Measurement of Laser Absorption in Underdense Plasmas Using Near-Field Imaging of the Incident and Transmitted Beams

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Measurements of laser absorption in high-temperature, underdense plasmas produced at the Omega Laser Facility are made using two near-field imaging detectors that diagnose the spatial profile and energy of the port P9 beam before and after it transmits through the plasma. By comparing the signal ratios of these detectors for shots with and without plasma, absorption is measured without the need for absolute energy calibration of either detector. Complementary diagnostics monitor laser backscatter and spatially resolve key plasma parameters,[1] including ion and electron temperature and electron density, along the beam propagation length. Simultaneous measurements of the plasma conditions and total beam absorption provide means to experimentally validate physics models used to predict absorption in plasmas relevant to inertial confinement fusion.

The experimental platform, shown in Fig. 1, utilizes a set of 351-nm heater beams to ionize a 2-mm-diam, cylindrical column of neutral gas that is injected into target chamber center (TCC) using a gas-jet delivery system. The 527-nm P9 probe beam is then fired into the plasma. Experimental conditions can be varied by adjusting the 351-nm heater-beam energies and timings or by changing the gas type and initial neutral gas density. Total absorption in these high-temperature (>100-eV), millimeter-scale-length plasmas are often a few percent or less. As such, high-precision measurements of the input and transmitted beam energies are required. It is also important to confirm that any potential energy loss to the transmitted beam from mechanisms other than absorption remain energetically insignificant.

The input beam is sampled using a partial reflection from a full-aperture, 30-cm-diam uncoated-wedge pickoff located before the target chamber vacuum window and final-focus lens assembly. An uncoated, concave mirror focuses the reflected beam at *f*/10, allowing it to be recorded directly with a 13 × 13-mm sensor. The P9 transmitted-beam diagnostic (P9TBD)[2] characterizes the transmitted light by terminating the expanded beam on a semi-transparent diffuser and imaging the illuminated surface using a lens and charge-coupled–device (CCD) camera. The near-field image measures both the transmitted beam energy and the degree of any potential beam filamentation or whole beam refraction. The nominal diameter of the expanded beam at the diffuser plane is 28 cm. The 45-cm (*f*/4) acceptance aperture of the P9TBD allows energy of the beam to be measured even in the presence of moderate levels of beam refraction or filamentation.[3]

For an ideal detector, the total signal recorded on the CCD images is proportional to the amount of energy present at TCC. The proportionality constant, K, given in analog-to-digital units (ADU) per joule of photon energy, is influenced by a number of factors including the optical throughput between the sample point and TCC, the sensor quantum efficiency, the camera digitizer gain, and the throughput of any optical filtration used to adjust signal levels. It is difficult to accurately quantify all of these components individually. If the energy loss in the transmitted beam is limited to absorption alone, however, knowledge of the individual instrument sensitivities is not required to determine absorption since the measurement depends only on the ratio of the instrument sensitives K and the total signals.

$$\mathrm{ABS} = 1 - \frac{c_{\mathrm{Trans}}}{\underbrace{c_0}_{K}} \frac{\sum \mathrm{CCD}e^{-}_{\mathrm{Trans}}}{\sum \mathrm{CCD}e^{-}_{0}},$$

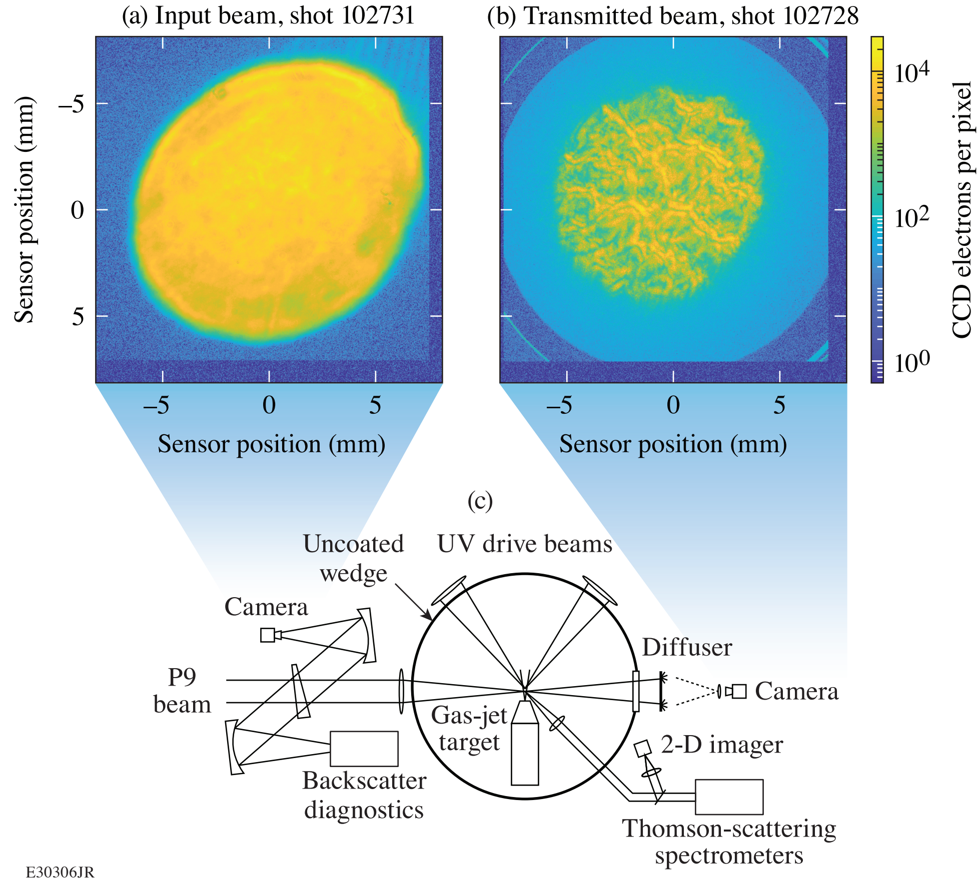

Figure 1
The amount of laser energy deposited in the plasma from a single beam is inferred by comparing input and output energies. Two CCD cameras measure the incident and transmitted beam spatial profiles and energies with high precision. Back and sidescatter diagnostics are used to verify that energy losses from laser–plasma instabilities are energetically insignificant.

where K is measured experimentally by taking a calibration shot with no plasma present. In this case, there is no absorption, $E_0 = E_{\text{Trans}}$, and K is given by the ratio of the input to transmitted signals. To the extent that c_0 and c_{Trans} remain stable over time, the accuracy of the absorption measurement is driven by the measurement precision of the two detectors. Two calibration shots are normally taken during a shot day to confirm the measurement stability and typically agree to within ±0.01%. Additionally, the measurement stability and precision of the two detectors was benchmarked using a full-aperture, Q-switched laser propagated along the P9 beamline through TCC. Synchronized images were recorded at 5-min intervals over a period of 8 h and the ratio of the detector sensitivities was measured. The measurement variation followed a normal distribution with a standard deviation of ±0.014% and showed no noticeable drifts as a function of time.

The amount of stray 2ω light from the other OMEGA drive beams that scatters into the P9 energy detectors is also measured. For these calibration shots, the plasma is heated by the drive beams but the P9 probe beam is turned off and the background level is measured directly. If a variety of beam energies are fielded during the shot day, the magnitude of the background subtraction is scaled by the total 2ω light present in the experiment, as measured by the harmonic energy diagnostic.[4] Baffling and optical filtration help limit the background signal levels to less than 0.05% of the primary signal.

Propagating the expected errors present in the calibrations and the statistical noise in the signal summations, the overall uncertainty of a typical absorption measurement is estimated to be ±0.07%. With these capabilities, the mechanics of inverse bremsstrahlung heating can be explored experimentally with exceptional quantitative detail.

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