermore National Laboratory

The prediction that laser-plasma heating distorts the electron distribution function (EDF) away from Maxwellian dates back four decades.[1] In conditions relevant to laser-based fusion, however, no direct evidence of this so-called “Langdon effect” has previously been observed. Here, measurements of the complete Thomson-scattering spectrum indicate the presence of super-Gaussian EDF’s that are consistent with Langdon theory. In such plasmas, ion-acoustic wave (IAW) frequencies increase monotonically with super-Gaussian exponent.[2] To match experiments that measured power transfer between crossed laser beams mediated by IAW’s, a model that accounts for the non-Maxwellian EDF is required, whereas the standard Maxwellian calculations overpredict power transfer over a wide region of parameter space. Including this effect is expected to improve the predictive capability of cross-beam energy transfer (CBET) modeling at the National Ignition Facility (NIF) and may restore a larger operable design space for inertial confinement fusion experiments. This is also expected to motivate further inquiry in other areas impacted by non-Maxwellian EDF’s, such as laser absorption, heat transport, and x-ray spectroscopy.

Laser fusion experiments require many overlapping laser beams to propagate through long, underdense plasmas in order to precisely deposit their energy at desired locations, but laser–plasma interactions can complicate the intended result. Cross-beam energy transfer is one example, whereby a frequency difference between two lasers in the plasma rest frame resonantly drives an ion-acoustic wave that scatters light from one beam to the other. The ability to manipulate this process in indirect-drive hohlraum targets via laser frequency detuning was initially seen as beneficial, providing control over implosion symmetry while operating the NIF at its maximum energy. However, when integrated observables indicated that there was less CBET than calculated, a tunable saturation clamp on IAW amplitudes was added to models, although the level ($\delta n/n = 10^{-3}$ to 10^{-4}) was too small to be explained by known saturation mechanisms.[3] Moreover, it varied between platforms—undermining the predictive capability of simulations and limiting fusion performance.

This motivated the development of a CBET platform at LLE, where a wavelength-tunable laser (TOP9) was built to study CBET in a well-characterized quasi-stationary plasma. Initial experiments reported here suggest that the Langdon effect may be responsible for overpredicting power transfer in indirect-drive–relevant conditions. The term comes from a 1980 Letter in which A. B. Langdon explained that inverse bremsstrahlung absorption of electromagnetic radiation in plasma preferentially heats low-energy electrons, distorting the electron distribution function away from Maxwellian and toward a super-Gaussian of the order of $m = 5$ (Ref. 1). He defined the scaling parameter $\alpha = Z_{\text{eff}} v_{\text{osc}}^2 / v_{\text{th}}^2$, where Z_{eff} is the effective ion charge state, v_{osc} is the velocity of electrons oscillating in the laser field, and v_{th} is the electron thermal velocity. Subsequent Fokker–Planck simulations under a wide range of laser heating conditions demonstrated that intermediate super-Gaussian EDF’s are produced in the form $f_m(v) = C_m \exp[-(v/v_m)^m]$, where $v_m^2 = \left(3k_{\text{B}}T_{\text{e}} / M_{\text{e}}\right)\left[\Gamma(3/m)/\Gamma(5/m)\right]$, $C_m = \left(N_{\text{e}}/4\pi\right)\left\{m/\left[\Gamma(3/m)v_m^3\right]\right\}$, Γ is the gamma function, and $m(\alpha) = 2 + 3/\left(1 + 1.66/\alpha^{0.724}\right)$ is only a function of α (Ref. 4).

Although it is often assumed that the Langdon effect only impacts absorption in high-Z plasmas, such non-Maxwellian distribution functions are known to affect the ion-acoustic wave dispersion relation $\omega = kc_{\text{s}}[3\Gamma^2(3/m)/\Gamma(1/m)/\Gamma(5/m)]^{1/2}$, which would directly impact CBET by shifting the ion-acoustic resonance.[2] The square root term modifies the usual dispersion relation and leads to a monotonic increase of IAW frequency with super-Gaussian order, which results from the smaller number of low-energy electrons [$f(v \approx 0)$] available to shield the ion oscillations.

In the CBET experiments, TOP9 was crossed with a single nearly co-propagating pump beam in a plasma that was preformed from a mixture of hydrogen and nitrogen gas; its power was then diagnosed using a transmitted beam diagnostic. Results will be shown with and without nearly counter-propagating heater beams, which (when present) enhanced the Langdon effect without contributing significantly to the CBET gain. Both spatially and temporally resolved Thomson scattering were used to characterize the plasma conditions (including m) in order to constrain the CBET modeling. A heater-only intensity (I) scan was performed by varying the number of beams from 1 to 4. In addition to electron temperature increasing with I to the ≈0.2 power, the non-Maxwellian super-Gaussian exponent m was observed to increase from 2.4 up to 2.85 in excellent agreement with theory.

On the CBET experiments with three heaters plus one pump, m was determined to be 2.82 from the Thomson-scattering spectrum, whereas it was only 2.4 for the case of the pump only. In the former case, accounting for the non-Maxwellian EDF (again, using the modified electron susceptibility) was required to match the data, whereas the standard Maxwellian model currently used in inertial fusion calculations overpredicted the energy transfer [shown in Fig. 1(a)]. Without heater beams, the effect is smaller and the data cannot easily distinguish between the Maxwellian and non-Maxwellian models [Fig. 1(b)]. Calculations for NIF-like plasma conditions yield $\alpha = 0.7$ and $m = 2.96$—even further from Maxwellian than the conditions produced in the TOP9 experiments because of the large number of overlapping beams. Since the Langdon effect suppresses gain on the rising edge of the ion-acoustic resonance and most resonances are outside the NIF's available wavelength tuning range in an indirect-drive fusion experiment, calculations suggest the Langdon effect uniformly reduces CBET gain on the NIF by 27.7% on average. This level of CBET reduction would significantly impact implosion symmetry. Accounting for the Langdon effect might therefore remove the need for an artificial saturation clamp and should improve the predictive capability of integrated modeling.

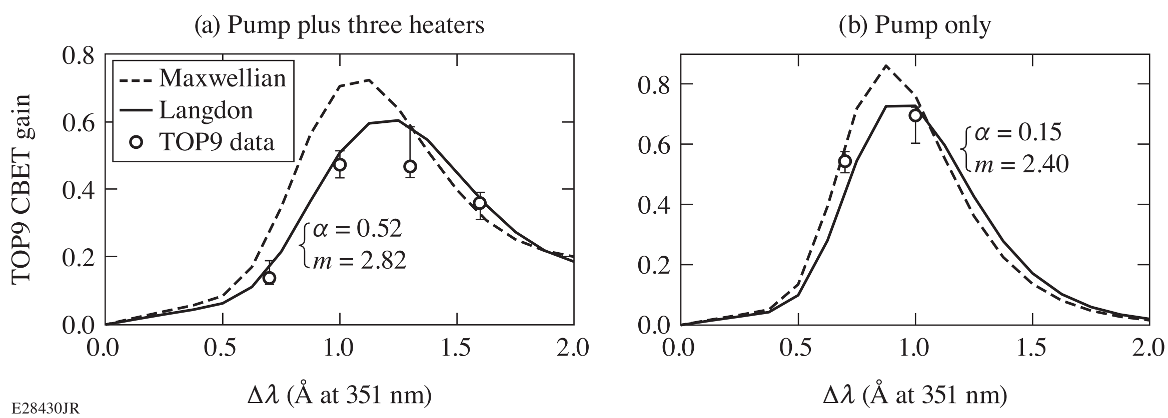

Figure 1
TOP9 CBET results. (a) TOP9 data are shown for the case in which three heater beams coexisted temporally with the pump and wavelength-tunable beam. A calculation that accounts for the non-Maxwellian EDF measured by Thomson scattering agrees with the data, but the Maxwellian calculation is discrepant. (b) Without the heater beams, the EDF was closer to Maxwellian and the data cannot easily distinguish between the two models.

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.

1. A. B. Langdon, Phys. Rev. Lett. **44**, 575 (1980).
2. B. B. Afeyan *et al*., Phys. Rev. Lett. **80**, 2322 (1998).
3. P. Michel *et al*., Phys. Rev. Lett. **109**, 195004 (2012).
4. J. P. Matte *et al*., Plasma Phys. Control. Fusion **30**, 1665 (1988).