Hot-Electron Generation at Direct-Drive Ignition-Relevant Plasma Conditions at the National Ignition Facility

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The direct-drive approach to laser fusion is vulnerable to hot-electron preheat as a result of the long scale length of plasma that exists near the quarter-critical density of the target [$n_{qc} = n_c/4$, where $n_c \approx 1.1 \times 10^{21}\ \lambda_0^{-2}\ \mathrm{cm}^{-3}$ is the critical density and λ_0 (in μm) is the laser wavelength]. This plasma enables instabilities such as stimulated Raman scattering (SRS)[1] that generate electrostatic plasma waves capable of accelerating electrons. For full-scale, direct-drive–ignition experiments, it is estimated that the target adiabat and performance will be negatively affected if more than ~0.15% of the laser energy is coupled into the cold fuel in the form of hot electrons.[2]

An experimental platform has been fielded at the National Ignition Facility (NIF) to investigate hot-electron production from laser–plasma instabilities at direct-drive ignition-relevant conditions. Planar-target experiments, designed using the radiation-hydrodynamic code *DRACO*,[3] generate plasma and interaction conditions comparable to direct-drive–ignition designs: $I_L \sim 10^{15}$ W/cm^2, $T_e > 3$ keV, and density-gradient scale lengths of $L_n \sim 600\ \mu$m in the quarter-critical density region. Planar targets are currently the only way to achieve direct-drive ignition-relevant plasma conditions on the NIF. A schematic of the experiment and the main diagnostics are shown in Fig. 1(a). All targets—CH or Si disks with a 4.4-mm diameter and thicknesses of 1.2 mm (CH) or 0.75 mm (Si)—were placed at the NIF target chamber center and irradiated from the southern (lower) hemisphere. NIF beams used standard indirect-drive phase plates at best focus and flattop power profiles with a 2-ns linear rise and a total duration of ~7.5 ns. This configuration allowed for the variation of laser–plasma interaction (LPI) conditions by changing the number of

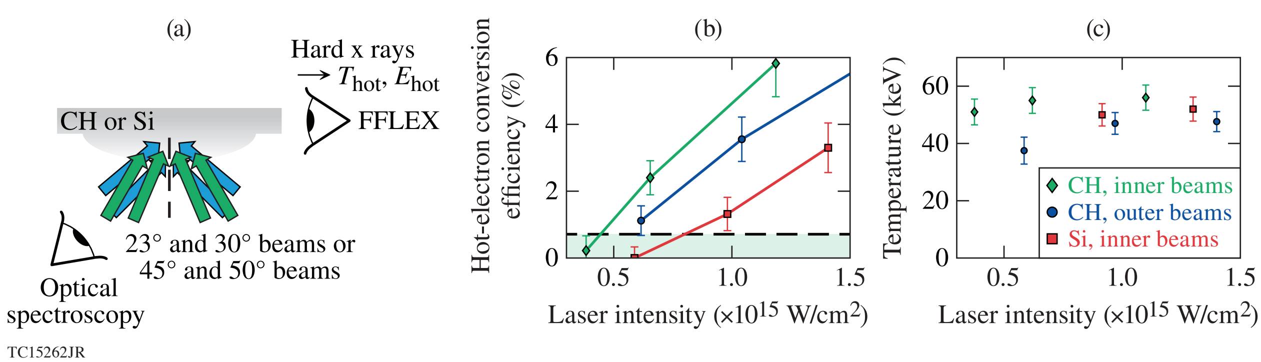

Figure 1
(a) A schematic of the experiment and the main diagnostics. (b) Laser-energy-to-hot-electron conversion efficiency and (c) hot-electron temperature versus laser intensity at the n_{qc}. The dashed horizontal line in (b) shows the hot-electron conversion efficiency of 0.7% considered to be the maximum-tolerable hot-electron preheat for divergent electron beams, as explained in the text. The preheat is tolerable in the light green region below the dashed line.

beams, single-beam intensities, and incidence angles of the beams by using beams in different cones. The higher-angle cones (45° and 50°) approximate irradiation conditions near the equator of a polar-direct-drive implosion, where the beams are incident from higher angles, while the lower-angle cones (23° and 30°) correspond to those near the poles. The use of planar targets reduces the level of cross-beam energy transfer (CBET) relative to spherical targets by excluding the outer parts of the beams, which can propagate around the target and seed CBET with beams from the opposite side.

Hot-electron production in the experiments was inferred by measuring the bremsstrahlung emission spectra using the NIF's ten-channel filter-fluorescer x-ray (FFLEX) diagnostic[4] located in the equatorial plane of the NIF chamber. The measured spectra are approximated well by the one-temperature exponential distributions. The Monte Carlo code EGSnrc[5] was used to relate the properties of hot electrons and measured hard x rays. In EGSnrc, hot electrons from 3-D Maxwellian distributions were injected from the location of the n_{qc} surface with temperatures close to the hard x-ray temperatures and with a full divergence angle of 2π toward the target.

Figure 1 shows (b) the laser-energy-to-hot-electron conversion efficiencies and (c) hot-electron temperatures inferred by comparing experiments and simulations versus the laser intensity at n_{qc} predicted by *DRACO*. The results are shown for CH targets illuminated either by inner beams (green diamonds) or outer beams (blue circles) and Si targets illuminated by inner beams (red squares). The dashed horizontal line in Fig. 1(b) shows the maximum-tolerable hot-electron conversion efficiency for divergent electron beams of 0.7%. It is obtained by estimating that with a near-2π angular divergence, only ~25% of the hot electrons will intersect the cold shell and result in preheat. Additionally, electrons at energies below ~50 keV will be stopped by the ablator. A large (near-2π) hot-electron divergence was demonstrated in previous spherical experiments on OMEGA and will be re-evaluated in the near-term implosion experiments on the NIF. Scattered-light spectrum measurements demonstrate that the most plausible mechanism of hot-electron generation in the NIF experiments is SRS.[6]

According to Figs. 1(b) and 1(c), in plastic ablators, hot-electron temperatures of ~40 keV to 60 keV and fractions of laser energy converted to hot electrons of ~0.5% to 5% were inferred when the laser intensity near the quarter-critical density increased from ~4 to 15×10^{14} W/cm^2. The intensity at n_{qc} is approximately 2× lower than the incident laser intensity due to inverse bremsstrahlung absorption. An acceptable hot-electron fraction of 0.7% of the laser energy (for divergent hot-electron beams) is exceeded if the overlapped intensity at the quarter-critical surface exceeds ~4×10^{14} W/cm^2 in plastic ablators.

Hot-electron preheat mitigation strategies are desired to extend the ignition design space to quarter-critical intensities above 4×10^{14} W/cm^2. Using mid-*Z* layers strategically placed in the plastic ablator materials was previously shown to suppress hot-electron generation by two-plasmon decay in smaller-scale implosions on OMEGA.[7] Our experiments using silicon planar targets demonstrate [Fig. 1(b)] that hot-electron production is also reduced in the longer-scale-length plasmas on the NIF, relevant to direct-drive ignition, in which SRS is the dominant LPI process. If the electron divergence is large, the direct-drive–ignition design space may potentially be extended to quarter-critical intensities up to ~8×10^{14} W/cm^2 by introducing silicon layers in the ablators.

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