

Direct Measurements of Hot-Electron Preheat in the Dense Fuel of Inertial Confinement Fusion Implosions

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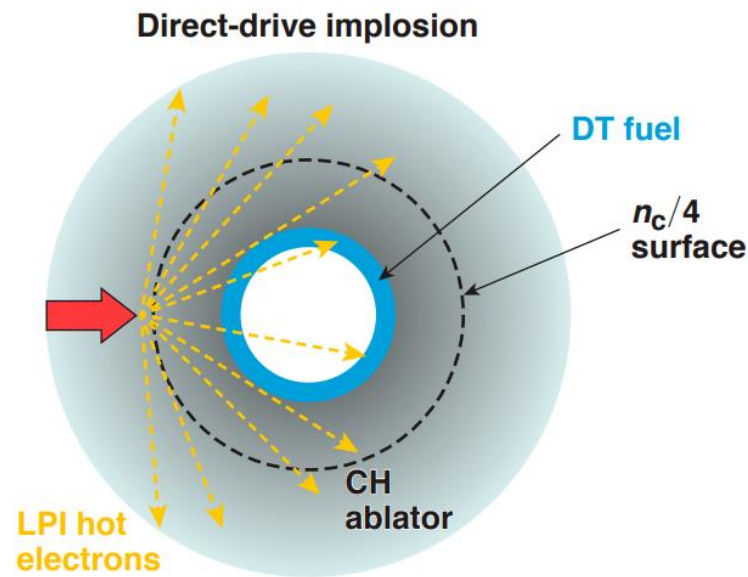
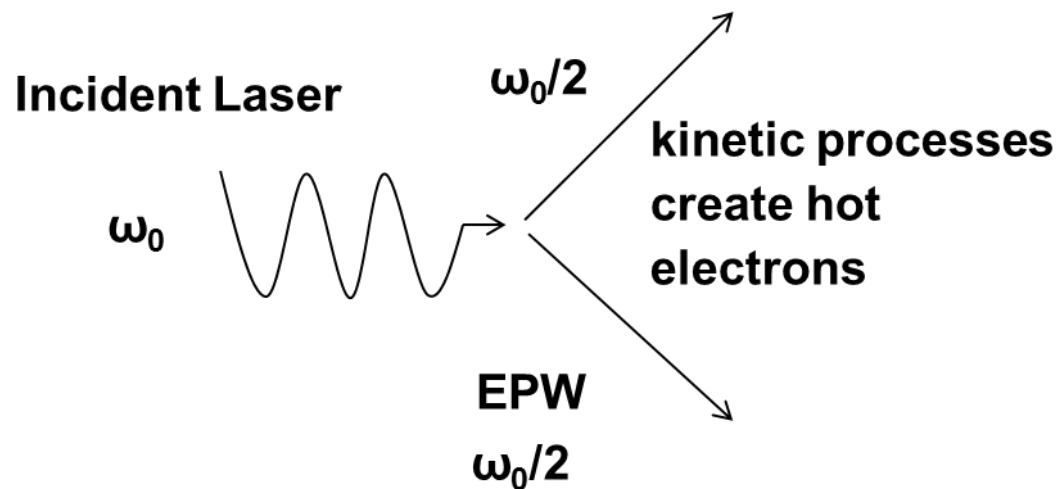


Summary: Preheat in cryogenic implosions is directly inferred by comparison of hard x rays between all-plastic and DT-layered implosions

- Differences in hard x-ray signals between mass-equivalent all-CH and cryo implosions can be used to infer hot-electron energy deposition into the payload
- Hot-electron deposition into the payload increases proportionally with the payload mass for OMEGA implosions
- Modeling of these experiments indicated an $\sim 20\%$ degradation in areal density as a result of hot-electron preheat for $\alpha = 4$ direct drive designs
- This platform is now being used to explore the feasibility of direct drive designs on both NIF and OMEGA

Hot electrons from laser plasma interactions can preheat the DT fuel, thus raising the adiabat and degrading the areal density

The TPD* instability is thought to be the prevalent source of hot electrons in direct-drive ICF on OMEGA




TPD occurs in the corona where the density is near quarter critical density ($0.2 n_c < n_e < 0.25 n_c$).

* Two Plasmon Decay

Hot-electrons from laser–plasma interactions can preheat the DT fuel, thereby raising the adiabat and degrading the areal density

$$\text{Lawson parameter } \chi = \left(\rho R_{\text{g/cm}^2} \right)^{0.61} \left(\frac{0.12 \text{ Yield}_{16}}{M_{\text{stag,mg}}} \right)^{0.34}$$

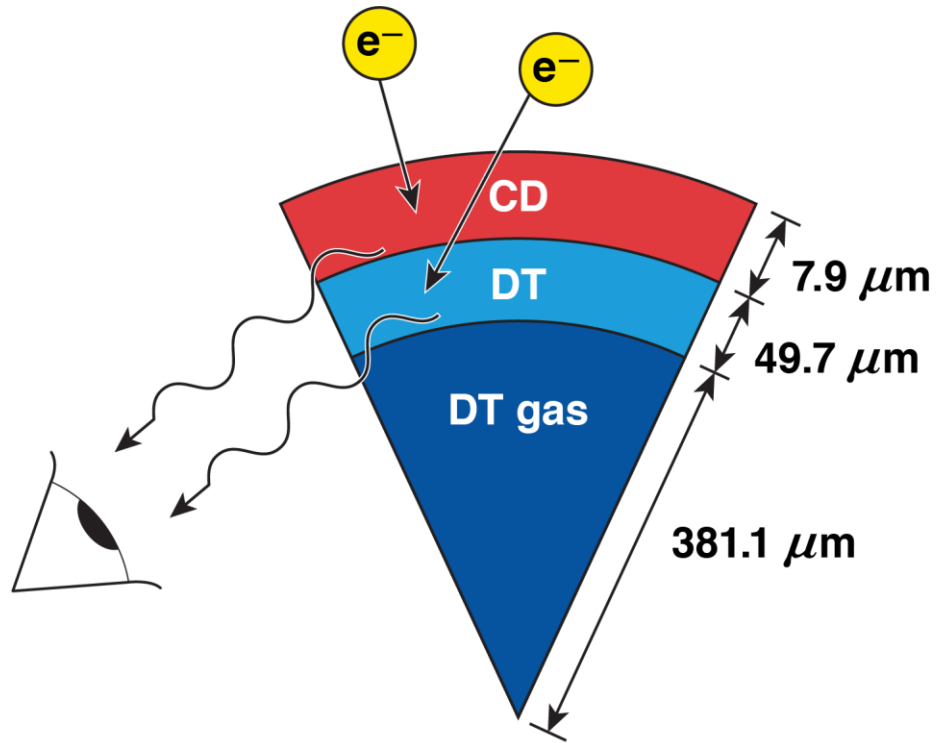
$$\chi \sim \frac{E_{\text{k}}^{0.35} P_{\text{max}}^{0.14} v_{\text{imp}}^2}{\alpha^{0.84}}$$


Hot electrons increase the adiabat and degrade performance

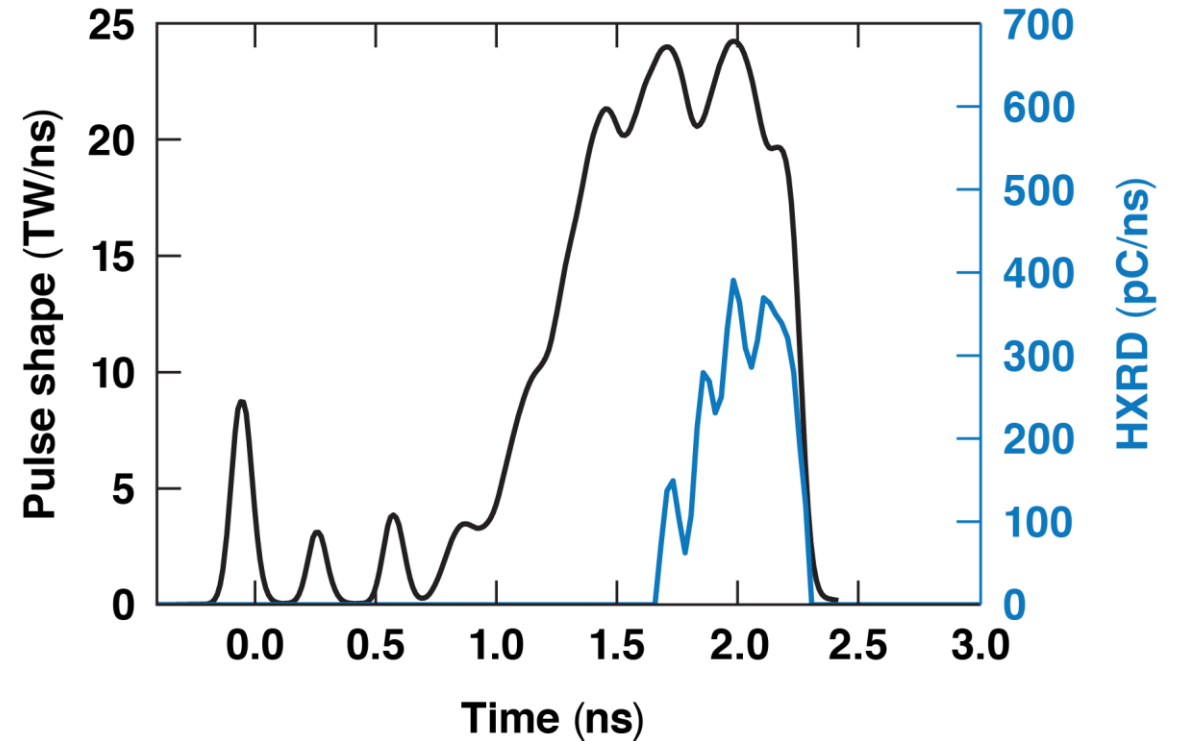
- α = shell adiabat
- E_{k} = shell kinetic energy
- v_{imp} = shell implosion velocity
- P_{max} = ablation pressure
- M_{stag} = stagnated DT mass

-
- C. Zhou *et al.*, *Phys. Plasmas* **15**, 102707 (2008).
 - P. Y. Chang *et al.*, *Phys. Rev. Lett.* **104** 135002 (2010).

A single hard x-ray measurement in a cryo implosion cannot discriminate between hard x rays emitted from electrons slowing down in DT versus CD



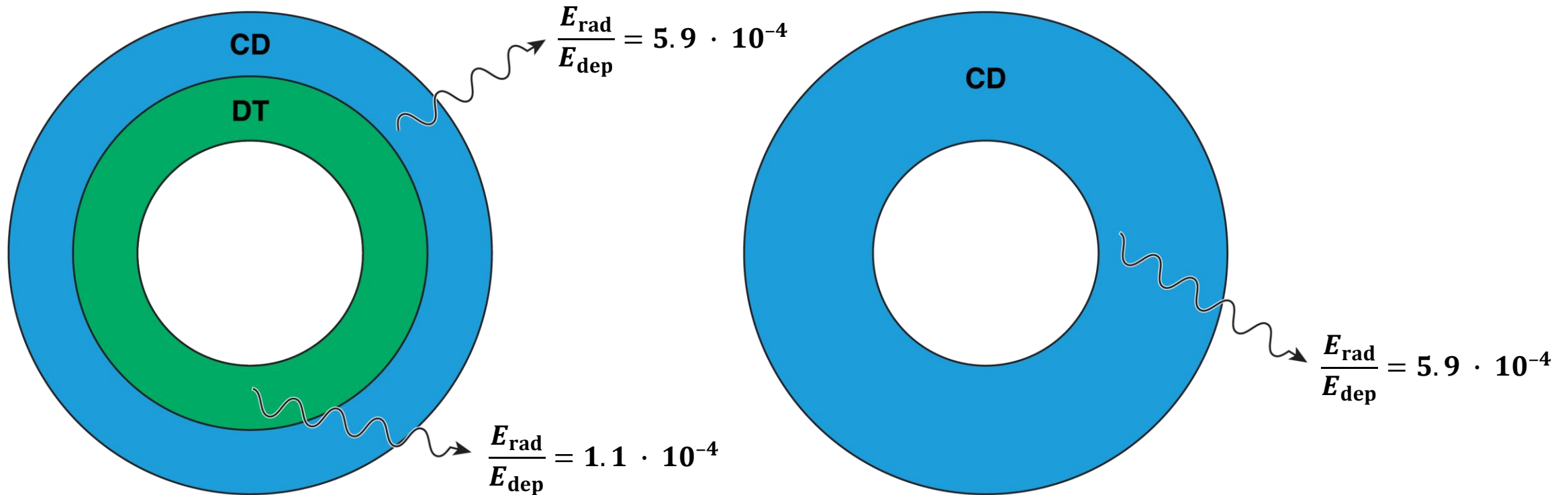
TC15199



TC15185

HXRD: hard x-ray diagnostic

Hot-electron energy deposited in DT is inferred by comparing hard x-ray signals of all-CD and DT-layered targets



TC15186

- The key parameter is “radiative power” $E_{\text{rad}}/E_{\text{dep}}$, which represents the radiated energy by the hot electrons per unit of energy lost via Coulomb collisions

The radiative power $E_{\text{rad}}/E_{\text{dep}}$ depends on background plasma atomic number Z and hot-electron temperature

- $E_{\text{rad}}/E_{\text{dep}}$ is proportional to $\langle Z^2 \rangle / \langle Z \rangle$
- $E_{\text{rad}}/E_{\text{dep}}$ depends on the hot-electron temperature that is measured by the multichannel hard x-ray detector (40 keV and up, assuming a Maxwellian distribution of hot-electrons)

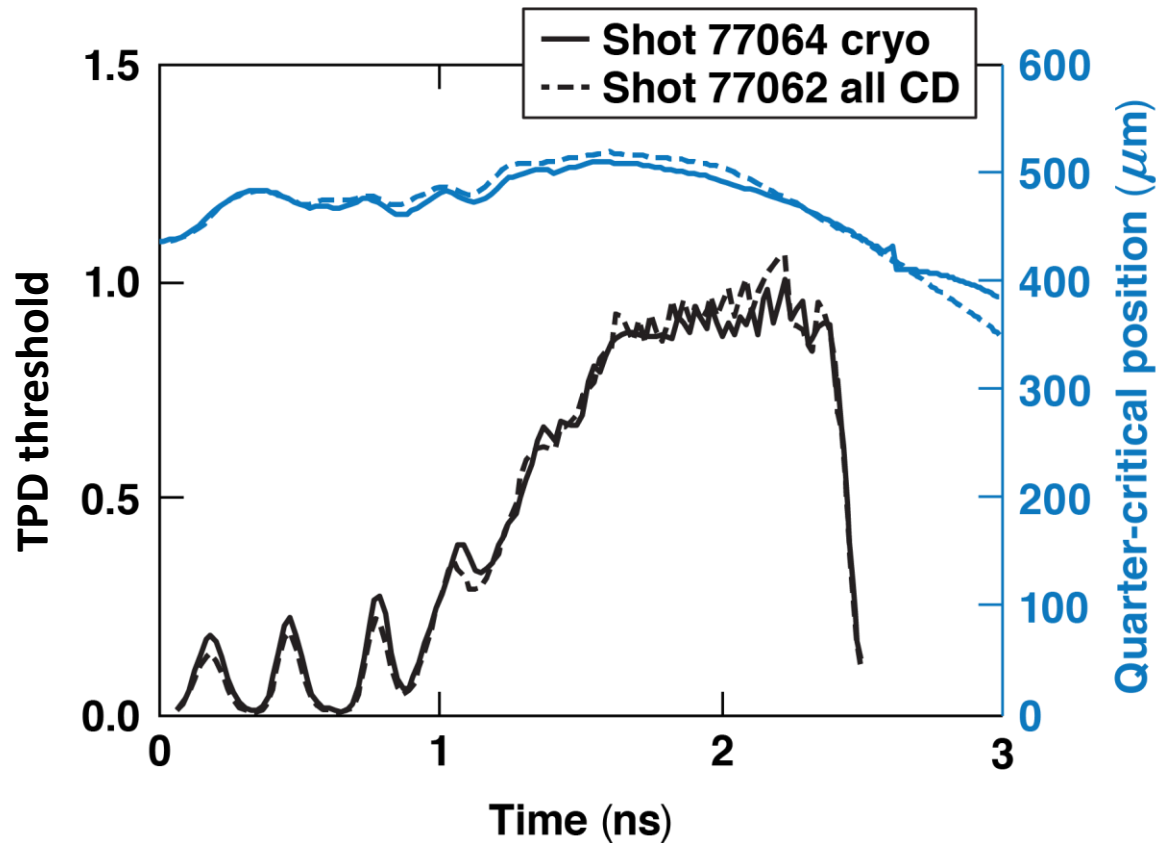
$$\frac{E_{\text{rad}}}{E_{\text{dep}}} = \frac{\int_0^{\infty} f(E_0) \int_0^{E_0} \frac{dE_{\text{rad}}}{dE_{\text{collision}}} dE dE_0}{\int_0^{\infty} f(E_0) E_0 dE_0}$$

The DT preheat energy is directly proportional to the difference in hard x-ray signals between the cryo and all-CD implosion

$$E_{\text{hot,DT}} = \frac{\text{HXR}_{\text{all CD}} - \text{HXR}_{\text{cryo}}}{\left(\frac{E_{\text{rad}}}{E_{\text{dep}}}\right)_{\text{CD}} - \left(\frac{E_{\text{rad}}}{E_{\text{dep}}}\right)_{\text{DT}}} + \sigma \left[\ln \left(\frac{\Lambda_{\text{dense CD}}}{\Lambda_{\text{coronal CD}}} \right) \right]$$

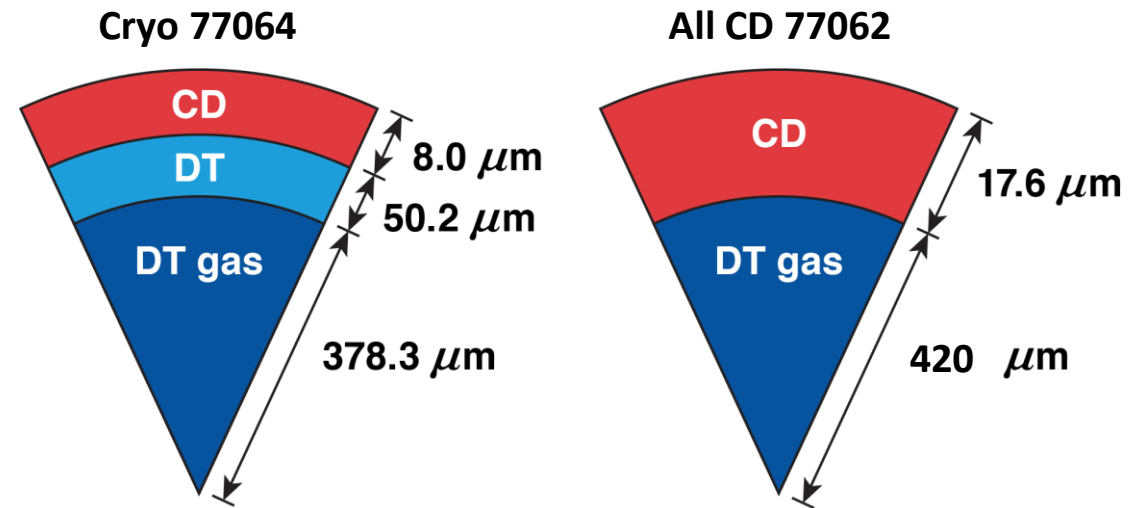
- Key assumption: the hot-electron source is the same for both the cryo and the all-CD experiments

One-dimensional *LILAC* simulations indicate that mass-equivalent all-CD and cryo targets have the same coronal plasma conditions, and therefore the same hot-electron source



TC15187

- The TPD threshold* $\eta = \frac{I_{14 \text{ W/cm}^2} L_{\mu\text{m}}}{233 T_{\text{keV}}}$



TC15188

TPD: two-plasmon-decay

* A. Simon *et al.*, Phys. Fluids **26**, 3107 (1983);

D. T. Michel *et al.*, Phys. Rev. Lett. **109**, 155007 (2012).

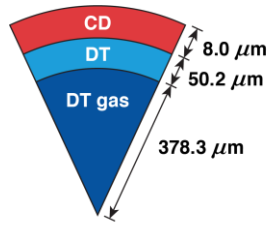
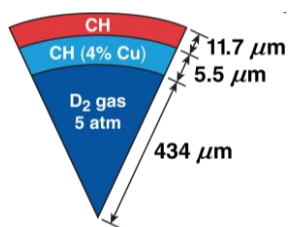
Preheat is modeled using the hot-electron deposition package in *LILAC*

- The 1-D code *LILAC* uses a straight-line model where electrons lose energy according to a slowing-down formula*
- The radiation emitted by hot electrons is calculated from NIST tables
- The hot-electron source is Maxwellian with the measured temperature
- Electrons are born at the quarter-critical surface and are initialized with a user-specified divergence angle

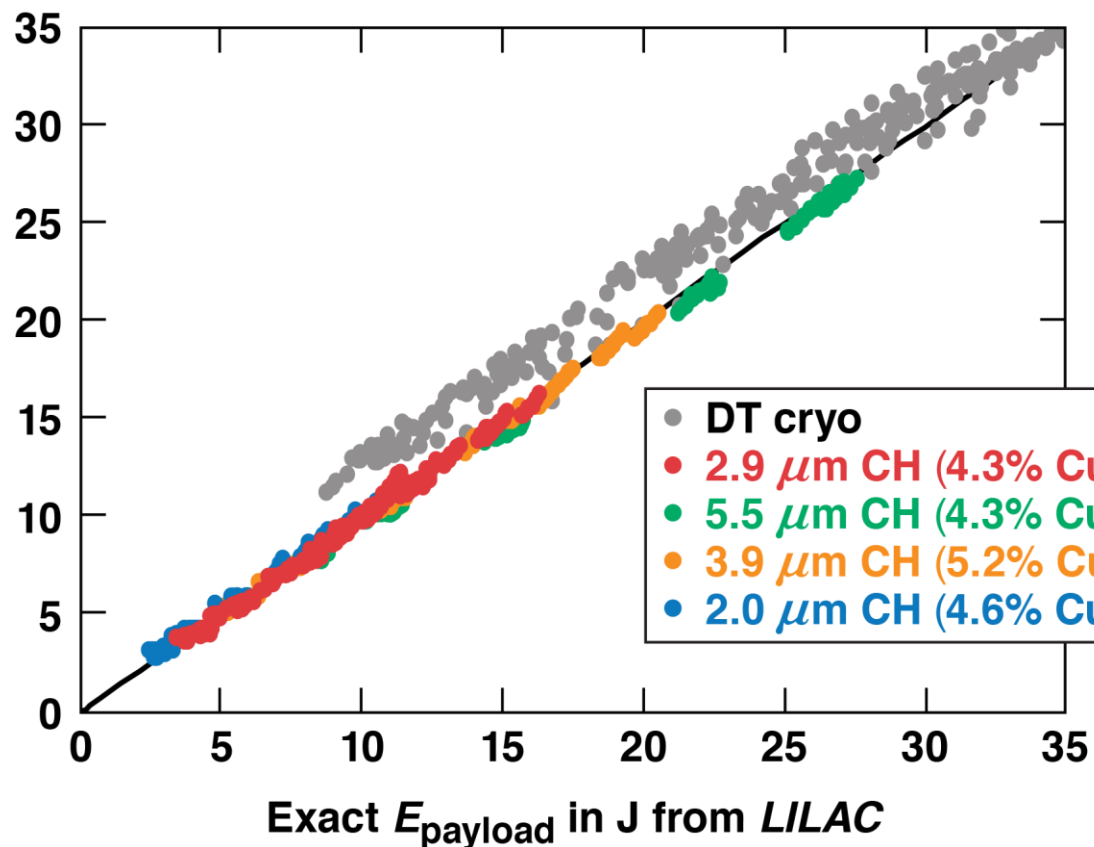
* A. A. Solodov and R. Betti, Phys. Plasmas 15, 042707 (2008).

LILAC simulations show that the preheat formula correctly predicts the energy deposited into the payload regardless of the payload material, divergence angle, and electron transport model

$$\frac{\text{HXR}_{\text{all CD}} - \text{HXR}_{\text{multilayered target}}}{\left(\frac{E_{\text{rad}}}{E_{\text{dep}}}\right)_{\text{CD}} - \left(\frac{E_{\text{rad}}}{E_{\text{dep}}}\right)_{\text{payload}}}$$

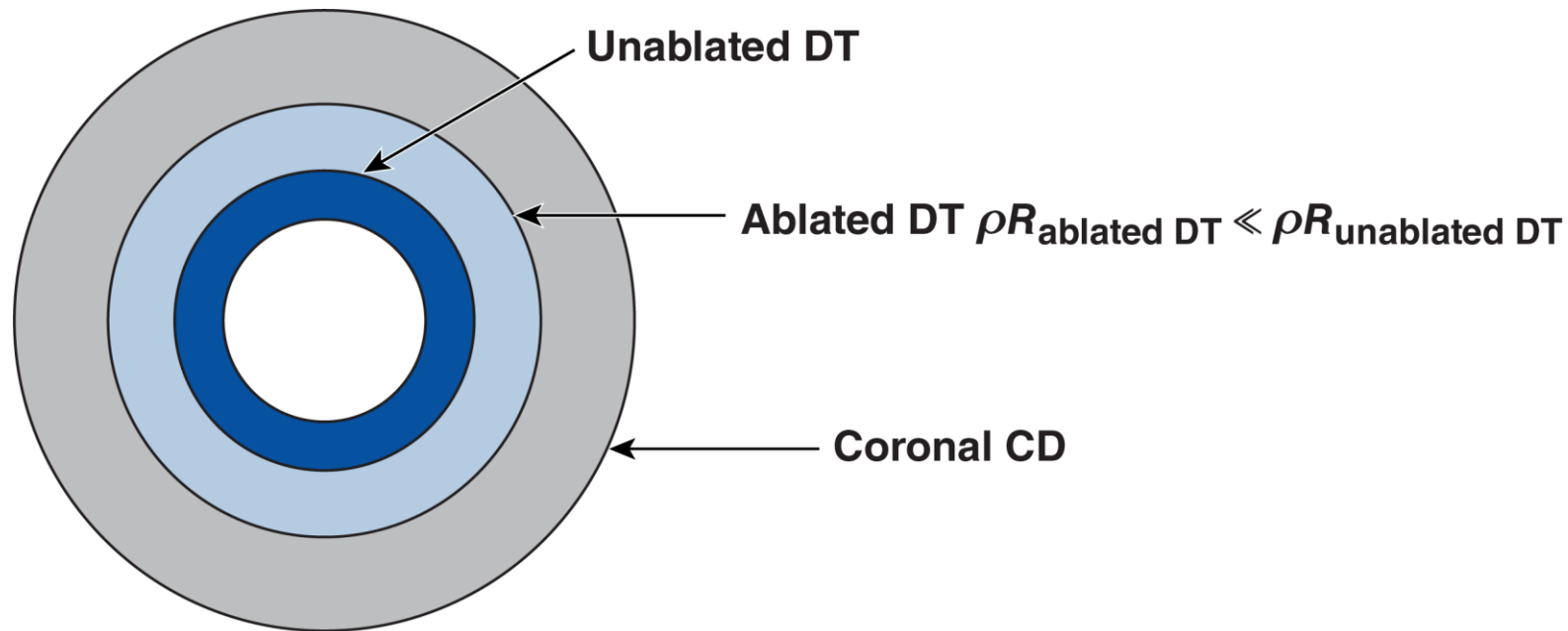


TC15189



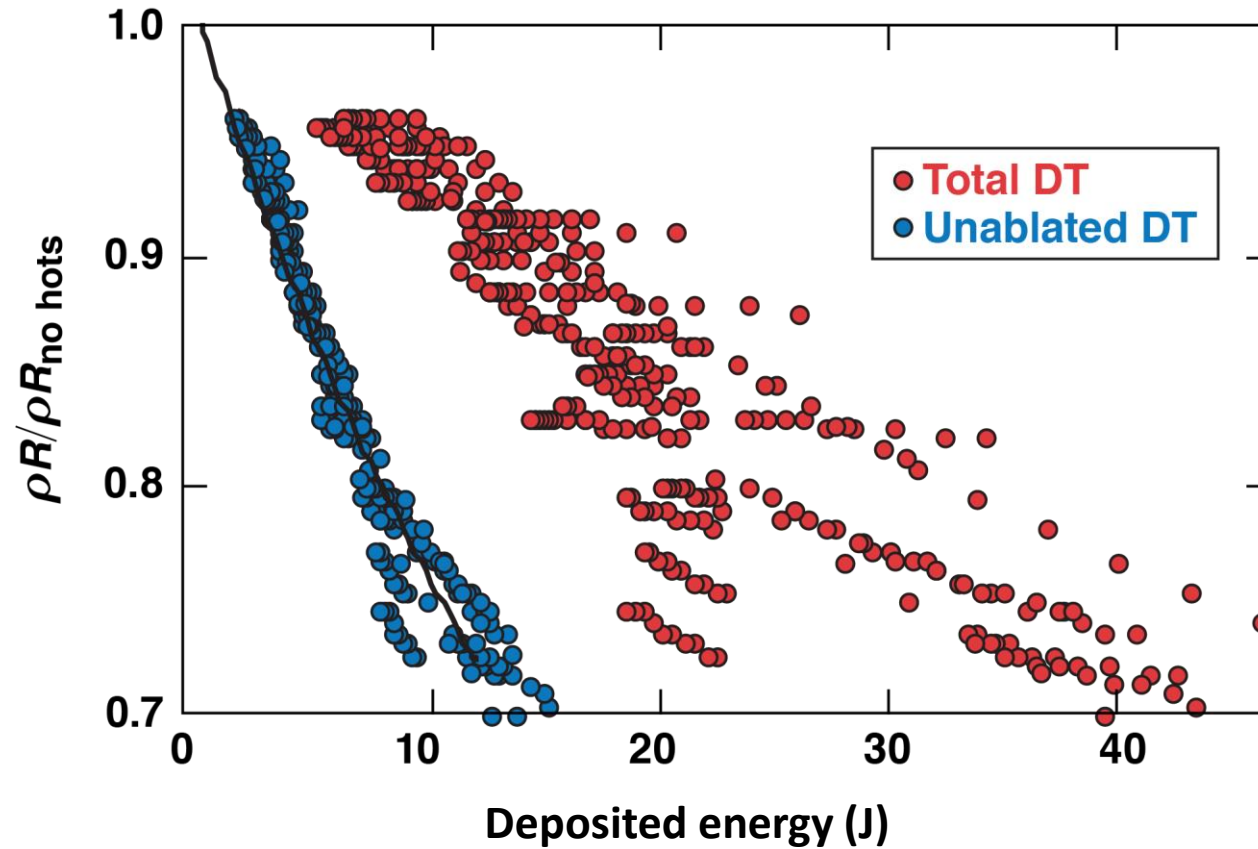
Although the preheat formula predicts electron energy into the total DT, the ρR degradation depends on electron energy into the unablated DT

- The difference in hard x-ray signal predicts electron energy into the total DT
- A fraction of DT mass is ablated during an OMEGA implosion



TC12371b

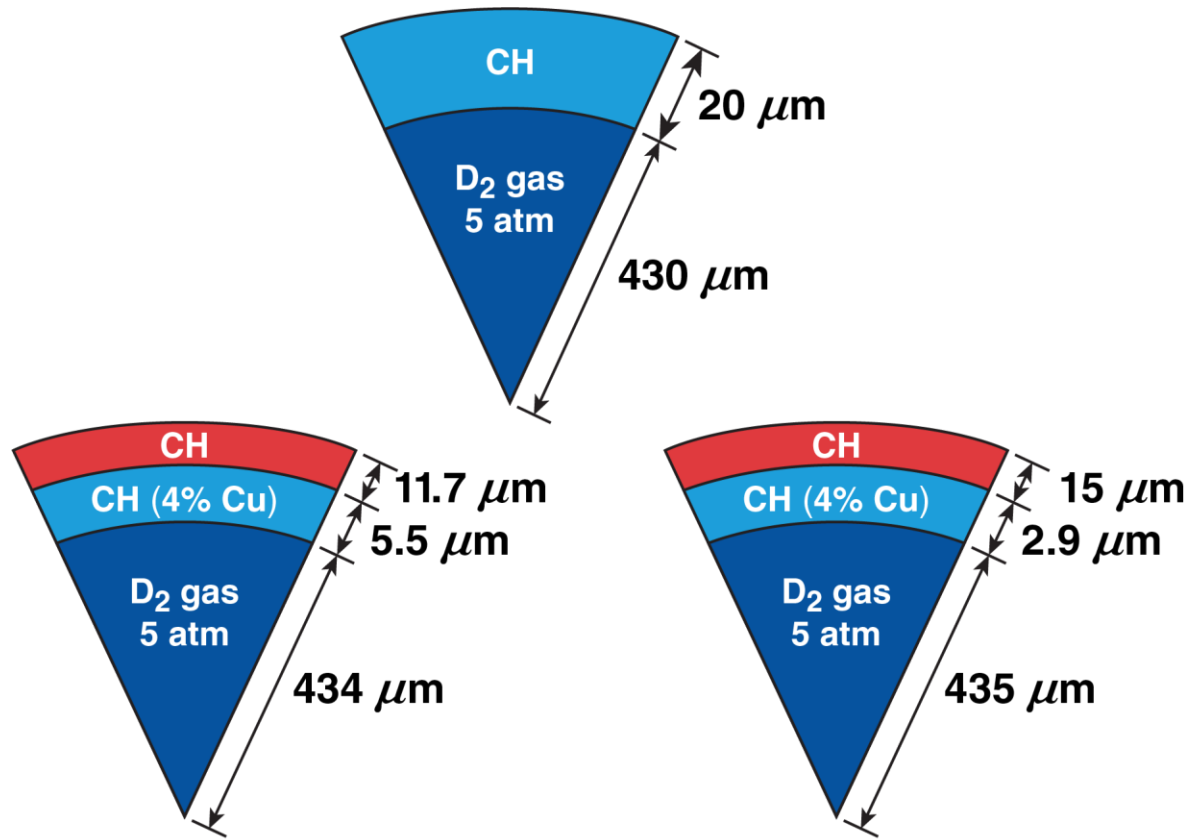
Although the preheat formula predicts hot electron energy into the total DT, the ρR degradation depends on hot electron energy into the unablated DT



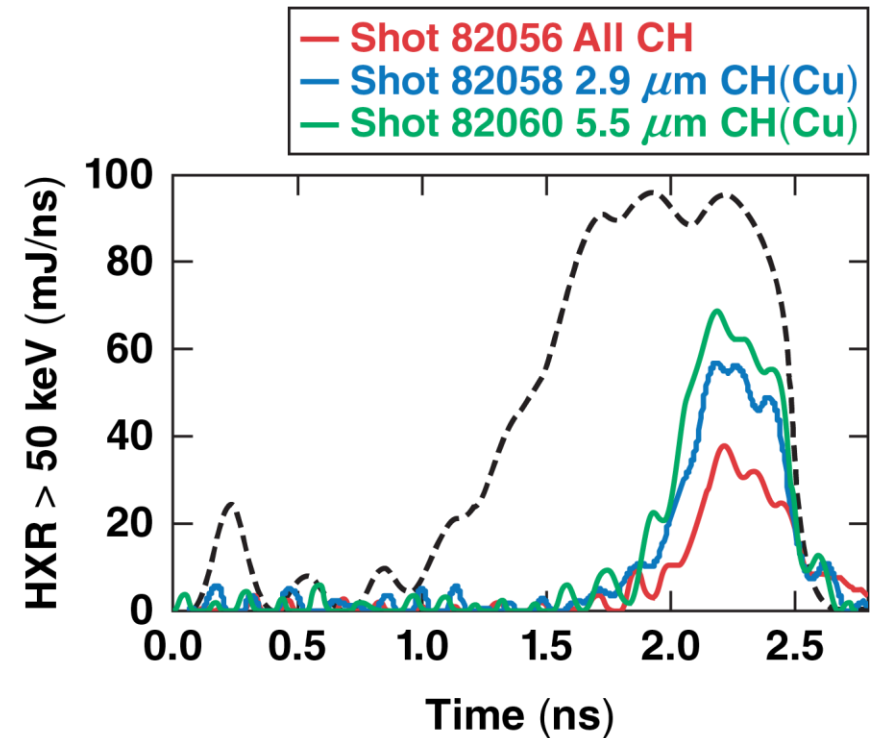
TC15192

V. A. Smalyuk *et al.*, Phys. Rev. Lett. 100, 185005 (2008).

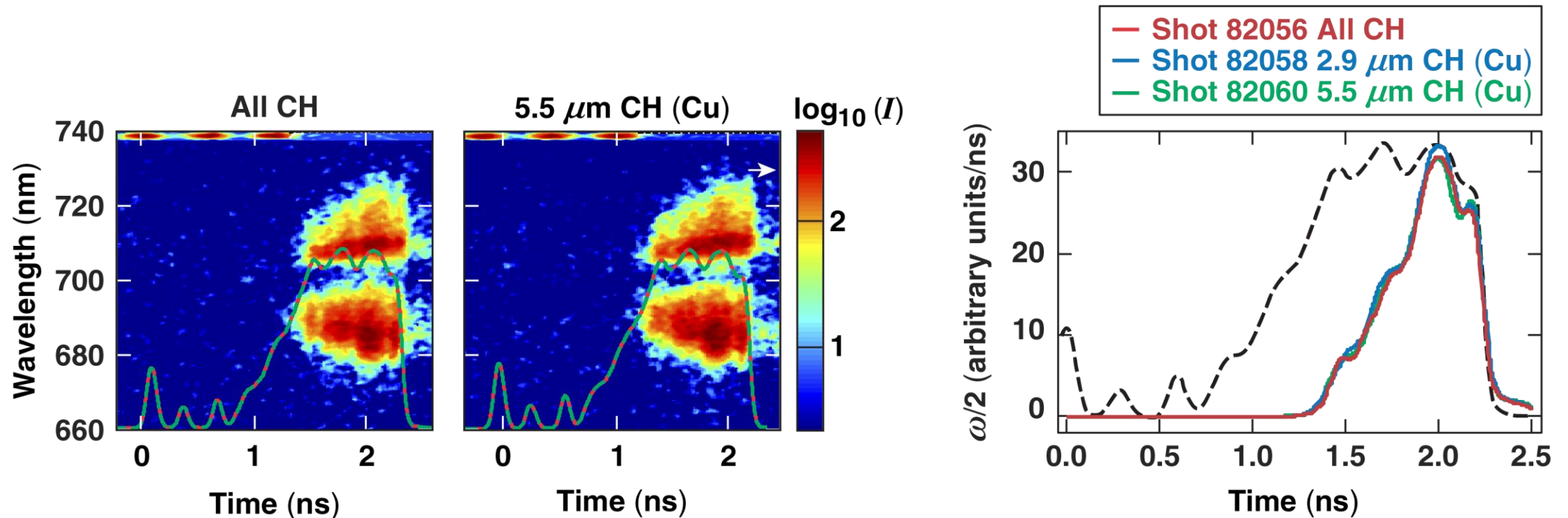
An experimental platform that utilized Cu-doped payloads of varying thicknesses was developed to measure where the hot electrons deposit their energy



TC13188a



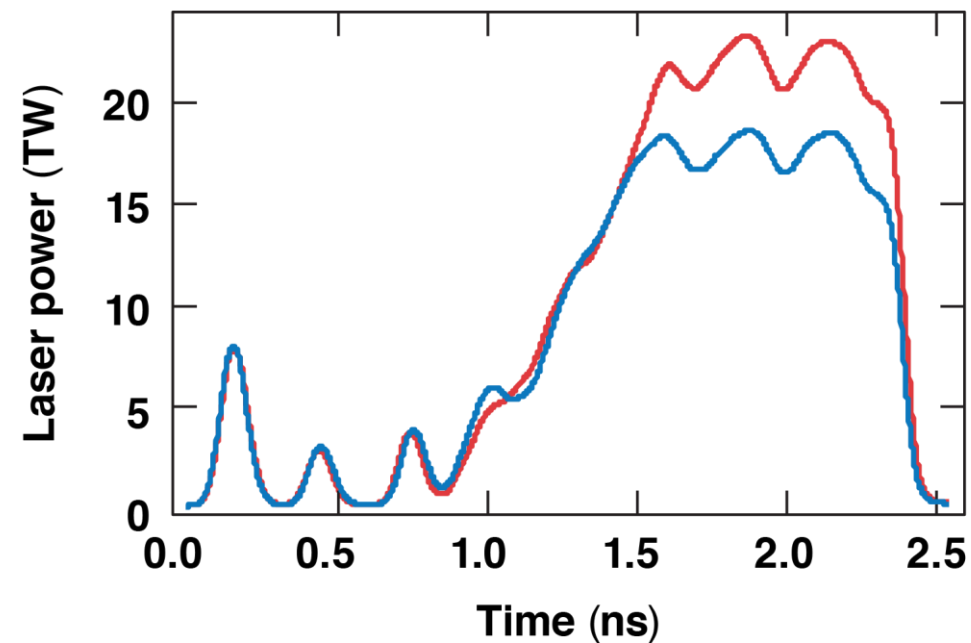
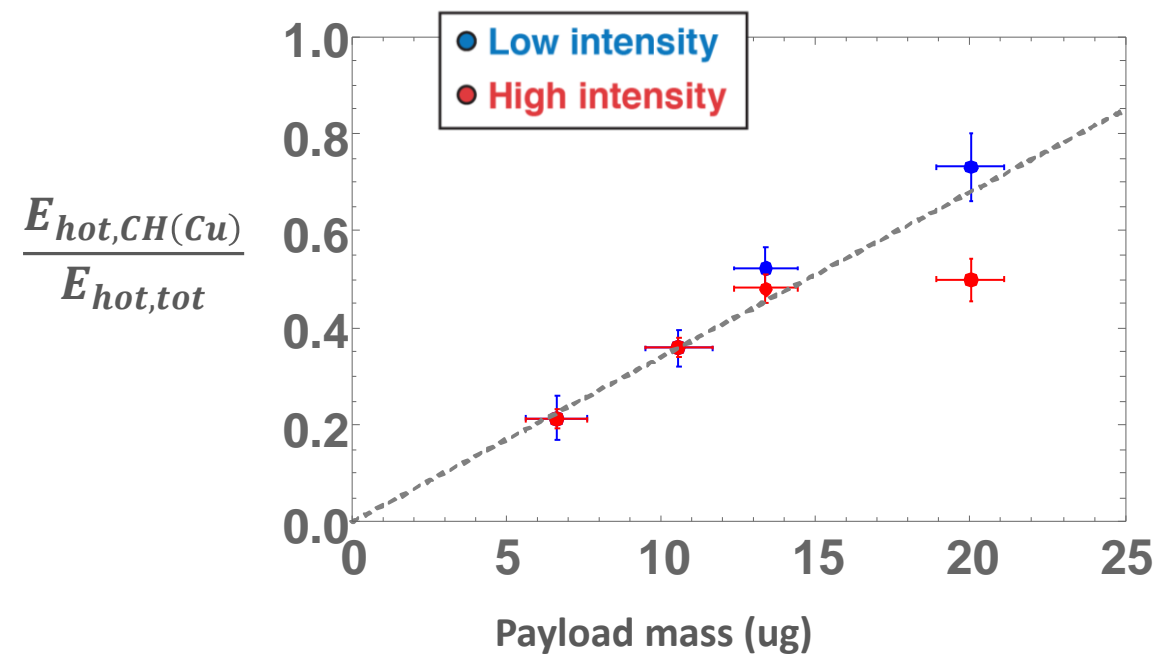
$\omega/2$ images indicate that the TPD activity in the corona is identical between the all-CH and CH(Cu) payload implosions



TC13189a

These data support the assumption that the hot-electron source between the all-CH and multilayered implosions is the same.

The energy deposition into the Cu-doped payload increases proportionately with the payload mass

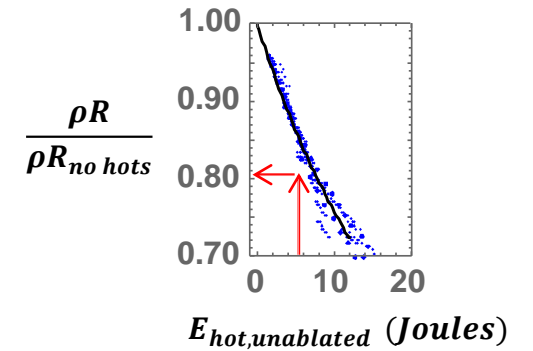


TC15235

The same model applied to DT layered targets of typical $\alpha \approx 4$ implosions* leads to areal density degradation of about 15-20% with respect to calculated 1D

$$E_{hot,DT} = \frac{HXR_{all\ CH} - HXR_{cryo}}{\left(\frac{E_{rad}}{E_{dep}}\right)_{CH} - \left(\frac{E_{rad}}{E_{dep}}\right)_{DT}}$$

$$E_{hot,unabladed} = E_{hot,DT} \left(\frac{M_{unabladed}}{M_{DT}} \right)$$

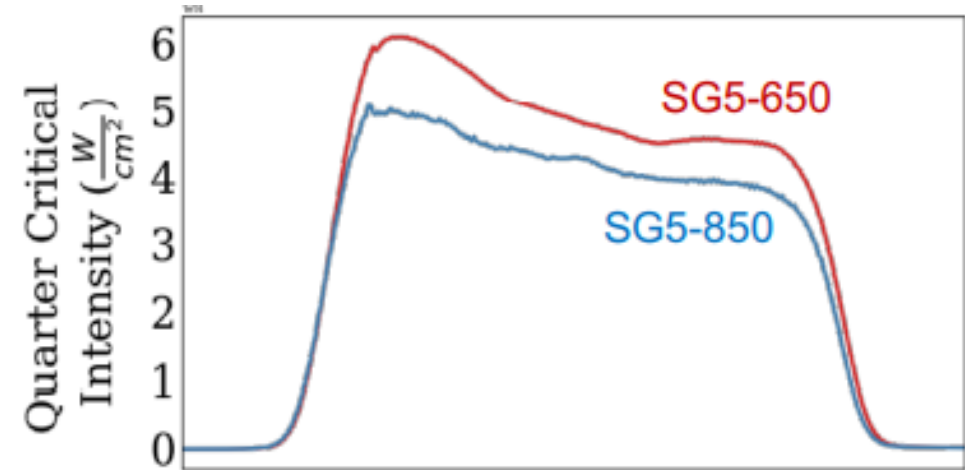
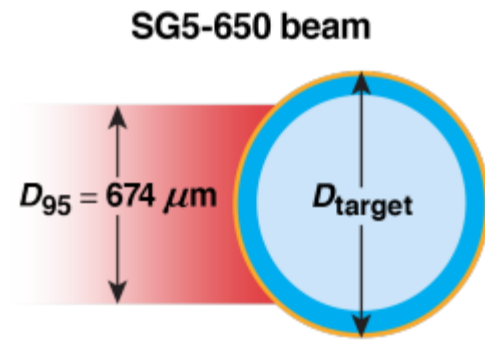
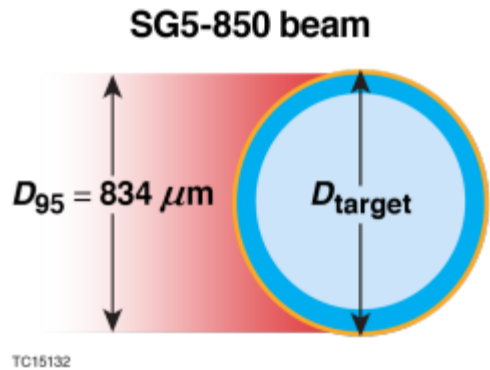


Shot number	$E_{hot,DT}$ in Joules	$E_{hot,unabladed}$ in Joules	$\rho R_{experiment}$	$\rho R_{LILAC, no\ hots}$	$\rho R_{LILAC, hots}$
77064	13 ± 5 J	5 ± 2 J	201 ± 17 mg/cm ²	225 mg/cm ²	190 ± 16 mg/cm ²
85784	22 ± 7 J	8 ± 3 J	154 ± 13 mg/cm ²	186 mg/cm ²	156 ± 13 mg/cm ²

* S. Regan et al, PRL 2015

Applications of the hot electron preheat platform

The preheat model predicts additional degradation in areal density for targets imploded with different phase plates



Shot number	$E_{\text{hot, DT}}$ in Joules	$E_{\text{hot, unablated}}$ in Joules	$\rho R_{\text{experiment}}$	$\rho R_{\text{LILAC, no hots}}$	$\rho R_{\text{LILAC, hots}}$
77064	$13 \pm 5 \text{ J}$	$5 \pm 2 \text{ J}$	$201 \pm 17 \text{ mg/cm}^2$	225 mg/cm^2	$190 \pm 16 \text{ mg/cm}^2$
91830	$48 \pm 12 \text{ J}$	$12 \pm 4 \text{ J}$	$127 \pm 11 \text{ mg/cm}^2$	188 mg/cm^2	$135 \pm 15 \text{ mg/cm}^2$

As implosions scale from OMEGA to the NIF, the scale length is also expected to increase, resulting in more expected LPI for the same coronal conditions

	NIF	OMEGA
Scale length at quarter-critical $L_{\mu\text{m}}$	$\sim 400 \mu\text{m}$	$\sim 150 \mu\text{m}$
Electron temperature at quarter-critical $T_{\text{e,keV}}$	$\sim 3.2 \text{ keV}$	$\sim 2.5 \text{ keV}$
Intensity at quarter-critical I_{14}	$\sim 4 \text{ to } 8 \times 10^{14} \text{ W/cm}^2$	$\sim 3.5 \times 10^{14} \text{ W/cm}^2$
η_{TPD}	$\sim 2\text{-}5$	~ 1
η_{SRS}	$\sim 5\text{-}10$	~ 1

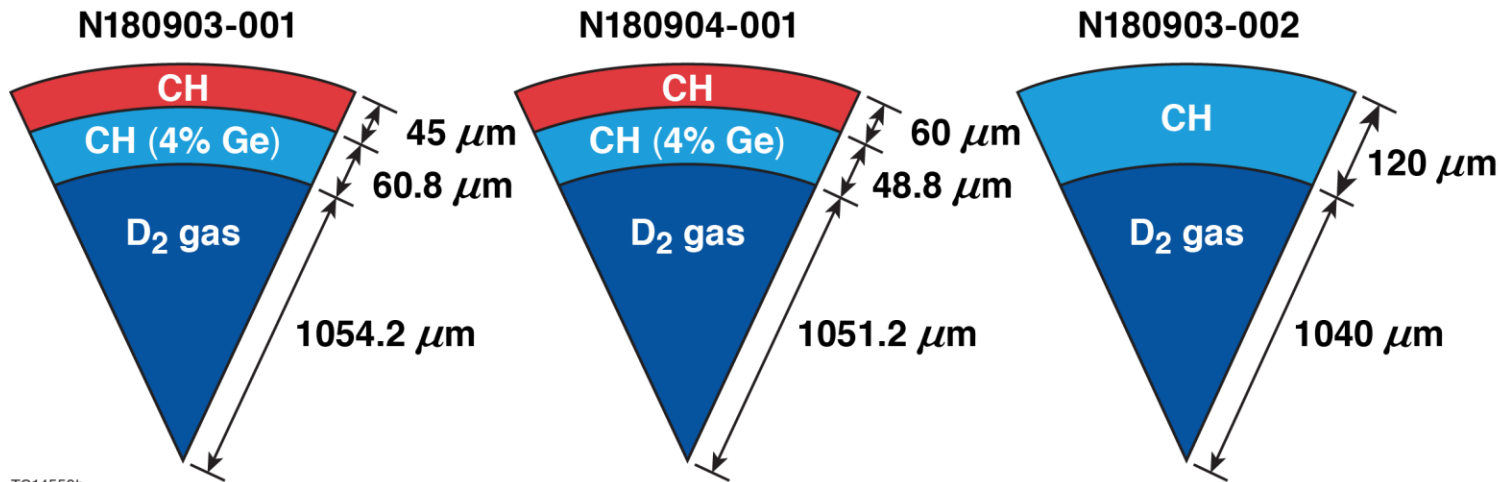
$$\eta_{\text{TPD}} = I_{14} L_{\mu\text{m}} / 233 T_{\text{e,keV}}$$

$$\eta_{\text{SRS}} = I_{14} L_{\mu\text{m}}^{4/3} / 2377$$

LPI: laser-plasma interaction
 TPD: two-plasmon-decay
 SRS: stimulated Raman scattering

The preheat platform has been developed on the NIF to measure the coupling of hot electrons into the target

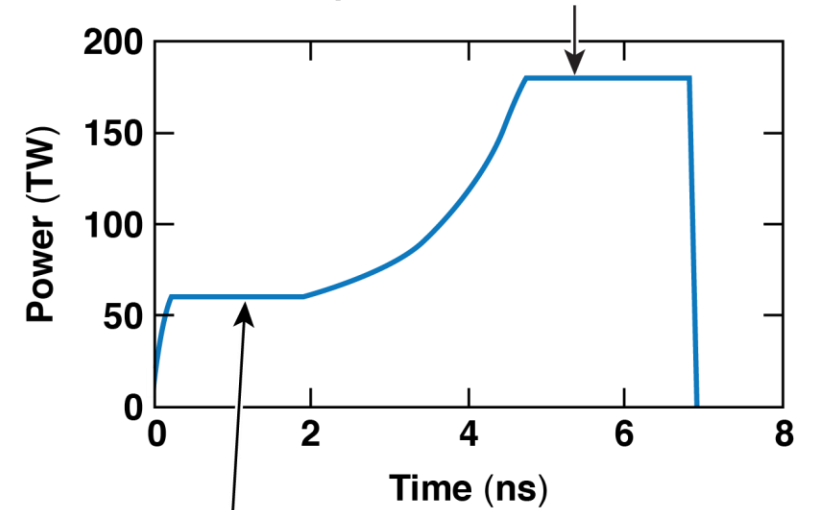
Mass-equivalent targets



TC14559b

Different buried depths of the Ge-doped layer are examined to diagnose the hot-electron deposition profile in the imploding shell

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

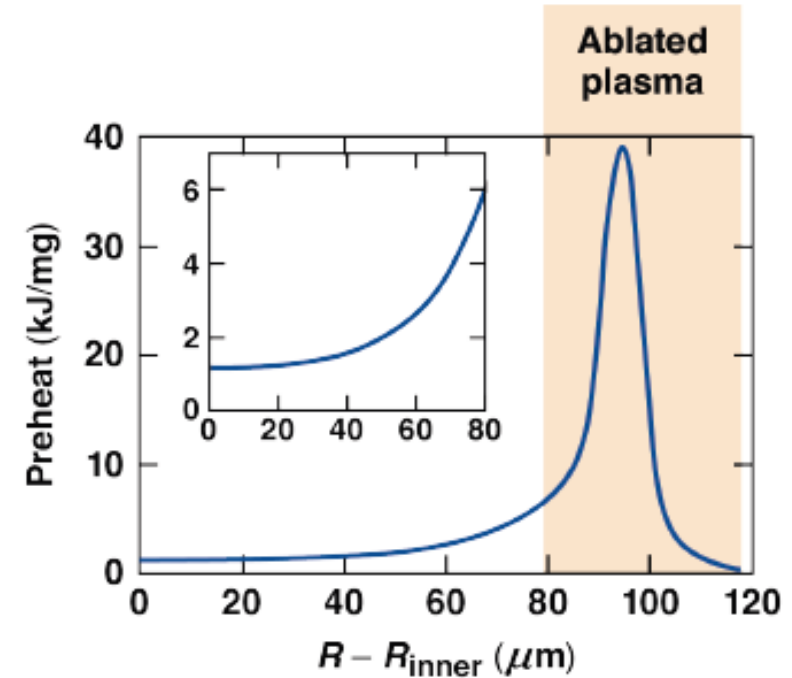
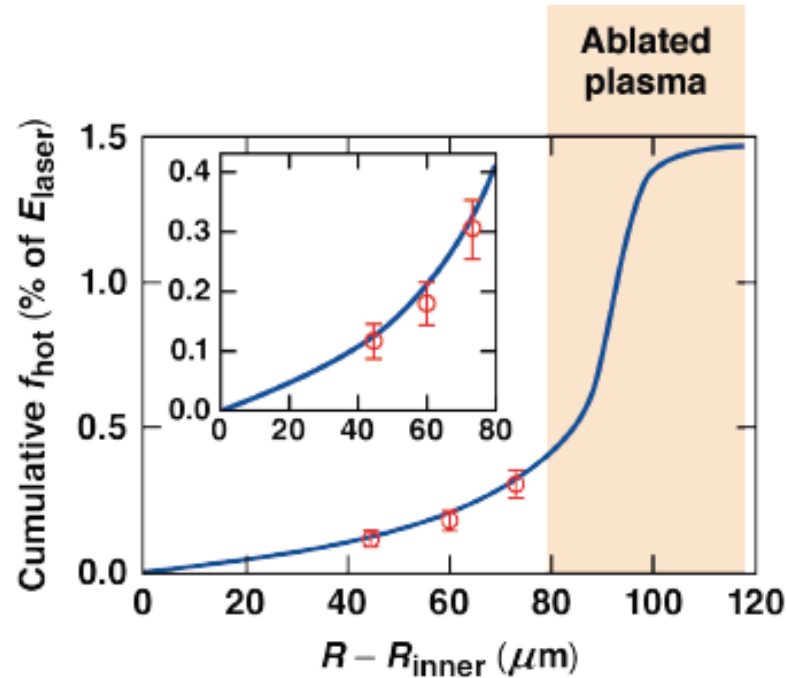
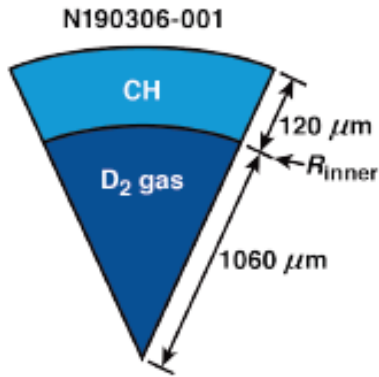


Increased foot power for a higher-adiabat, more-stable implosion

*A. A. Solodov and M. J. Rosenberg et al, 50th Anomalous Absorption Conference Skytop, PA 5–10 June 2022

The preheat results from NIF indicate that approximately 1/3 of the total preheat energy is deposited in the unablated plasma

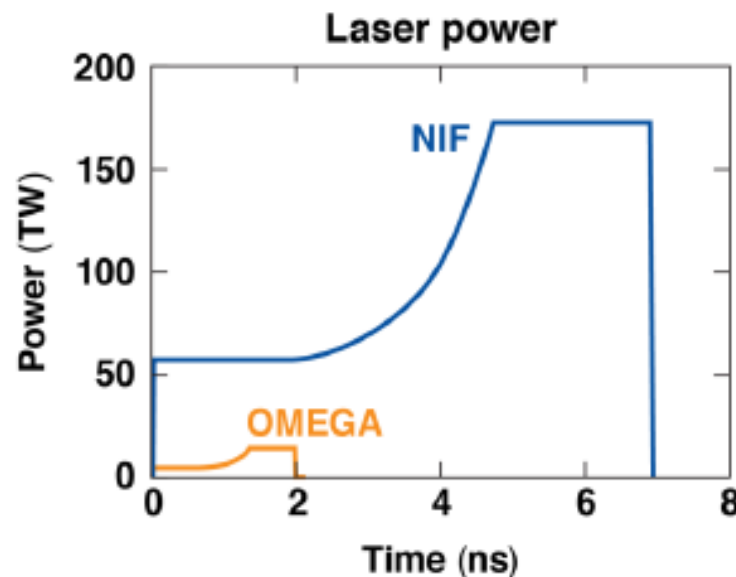
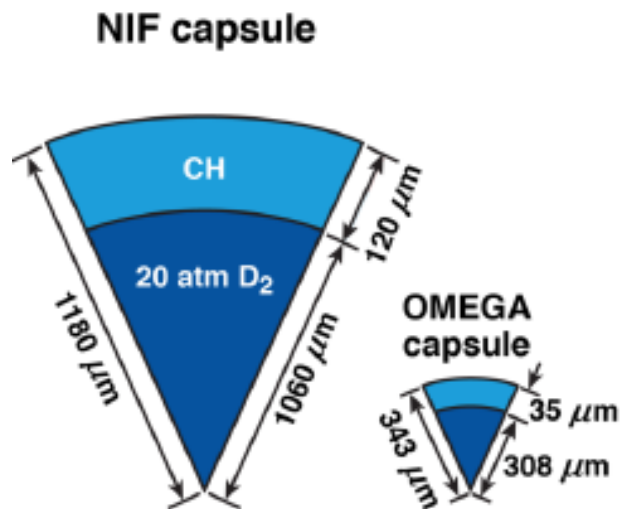
Incident intensity = 10^{15} W/cm²



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

*A. A. Solodov and M. J. Rosenberg et al, 50th Anomalous Absorption Conference Skytop, PA 5–10 June 2022

Experiments have been conducted to assess preheat differences between hydro-scaled OMEGA and NIF experiments

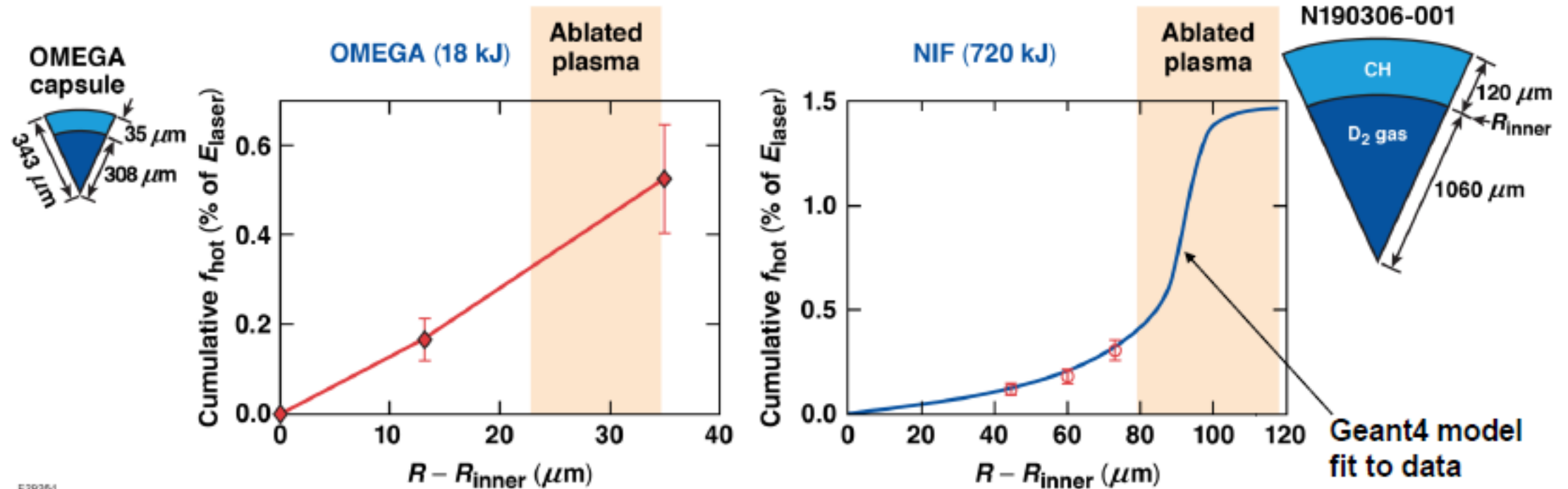


Parameter	NIF	OMEGA
E_L	720 kJ	18 kJ
P_L	172 TW	15 TW
$\langle I_L \rangle$ (W/cm ²)*	1.0×10^{15}	1.0×10^{15}
Pulse length	6.9 ns	2.0 ns
Capsule OD	2360 μm	690 μm
Shell thickness	120 μm	35 μm

*Average on-target laser intensity

*M. J. Rosenberg and A. A. Solodov et al, 63 annual meeting of the APS division of plasma physics, Pittsburgh, PA, 8-12 November 2021

Although the NIF experiment generates more hot electrons, the fraction of laser energy converted into preheat of the unablated plasma is the same

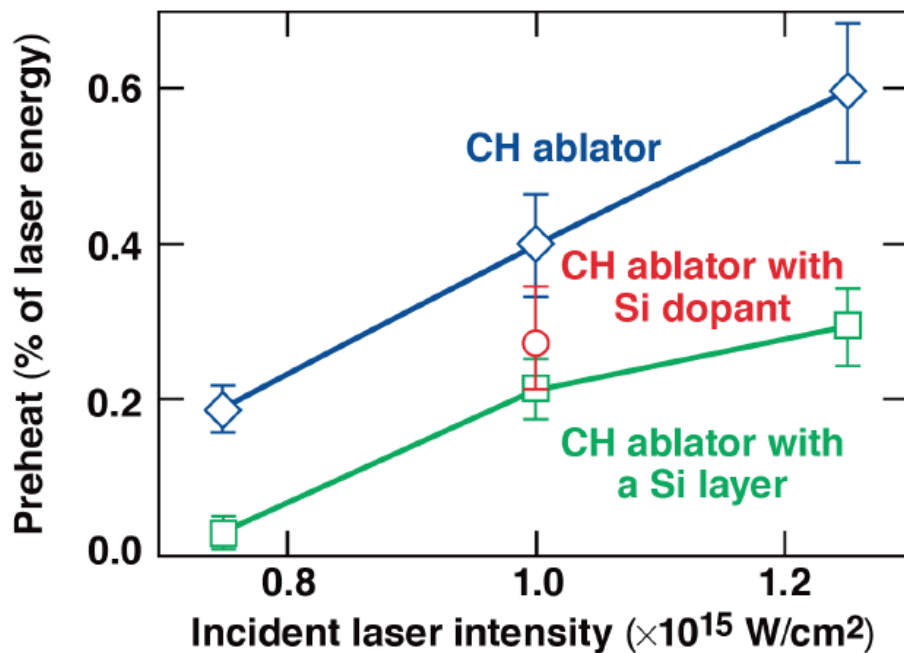


E2R264

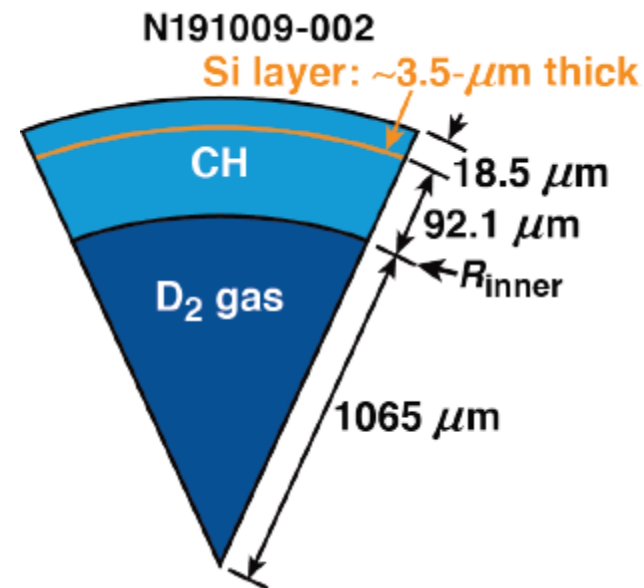
*M. J. Rosenberg and A. A. Solodov et al, 63 annual meeting of the APS division of plasma physics, Pittsburgh, PA, 8-12 November 2021

Experiments have been conducted to measure the reduction in hot electron preheat in ablators with Silicon dopants and layers

Hot-electron energy deposition in an unablated shell



TC16119



*A. A. Solodov et al, 50th Anomalous Absorption Conference Skytop, PA 5–10 June 2022

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- Modeling of these experiments indicated an $\sim 20\%$ degradation in areal density as a result of hot-electron preheat for $\alpha = 4$ direct drive designs
- This platform is now being used to explore the feasibility of direct drive designs on both NIF and OMEGA



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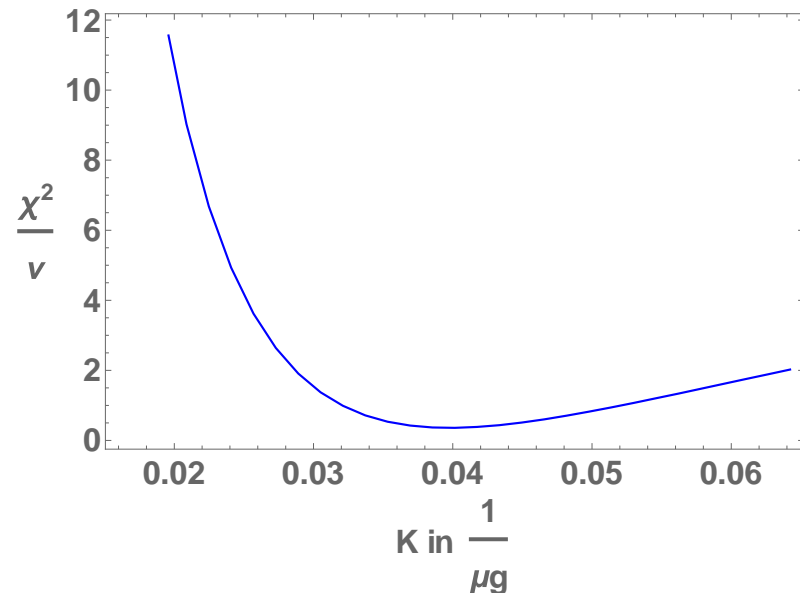
A simple model based on uniform deposition per unit mass is developed to describe the multi-layered experiments

$$K \equiv \frac{1}{E_{hot,tot}} \frac{dE_{dep}}{dM} = const$$

$$E_{hot,CH(Cu)} = KE_{tot}M_{payload}$$

$$E_{hot,tot} = \frac{HXRD_{All\ CH}}{[E_{rad}/E_{dep}]_{CH}}$$

$$HXRD_{CH(Cu)} = E_{hot,CH(Cu)} \left[\frac{E_{rad}}{E_{dep}} \right]_{CH(Cu)} + (E_{hot,tot} - E_{hot,CH(Cu)}) \left[\frac{E_{rad}}{E_{dep}} \right]_{CH}$$



$M_{payload}$ = payload mass

$E_{hot,CH(Cu)}$ = energy deposited into CH(Cu)

$E_{hot,tot}$ = total hot electron energy

$\frac{dE_{dep}}{dM}$ = electron energy deposited per unit mass