Diagnostic of laser contrast using target reflectivity

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Using three different laser systems, we demonstrate a convenient and simple plasma based diagnostic of the contrast of high-power short-pulse lasers. The technique is based on measuring the specular reflectivity from a solid target. The reflectivity remains high even at relativistic intensities above 10^{19} W/cm^2 in the case of a high-contrast prepulse-free laser. On the contrary, the specular reflectivity drops with increasing intensities in the case of systems with insufficient contrast due to beam breakup and increased absorption caused by preplasma. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3148330]

As the achievable intensity of high-power lasers[1] increases, contrast has become a major issue. However, the accurate determination of contrast is a challenge, considering the required high dynamic range, long time measurement interval, and desirability for on-target sampling. Conventionally, the power contrast is measured with a high-dynamic range third-order cross correlator,[2] which requires many thousands of shots. Further, cross correlators tend to produce artificial prepulses, which are difficult to distinguish from the real prepulses generated from postpulses by cross-phase modulation in the chirped pulse amplifiers (CPA).[3] In addition, the focal spot of the amplified spontaneous emission (ASE) and prepulses may differ from that of the main pulse.

Imaging and interferometry[4] can be used to measure the preplasma scale length (typically of dimension >10 μm). Extreme ultraviolet emission from a preplasma can also be used to monitor[5] the ASE. Here, we demonstrate a complementary technique which is simple, experimentally convenient, and answers the most important question whether the on-target contrast is sufficient or not, and in the latter case how much improvement is required.

Using three laser systems and different contrast conditions (Table I), we measured the dependence of the specular reflectivity R of flat targets, irradiated with full power laser shots as the target position T was varied. T is measured along the beam direction, with $T=0$ corresponding to best focus. We used p-polarized pulses at 35° or 45° incidence angle, which is typical for ion acceleration and harmonic generation experiments [Fig. 1(a)].

Experiment A was performed with Astra Ti:sapphire (Ti:S) laser[6] using both normal contrast and high contrast modes employing a plasma mirror[7,8] (PM) with reflectivity of 0.6. The targets were Al with a thickness of 2 μm without and 50 nm with PM. Experiment B was performed with Ti:S laser at Advanced Photonics Research Institute, Gwangju Institute of Science and Technology.[9] The ASE energy of 3% of the main pulse was measured using the transmission through a polyimide target in the plasma mirror regime; the details will be described elsewhere. The targets were 7.5 and 12.5 μm polyimide tapes. Experiment C was performed with J-KAREN laser[10] consisting of a high-energy CPA oscillator, saturable absorber improving the contrast, three-stage optical parametric CPA, and two four-pass Ti:S amplifiers. The target was 7.5 μm polyimide tape.

In all experiments, care was taken to ensure reliable calorimeter measurements with the measured noise being included in the error bars (Fig. 1). The measured reflectivity curves $R(T)$ shown in Figs. 1(b) and 1(c) all essentially dip as the intensity increases. The size of the dip decreases as the contrast increases. When the contrast was sufficiently good,

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TABLE I. On-target laser parameters: E_0, τ_0, and λ_0 are the laser pulse energy, duration, and wavelength; $f/\#$ is the off-axis parabola f-number; d_0 is the focal spot diameter [full width at half maximum (FWHM)]; I_0 is the peak intensity (average over FWHM) at the incidence angle θ; C_{ASE}, τ_{ASE}, and E_{ASE}/E_0 are the ASE contrast, duration, and energy fraction.

Experiment	E_0 (J)	τ_0 (fs)	λ_0 (nm)	$f/\#$	d_0 (μm)	I_0 (W/cm^2)	θ (deg)	C_{ASE}	τ_{ASE} (ns)	E_{ASE}/E_0
A	0.7	50	800	3	5	3×10^{19}	35	10^7	1	2×10^{-3}
A(PM)	0.4	50	800	3	5	2×10^{19}	35	10^9	1	2×10^{-5}
B	0.8/1.6	35	800	3.4	4	4×10^{19}	45	10^6	0.9	3×10^{-2}
C	0.5	35	820	3	3.4	5×10^{19}	45	5×10^8	3	2×10^{-4}

the target reflectivity remained high even at best focus, where the intensity exceeded 10^{19} W/cm^2 [Fig. 1(d)]. At the lower contrast conditions, the specular reflectivity dropped to zero near the focus because of the reflected beam breakup and an increased absorption in the preformed plasma.[11] The threshold value of the ASE fluence F_{ASE} where the reflectivity significantly drops, $F_{th}\approx 40$ J/cm^2 [Fig. 1(e)], coincides with the nanosecond laser-induced damage threshold, which suggests that the target was disturbed mainly by the ASE rather than possible prepulses. The nearly identical thresholds in the three independent experiments suggest that the absolute error of F_{ASE} was relatively small. For $F_{ASE} \ll F_{th}$, the ASE has no effect and the reflectivity depends on the main pulse fluence[8] rather than on F_{ASE} [Figs. 1(d) and 1(e)].

In the highest contrast case, the reflectivity was high even in the strongly relativistic regime $a_0 \gg 1$, where $a_0 = [I(\mathrm{W/cm^2})\lambda_0^2(\mu\mathrm{m})/1.37\times10^{18}]^{1/2}$ is the dimensionless laser amplitude. In some shots, the high-contrast reflectivity reaches 0.75 ± 0.1 at relativistic intensities. We attribute the high reflectivity to sharp density gradients and lower absorption in the relativistic regime due to the reduced collision rate[12] and absence of the resonance due to the relativistic nonlinearity. The fluctuations in high-contrast reflectivity at $I > 10^{18}$ W/cm^2 [Figs. 1(c)–1(e)] are attributed to the onset of the preplasma formation because the estimated peak ASE fluence of 40 J/cm^2 coincides with F_{th}.

The reflectivity curve $R(T)$ can be used as a quick and convenient check of the actual effect of the prepulses, pedestal, and/or ASE on the target. The ratio of spot area at the target position where the reflectivity starts to drop to the minimum achievable focal spot area gives an estimation of the necessary contrast improvement. The technique requires relatively simple diagnostics and only tens of shots. Small preplasma (with scale lengths $\leqslant\lambda/5$, Ref. 13) and therefore high specular reflectivity is the necessary prerequisite for the relativistic harmonics[14] generated by the oscillating mirror[15] or sliding mirror[16] mechanisms. At optimum conditions, harmonics can contain a substantial part of laser energy.[16]

In the experiments A and B, the detector surface itself was imaged, which revealed the reflected beam break-up at $F_{ASE} > 60$ J/cm^2, so the laser energy was scattered rather than specularly reflected. With the PM present to give high contrast (experiment A), the beam did not break up even at $I > 10^{19}$ W/cm^2 corresponding to a main pulse fluence of $F = 1$ MJ/cm^2. This is attributed to plasma formation only occurring near the peak of the pulse when hydrodynamic motion of the reflecting surface is insufficient to significantly perturb the reflected wave front.

Simultaneously with the reflectivity, we measured the single-shot proton energy spectra along the rear target normal direction either with a Thomson parabola ion spectrometer (Experiment A) or time-of-flight spectrometers[17] [Fig. 1(f)]. For both micrometer- and nanometer-thick targets,[18] in the high-contrast cases the proton energy was largest at best focus and slowly decreased with defocusing to either side. In the low-contrast case, the maximum proton energy decreased

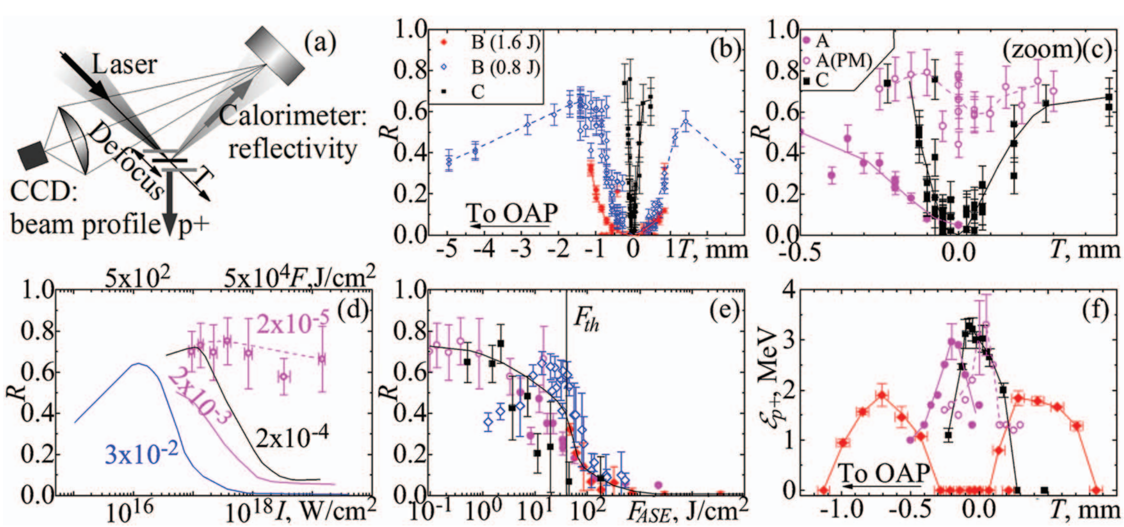

FIG. 1. (Color) (a) Experimental setup. P-polarized multiterawatt laser irradiates few micrometer- or nanometer-thick target at 35° (experiment A) or 45° (B and C). The target specular reflectivity R is measured as the spot size and corresponding intensity and fluence are varied by moving the target by distance T from best focus. Figures 1(b) and 1(c) show R vs T. Figure 1(d) shows R vs intensity; for clarity, trend lines for all data sets and one data set is plotted to show typical experimental data. Each trend line in Fig. 1(d) is labeled with the fraction E_{ASE}/E_0. Figures 1(e) and 1(f) show R vs the ASE fluence and the maximum proton energy $\mathcal{E}_{p+}$ vs T.

near the focus because the target rear side was disrupted[19] and far away from focus due to decreasing intensity.

We believe that this technique could be validly extended for the intensities up to at least mid-10^{21} W/cm^2 for non-relativistically moving targets; for instance, the reflectivity remains high (~ 0.6) at the intensity 5×10^{21} W/cm^2 in two-dimensional particle-in-cell simulations.[20] In general, the high-contrast reflectivity remains high when in the target rest frame $a_0 < n_e/n_{cr}$ for thick and $a_0 < \pi n_e l/n_{cr}\lambda_0$ for thin targets[16] (here, n_e and n_{cr} are the plasma density and critical density and l is target thickness). In these experiments we used 35–50 fs pulses. It would be interesting to study the reflectivity of longer (0.1–1 ps) pulses, which can create an absorbing density gradient or make a hole in the nanometer-thick target. The proposed technique could also be used in the radiation pressure dominant ion acceleration[21] experiments, where account would need to be made of the decrease in reflected energy due to the frequency downshift.

In conclusion, using three different laser systems we have demonstrated that by measuring the specular reflectivity of targets irradiated at full power, one can monitor the contrast of short-pulse high-intensity lasers. If the contrast is sufficiently good, the target reflectivity remains high even in the case of ultrarelativistic intensity; in the case of an insufficient contrast, the reflectivity is low due to the reflected beam breakup and increased absorption in the preformed plasma. Characterizing the specular reflectivity or reflected beam wave front can be used to monitor contrast in experiments employing solid targets, in particular, ion acceleration and harmonic generation experiments.

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