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

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## ABSTRACT

Laser–plasma interaction instabilities can be detrimental for direct-drive inertial confinement fusion by generating high-energy electrons that preheat the target. An experimental platform has been developed and fielded on the National Ignition Facility to investigate hot-electron production from laser–plasma instabilities at direct-drive ignition-relevant conditions. The radiation-hydrodynamic code *DRACO* has been used to design planar-target experiments that 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. The hot-electron properties were inferred by comparing the experimentally observed hard x-ray spectra to Monte Carlo simulations of hard x-ray emission from hot electrons depositing energy in the target. Hot-electron temperatures of ~40 keV to 60 keV and the fraction of laser energy converted to hot electrons of ~0.5% to 5% were inferred in plastic targets for laser intensities at the quarter-critical density surface of (~4 to 14) × $10^{14}$ W/cm$^2$. The use of silicon ablators was found to mitigate the hot-electron preheat by increasing the threshold laser intensity for hot-electron generation from ~3.5 × $10^{14}$ W/cm$^2$ in plastic to ~6 × $10^{14}$ W/cm$^2$ in silicon. The overall hot-electron production is also reduced in silicon ablators when the intensity threshold is exceeded.

## I. Introduction

In direct-drive inertial confinement fusion (ICF),[1] a capsule containing cryogenic deuterium–tritium (DT) fusion fuel surrounded by an ablator such as plastic (CH) is irradiated by multiple laser beams. The beams ablate the outer material, driving the implosion, and compress the cryogenic DT to fusion conditions. Fusion reactions are initiated in the central hot spot when the capsule reaches maximum compression, followed by a fusion burn wave (ignition) that propagates in the fuel.[2] For efficient implosion and compression, the thermonuclear fuel should stay at a low adiabat. The adiabat is defined as the ratio of the DT pressure to the Fermi-degenerate pressure. Preheat by suprathermal electrons generated by laser–plasma interaction (LPI) instabilities can increase the pressure, degrade the implosion, and prevent the ignition; therefore, the generation of suprathermal (or hot) electrons must be controlled.

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 $n_c \approx 1.1\times 10^{21}\lambda_0^{-2}$ cm$^{-3}$ is the critical density and $\lambda_0$ (in $\mu$m) is the laser wavelength]. This plasma enables instabilities such as stimulated Raman scattering (SRS)[3–5] and two-plasmon decay (TPD),[5–8] which generate electrostatic plasma waves capable of accelerating electrons. SRS, representing a decay of the laser field into a plasma wave and a frequency-downshifted light field, can occur at the quarter-critical density and below, while TPD takes place only near the quarter-critical density. If the instabilities' thresholds are exceeded at the quarter-critical density, the instabilities are absolute. SRS at lower densities is usually convective but can be absolute as well. Absolute instability refers to the case where the amplitude of the unstable waves grows exponentially in time. Typically, this growth time is not resolved in experiments since it is on the subpicosecond scale. Only the nonlinearly saturated state is therefore observable for absolute instabilities. A convective instability grows (exponentiates) in space and not time. It can be observed in the linear growth phase provided that the spatial gain (number of *e* foldings in wave amplitude) is not too large.

Experimental work demonstrating the connection between SRS and TPD instabilities and the generation of energetic electrons goes back into 1970–80s. The first demonstration of hot-electron generation resulting from the TPD instability was reported in 1980 by Ebrahim *et al.*[9] in experiments using $CO_2$ laser. The experiments of Keck *et al.*[10] and Mead *et al.*[11] demonstrated hot-electron generation by TPD in single-beam experiments using 0.35-$\mu$m laser light. The multibeam nature of TPD and resulting hot-electron production was first demonstrated by Stoeckl *et al.*[12] in planar and spherical implosion experiments using the 0.35-$\mu$m, 60-beam OMEGA laser. Further detailed long-scale-length experiments investigating hot-electron generation by multibeam TPD were carried out on the OMEGA EP and OMEGA lasers,[13–16] where the hot-electron fraction was inferred to be a universal function of the common (shared) plasma wave gain.

SRS was shown to be one of the important hot-electron–producing mechanisms in the early experiments at 1-$\mu$m wavelength on the Shiva and Novette lasers, which hindered early development of indirect drive.[17] Raman-scattered light fraction was found to correlate closely over nearly three orders of magnitude with the hot-electron fraction obtained from the hard x-ray spectrum in the experiments using Au targets at 0.53-$\mu$m wavelength by Drake *et al.*[18] Turner *et al.*[19] demonstrated that SRS could be suppressed by collisionality in high-$Z$ targets using short-wavelength irradiation. Suppression of filamentation by laser phase plates and smoothing techniques, such as smoothing by spectral dispersion and induced spatial incoherence, made it possible to reduce SRS at 0.35 $\mu$m in low-$Z$ plastic targets.[20–22] Recently Raman multibeam tangential sidescatter was proposed as the generating mechanism for the observation of suprathermal electrons in indirect-drive ICF experiments[23,24] and was also identified in experiments using foam targets at the Omega Laser Facility. [25]

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.[26] To compute the preheat resulting from a given hot-electron source, several factors must be taken into account. A large radial displacement of the quarter-critical surface to the compressed shell at the time when hot electrons are generated decreases the angular size of the cold shell from the point where hot electrons are produced. With a near-2$\pi$ angular divergence of hot electrons inferred in OMEGA spherical experiments, it is estimated that only ~25% of the hot electrons will intersect the cold shell and result in preheat.[27] Additionally, electrons at energies below ~50 keV will be stopped by the ablator (of thickness ~40 $\mu$m) and will not contribute to the preheat of the compressed fuel. At the level of hot-electron temperatures inferred in the present experiment (~50 keV), this increases the tolerable absolute conversion efficiency of laser energy to hot electrons to ~0.7%. The recent discovery of a regime dominated by SRS in experiments[28,29] at the National Ignition Facility (NIF),[30,31] rather than by TPD as on OMEGA, necessitates a re-evaluation of the angular divergence of hot electrons at direct-drive-ignition–relevant conditions and may also require reconsideration of mitigation strategies.

A series of experiments have been conducted at the Omega Laser Facility to investigate the scaling of hot electrons with the laser intensity and plasma conditions. This includes spherical implosion and planar-target experiments on the OMEGA and OMEGA EP lasers.[13–16,32–35] Table I (column 2) summarizes the coronal plasma parameters at the quarter-critical surface in those experiments, as predicted by simulations[34] using the code *DRACO*.[36] The laser-to-hot-electron energy conversion efficiencies of ~1% were inferred in those experiments. TPD was found to be the dominant hot-electron generation mechanism in OMEGA experiments based on scattered-light spectrum diagnostics. While capsule implosion hydrodynamics scales with the total laser energy, so that the implosion experiments on the ~25-kJ OMEGA laser can be used to predict implosion dynamics of significantly larger ignition-scale targets on the MJ-class

NIF laser, LPI is not directly scalable because the instabilities' thresholds and gains depend on the coronal plasma parameters.

Direct-drive–ignition designs[37–39] to be used on the NIF include the spherical direct-drive design and polar-direct-drive (PDD) design, developed to support direct-drive ICF experiments on the NIF in its indirect-drive beam configuration. The laser and plasma conditions at the quarter-critical surface in those designs, based on *DRACO* simulations,[37–39] are shown in the third column of Table I. The impact of LPI has been recently tested in the subscale PDD implosion experiments on the NIF.[40–42] *DRACO* predictions for the plasma parameters at the quarter-critical surface in those experiments are shown in column 4 of Table I. Those experiments do not achieve ignition-relevant coronal conditions because they use 2.2-mm-diam targets designed to match the spot size of the current NIF beams with indirect-drive phase plates—the only phase plates currently available on the NIF. Full-scale direct-drive–ignition experiments on the NIF require larger 3.5-mm-diam capsules and dedicated direct-drive phase plates are not yet available. In addition, cross-beam energy transfer (CBET) reduces the laser beam energy reaching the quarter-critical surface in current sub-scale NIF PDD experiments. Wavelength detuning holds promise to significantly reduce CBET,[42] but it would require additional engineering modifications on the NIF. The conversion efficiency of laser energy to hot electrons was found to be 0.25% to 0.6% in the subscale NIF PDD experiments.

This paper reports on the development of a planar-target experimental platform for the NIF, previously described in Ref. 28, which is presently the only way to simultaneously achieve the density scale length, laser intensity, electron temperature, and transverse plasma dimensions characteristic of ignition-scale direct-drive implosions. Column 5 of

Table I summarizes the coronal plasma conditions at the quarter-critical surface achieved in the NIF planar experiments, as predicted by *DRACO* simulations. It shows that the plasma density scale length and temperature at the quarter-critical surface are similar to those in the ignition design, while the overlapped laser intensity is similar or exceeds, by up to a factor of 2, the overlapped intensity. These experiments, for the first time, provided a platform to study LPI and hot-electron production at plasma conditions relevant to direct-drive–ignition designs, either polar or spherical. Hot-electron generation in these experiments is inferred from hard x-ray bremsstrahlung measurements using the NIF's filter-fluorescer x-ray (FFLEX) diagnostic.[43] Signatures of the dominant LPI-generation mechanism were obtained from the measured scattered-light spectra near the half-harmonic of the incident laser frequency. As discussed in prior publications,[28,29] unlike in shorter-scale-length plasmas on OMEGA, scattered-light spectra on the NIF suggest that the near-quarter-critical LPI physics is dominated by SRS rather than by TPD.

The present paper expands findings of Refs. 28 and 29 with an emphasis on hot-electron generation at direct-drive ignition-relevant plasma conditions and hydrodynamic simulations of the coronal plasmas. Hard x-ray spectra presented in this paper validate the inference of the hot-electron energy fractions and temperatures. *DRACO* hydrodynamic simulations of the coronal plasmas demonstrate evolution of the plasma parameters at the quarter-critical surface. Attention is devoted to comparing the experiments and simulations. Measurements of the coronal temperature and location of the quarter-critical surface justify the surrogacy of the simulations and demonstrate that direct-drive ignition-relevant laser and plasma conditions were reached.

The outline of this paper is as follows: Section II discusses the setup of NIF planar-target experiments, the 2-D *DRACO* code used to model the target hydrodynamics, and the Monte Carlo code EGSnrc[44] modeling of hot-electron transport and hard x-ray bremsstrahlung emission. Section III describes planar-target experiments using CH targets that infer hot-electron production at direct-drive ignition-relevant coronal conditions. Section IV describes planar-target experiments using Si, which, as a mid-$Z$ material in multilayer ablator targets,[38] can be used to mitigate hot-electron production if needed. Section V presents the conclusions. Comparison of the coronal plasma parameters in the experiments and simulations is discussed in the Appendix.

## II. EXPERIMENTAL SETUP AND TWO-DIMENSIONAL *DRACO* SIMULATIONS

Planar targets were chosen to study LPI because they are currently the only way to achieve direct-drive ignition-relevant plasma conditions at a reduced laser energy (~100 to 200 kJ) on the NIF. On the NIF, 192 laser beams with 351-nm wavelength are divided into 48 groups of four beams (quads), arranged in four cones per hemisphere sharing the same polar angles of 23.5° and 30° ("inners," 32 beams in each hemisphere) and 44.5° and 50° ("outers," 64 beams in each hemisphere), respectively. The beams use 1-D smoothing by spectral dispersion (SSD)[45] at 90 GHz. All targets described here—CH or Si disks with a 4.4-mm diameter and thicknesses of 1.2 mm (CH) or 0.75 mm (Si)—were irradiated from the southern (lower) hemisphere. A schematic of the experiment and the main diagnostics are shown in Fig. 1. All the beams used standard NIF indirect-drive phase plates[46] at best focus. Having elliptical focal spots, the phase plates are designed to produce approximately circular focal-spot projections onto a target oriented normal to the NIF polar axis. The projected focal-spot diameters (FWHM) differ for the beams in different cones: 1.76 mm for 23.5° beams, 1.65 mm for 30° beams, 1.27 mm for 44.5° beams, and 1.19 mm for 50° beams.[46] Polarization smoothing on the NIF is implemented on a quad basis by having two pairs of beams with orthogonal polarizations. The targets were placed at the NIF target chamber center and oriented horizontally or tilted slightly to vary the angle between the target normal and the full-aperture backscatter station (FABS)[47] diagnostics used to measure the scattered-light spectra. This configuration allowed for the variation of LPI conditions by changing the number of beams, single-beam intensities, and incidence angles of the beams by using beams in different cones. The higher-angle cones approximate irradiation conditions near the equator of a PDD implosion, where the beams are incident from higher angles, while the lower-angle cones correspond to those near the poles. The use of planar targets reduces the level of 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. This allows for higher laser intensities at quarter critical and improves confidence in hydrodynamic modeling of the experiment.

The experiments described in this paper were designed using the 2-D radiation-hydrodynamic code *DRACO*;[36] this study uses the Eulerian version of *DRACO*. Laser absorption in the plasma corona by inverse bremsstrahlung was modeled by 3-D ray tracing with the NIF laser system's port geometry.[48] The equation of state of the target materials was determined from the *SESAME* tables.[49] A multigroup diffusion model was used for the radiation transport. For the low-$Z$ plastic, the Astrophysical Opacity Tables[50] were applied; while for the mid-$Z$ silicon, the average-ion model in collisional radiative equilibrium[51] was used for opacity tables and nonlocal thermodynamic equilibrium tables were used for ionization. A nonlocal electron thermal transport model[52,53] was used to model the target hydrodynamics and coronal plasma conditions. For the electron–ion thermal equilibration, the Lee–More model[54] was adopted in the code. The Eulerian code *DRACO* uses polar ($r$, $\theta$) coordinates with the assumption of azimuthal symmetry. For these planar geometry simulations, the target was located along the polar $z$ axis at the radius $r \approx 30$ cm intentionally made so large that the grid is approximately planar there.

Hot-electron production in the experiments was inferred through measurements of the bremsstrahlung emission using the ten-channel FFLEX diagnostic[43] located in the equatorial plane of the NIF chamber. The Monte Carlo code EGSnrc[44] was used to relate the properties of hot electrons and measured hard x rays. EGSnrc models the transport of hot electrons from the quarter-critical density region, where they are generated, to the target and includes important processes responsible for hot-electron collisional transport and x-ray emission. The range of most hot electrons is smaller than the target thickness, so that most of the hot-electron energy deposition is included without modeling electron recirculation. Indeed, only electrons above ~450 keV (~500 keV) can penetrate through 1.2 mm of plastic (0.75 mm of silicon).[55,56] They represent ~0.3% (~0.1%) of the total energy converted to hot electrons based on the inferred hot-electron temperature of ~50 keV. The hot-electron temperature and total energy were inferred from comparisons of the bremsstrahlung spectra measured in the experiment and those predicted by the code. This method accounts for all electrons that deposit their energy to the target in the experiment, including those that can be generated in the direction away from the target but are redirected back by the electrostatic sheath fields. In the simulations hot electrons were injected with a full divergence angle of $2\pi$ toward the target (which makes it possible to include electrons redirected into the target by the sheath fields as well).

## III. PLANAR-TARGET EXPERIMENTS USING PLASTIC TARGETS

### A. Planar-target experiments using outer beams

To approximate irradiation conditions near the equator of PDD implosions, where laser beams are incident at large angles, planar-target experiments were performed using the outer 44.5° and 50° cone beams. In these experiments, 1.2-mm-thick CH disks were tilted by 7° from the direction to the south pole toward the optical spectrometer located at the position of beam 33B at a polar angle of 23.5°. The experiments used laser pulses with a 2-ns linear power rise from zero to the maximum value followed by a flattop with a total duration of 7.5 ns. The total flattop power was varied in three shots, and the actual pulse power profiles in the experiments are shown in Fig. 2. All 64 outer beams were pointed at 275 $\mu$m away from the target surface, at the averaged-over-time position of the $n_{qc}$ surface in these shots (according to *DRACO* simulations).

Figure 3 shows (a) the electron density and (b) electron temperature profiles of the coronal plasma at $t = 5$ ns predicted by *DRACO* for shot N151118-002 with an intermediate flattop power. Figures 4(a)–4(c) show the predicted time evolution of the plasma parameters at the $n_{qc}$ surface on axis ($r = 0$) for the three shots. After the initial 2-ns laser power rise, the plasma reaches quasi-stationary coronal conditions at the $n_{qc}$ surface. They are characterized by an almost-stationary density scale length $L_n = n/|\mathrm{d}n/\mathrm{d}z|$ and temperature $T_e$ and a slightly decreasing-in-time overlapped laser intensity *I*. The density scale length $L_n \approx 500$ $\mu$m is almost the same in these three shots with different flattop powers. As the flattop power increases from 15 TW to 30 TW, the overlapped laser intensity increases from $6.5 \times 10^{14}$ W/cm$^2$ to $1.5 \times 10^{15}$ W/cm$^2$ and the temperature from 3 keV to 5 keV. Note that the intensity at $n_{qc}$ is approximately half of the incident laser intensity, which is caused by inverse bremsstrahlung absorption in the lower-density plasma on the way to the $n_{qc}$ surface.

Figure 5 shows the time-integrated hard x-ray spectra obtained using the FFLEX diagnostic in these shots. FFLEX[43] is a multichannel, hard x-ray spectrometer, operating in the 20- to 500-keV range, that provides time-resolved, absolute measurements of the bremsstrahlung spectra with ~300-ps resolution. FFLEX integrates the x-ray emission over a field of view of ~100 mm at target chamber center without spatial resolution. The FFLEX diagnostic has been recently reanalyzed. The field-of-view solid angles onto the NIF target chamber center and the photomultiplier sensitivities to the x rays have been updated. As a result of FFLEX recalibration, the hot-electron conversion efficiencies here are higher and the hot-electron temperatures are lower than reported in Ref. 28. This, however, does not affect the overall conclusions of Ref. 28 on the origins and scaling of SRS and hot-electron generation. The symbols in Fig. 5 show the measured, time-integrated x-ray emission for the ten FFLEX channels, and the solid lines represent the one-temperature x-ray emission fits through the data. The measured spectra are approximated well by the exponential distributions. The standard fits to the FFLEX spectra yield time-averaged slope temperatures of 37.5±4.7 keV, 47±3.8 keV, and 47.6±3.5 keV in the three shots with increasing power: N151117-003, N151118-002, and N151118-001, respectively.

EGSnrc Monte Carlo simulations were performed in which hot electrons from 3-D Maxwellian distributions were injected ~275 $\mu$m in front of the target surface, close to the location of the $n_{qc}$ surface. Electrons were injected with temperatures close to the hard x-ray slope temperatures inferred in the experiments and with a full divergence angle of $2\pi$ toward the target. The simulated EGSnrc bremsstrahlung energy spectra are exponential above ~10 keV. Below 10 keV, deviations from exponential spectra are caused by absorption of the emitted x rays in CH. The temperature of the hot electrons and the slope temperature of the x rays are very close in the simulations. The total number of hot electrons in the simulations was varied until the absolute value of the x-ray emission in the experiments was matched. The laser-energy-to-hot-electron conversion efficiencies inferred by comparing experiments and simulations are shown in Fig. 6. The hot-electron conversion efficiencies are plotted versus the laser intensity at $n_{qc}$ predicted by *DRACO* by blue circles for the outer-beam shots, connected by a solid line to guide the eye. The conversion efficiencies between $t$ = 4.5 ns and 7.5 ns are shown (based on FFLEX spectra integrated over that time period) for a fair comparison with inner-beam shots below (for which the conversion efficiencies for the same time interval are shown). The hot-electron conversion efficiency increases from 1±0.4% to 5.1±0.9% as the laser intensity increases from $6 \times 10^{14}$ W/cm$^2$ to $14 \times 10^{14}$ W/cm$^2$. Figure 7 plots the corresponding hot-electron temperature inferred in these shots versus the laser intensity at $n_{qc}$ (blue circles). The uncertainty in the hot-electron conversion efficiency and temperature is based on the statistical uncertainty in the single-temperature fit to the hard-x-ray spectra.

## B. Planar-target experiments using inner beams

Planar-target experiments were also performed using inner-beam illumination, providing a better approximation of the irradiation conditions near the poles of PDD implosions. The NIF has 64 outer beams and 32 inner beams in each hemisphere. Using 7.5-ns pulses and total powers similar to those in Sec. III.A for outer beams would exceed the optics damage threshold for inner beams because 2× larger power per beam is required. To reduce impact on NIF beam optics we first used outer beams drive to generate a long-scale-length plasma, followed by 32 inner beams' illumination. Figure 8 shows the power profiles of outer- and inner-beam pulses in dashed and solid lines, respectively, in shots N171012-001, N160719-003, and N160421-001. In all the shots the inner-beam drive is preceded by a similar 4.5-ns outer-beam drive with a 2-ns linear rise and 2.5-ns flattop, creating similar coronal conditions before the onset of the inner beams. The flattop power of the inner beams was varied between 14 TW and 32 TW. The target was oriented normally to the NIF beams' axis in these experiments. Figures 9(a)–9(c) show the coronal conditions at the $n_{\mathrm{qc}}$ surface, as predicted by *DRACO*. The plasma conditions are quasi-stationary during the inner-beam drive with a density scale length $L_{\mathrm{n}} \sim 600$ $\mu$m, while the overlapped laser intensity and electron temperature varied.

Figure 10 shows the hard x-ray spectra measured using FFLEX integrated over the duration of the inner-beam drive. Hot-electron production was inferred by comparing the EGSnrc-simulated bremsstrahlung spectra with the measurements. Figures 6 and 7 show the hot-electron conversion efficiencies and temperatures for the inner beams by green diamonds, connected in Fig. 6 by a solid line to guide the eye. The experiments exhibit somewhat higher hot-electron conversion efficiencies using inner beams, compared to outer beams, and hot-electron temperatures close to 55 keV with inner beams. The hot-electron conversion efficiency increases from 0.2±0.2% to 5.3±0.9% as the laser intensity at the $n_{qc}$ surface increases from $3.5 \times 10^{14}$ W/cm$^2$ to $11 \times 10^{14}$ W/cm$^2$.

Scattered-light spectrum measurements using FABS diagnostics [see Figs. 1(a)–1(c) of Ref. 28] indicate the presence of absolute SRS at $n_{qc}$ (scattered light at ~702-nm wavelength, corresponding to half the laser frequency), as well as SRS at lower densities $0.15 < n/n_c < 0.22$ (scattered light at 600- to 670-nm wavelength). No signatures of TPD in the half-harmonic emission spectrum were present. Near-backscatter and sidescatter SRS were observed. The energy of the SRS scattered light was estimated in Ref. 28 based on the absolutely calibrated photodiodes measurements at two locations with 50° and 30° polar angles. These measurements were extrapolated to account for the total emission, assuming $2\pi$ azimuthal symmetry around the target normal and accounting for refraction and reabsorption of the scattered light. These resulted in between 2% and 6% of incident laser energy converted to SRS light. From conservation of wave action (i.e., the Manley–Rowe relations) the total energy in the plasma waves, capable to accelerate hot electrons, is 70% to 100% of the energy in SRS. It is sufficient to explain the inferred energy of hot electrons ranging from 1% to 5.5% of the laser energy in these experiments. While the associate uncertainties can allow some contribution to hot-electron production from another source, which could be TPD, the characteristic spectral features associated with TPD are absent. We propose that future experiments use optical Thomson scattering to directly measure the spectrum of plasma waves in the $n_{qc}$ region to definitively assess the presence or absence of TPD.

## IV. PLANAR-TARGET EXPERIMENTS USING SILICON TARGETS

The dashed horizontal line in Fig. 6 shows the maximum-tolerable hot-electron conversion efficiency for divergent electron beams of 0.7%, as explained in Sec. I. The experiments using planar CH targets show that this limit is exceeded if the laser intensity at the $n_{qc}$ surface is greater than ~$4 \times 10^{14}$ W/cm$^2$ in current direct-drive ignition designs. Hot-electron preheat mitigation strategies can extend the ignition-design space to higher intensities. Using multilayer ablator targets with a strategically placed mid-*Z* layer was originally proposed to mitigate TPD.[38] Ablation of a mid-*Z* material shortens the density scale length, increases the electron temperature, enhances electron–ion collisional damping, and reduces Landau damping of ion-acoustic waves, limiting the growth of electron plasma waves.[19,57–59] These processes can be helpful in suppressing SRS as well. To test this strategy, planar experiments were conducted using Si targets. The laser and target setup was similar to that in the inner-beam plastic-target experiments, and the total laser intensity during the inner-beam drive was varied. Figure 11 shows the power profiles of the outer and inner beams in dashed and solid lines, respectively, in shots N161010-001, N160719-001, and N161010-002. Figures 12(a)–12(c) show the coronal conditions at the $n_{qc}$ surface, as predicted by *DRACO*. Note that the laser power profiles were almost identical in CH and Si shots N160421-001 and N160719-001, and indeed a reduction in scale length and an increase in temperature are predicted for the Si shot: $L_n$ from ~690 $\mu$m in CH to ~560 $\mu$m in Si; $T_e$ from ~4.4 keV in CH to ~5.2 keV in Si.

The hot-electron properties were again inferred by comparing the measured hard x-ray spectra and EGSnrc simulations. Figure 13 shows the bremsstrahlung spectra for shots N160719-001 and N161010-001. Minimal hard x rays were observed on shot N161010-002 at the lowest intensity. One-temperature fits were constructed by excluding the first four lowest-energy channels, which indicated the presence of another lower-temperature distribution (absent in CH targets) at energies below 50 keV. This second distribution corresponds to hot electrons with energies below 50 keV, which are stopped in the ablator and do not contribute to preheat. The hot-electron conversion efficiencies and temperatures in the Si shots are included in Figs. 6 and 7. Figure 7 shows that the temperatures of hot electrons in the Si-target shots are only slightly less than in the CH-target shots using similar inner-beam illumination. Figure 6, however, demonstrates a significant reduction in hot-electron conversion efficiency using Si targets, compared to the similar inner-beam CH-target shots. Both the threshold for hot-electron production is shifted to higher intensities in Si—from ~$3 \times 10^{14}$ W/cm$^2$ to $6 \times 10^{14}$ W/cm$^2$—and the total hot-electron production is reduced for intensities that are above threshold. The dashed line in Fig. 6 indicates that the tolerable preheat is not exceeded if the laser intensity at $n_{qc}$ is below ~$7.5 \times 10^{14}$ W/cm$^2$ in Si targets, compared to $4 \times 10^{14}$ W/cm$^2$ in CH targets with inner beams. It is noteworthy that reduction of hot-electron production in Si targets correlates with a reduced level of the observed SRS scattered light in these experiments.[60] A shorter density scale length reduces the size of the resonant region near $n_{qc}$, where SRS can grow, lowering the SRS gain.[5] An increased electron–ion collisional rate ($\nu_{ei} \propto Z_{eff} = \langle Z^2 \rangle / \langle Z \rangle$, where $Z$ is the ion charge state) increases laser absorption (consequently increasing the temperature), increases absorption of the scattered light, and damps the electron plasma waves, which lowers the SRS gain as well.[19,58] Higher $Z_{eff}$ also lowers the Landau damping of ion-acoustic waves, which have been shown to lower the saturation amplitudes of electron plasma waves.[59,61] These effects should decrease hot-electron production. Our experiments demonstrate that Si mitigates hot-electron production and motivate the use of mid-*Z* layers in a multilayer ablator in direct-drive ignition designs.[38]

## V. CONCLUSIONS

A planar-target experimental platform has been developed and fielded on the NIF to investigate the impact of hot-electron generation on direct-drive–ignition designs. The present work utilizes *DRACO* radiation-hydrodynamic simulations for predictions of the coronal plasma parameters in the experiments. As part of the experimental platform development, independent measurements of the coronal electron temperature and longitudinal position of the quarter-critical surface were performed for some shots and compared to *DRACO* predictions, which is described in the Appendix. A good agreement of the experiments and simulations justifies the surrogacy of the simulations. The experimental measurements also support the claim that the coronal temperature increases in Si plasma compared to CH plasma for similar incident laser powers. Additional measurements of the longitudinal density profile can become possible on the NIF once the $5\omega$ Thomson-scattering probe diagnostic becomes available.

In summary, hot-electron production by laser–plasma instabilities at direct-drive ignition-relevant plasma conditions has been studied in planar-target experiments on the NIF. Plasma and interaction conditions in these experiments are relevant to coronal plasmas in direct-drive–ignition designs, as predicted by *DRACO* simulations: $I_L \sim (3$ to $15) \times 10^{14}$ W/cm$^2$, $T_e \sim 3$ to 5 keV, and density gradient scale lengths of $L_n \sim 500$ to

600 $\mu$m. 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 at direct-drive ignition-relevant plasma conditions because of inverse bremsstrahlung absorption of the incident light in the lower-density plasma on the way toward $n_{qc}$. Based on an assumed large hot-electron divergence, a hot-electron fraction of 0.7% of the laser energy is thought to be tolerable in present direct-drive ignition designs. It is exceeded if the overlapped intensity at the quarter-critical surface exceeds ~4 × $10^{14}$ W/cm$^2$. A large hot-electron divergence has been demonstrated in previous spherical LPI experiments on OMEGA dominated by TPD. Since LPI in the direct-drive ignition-relevant conditions on the NIF is dominated by SRS, the hot-electron divergence will need to be re-evaluated. Spherical implosion experiments currently scheduled on the NIF will investigate the divergence and coupling of hot electrons to the imploded shell and will be discussed in a future publication.

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 TPD in smaller-scale implosions on OMEGA.[55] Our experiments using silicon planar targets demonstrate 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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## APPENDIX: COMPARISON OF THE CORONAL PLASMA PARAMETERS IN EXPERIMENTS AND SIMULATIONS

The electron temperature at the $n_{\mathrm{qc}}$ surface was obtained in some experiments by measuring the wavelength shift of the narrow feature in the scattered-light spectrum at a wavelength slightly above 702 nm corresponding to the absolute SRS instability.[28] Figure 14 plots a part of the scattered-light spectrum in shot N160420-003 including this spectral feature. The averaged wavelength shift of this feature, used to infer the plasma temperature at $n_{qc}$, is also plotted as a function of time. A CH target was used in this shot oriented normal to the light spectrometer location at a 23.5° polar angle in the NIF chamber, for optimal observation of the half-harmonic spectrum. The laser power was approximately constant after 2 ns in this shot, with a ~7% power increase after 4.5 ns due to an additional NIF beam quad turned on at 4.5 ns. The dispersion relation for the plasma waves generated at $n_{qc}$ leads to $T_{e,keV} = \Delta\lambda_{p,nm}/3.09$ (Ref. 7), where $\Delta\lambda_p$ is the shift of the spectral peak from $2\lambda_0$ after applying corrections for Doppler and Dewandre shifts.[62] The measured wavelength shift $\Delta\lambda = DL_p + \Delta\lambda_{Doppler} + \Delta\lambda_{Dewandre}$. The Doppler and Dewandre shifts are blue shifts (negative). The Doppler shift is due to plasma flow and affects the wavelength of both incoming 351-nm light and outgoing $\omega/2$ light. The flow velocity is close to the sound speed; it is not measured and is estimated from the simulation, $V_p \approx 6.1 \times 10^7$ m/s. The Doppler shift is $\Delta\lambda_{Doppler} = -4V_p\lambda_0/c = -2.85$ nm. The Dewandre shift results from the time-dependent optical path length of the expanding plasma and more strongly affects the lower-frequency $\omega/2$ light propagating outward, $\Delta\lambda_{Dewandre} \approx -0.15$ nm. As a result, $T_e = 4.5\pm0.2$ keV at $t > 4.5$ ns. Note that the uncertainty here is determined by the spectrometer calibration and is larger than the uncertainties in the modeling-based corrections for $\Delta\lambda_{Doppler}$ and $\Delta\lambda_{Dewandre}$ The electron temperature inferred from the measured wavelength shift is in excellent agreement with the *DRACO* calculation for that shot, predicting a temperature of 4.5 keV.

This method was also used to measure the temperature at the $n_{qc}$ surface in the similar silicon-target shot N170111-002. The measured temperature of $T_e = 5.3\pm0.3$ keV was again in agreement with the simulated temperature of 5.4 keV. This supports the claim that the coronal temperature increases in Si plasma compared to CH plasma for similar incident laser powers in the two shots (~34 TW).

Additionally, the temperature was estimated from the lower-wavelength limit of the SRS scattered-light spectra,[60] which is thought to correspond to Landau cutoff ($k_{\mathrm{p}}\lambda_{\mathrm{D}}$ ; 0.25, where $k_p$ is the plasma wave vector and $\lambda_{\mathrm{D}}$ is the Debye length). The lower-wavelength limit was around 600 nm (SRS from electron density ~$0.17n_{\mathrm{c}}$) for the CH target shot N160420-003 and around 625 nm (SRS from density ~0.19 $n_{\mathrm{c}}$) for the Si target shot N170111-002. For SRS sidescatter, this cutoff corresponds to around or above 4 keV for the CH target shot and around 5 keV for the Si target shot. This is consistent with temperatures of 4.6 keV and 5.5 keV, respectively, at aforementioned densities in *DRACO* simulations for those shots.

The plasma electron temperature was also measured using spectroscopic methods in the two shots in which a 240-$\mu$m-wide, 1040-$\mu$m-long, 0.324-$\mu$m-thick Mn/Co microstrip was buried 2.5 $\mu$m below the irradiated surface.[63] Temperatures up to 3 keV were inferred at the location of the Mn/Co microstrip ablated in the corona, in reasonable agreement with the predictions of *DRACO* simulations that did not include the microstrip. Somewhat lower temperatures inferred experimentally (~2.4 keV) compared to *DRACO* predictions (~3 keV) around the time when the microstrip passes the $n_{\mathrm{qc}}$ surface were attributed to the constraints of the single-temperature fitting procedure used in the spectroscopic methods.[63]

Comparisons of the coronal density profiles and the density scale length in the $n_{\mathrm{qc}}$ region in the experiments and simulation are more complicated. In some of the experiments the NIF optical Thomson-scattering (OTS) diagnostic[64,65] was configured to collect the $3\omega/2$ scattered light from a narrow plasma volume (with a diameter of ~60 $\mu$m) perpendicular to the target axis. The $3\omega/2$ light was collected when the scattered volume crossed the $n_{qc}$ surface, where the $3\omega/2$ light is generated by Thomson upscattering of the incident laser light by the $\omega/2$ plasmons. OTS located the time of arrival of the $n_{qc}$ surface in the scattering volume and the time of departure. These times agreed with an error less than 0.5 ns with the times we obtained from ray-trace calculations of the $3\omega/2$ scattered-light propagation in coronal density profiles from *DRACO* simulations. This supports that *DRACO* models the longitudinal position of the $n_{qc}$ surface correctly and is another useful check of hydrodynamics.

These comparisons of the experiments and simulations give some confidence in the hydrodynamic modeling of the corona. Measurements of the longitudinal density profile can become possible once the $5\omega$ Thomson-scattering probe will be available on the NIF in the near future. This can provide information about the density scale length in the corona, which can be compared with simulations. Note that small longitudinal shifts of the $n_{qc}$ surface (by less than ~300 $\mu$m) do not result in significant changes in the overlapped intensity at $n_{qc}$ because of large beam focal spot sizes (1.2 to 1.8 mm FWHM). Changes in the density scale length and temperature, however, can affect the laser collisional absorption before the $n_{qc}$ surface and intensity at $n_{qc}$.

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## FIGURE CAPTIONS

FIG. 1. A schematic of the experiment and the main diagnostics. Planar CH or Si targets were irradiated by subsets of NIF beams from the southern hemisphere. “Inner” cones of beams have angles of 23.5° and 30° (32 beams), while “outer” cones have angles of 44.5° and 50° (64 beams) with respect to the NIF polar axis. Main diagnostics include FFLEX, measuring the time-resolved bremsstrahlung emission spectra, and FABS, measuring the time-resolved scattered-light spectra. FABS measurements of scattered-light spectra have been presented in prior work.[28,29]

FIG. 2. Total laser power profiles in the CH planar-target experiments using the outer beams.

FIG. 3. Electron density (a) and temperature (b) in the coronal plasma at $t$ = 5 ns (electron density is capped at $10^{22}$ $cm^{-3}$ inside the target), as predicted by a 2-D cylindrically symmetric *DRACO* simulation for shot N151118-002. The solid black line represents the position of the quarter-critical density surface. $Z$ is the symmetry axis of the laser beams, which are incident from the right onto the CH target with a front surface at $z$ = 0. The simulations neglect a 7° target tilt angle with respect to the NIF polar axis.

FIG. 4. Time evolution of the laser and plasma parameters at the $n_{qc}$ surface on axis ($r$ = 0) in *DRACO* simulations for the shots: (a) N151117-003, (b) N151118-002, and (c) N151118-001.

FIG. 5. Time-integrated hard x-ray bremsstrahlung spectra, measured by FFLEX, in the experiments using CH targets and outer beams. The solid lines are exponential fits.

FIG. 6. Laser-energy to hot-electron conversion efficiency versus laser intensity at the $n_{qc}$ surface in the experiments using CH targets and outer-beam illumination (blue circles), CH targets and inner-beam illumination (green diamonds), and Si targets and inner-beam illumination (red squares). The data points are connected by solid lines to guide the eye. Dashed horizontal line 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 Sec I. The preheat is tolerable in the light green region below the dashed line.

FIG. 7. Hot-electron temperature versus laser intensity at the $n_{qc}$ surface in the experiments using CH targets and outer-beam illumination (blue circles), CH targets and inner-beam illumination (green diamonds), and Si targets and inner-beam illumination (red squares).

FIG. 8. Total inner- (solid) and outer- (dashed) beams power profiles in the CH planar target experiments using outer beams followed by inner beams.

FIG. 9. Time evolution of the laser and plasma parameters at the $n_{qc}$ surface on axis ($r$ = 0) in *DRACO* simulations for the CH-target shots: (a) N160421-001, (b) N160719-003, and (c) N171012-001.

FIG. 10. Hard x-ray bremsstrahlung spectra time integrated over the duration of inner-beam illumination, measured by FFLEX, in the experiments using CH targets and outer beams followed by inner beams.

FIG. 11. Total inner- (solid) and outer- (dashed) beams power profiles in the Si planar target experiments using outer beams followed by inner beams.

FIG. 12. Time evolution of the laser and plasma parameters at the $n_{qc}$ surface on axis ($r$ = 0) in *DRACO* simulations for the Si-target shots: (a) N161010-001, (b) N160719-001, and (c) N161010-002.

FIG. 13. Hard x-ray bremsstrahlung spectra time integrated over the duration of inner-beam illumination, measured by FFLEX, in the experiments using Si targets and outer beams followed by inner beams. Open symbols for FFLEX channels 1 to 4 indicate that these channels were not used in the fit.

FIG. 14. Time-resolved scattered-light spectrum near $\lambda = 702\ \mathrm{nm}$ measured in the direction of target normal in CH-target shot N160420-003. The average wavelength shift of the spectral feature due to the absolute SRS instability, used to infer the plasma temperature at $n_{qc}$, is plotted as a function of time. This wavelength shift approaches 11 nm at $t > 4.5$ ns.

TABLES

TABLE I. Plasma parameters at the $n_{qc}$ surface in OMEGA and current NIF PDD experiments, ignition NIF PDD design, and planar CH targets in this paper, as predicted by *DRACO* simulations.

| Parameters at $n_{qc}$ surface | OMEGA | Current NIF PDD | Ignition NIF PDD | Planar NIF |
|---|---|---|---|---|
| $I_L$ (W/cm$^2$) | <4 × $10^{14}$ | <4.6 × $10^{14}$ | 5 to 9 × $10^{14}$ | 3 to 15 × $10^{14}$ |
| $L_n$ ($\mu$m) | <350 | <360 | 600 | 500 to 600 |
| $T_e$ (keV) | <2.5 | <3.5 | 4 to 5 | 3 to 5 |