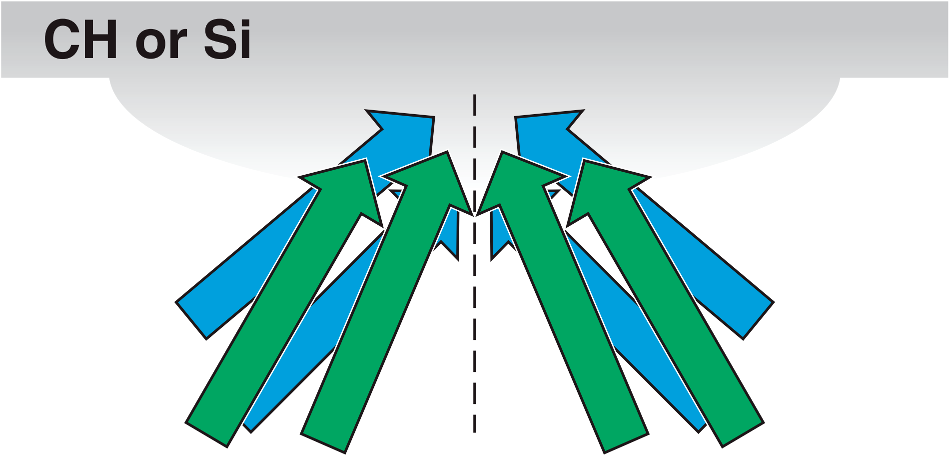
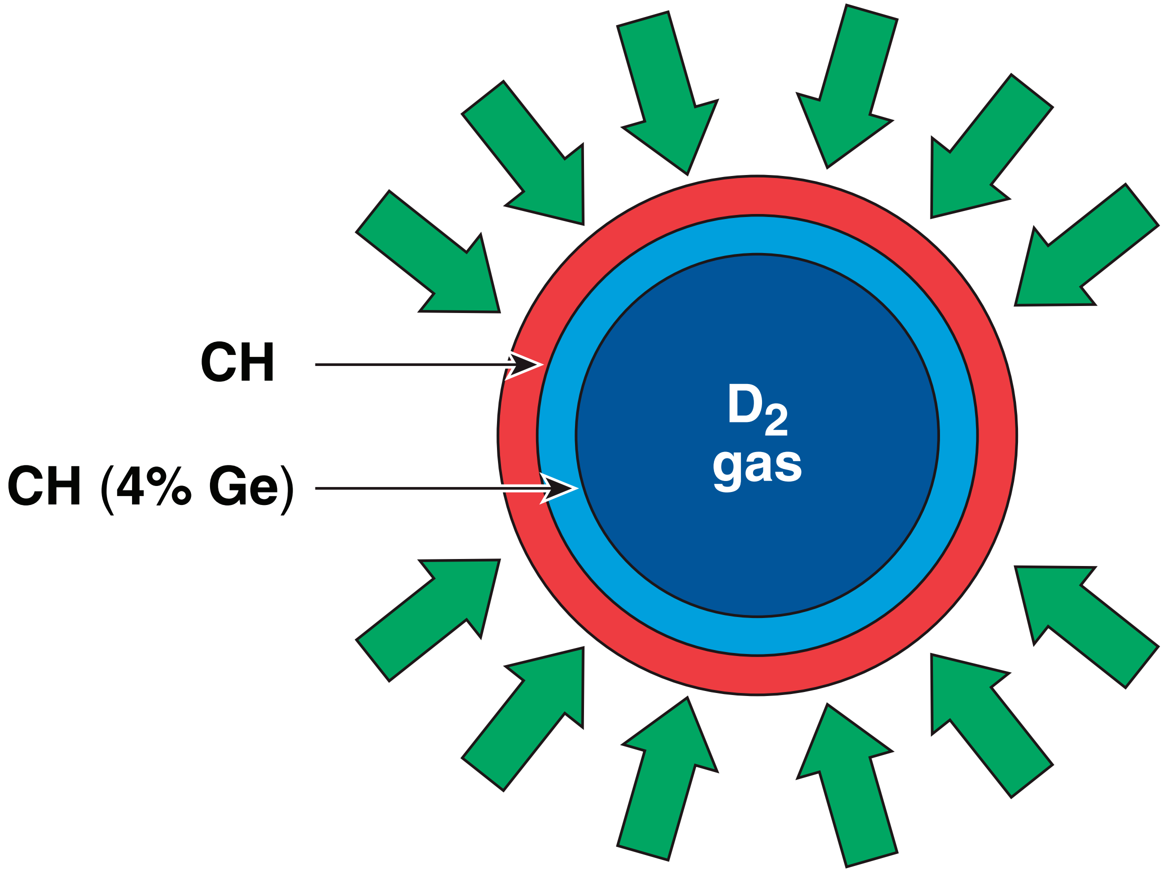
Hot-Electron Generation and Preheat in Direct-Drive Experiments at the National Ignition Facility



23° and 30° beams or
45° and 50° beams



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Bar Harbor, ME
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Summary

Laser–plasma instability (LPI) hot-electron production and preheat at direct-drive ignition-relevant plasma conditions were investigated

- National Ignition Facility (NIF) planar-target experiments achieve direct-drive (DD) ignition-relevant scale lengths (L_n ~ 400 to 700 μm) and electron temperatures (T_e ~ 4 to 5 keV)
- Planar experiments suggest that hot-electron preheat is tolerable in DD ignition designs with CH ablators if $I_{n_c/4} < 5 \times 10^{14}$ W/cm^2 ($I_{n_c/4} < 7 \times 10^{14}$ W/cm^2 with Si ablators)
- Spherical multilayer target experiments will infer hot-electron coupling to the imploding shell

TC14308

Collaborators

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Lawrence Livermore National Laboratory

J. W. Bates and A. J. Schmitt

Naval Research Laboratory

Hot-electron preheat can degrade fuel compression in DD ignition designs

- Fuel compression is negatively affected if more than ~0.15% of the laser energy is coupled into the fuel in the form of hot electrons*
- Hot-electron coupling to implosion depends on the electron divergence
  - if electron divergence is large (like on OMEGA**), only ~25% of the electrons will intersect the cold fuel and result in preheat
  - hot-electron divergence or coupling to implosion needs to be measured on the NIF
- Electrons with energy below ~50 keV will be stopped in the ablator and will not preheat the compressed fuel

If the divergence is large, preheat mitigation is needed if more than ~0.7% of the laser energy is converted to hot electrons with temperature T_{hot} ~ 50 keV.

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* J. A. Delettrez, T. J. B. Collins, and C. Ye, Bull. Am. Phys. Soc. 59, BAPS.2014.DPP.JO4.3 (2014).

** B. Yaakobi *et al.*, Phys. Plasmas 20, 092706 (2013).

Planar NIF experiments explore LPI instabilities and hot-electron production in DD ignition-relevant plasma conditions

Coronal conditions predicted by *DRACO* radiation–hydrodynamic simulations

Parameters at $n_c/4$ surface	Ignition NIF DD*	Planar NIF
I_L (W/cm^2)	6 to 8 $\times$ 10^{14}	5 to 15 $\times$ 10^{14}
L_n (μm)	600	500 to 700
T_e (keV)	3.5 to 5	3 to 5

- Incident laser intensity is ~2× intensity at $n_c/4$ at ignition-relevant L_n and T_e

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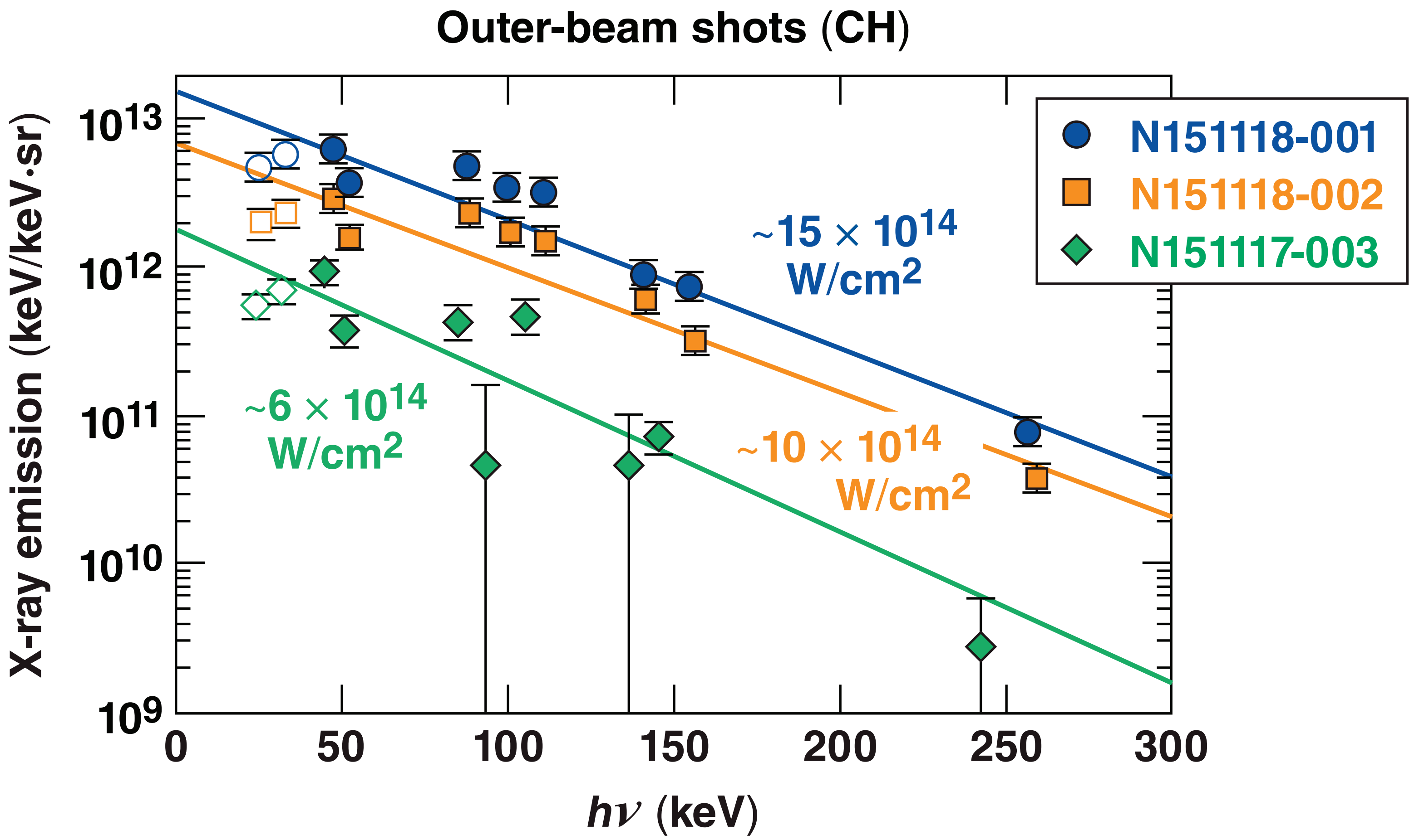
*V. N. Goncharov *et al.*, Bull. Am. Phys. Soc. 61, BAPS.2016.DPP.TO5.3 (2016).

Hot-electron properties were inferred using the measured hard x-ray spectra

- **Time-integrated hard x-ray spectra obtained using FFLEX***



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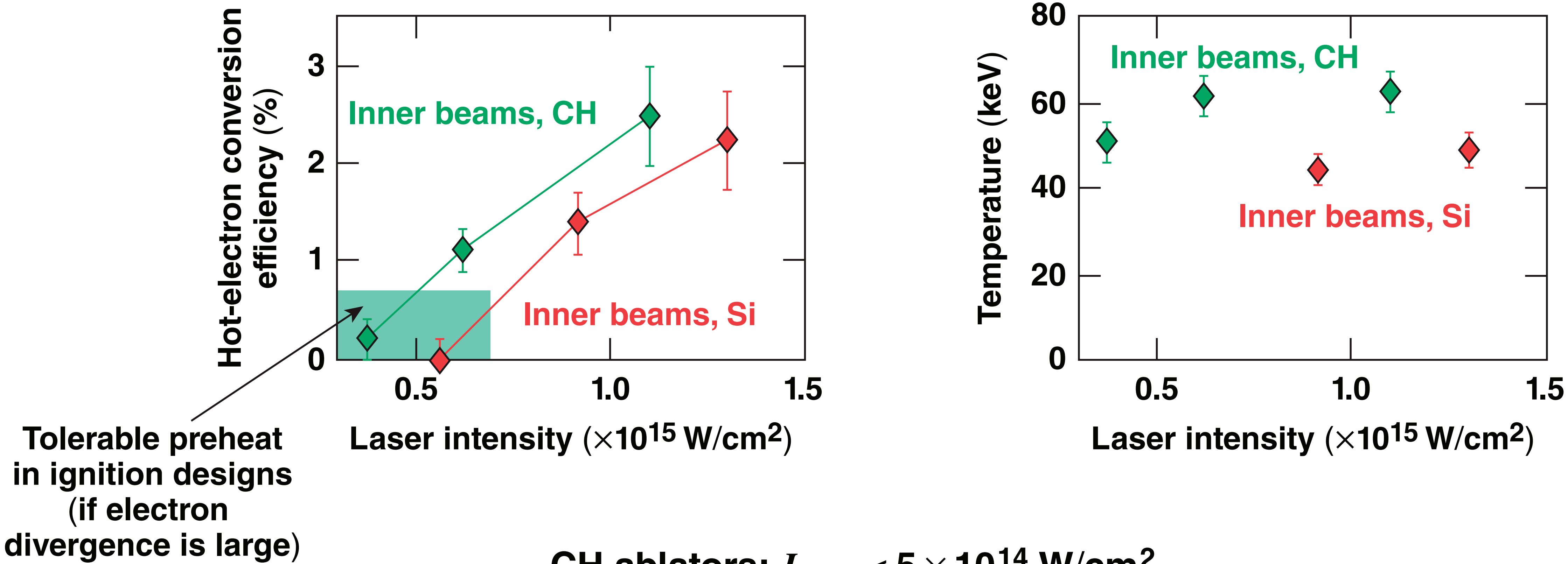
*M. Hohenberger *et al.*, Rev. Sci. Instrum. 85, 11D501 (2014).
FFLEX: filter-fluorescer x-ray diagnostic

Hot-electron conversion efficiency and temperature at DD ignition-relevant coronal conditions were inferred

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



Tolerable preheat in ignition designs (if electron divergence is large)

CH ablators: $I_{n_c/4} < 5 \times 10^{14}$ W/cm^2
Si ablators: $I_{n_c/4} < 7 \times 10^{14}$ W/cm^2

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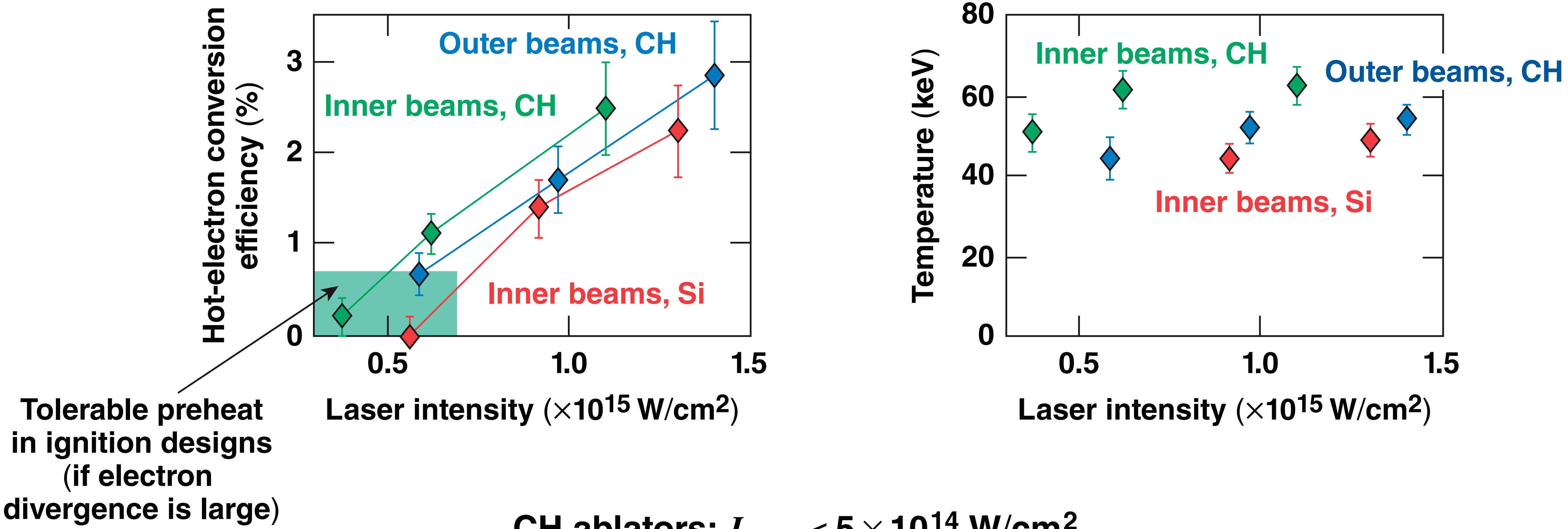
Hot-electron conversion efficiency and temperature at DD ignition-relevant coronal conditions were inferred

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



Tolerable preheat in ignition designs (if electron divergence is large)

CH ablators: $I_{n_c/4} < 5 \times 10^{14}$ W/cm^2
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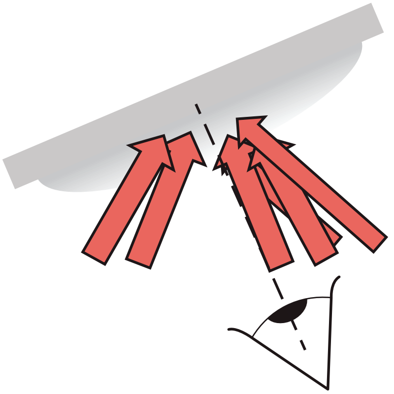
TC13432b

Measurements of hot-electron angular divergence or coupling to implosion on the NIF are needed

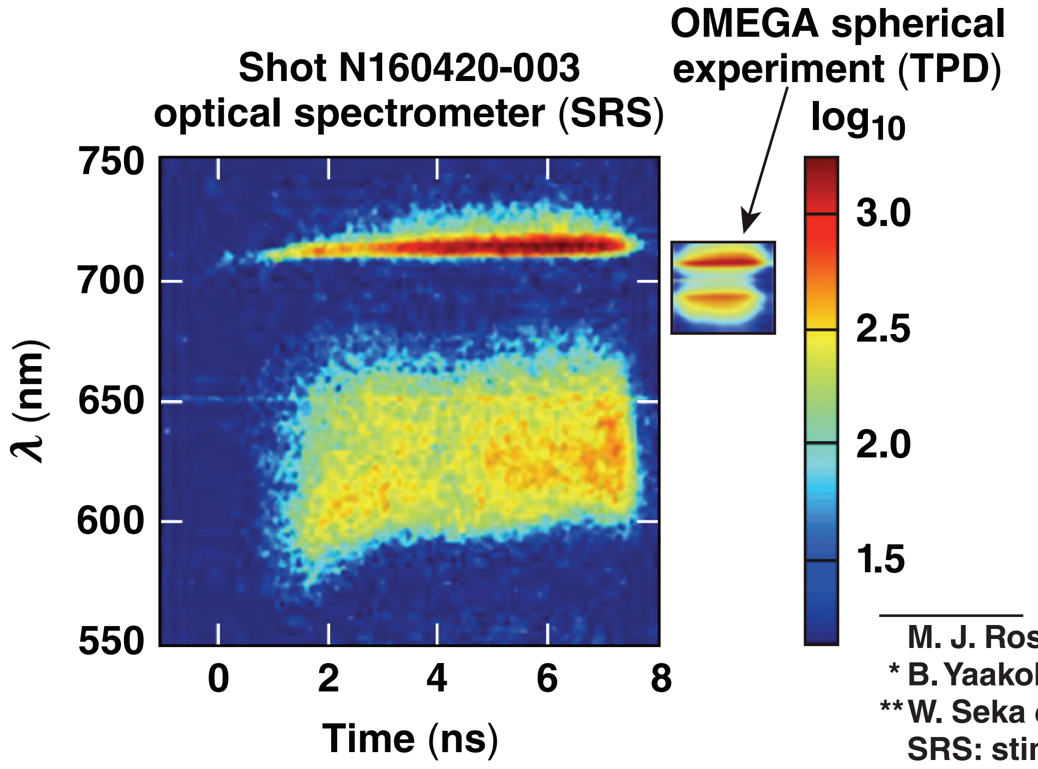
- Measurements of hot-electron divergence on OMEGA* are not applicable to NIF experiments because LPI physics on the NIF and OMEGA are different:
  - SRS dominates the scattered light spectrum on the NIF, while TPD dominates on OMEGA

NIF: $L_n = 525\ \mu\text{m}$
$T_e = 4.5$ keV

OMEGA:** $L_n = 150\ \mu\text{m}$
$T_e = 2.8$ keV



Optical streaked spectrometer (NBI Q33B)



Shot N160420-003 optical spectrometer (SRS)

OMEGA spherical experiment (TPD)

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

* B. Yaakobi *et al.*, Phys. Plasmas 20, 092706 (2013).

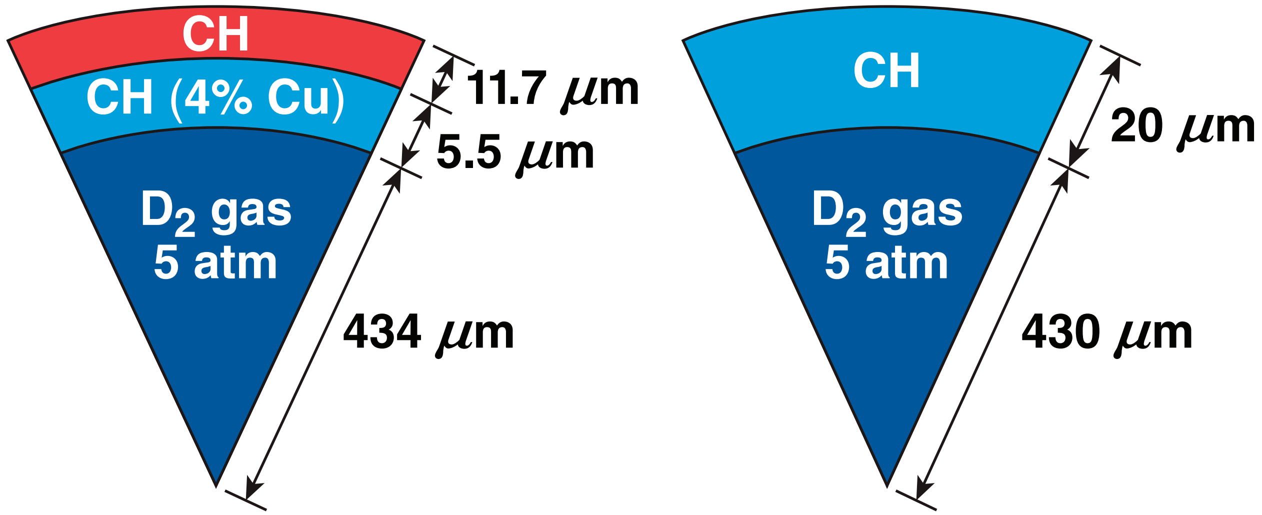
** W. Seka *et al.*, Phys. Plasmas 16, 052701 (2009).

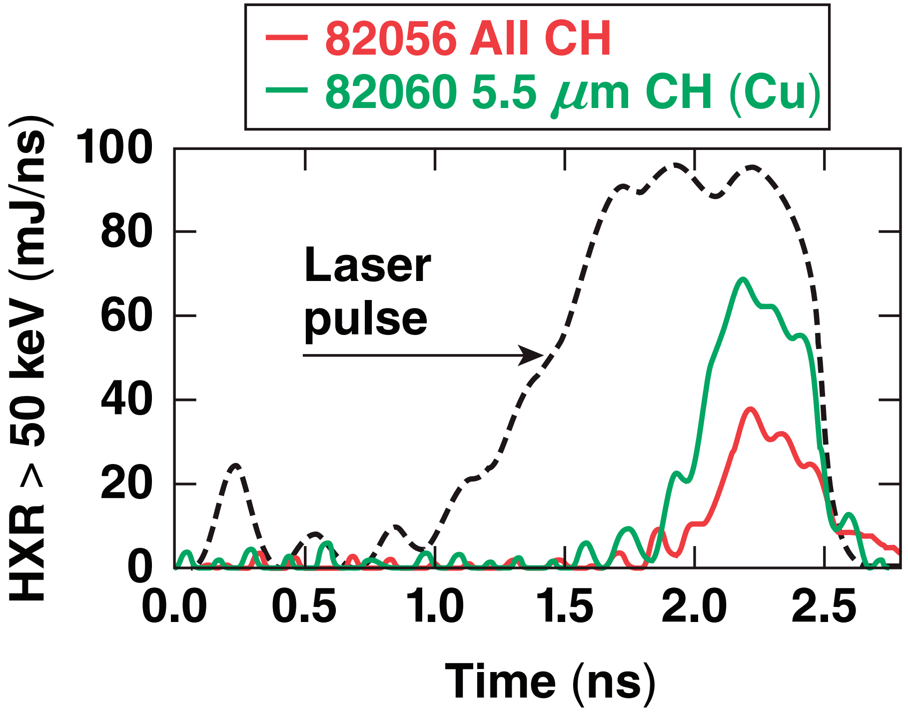
SRS: stimulated Raman scattering

TPD: two-plasmon decay

An OMEGA platform—to be adapted to the NIF—has been developed to diagnose hot-electron coupling to the unablated shell in implosions

OMEGA hot-electron coupling experiment ported to the NIF





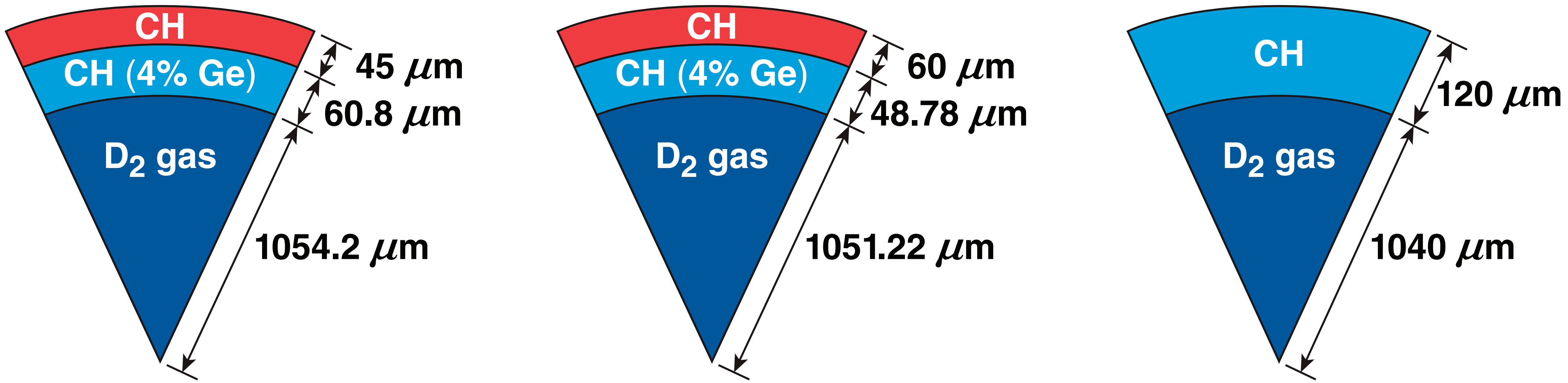
NIF experiments will be scaled up; use Ge dopant

A. R. Christopherson *et al.*, Bull. Am. Phys. Soc. 61, BAPS.2016.DPP.NO5.7 (2016).

The difference in hard x-ray (HXR) signals between mass-equivalent CH and multilayered implosions → hot-electron energy deposited in the inner shell layer.

NIF experiments will study hot-electron coupling to an unablated shell

Targets for NIF experiments in September 2018



- Mass-equivalent targets consist of CH and Ge-doped layers of various thicknesses, plus a baseline pure-CH case
- Hydro simulations predict that ~40 μm of CH is ablated
- The thicknesses of the outer-CH and Ge-doped payloads are varied to measure where the hot electrons deposit their energy
- If hydro instability is an issue, a thicker outer CH layer prevents Ge from getting into the corona

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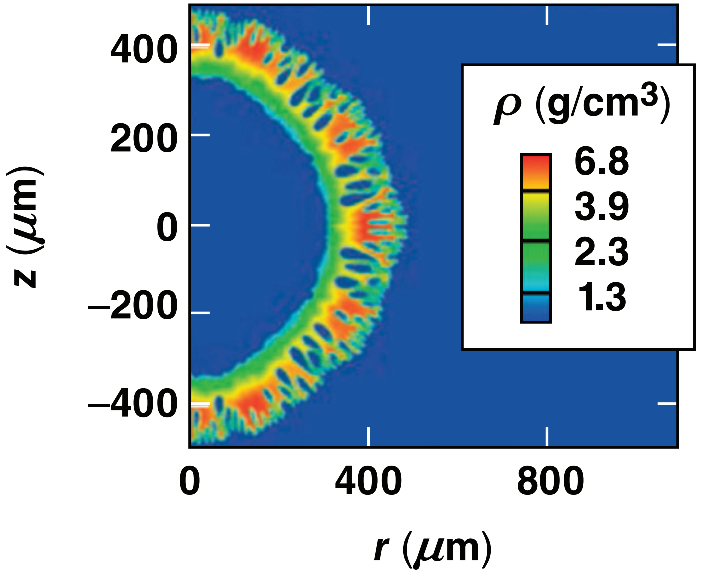
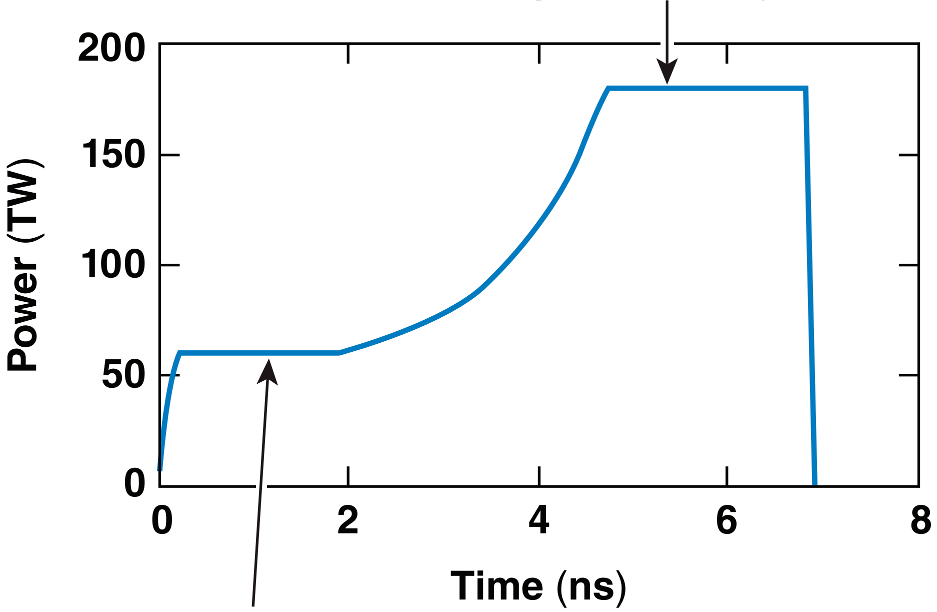
The experiments will use thicker shells and higher-adiabat implosions than in the standard polar-direct-drive (PDD) design* to reduce possible hydro instabilities

Imprint simulation in the standard PDD design**



180-TW peak power for increased hot-electron production (as in N140306)



Foot power is increased from 30 TW to 60 TW

- *LILAC* simulations predict the adiabat in the compressed shell of 3.6 and the adiabat at the ablation surface of ~10
- Pressure and temperature gradients are collinear at the CH/CH (4% Ge) interface → no Rayleigh–Taylor instability growth (a weaker Richtmyer–Meshkov growth is possible)

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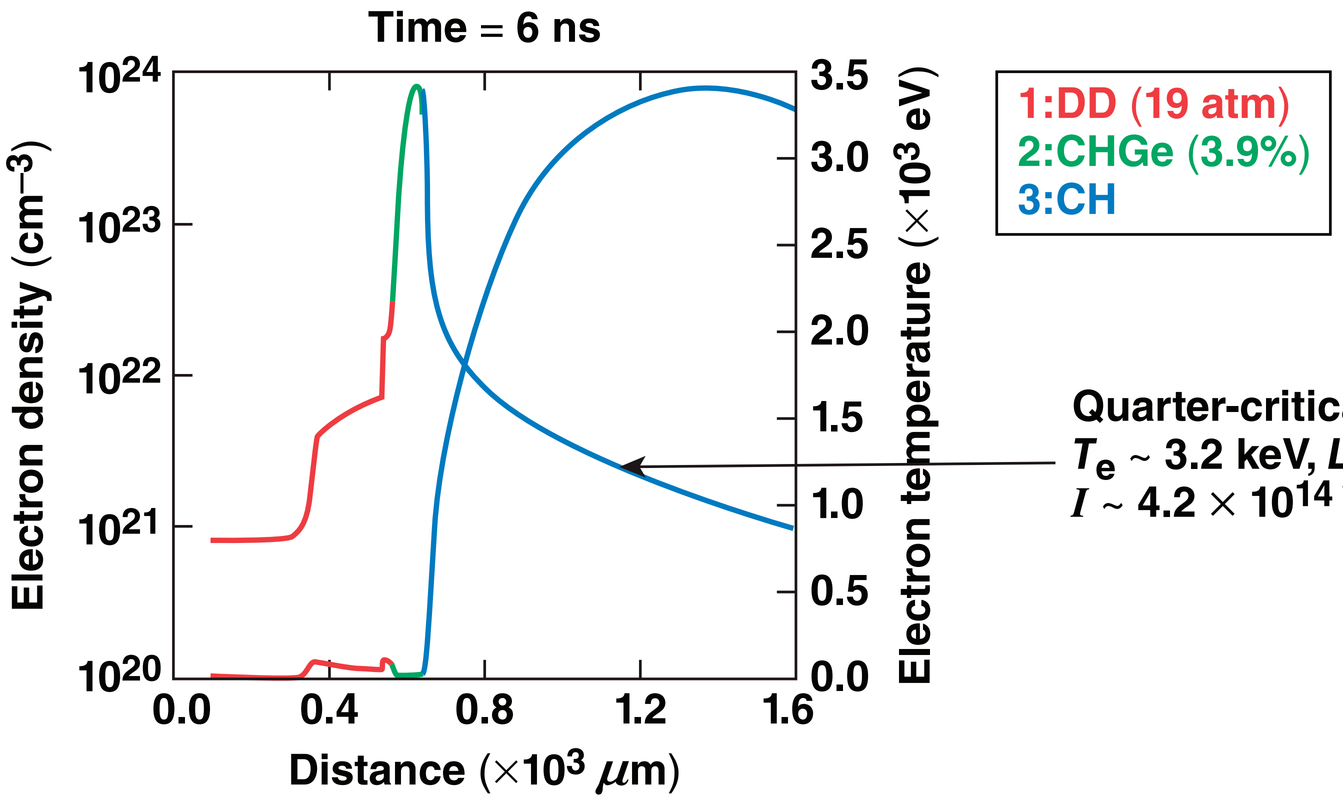
*M. Hohenberger *et al.*, Phys. Plasmas 22, 056308 (2015).

**P. B. Radha *et al.*, Phys. Plasmas 23, 056305 (2016).

LILAC simulations predict coronal conditions for the mass-equivalent implosions

- Simulation for a target with a Ge-doped layer (coronal conditions are similar for mass-equivalent all-CH implosions)



Quarter-critical surface:
$T_e \sim 3.2$ keV, $L = 400$ μm
$I \sim 4.2 \times 10^{14}$ W/cm^2

$$\eta_{\mathrm{SRS}} = I_{14}\, L_{\mathrm{n},\,\mu\mathrm{m}}^{4/3} \Big/ 2377 \sim 3.6 \text{ to } 5.6$$

$$\eta_{\mathrm{TPD}} = I_{14}\, L_{\mathrm{n},\,\mu\mathrm{m}} \Big/ \left(230\, T_{\mathrm{e,\,keV}}\right) \sim 1.7 \text{ to } 2.3$$

The SRS and TPD absolute-instability thresholds* are exceeded in this experimental design.

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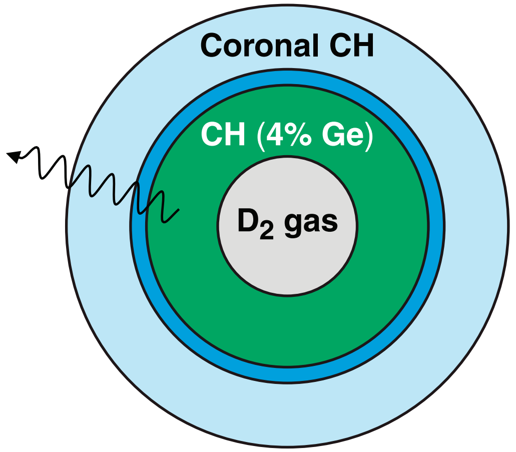
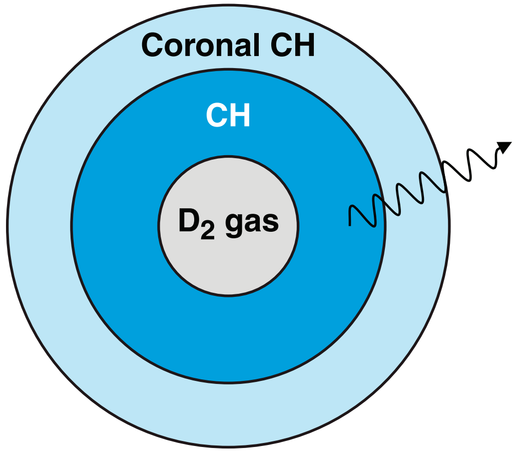
*C. S. Liu, M. N. Rosenbluth, and R. B. White, Phys. Fluids 17, 1211 (1974); A. Simon *et al.*, Phys. Fluids 26, 3107 (1983).

The energy deposited into a payload can be inferred by subtracting the all-CH HXR from the HXR of a Ge-doped layered target

$$\left(\frac{E_{\text{rad}}}{E_{\text{lost}}}\right)^{\text{payload}}_{\text{Ch (4\% Ge)}} = 1.5 \times 10^{-3}$$





$$\left(\frac{E_{\text{rad}}}{E_{\text{lost}}}\right)_{\text{CH}} = 5.9 \times 10^{-4}$$

- "Radiative power" $\frac{E_{\text{rad}}}{E_{\text{lost}}}$ is proportional to $\frac{\langle Z^2 \rangle}{\langle Z \rangle}$
- $E^{\text{payload}}_{\text{CH (4\% Ge)}} \approx E_{\text{CH}}$ are energies deposited by hot electrons into the CH (4% Ge) payload and CH replacing the payload in an all-CH target

Preheat formula*: $$E^{\text{payload}}_{\text{CH (4\% Ge)}} = \frac{E^{\text{layered}}_{\text{rad}} - E^{\text{all-CH}}_{\text{rad}}}{\left(\frac{E_{\text{rad}}}{E_{\text{lost}}}\right)^{\text{payload}}_{\text{CH (4\% Ge)}} - \left(\frac{E_{\text{rad}}}{E_{\text{lost}}}\right)_{\text{CH}}}$$

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*A. R. Christopherson *et al.*, presented at IFSA 2015, Seattle, WA, 20–25 September 2015.

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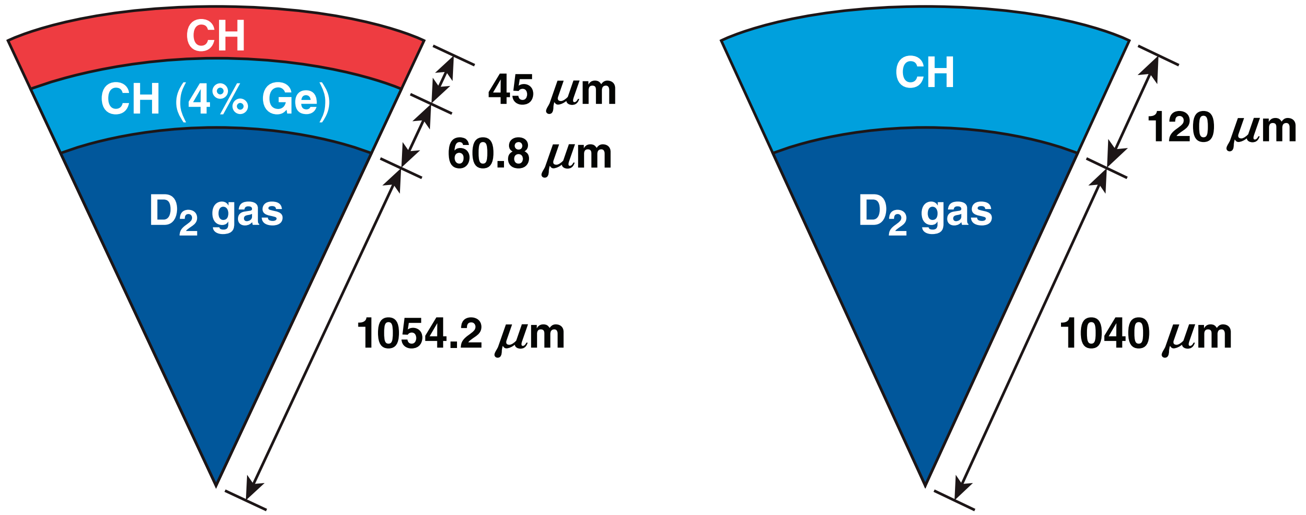
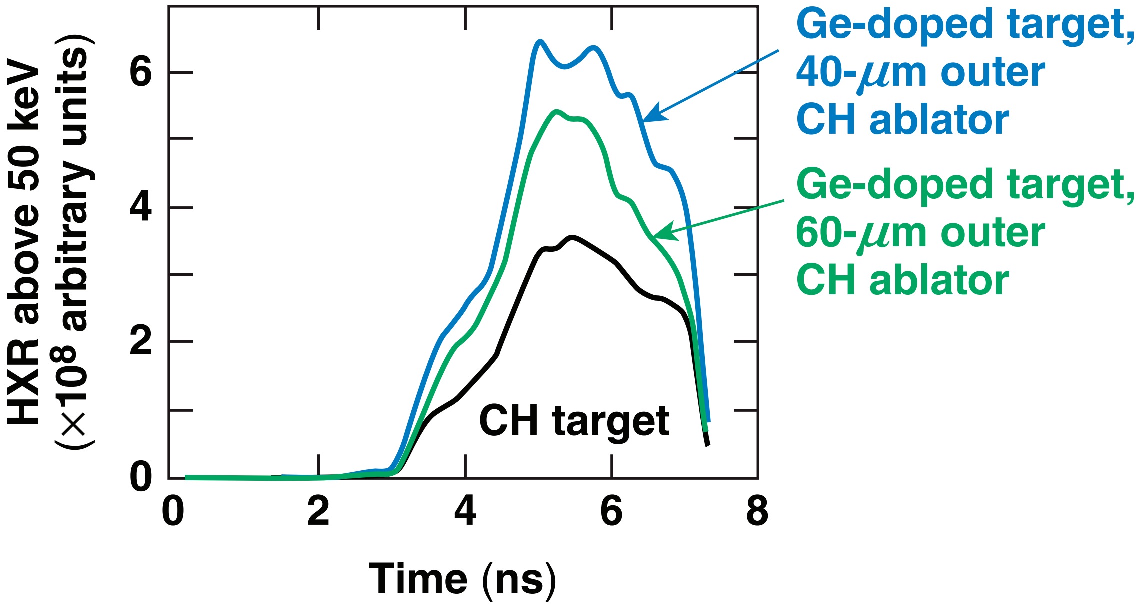
The preheat formula is compared to the results of 1-D *LILAC* hydro simulations with hot electrons

Predicted NIF hard x-ray data



LILAC simulations for T_{hot} = 55 keV, hot-electron divergence full angle of 2π, Ge-doped target at 3.9%



- The fraction of laser energy into superthermals and the source divergence angle will be constrained by the two measured HXR signals

Hot-electron energy coupled to an implosion constrains usable laser intensities in direct-drive ignition designs.

TC12370b

Summary/Conclusions

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