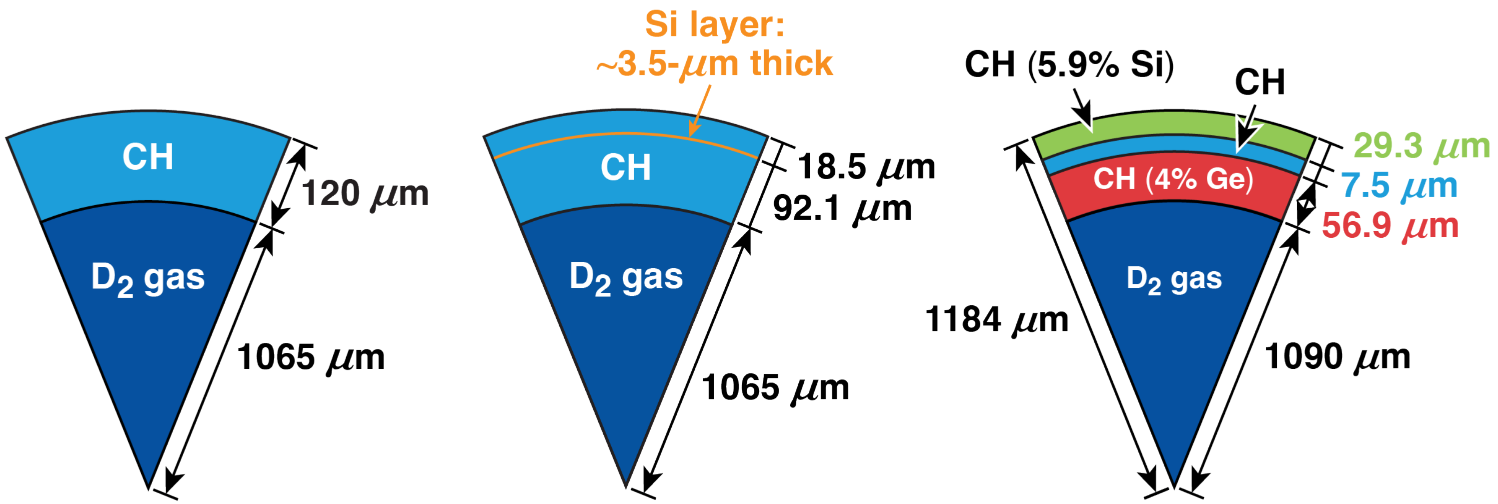
Hot-Electron Preheat and Mitigation in Polar-Direct-Drive Inertial Confinement Fusion Implosions at the National Ignition Facility



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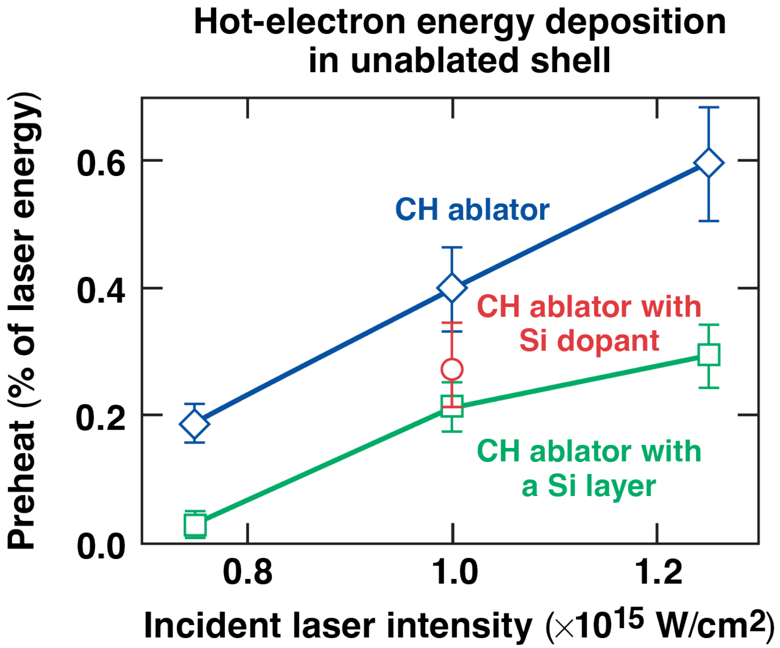

A. A. Solodov
University of Rochester
Laboratory for Laser Energetics

64th Annual Meeting of the APS
Division of Plasma Physics
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Summary

Mid-Z Si layers and dopants provide a promising hot-electron preheat mitigation strategy for direct-drive–ignition designs

- Implosion experiments were performed at the National Ignition Facility (NIF) to quantify preheat levels and directly measure the spatial hot-electron energy deposition profile
- From 0.2% to 0.6% of the laser energy is coupled via hot electrons to the unablated shell for incident laser intensities from (0.75 to 1.25) $\times$ 10^{15} W/cm^2, with half of the preheat coupled to the inner 80% of the unablated shell
- Buried Si layers mitigate growth of laser–plasma instabilities (LPI's), suppressing preheat or reducing it by a factor of $\sim$2; hot-electron preheat is reduced by 30% using Si dopant at 10^{15} W/cm^2
- Shell convergence significantly reduces hot-electron preheat late in the implosion

The present results show acceptable preheat levels for on-target intensities around 10^{15} W/cm^2, for MJ-scale laser direct drive.

Collaborators

M. J. Rosenberg, M. Stoeckl, R. Betti, W. Seka, R. Epstein, C. Stoeckl, R. K. Follett, P. B. Radha, S. P. Regan, D. H. Froula, J. P. Palastro, E. M. Campbell, and V. N. Goncharov

University of Rochester
Laboratory for Laser Energetics

A. R. Christopherson, B. Bachmann, M. Hohenberger, and P. Michel

Lawrence Livermore National Laboratory

J. F. Myatt

University of Alberta

Hot-electron preheat can degrade fuel compression in direct-drive–ignition designs

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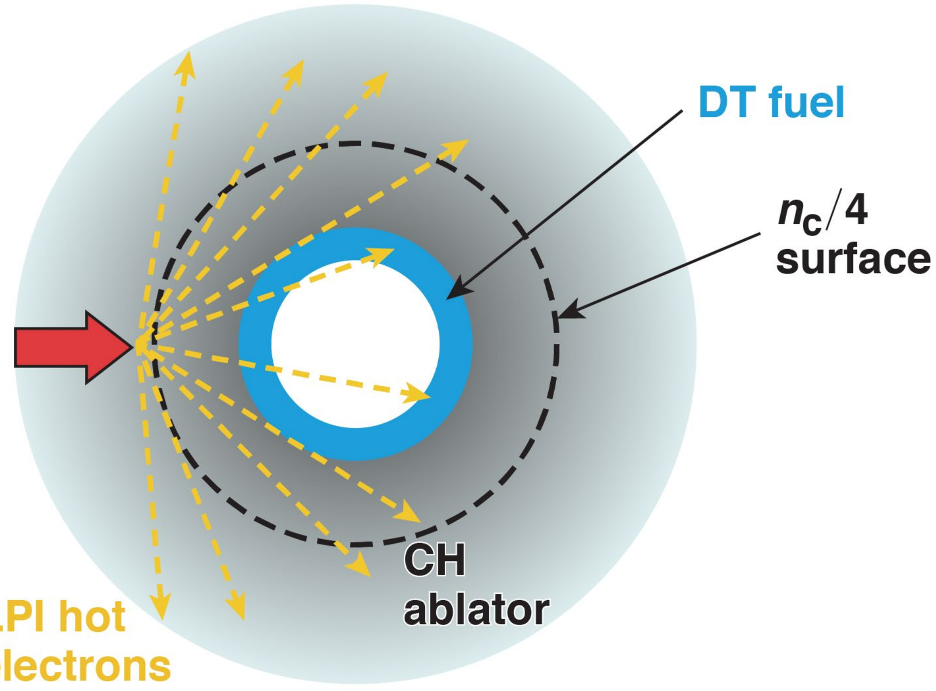
Direct-drive implosion



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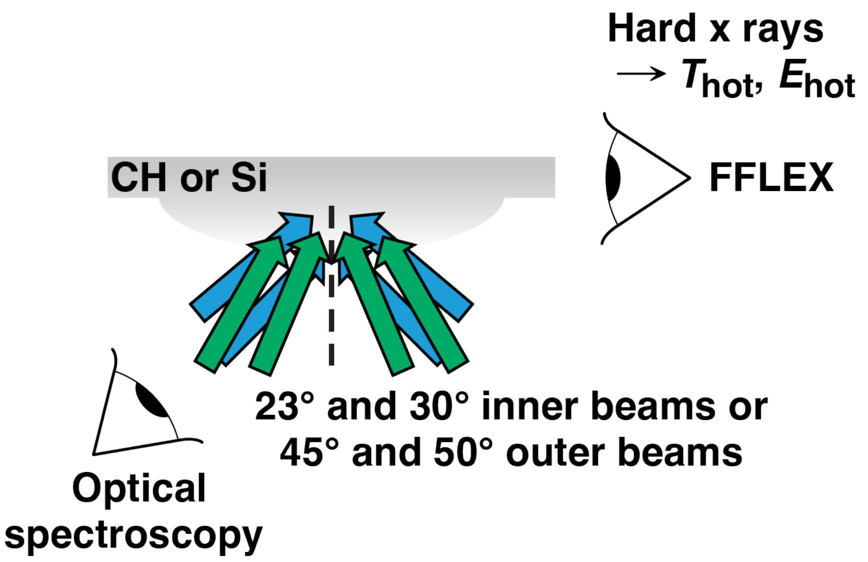
- For efficient implosion and compression, the thermonuclear fuel should stay at a low adiabat, which is defined as the ratio of the DT pressure to the Fermi-degenerate pressure
- Preheat by suprathermal (hot) electrons generated by laser–plasma instabilities can increase the pressure, degrade the implosion, and prevent the ignition
- Fuel compression is negatively affected if more than ~0.15% of laser energy is coupled into fuel preheat*

*J. A. Delettrez, T. J. B. Collins, and C. Ye, Phys. Plasmas 26, 062705 (2019).

Previous planar NIF experiments explored LPI and hot-electron production at direct-drive ignition-relevant plasma conditions*



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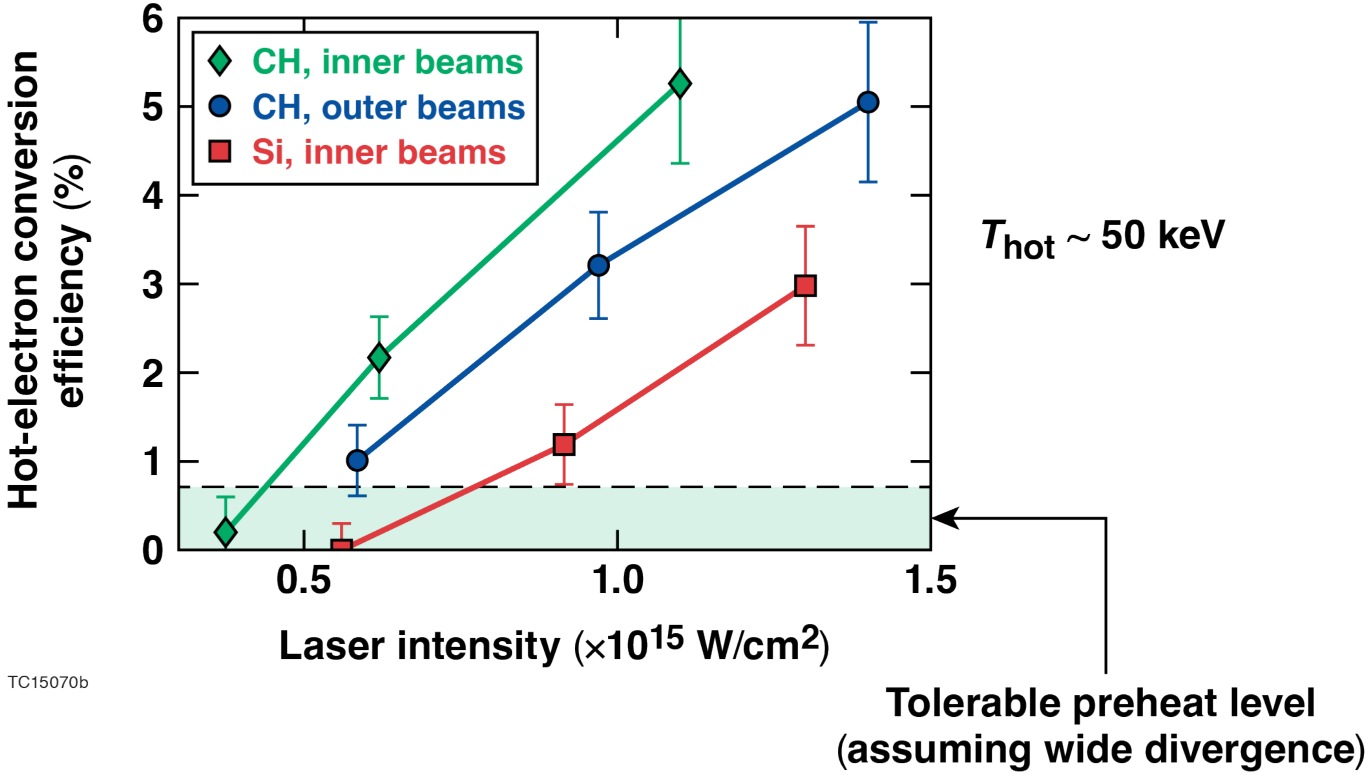
Hot-electron conversion efficiency versus laser intensity at $n_c/4$



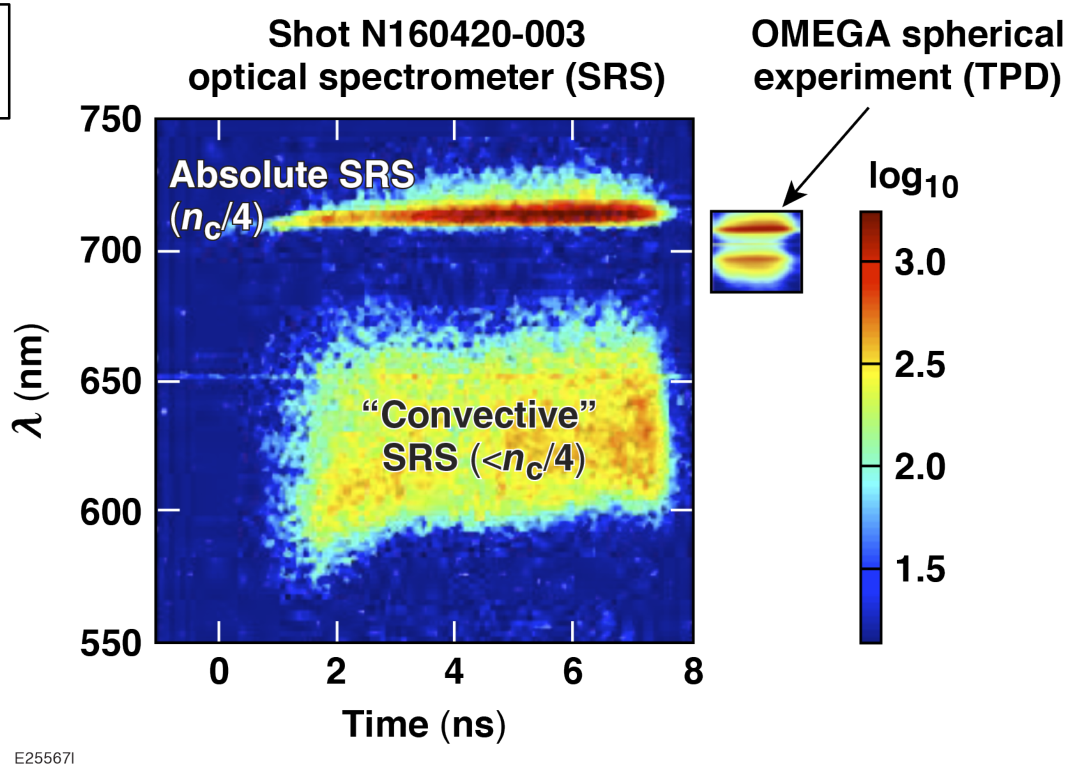
TC15070b

- Incident laser intensity is ~2× intensity at $n_c/4$ at ignition-relevant density scale length L_n ~ 600 μm and T_e ~ 3 to 5 keV

*M. Rosenberg *et al.*, Phys. Rev. Lett. 120, 055001 (2018);
A. Solodov *et al.*, Phys. Plasmas 27, 052706 (2020).
FFLEX: filter-fluorescer x-ray diagnostic

Planar NIF LPI experiments established the predominance of SRS as a hot-electron source at direct-drive ignition-relevant plasma conditions

NIF: L_n = 525 μm
T_e = 4.5 keV



OMEGA: L_n = 150 μm
T_e = 2.8 keV

Hot-electron generation and preheat need to be studied at scale because LPI mechanisms depend on the plasma scale length and are different on the NIF and OMEGA.

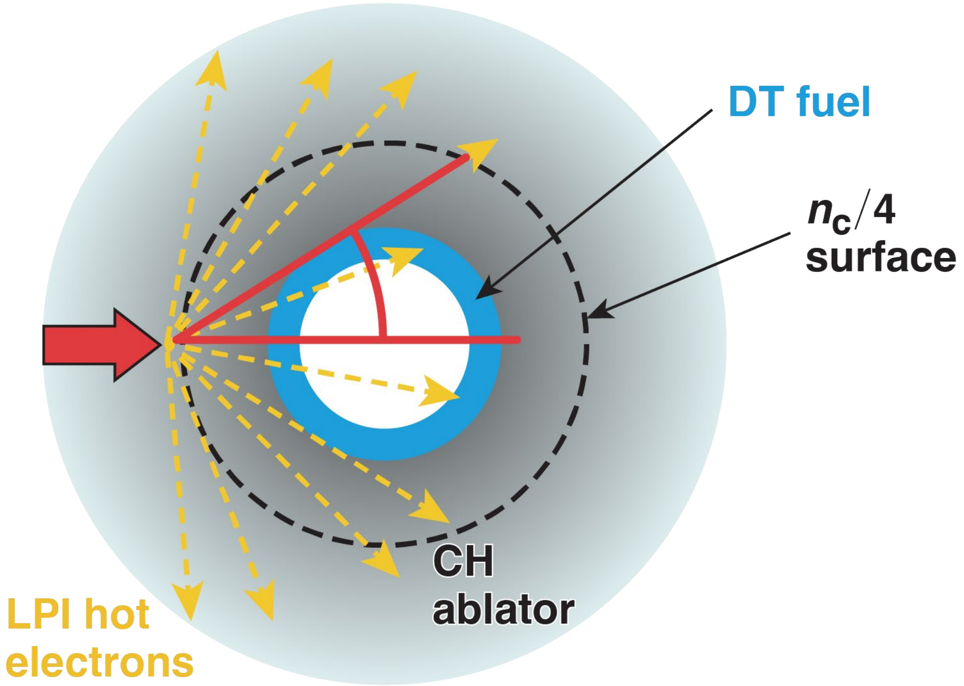
M. Rosenberg *et al.*, Phys. Rev. Lett. 120, 055001 (2018).

SRS: stimulated Raman scattering

TPD: two-plasmon decay

However, preheat in implosions depends not only on hot-electron production, but divergence and coupling to the inner portion of the shell

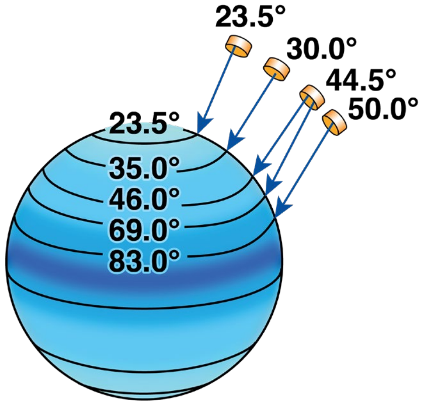
Direct-drive implosion



- If electron divergence is large, only ~25% of electrons intersect the cold fuel
- Electrons below ~50 keV are stopped in the ablator
- Hot-electron coupling to the inner portion of the shell is important, which is compressed at bang time by the return shock and ignites

Hot-electron energy deposition in the unablated shell needs to be characterized.

Hot-electron preheat and mitigation using Si layers and dopant have been studied in polar-direct-drive (PDD) experiments on the NIF*



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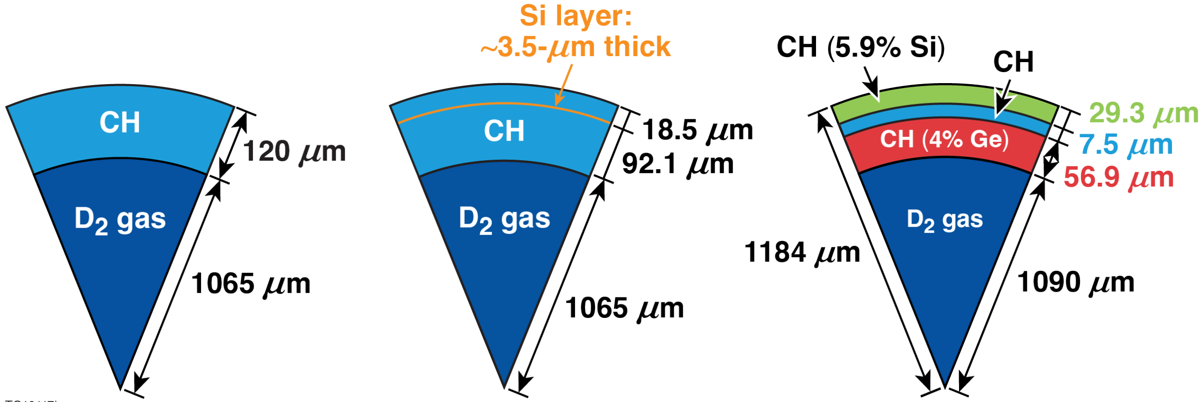

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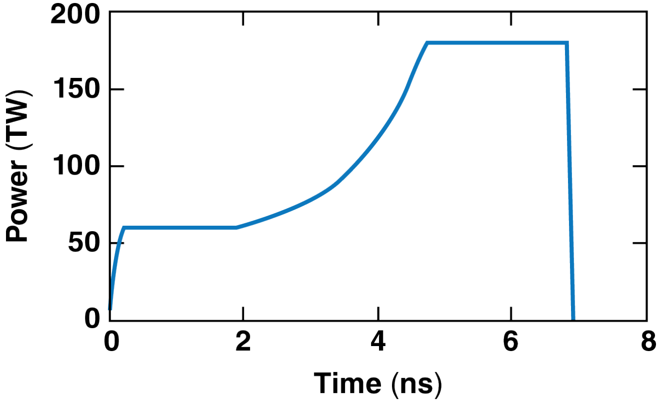

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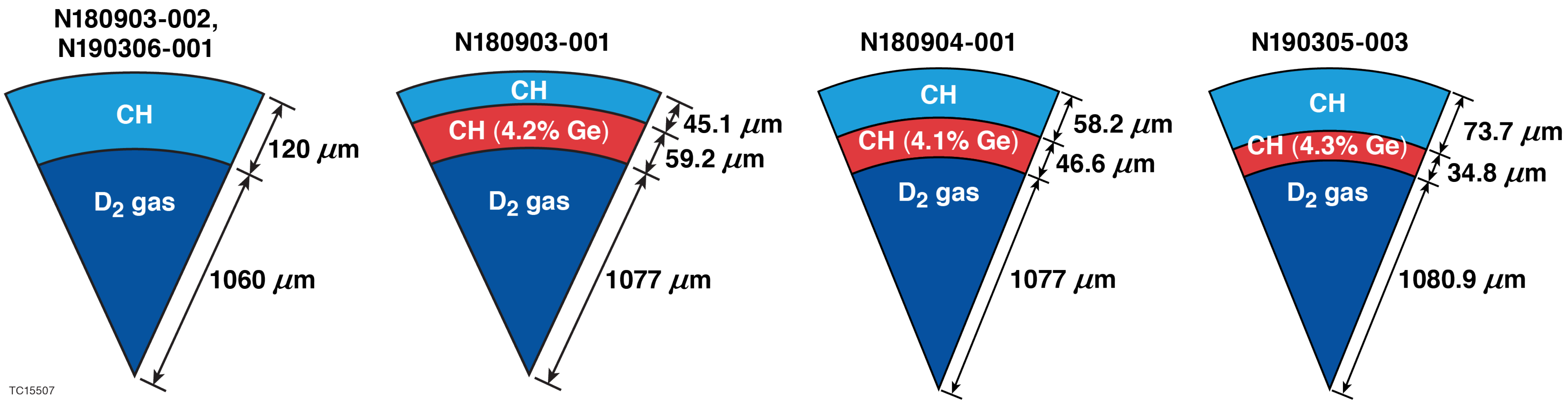
- The experiments used ~2.4-mm-diam capsules, chosen to match the size of the indirect-drive phase plates
- Such capsules are only ~30% smaller than the targets in the proposed ignition NIF PDD design**

* A. A. Solodov *et al.*, to be published in Phys. Rev. E.
** T. J. B. Collins *et al.*, Phys. Plasmas 25, 072706 (2018).

Hot-electron preheat in NIF PDD implosions was studied by comparing hard x-ray emission between plastic and multilayered implosions*

Mass-equivalent targets

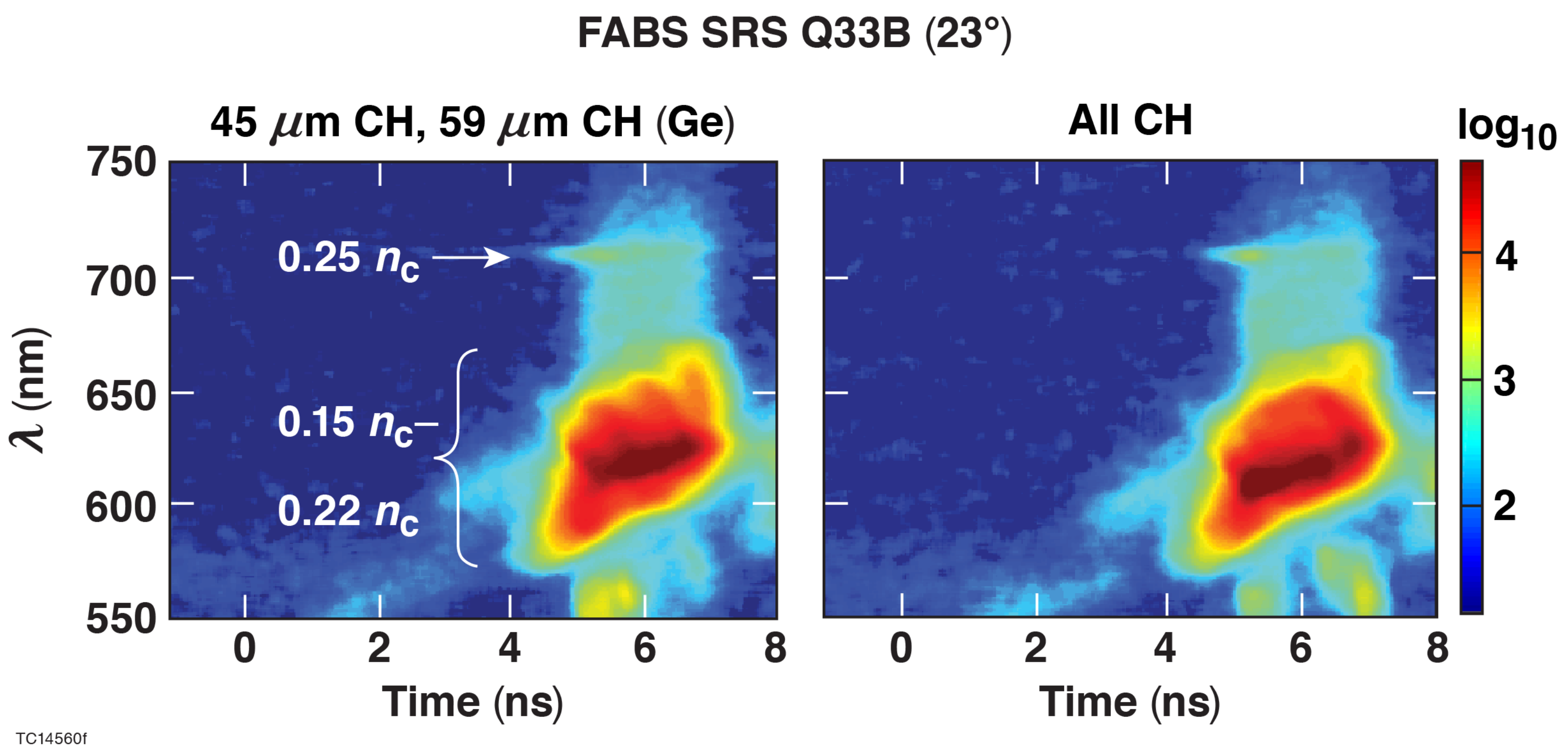


- **Hot-electron energy deposited in the inner shell layer is proportional to the difference in hard x-ray (HXR) emission between CH and multilayered implosions***

Different thicknesses of the Ge-doped layer were examined to diagnose the hot-electron deposition profile in the imploding shell.

*Platform based on A. Christopherson *et al*., *Phys. Rev. Lett.* 127, 055001 (2021).

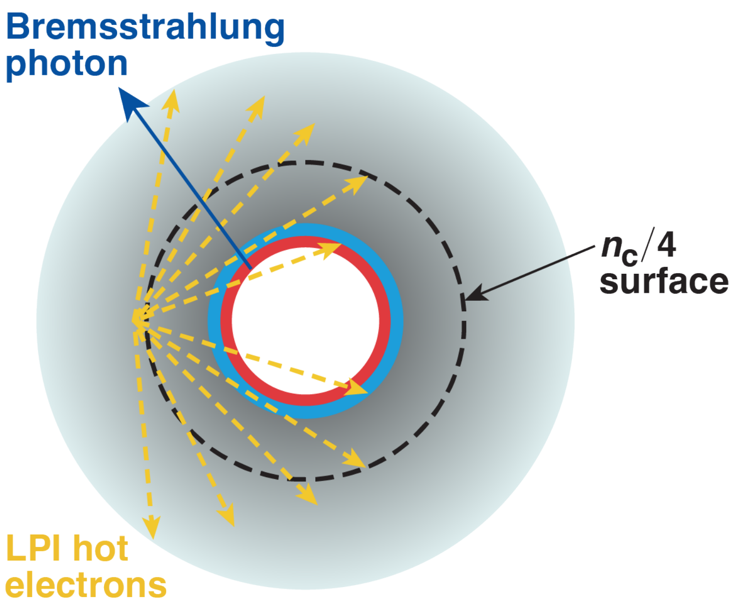
Time-resolved scattered-light spectra indicate that LPI is dominated by SRS and is similar between the all-CH and Ge-doped payload implosions



Similar LPI → similar hot-electron energy source

FABS: full-aperture backscatter station

Hot-electron preheat was inferred by comparing the measured HXR spectra to simulations using the hydrocode *LILAC** and the Monte Carlo code Geant4**



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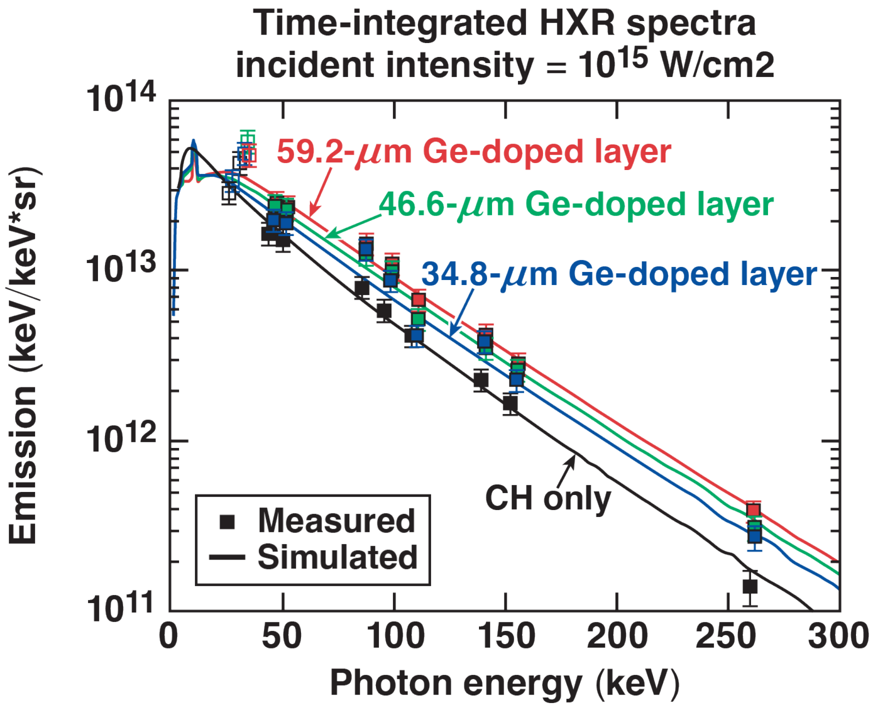


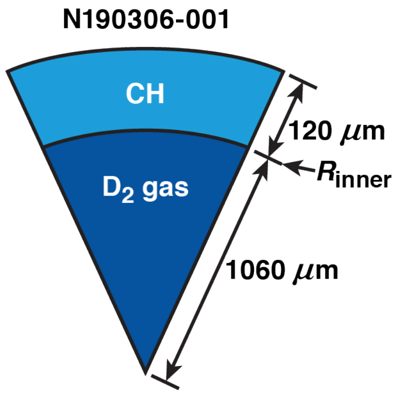
$T_{hot} \approx 55$ keV

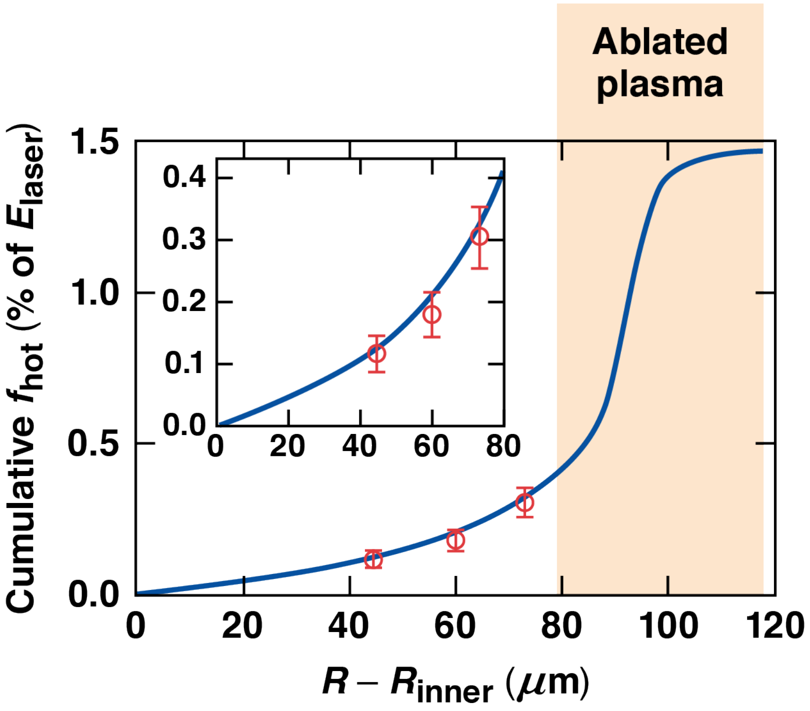
- Hot-electron temperature, total energy, divergence angle, and refluxing fraction were varied to reproduce the measured HXR spectra
- The hot-electron divergence half-angle is found to exceed 45°, the angular size of the cold shell from the $n_c/4$ surface

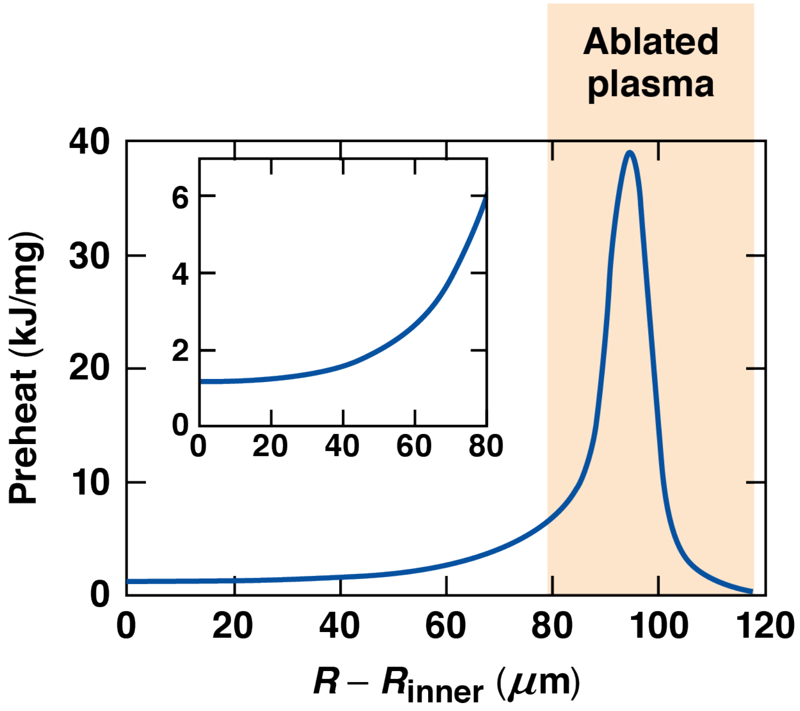
* J. Delettrez *et al*., Phys. Rev. A 36, 3926 (1987).
** J. Allison *et al*., Nucl. Instrum. Methods Phys. Res. A 835, 186 (2016).

The hot-electron energy deposition profile was inferred from Geant4 Monte Carlo simulations

Incident intensity = 10^{15} W/cm^2





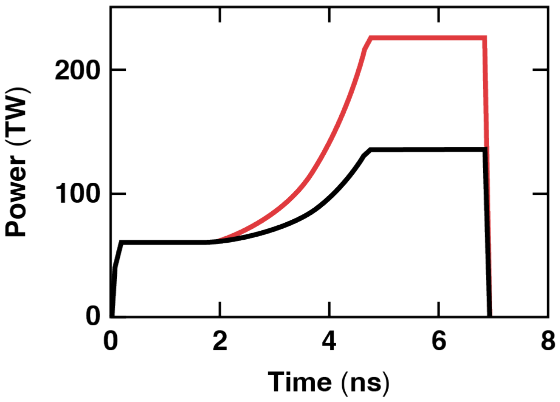


TC15514

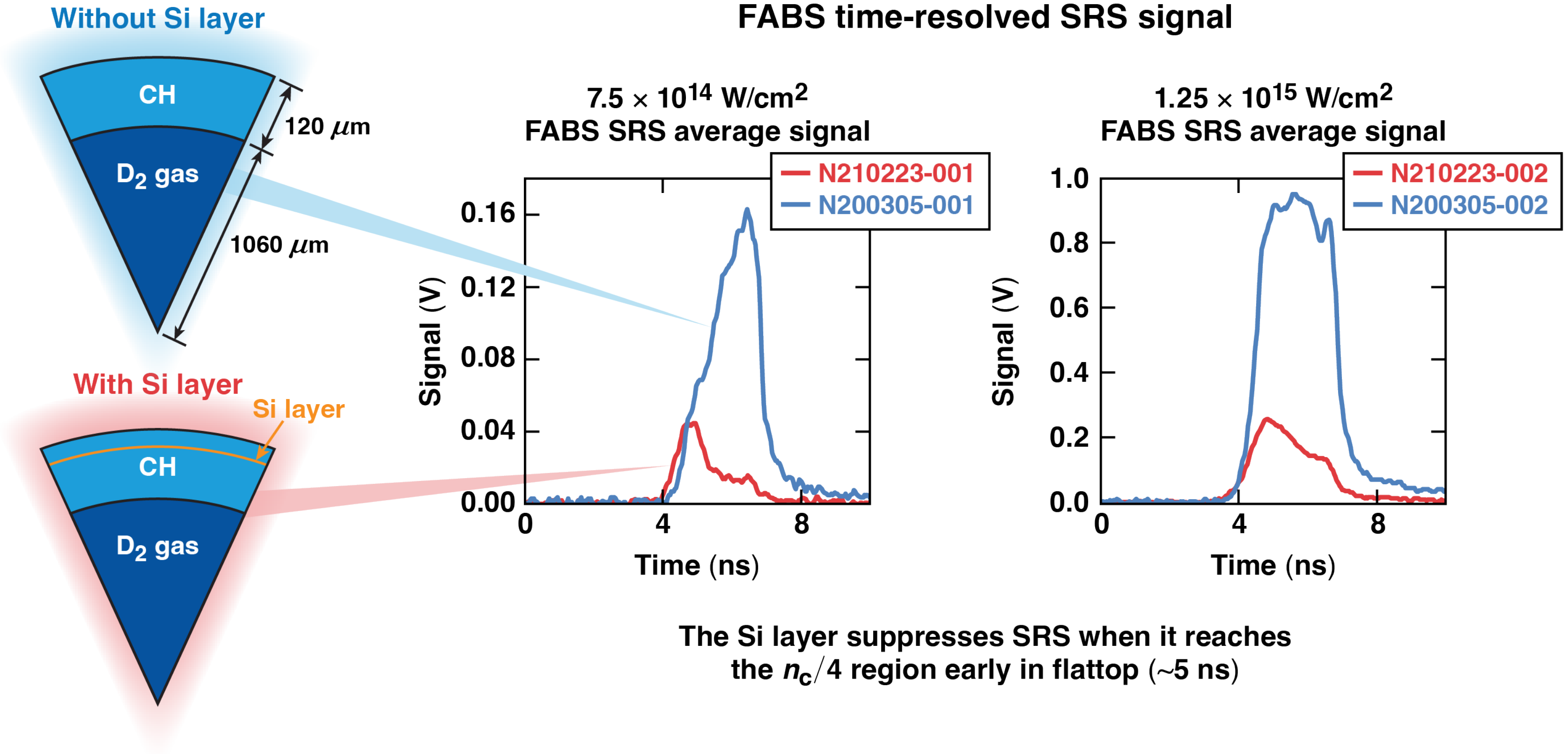
- Red circles: energy deposition in the Ge-doped layer in multilayered targets

About half of the preheat (~0.2% of E_{laser}) is deposited in the inner 80% of the unablated shell.

Si layers strategically placed in the ablator were found to mitigate LPI and hot-electron preheat



TC15873a

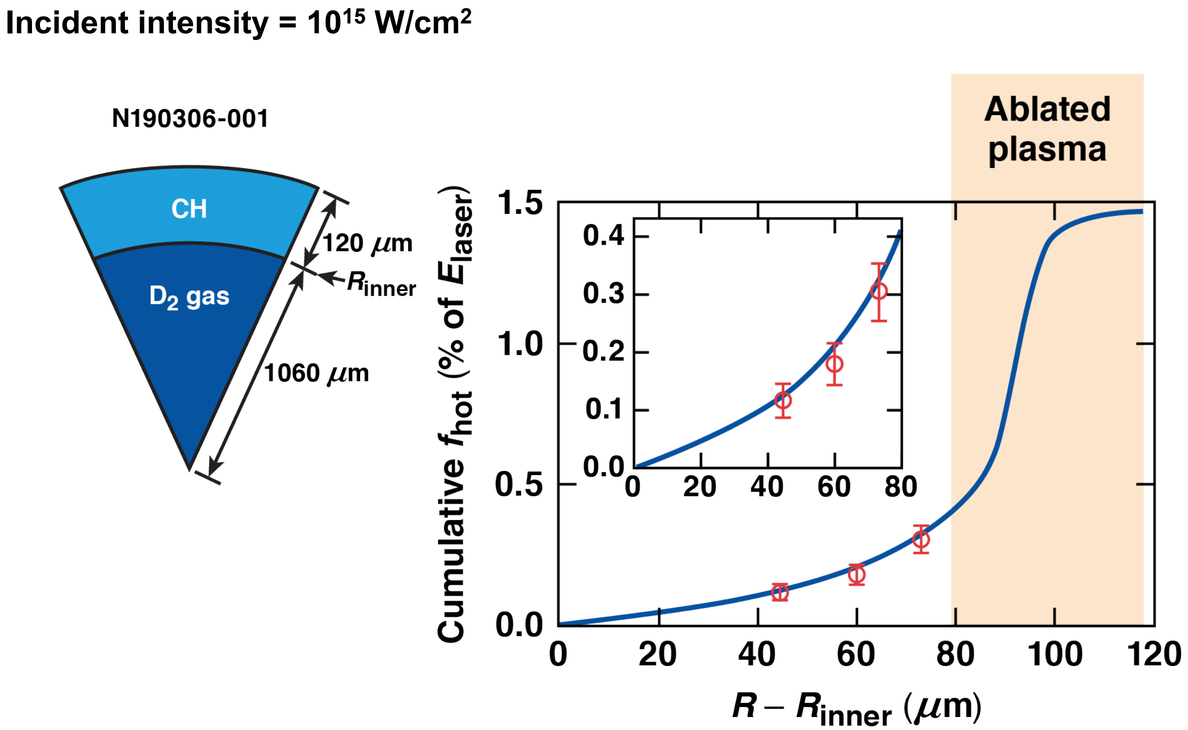


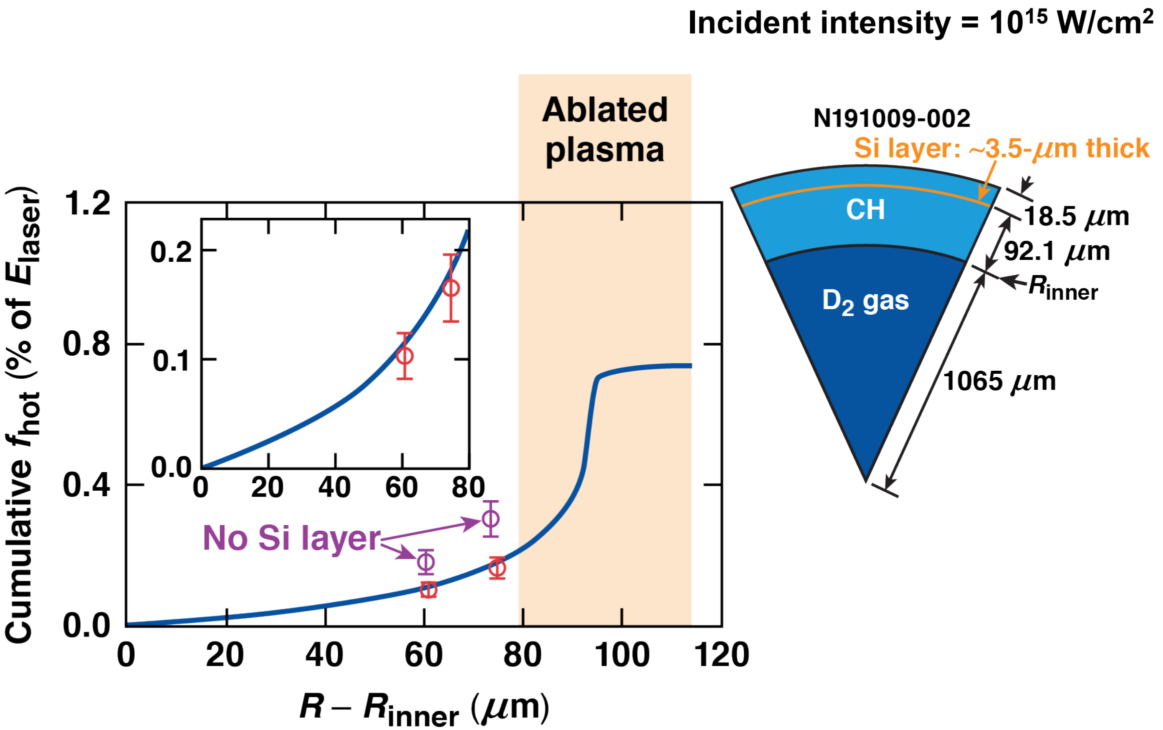
The Si layer suppresses SRS when it reaches the $n_c/4$ region early in flattop (~5 ns)

- SRS is mitigated* in Si by
  - shortening the density scale length at $n_c/4$ from ~420 μm to ~340 μm according to hydro simulations
  - increasing the electron–ion collisionality $\nu_{ei} \propto Z_{eff} = \langle Z^2 \rangle / \langle Z \rangle$, which enhances absorption of the incident and scattered light and damps electron plasma waves

*C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974);
R. E. Turner *et al.*, Phys. Rev. Lett. 54, 189 (1985); 1878(E);
J. R. Fein *et al.*, Phys. Plasmas 24, 032707 (2017);
J. F. Myatt *et al.*, Phys. Plasmas 20, 052705 (2013).

Hot-electron preheat is reduced by ~2× with a Si layer at an incident intensity of 10^{15} W/cm^2





TC15874

About half of the preheat is deposited in the inner 80% of the unablated shell.

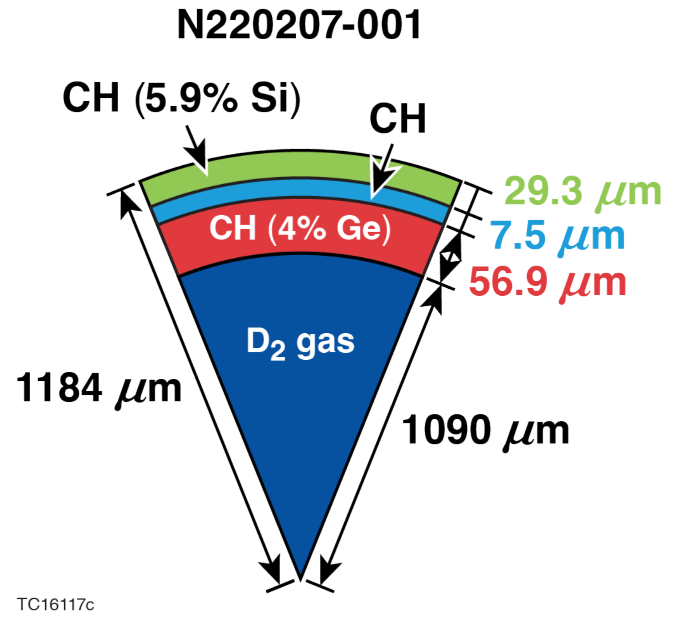
Although a mid-*Z* Si layer reduces hot-electron preheat, its effect on implosion hydrodynamics must be considered*

Beneficial effects:
- increases laser inverse bremsstrahlung absorption
- reduces cross-beam energy transfer

Negative effects:
- lowers hydrodynamic efficiency
- increases radiation losses and radiation preheat
- can be unstable, although Si expansion by absorbed coronal radiation helps to mitigate the Rayleigh–Taylor instability

Conclusion:
- keep the mid-*Z* layer thin and place it inside the lower-*Z* material to combine the higher laser absorption with the larger ablation efficiency of the innermost layer in the ablator

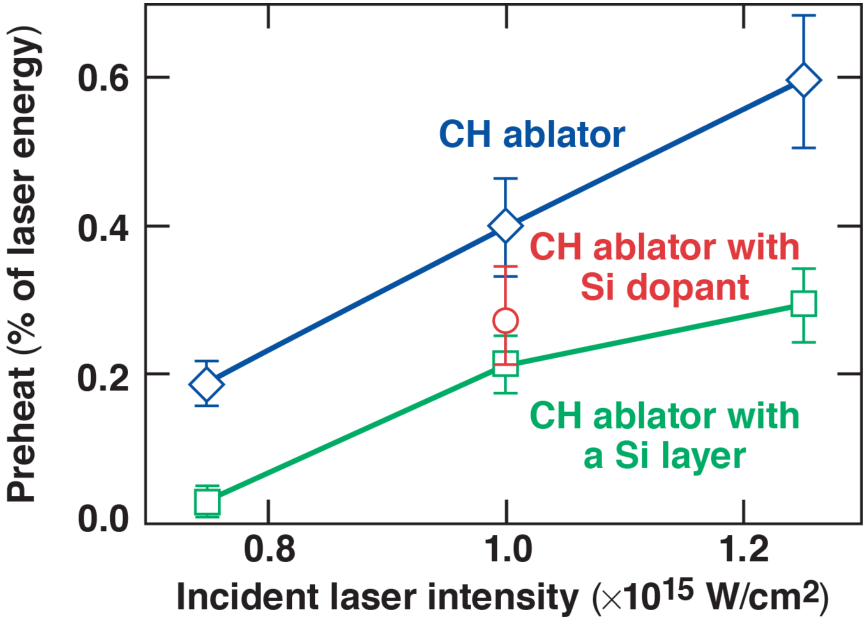
- Si-doped plastic ablators combine the beneficial properties of the mid-*Z* material with useful imprint reduction and better hydrodynamic stability



*V. N. Goncharov *et al.*, Phys. Plasmas 21, 056315 (2014) and references therein.

Hot-electron preheat scaling with the incident laser intensity has been obtained with and without mitigation using a Si layer or dopant

Hot-electron energy deposition in an unablated shell



TC16119

About half of the preheat is deposited in the inner 80% of the unablated shell:

- 0.1% to 0.15% of E_L at $I \sim (1 \text{ to } 1.25) \times 10^{15}$ W/cm^2 with a Si layer
- 0.14% of E_L at $I = 10^{15}$ W/cm^2 with Si dopant

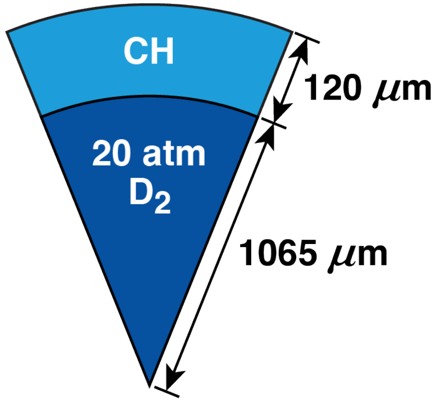
~0.15% of the laser energy is an acceptable preheat fraction for high-gain ignition designs*

Si layers and dopants provide a promising preheat mitigation strategy for ignition designs at an on-target intensity of about 10^{15} W/cm^2.

*J. A. Delettrez, T. J. B. Collins, and C. Ye, Phys. Plasmas 26, 062705 (2019).

The effect of shell convergence on preheat has been studied by increasing the laser pulse duration

N220208-001



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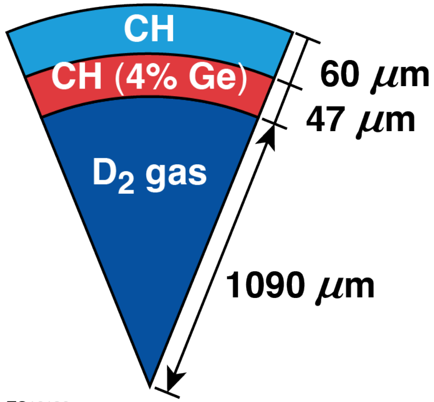

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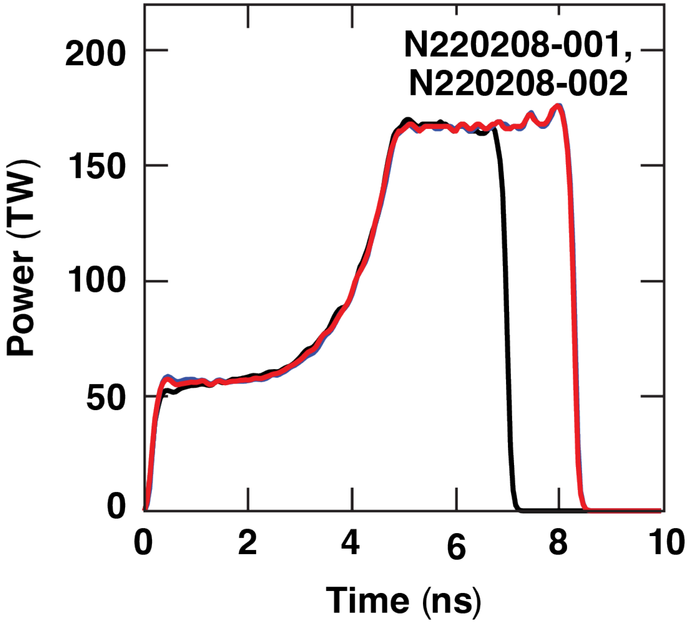
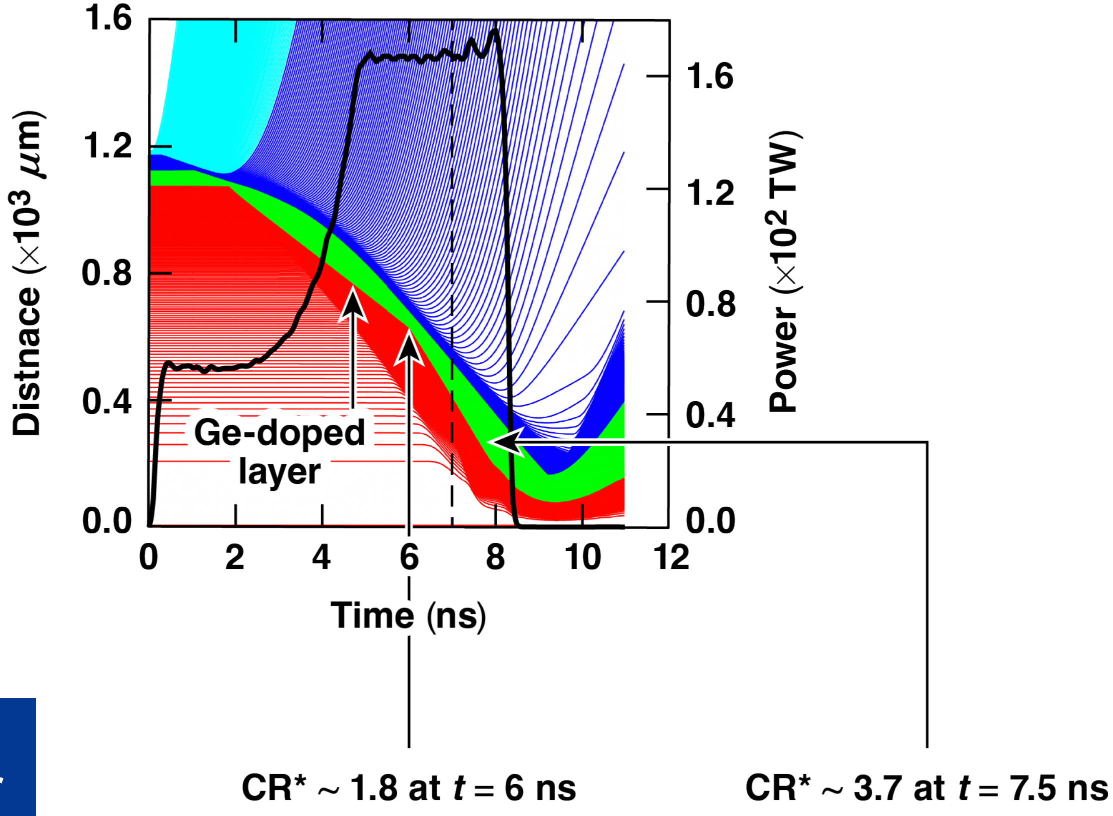
Laser flattop duration was increased by 1.3 ns



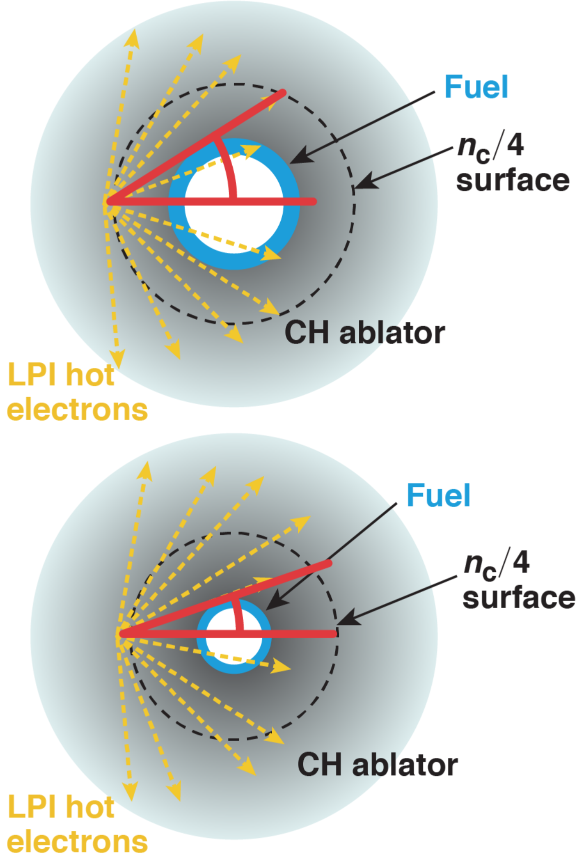
Lagrangian shell positions from LILAC simulations



Shell convergence at the end of the extended pulse is ~2× higher than in the early part of the pulse.

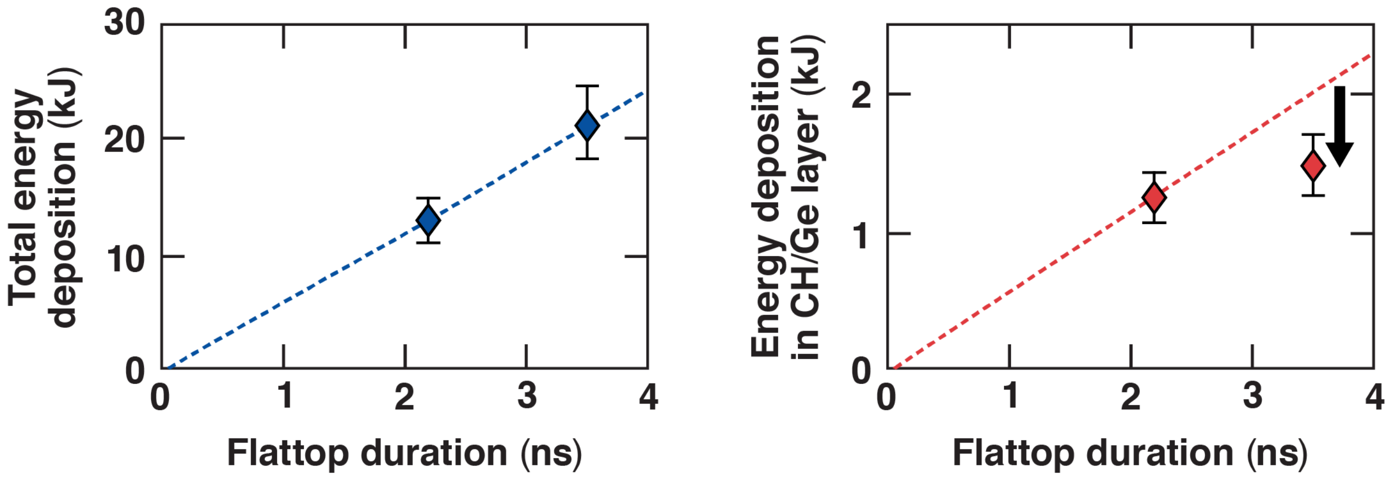
*CR: Shell convergence ratio, $R_{shell}(t=0)/R_{shell}(t)$

Hot-electron preheat decreases as the shell converges



TC16121

Inferred hot-electron energy deposition: total and in the Ge-doped layer



- Energy deposition in the Ge-doped layer decreases as the solid angle of the dense shell from the $n_c/4$ surface: by a factor of ~4 during the last 1.3 ns of the 3.5-ns flattop pulse

Shell convergence can decrease preheat in high-gain ignition cryo designs* in which convergence of 2 to 4 at peak hot-electron production is expected.

*T. J. B. Collins *et al.*, Phys. Plasmas 25, 072706 (2018).

Hot-electron preheat in 3-mm-diam ignition-scale PDD implosions on the NIF has been accessed*

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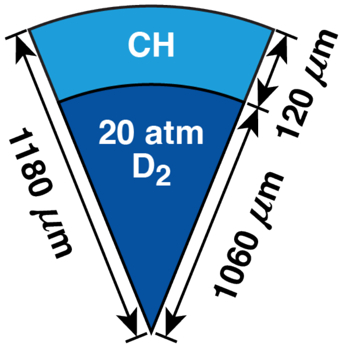
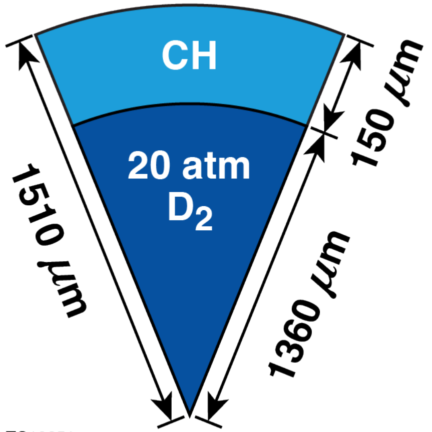
NIF 2.4-mm-diam



NIF 3-mm-diam



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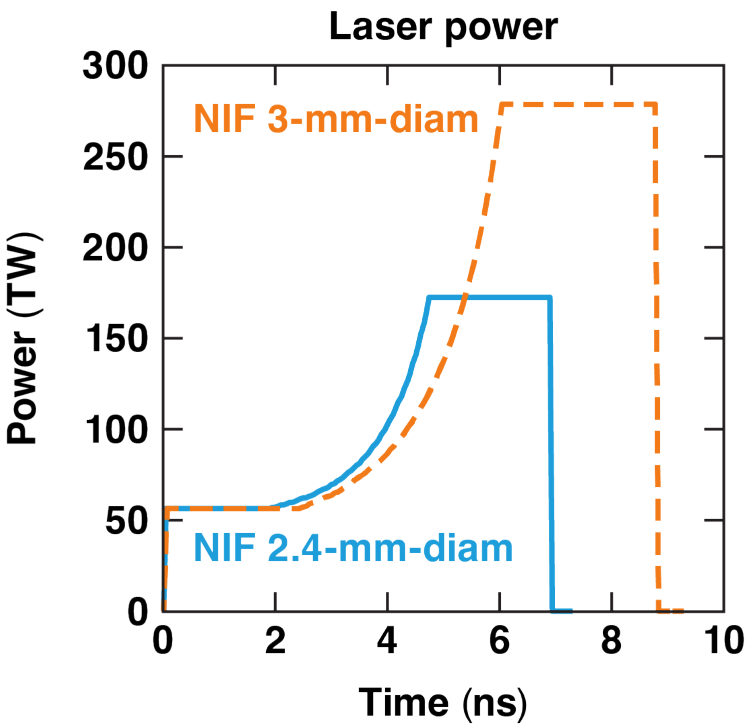
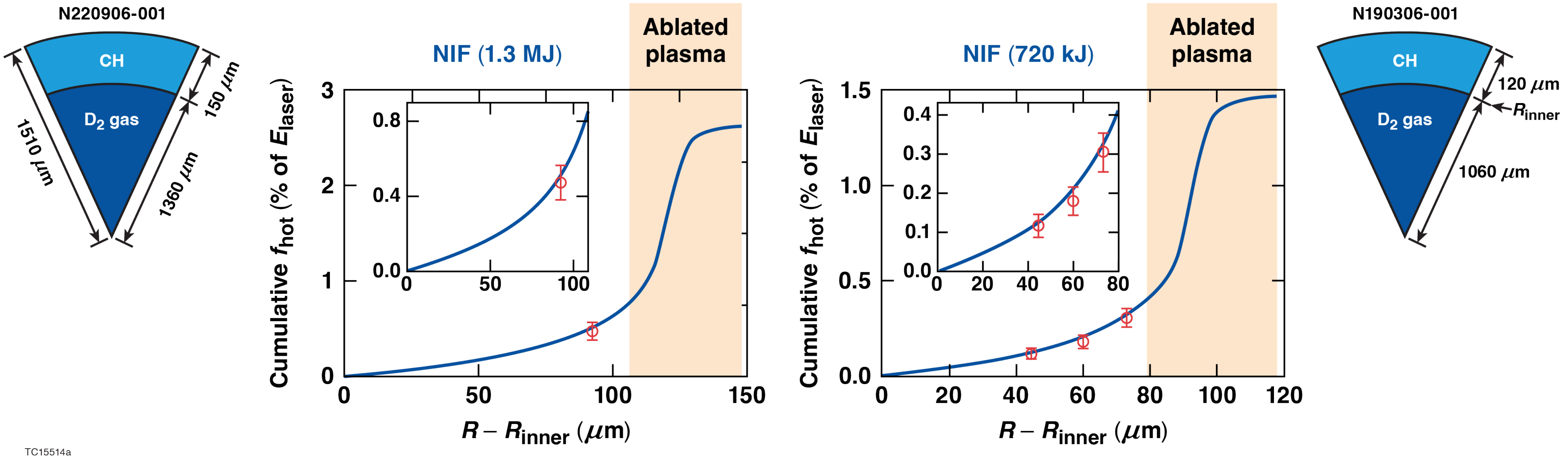


Parameter	NIF 3-mm-diam	NIF 2.4-mm-diam
E_L	1320 kJ	720 kJ
P_L	279 TW	172 TW
$\langle I_L \rangle$ (W/cm^2)**	1.0×10^{15}	1.0×10^{15}
Pulse length	8.8 ns	6.9 ns
Capsule OD	3020 μm	2360 μm
Capsule thickness	150 μm	120 μm

* M. J. Rosenberg *et al.*, CO04.00013, this conference.
** Average on-target laser intensity

Full scale (3-mm) NIF experiments show a factor of ~2 more preheat energy deposited in the unablated shell than subscale (2.3-mm) experiments



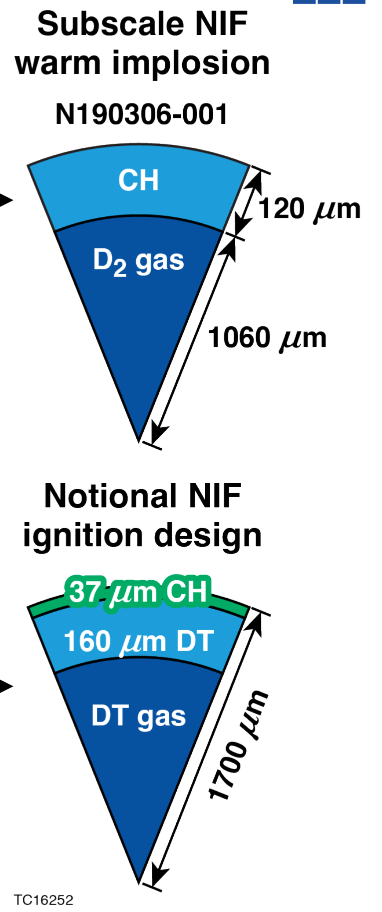
Caveat: the full-scale pulse shape is not exactly hydrodynamically scaled

- implosion convergence is lower when hot electrons are generated: a hydro-scaled pulse would have lower preheat by up to ~27%
- E_{laser} lower than pure hydro scale, so a hydro-scaled pulse would have lower $f_{hot} = E_{hot}/E_{laser}$ by definition, by ~13%

Hydro-scaled 3-mm NIF implosions would show ~30% to 50% more preheat than 2.3-mm experiments.

Preheat levels in ignition-scale cryogenic implosions are estimated for 10^{15} W/cm^2 on-target intensity based on existing spherical and planar data

	Multiplier	Preheat (% of laser)
Preheat into inner 80% of unablated shell in warm subscale NIF implosion	-	~0.2%
Increase scale length to full scale*	~1.5 to 2.0	
Increase convergence ratio at end of pulse	~0.4 to 0.8	
DT shell and some DT in ablator	~1.0 to 1.8	
Improve beam smoothing	~0.8	
Si layer	~0.5	
Total	**~0.5 to 1.0**	**~0.1% to 0.2%**



~0.15% is an acceptable preheat fraction for ignition designs**
→ Intensities around 10^{15} W/cm^2 produce acceptable preheat for ignition designs

* An upper limit for preheat increase by ~2× is established based on the NIF planar experiments at an ignition-relevant density scale length for a similar number of overlapped laser beams (15 to 30).
** J. A. Delettrez, T. J. B. Collins, and C. Ye, Phys. Plasmas 26, 062705 (2019).

Mid-Z Si layers and dopants provide a promising hot-electron preheat mitigation strategy for direct-drive–ignition designs

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- Implosion experiments were performed at the National Ignition Facility (NIF) to quantify preheat levels and directly measure the spatial hot-electron energy deposition profile
- From 0.2% to 0.6% of the laser energy is coupled via hot electrons to the unablated shell for incident laser intensities from (0.75 to 1.25) $\times 10^{15}$ W/cm^2, with half of the preheat coupled to the inner 80% of the unablated shell
- Buried Si layers mitigate growth of laser–plasma instabilities (LPI's), suppressing preheat or reducing it by a factor of $\sim$2; hot-electron preheat is reduced by 30% using Si dopant at 10^{15} W/cm^2
- Shell convergence significantly reduces hot-electron preheat late in the implosion

The present results show acceptable preheat levels for on-target intensities around 10^{15} W/cm^2, for MJ-scale laser direct drive.