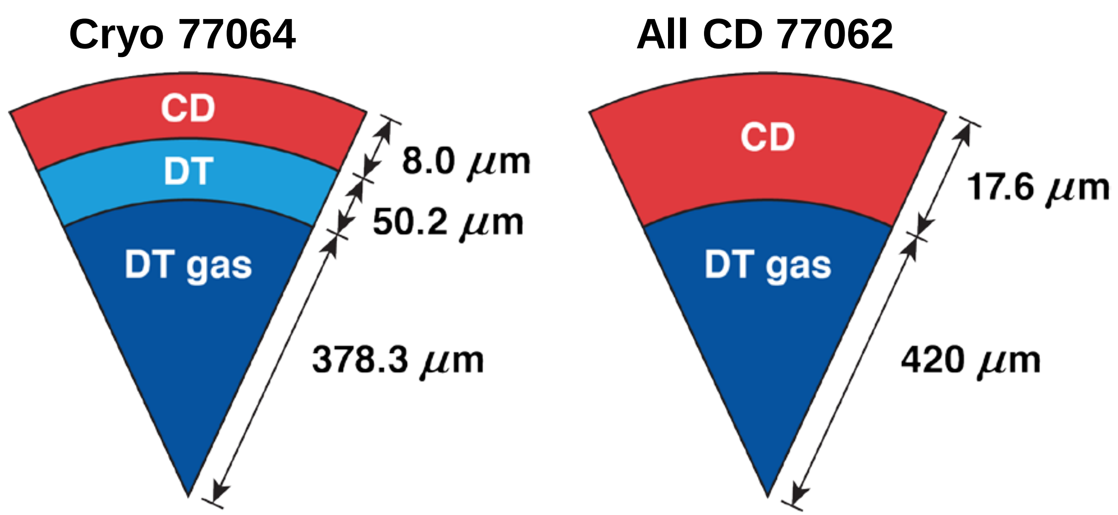
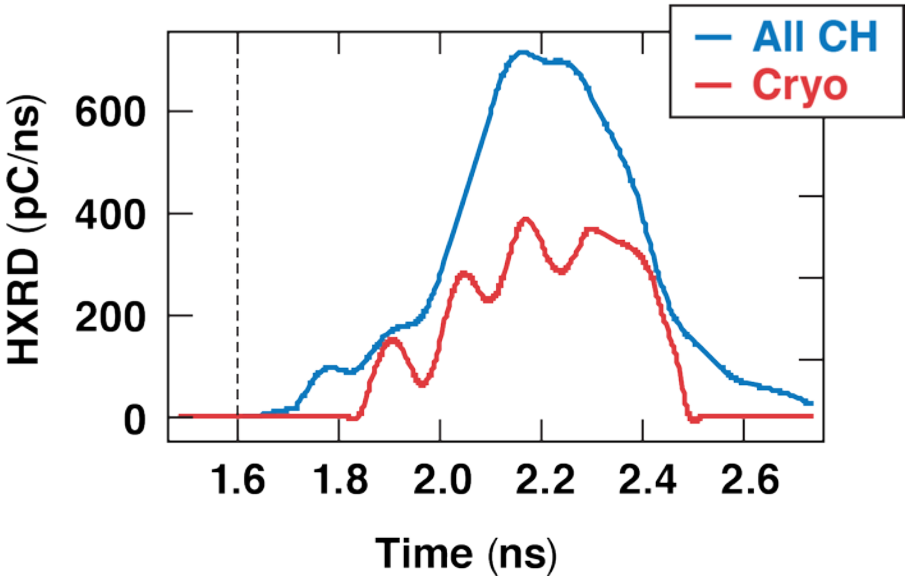
Direct Measurements of Hot-Electron Preheat in the Dense Fuel of Inertial Confinement Fusion Implosions





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Division of Plasma Physics
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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
- Modeling of these experiments indicated an ~10-20% degradation in areal density as a result of hot-electron preheat for typical α = 4 designs
- A similar experimental campaign is underway on the NIF to assess the viability of direct drive on the NIF

NIF: National Ignition Facility

Collaborators

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Outline

- Hot-electron preheat and the preheat formula
- Hot-electron transport experiments and modeling on OMEGA
- Hot-electron transport experiments on the NIF

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

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

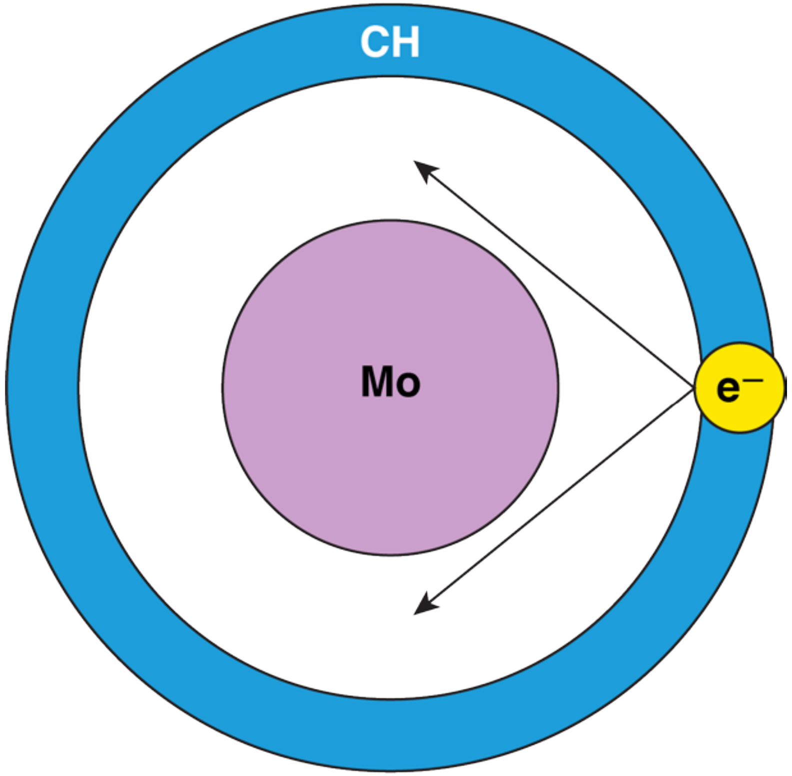
$$\chi \sim \frac{E_{\mathrm{k}}^{0.35} P_{\mathrm{max}}^{0.14} v_{\mathrm{imp}}^{2}}{\alpha^{0.84}}$$

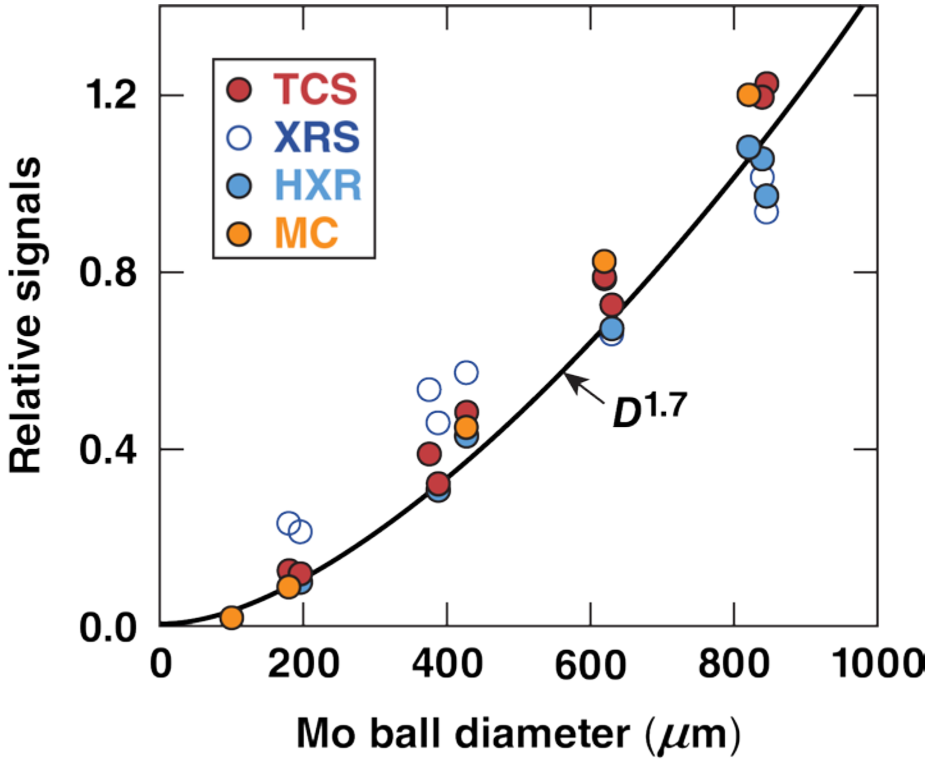
Hot electrons increase the adiabat and degrade performance

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

* C. Zhou *et al*., Phys. Plasmas 15, 102707 (2008).

Previous studies* of hot-electron transport on OMEGA suggest that hot electrons intersect the target at a large divergence angle or are transported isotropically





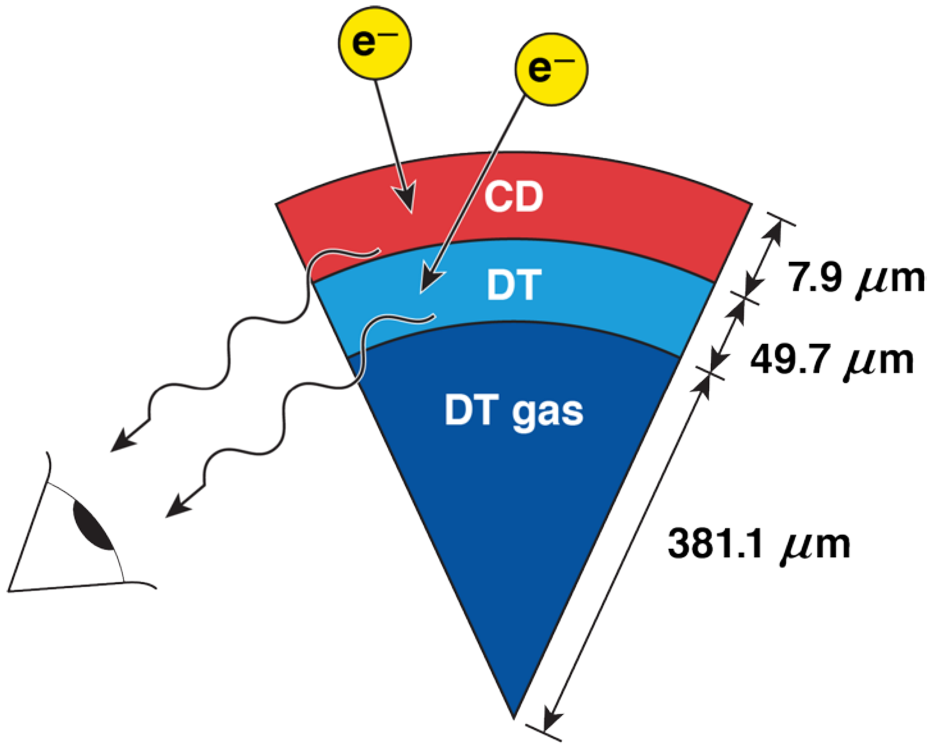
Although the divergence of electrons was measured, the exact amount coupled into the dense fuel of cryo implosions is still unknown.

TCS: type quartz crystal spectrometer
XRS: x-ray spectrometer

HXR: hard x ray
MC: moving cryostat

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

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



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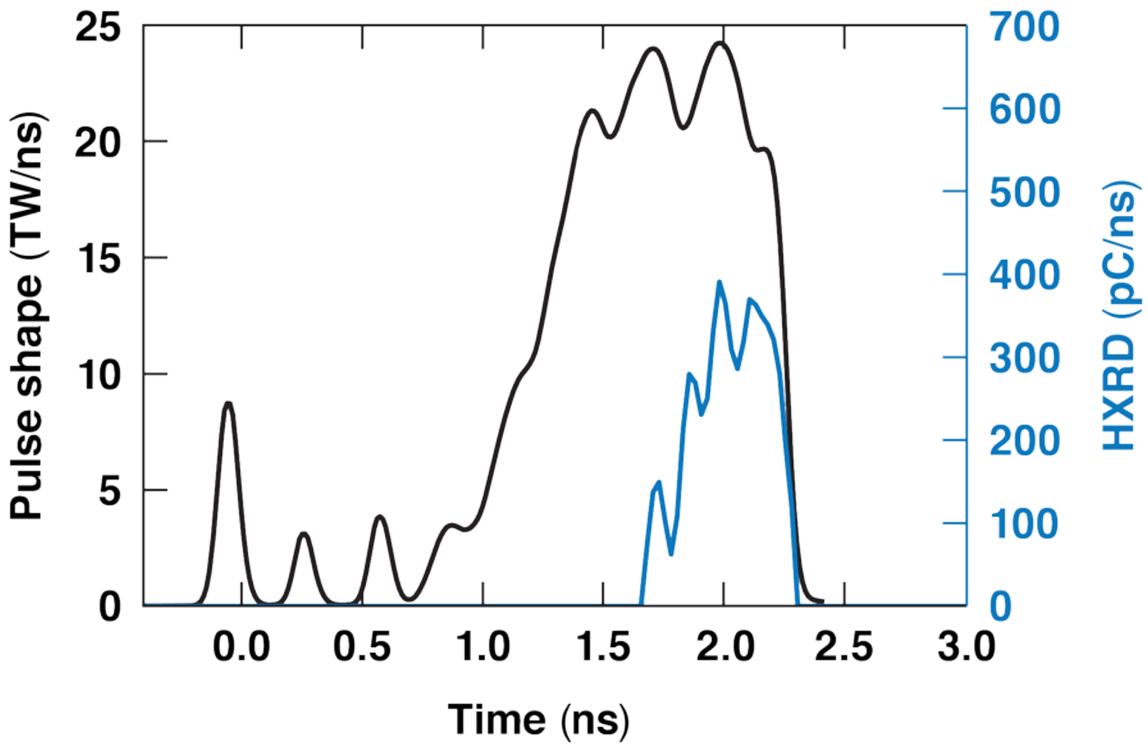

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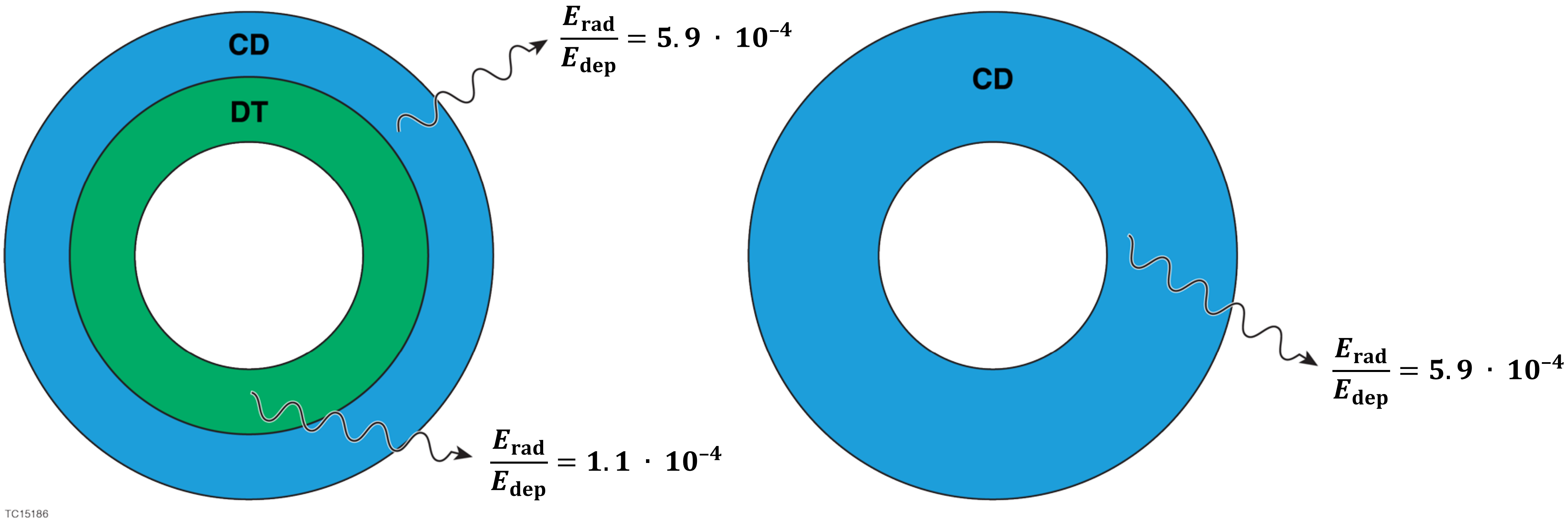
HXRD: hard x-ray diagnostic

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



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

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

- $E_{\mathrm{rad}}/\,E_{\mathrm{dep}}$ is proportional to $\langle Z^2 \rangle / \langle Z \rangle$
- $E_{\mathrm{rad}}/\,E_{\mathrm{dep}}$ 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)

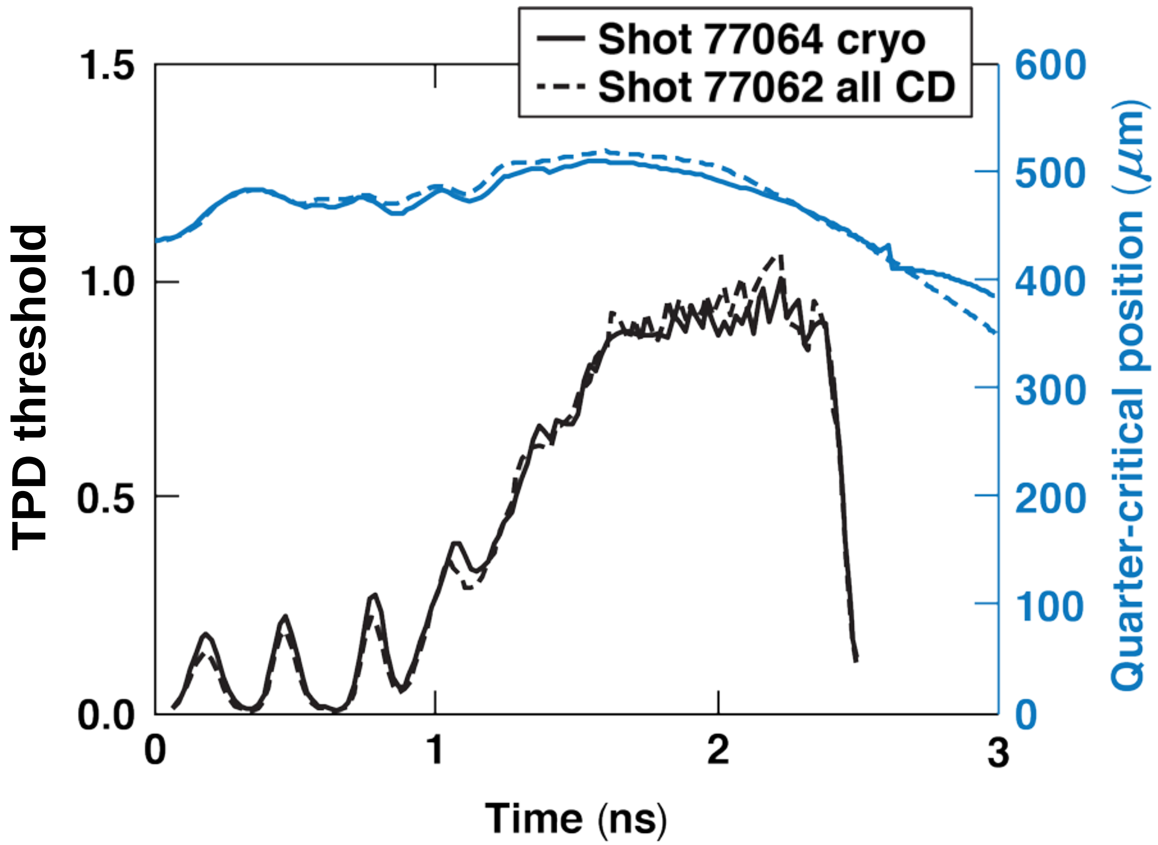
$$\frac{E_{\mathrm{rad}}}{E_{\mathrm{dep}}} = \frac{\int_0^\infty f(E_0)\,\int_0^{E_0} \frac{\mathrm{d}E_{\mathrm{rad}}}{\mathrm{d}E_{\mathrm{collision}}}\,\mathrm{d}E\,\mathrm{d}E_0}{\int_0^\infty f(E_0)\;E_0\,\mathrm{d}E_0}$$

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

$$\boldsymbol{E}_{\mathbf{hot,DT}} = \frac{\mathbf{HXR}_{\mathbf{all\ CD}} - \mathbf{HXR}_{\mathbf{cryo}}}{\left(\frac{\boldsymbol{E}_{\mathbf{rad}}}{\boldsymbol{E}_{\mathbf{dep}}}\right)_{\mathbf{CD}} - \left(\frac{\boldsymbol{E}_{\mathbf{rad}}}{\boldsymbol{E}_{\mathbf{dep}}}\right)_{\mathbf{DT}}}$$

- **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



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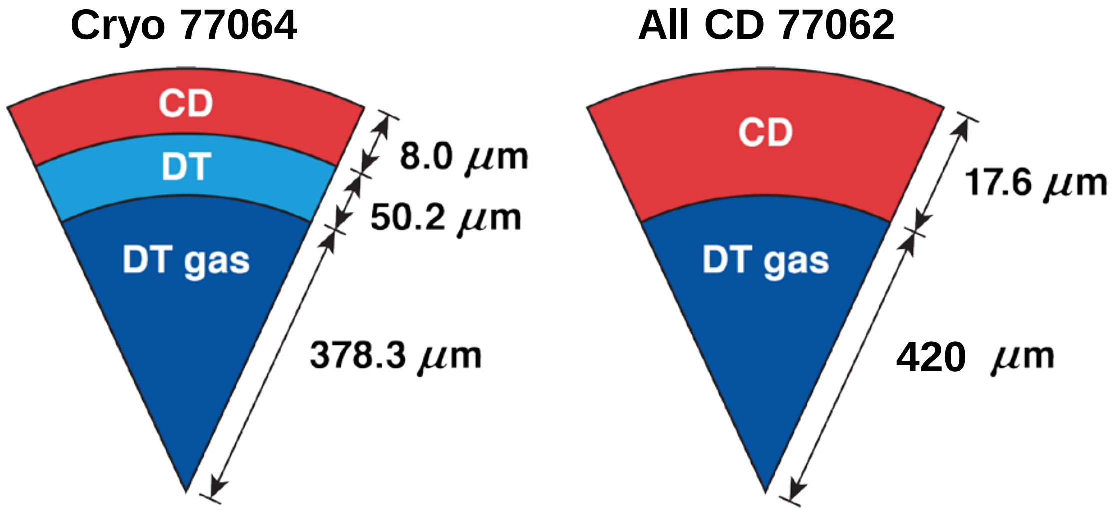
- The TPD threshold* $\eta = \dfrac{I_{14\,\mathrm{W/cm^2}}\,L_{\mu\mathrm{m}}}{233\,T_{\mathrm{keV}}}$



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).

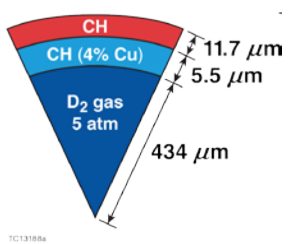
Preheat is modeled using the hot-electron deposition package in *LILAC*

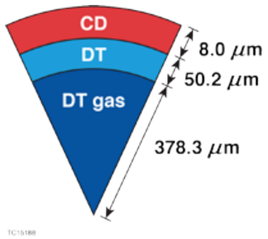
- The 1-D code *LILAC* uses a straight-line model where electrons lose energy according to a slowing-down formula*
- The radiation emitted by hot electrons is calculated from NIST tables
- The hot-electron source is Maxwellian with the measured temperature
- Electrons are born at the quarter-critical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

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





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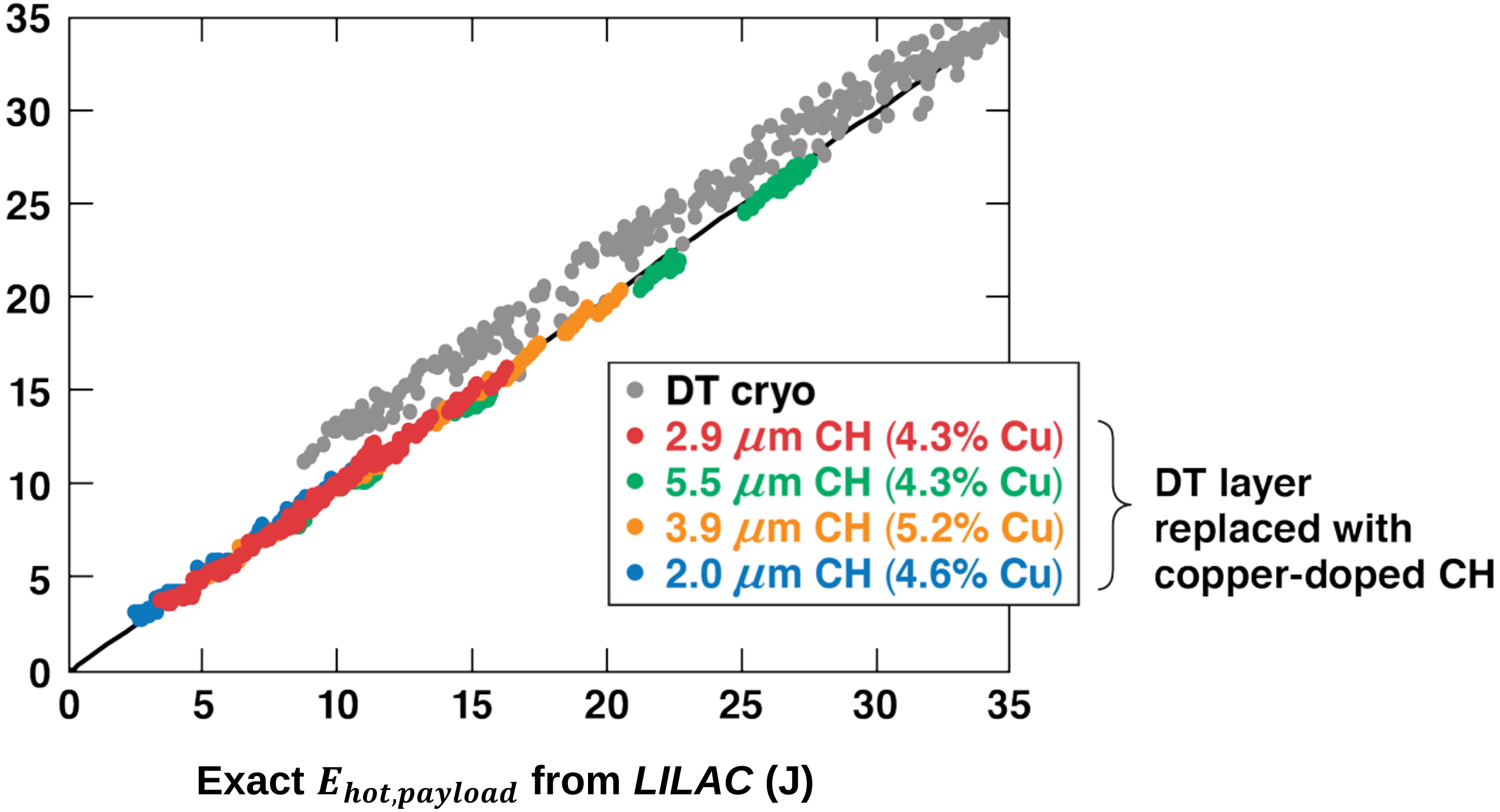
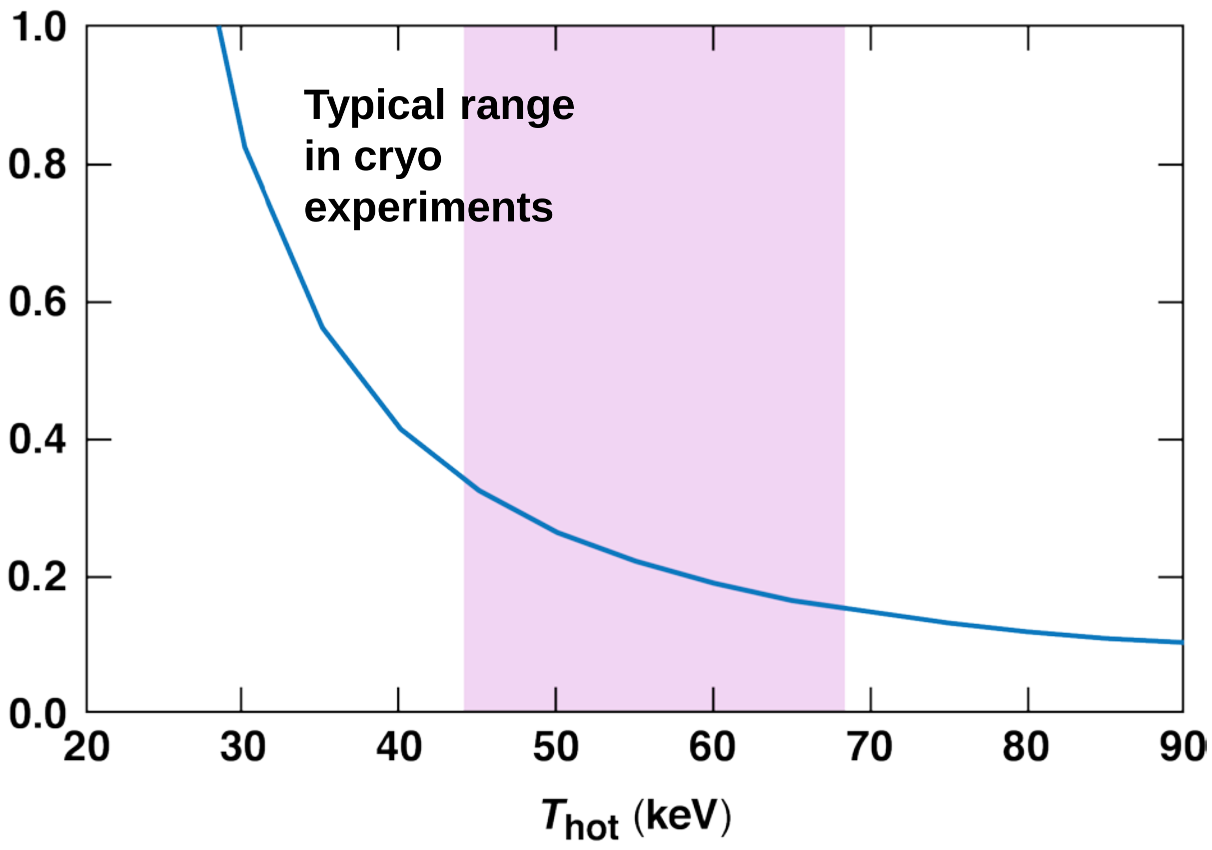


The ratio of DT preheat energy to hard x-ray difference is a function of the hot-electron temperature

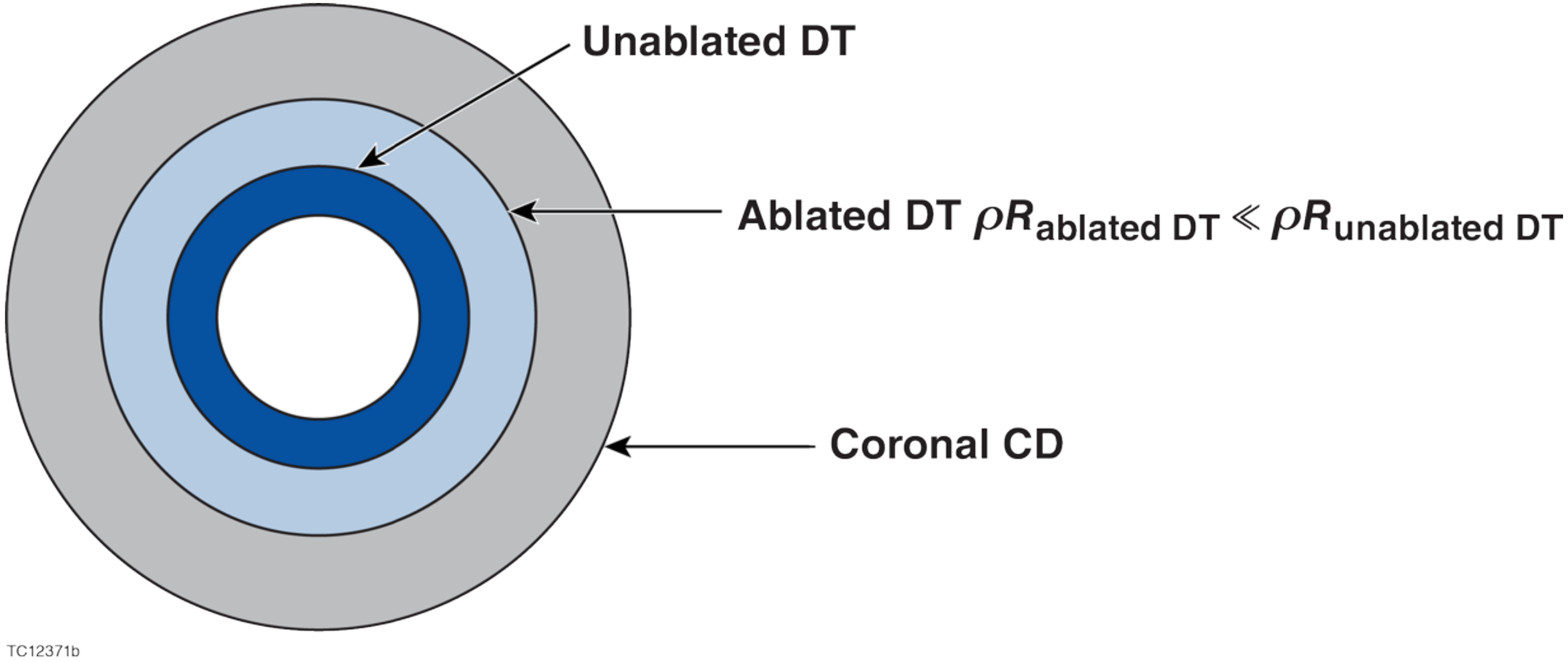
$$\frac{\textbf{Hot electron energy deposited into DT (J)}}{\textbf{HXRD}_{\textbf{All CH,pC}} - \textbf{HXRD}_{\textbf{cryo,pC}}}$$



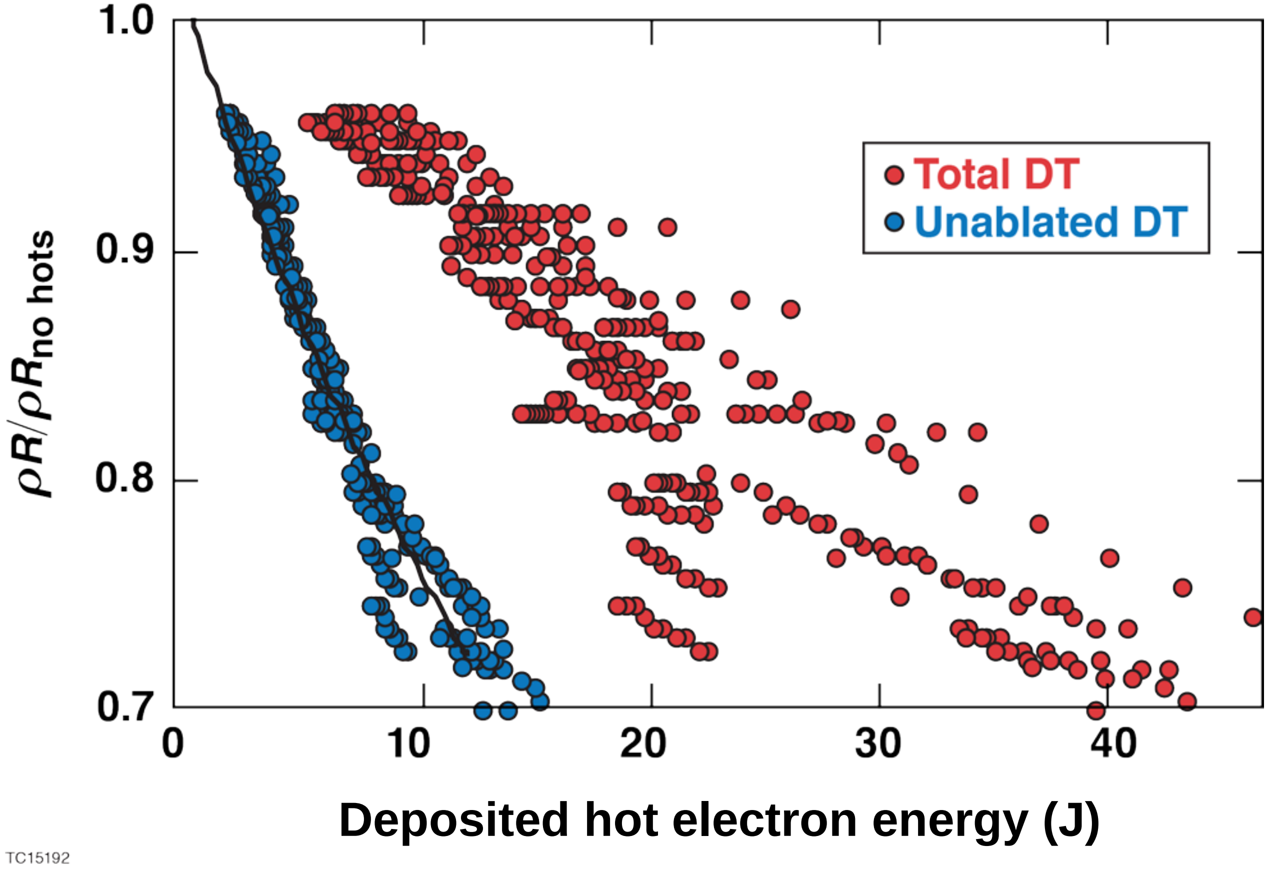
TC15190

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



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



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

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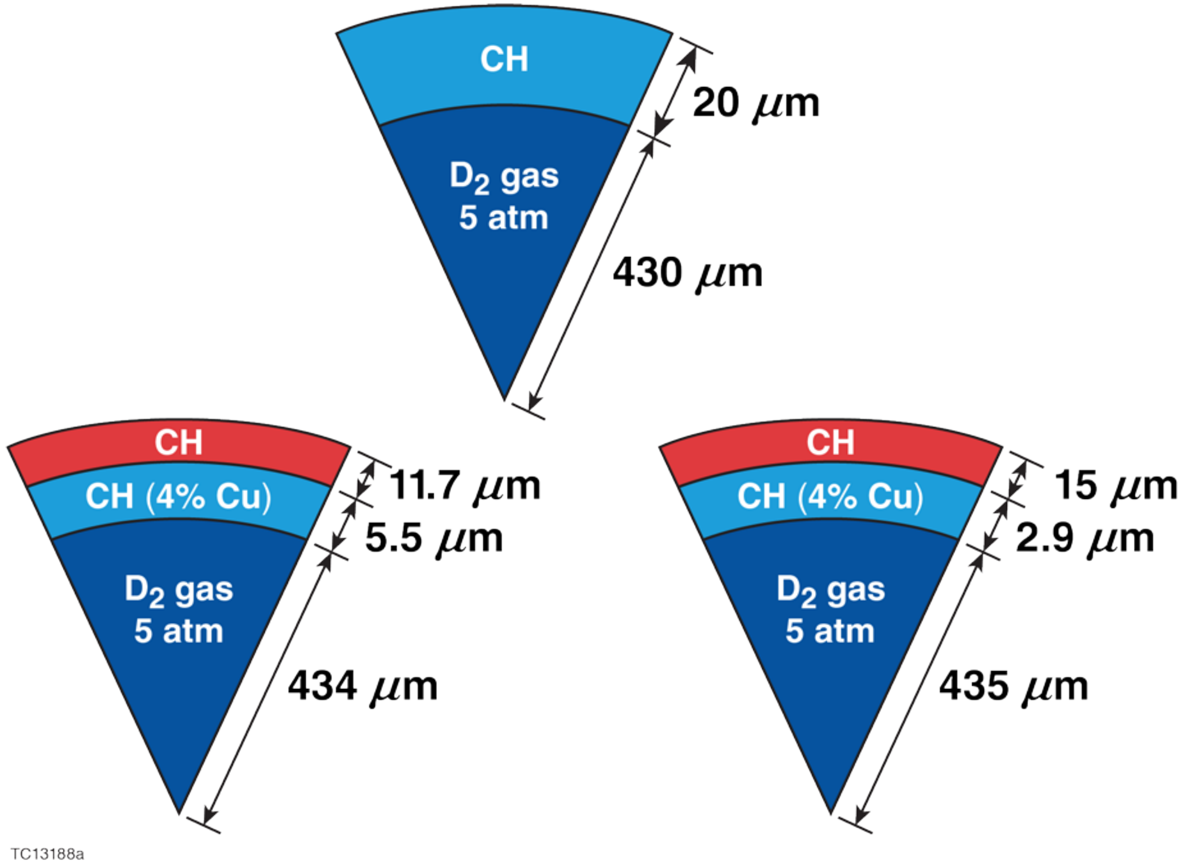
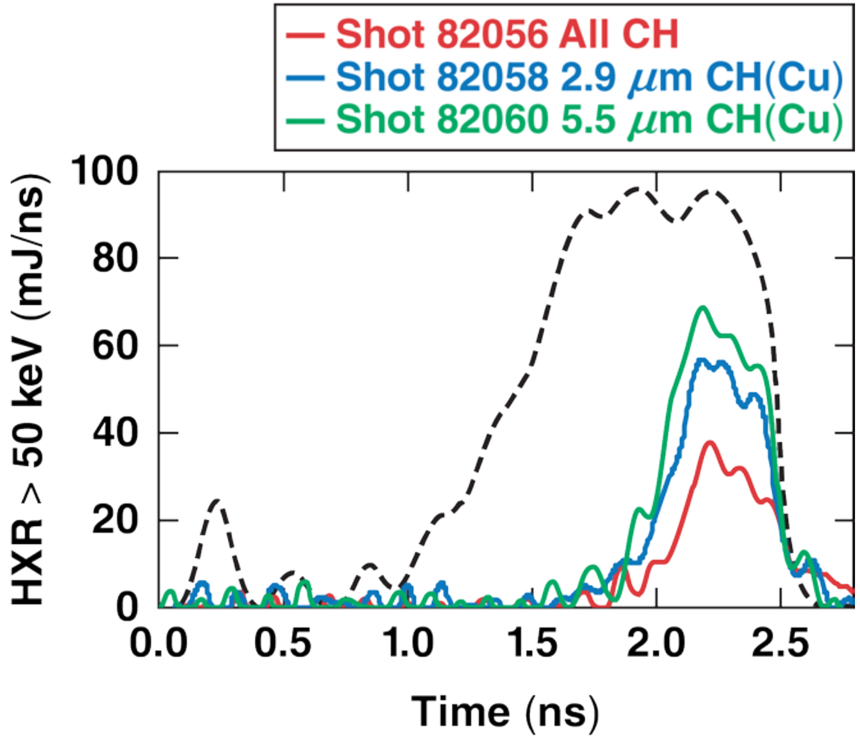
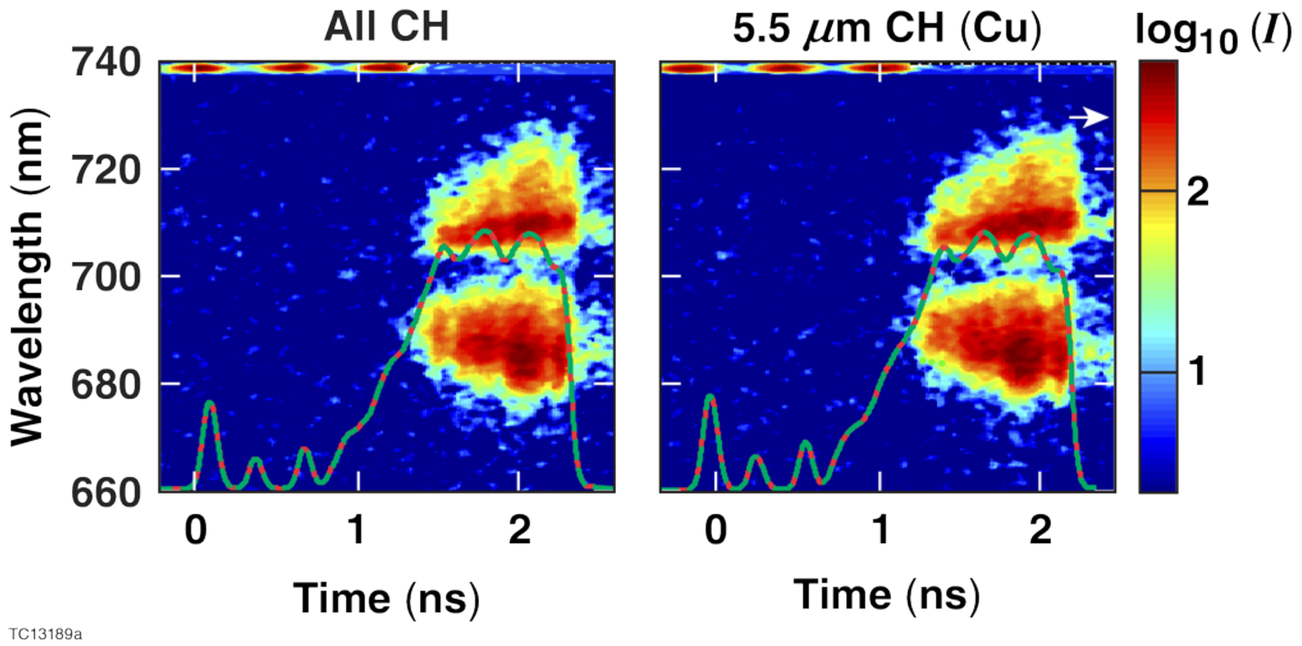
- Hot-electron preheat and the preheat formula
- **Hot-electron transport experiments and modeling on OMEGA**
- Hot-electron transport experiments on the NIF

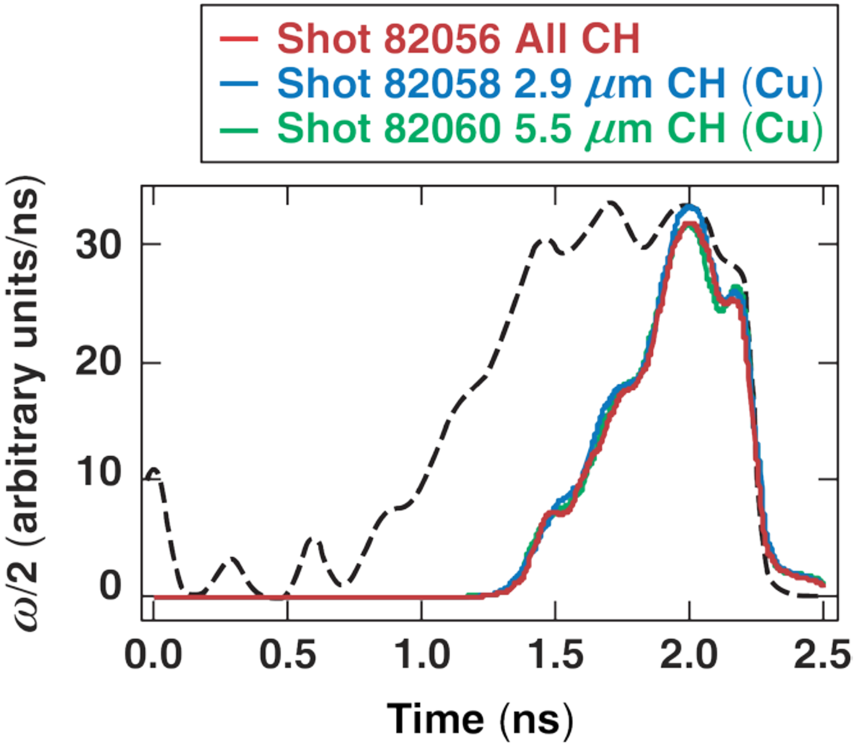
An experimental platform that utilized Cu-doped payloads of varying thicknesses was developed to measure where the hot electrons deposit their energy





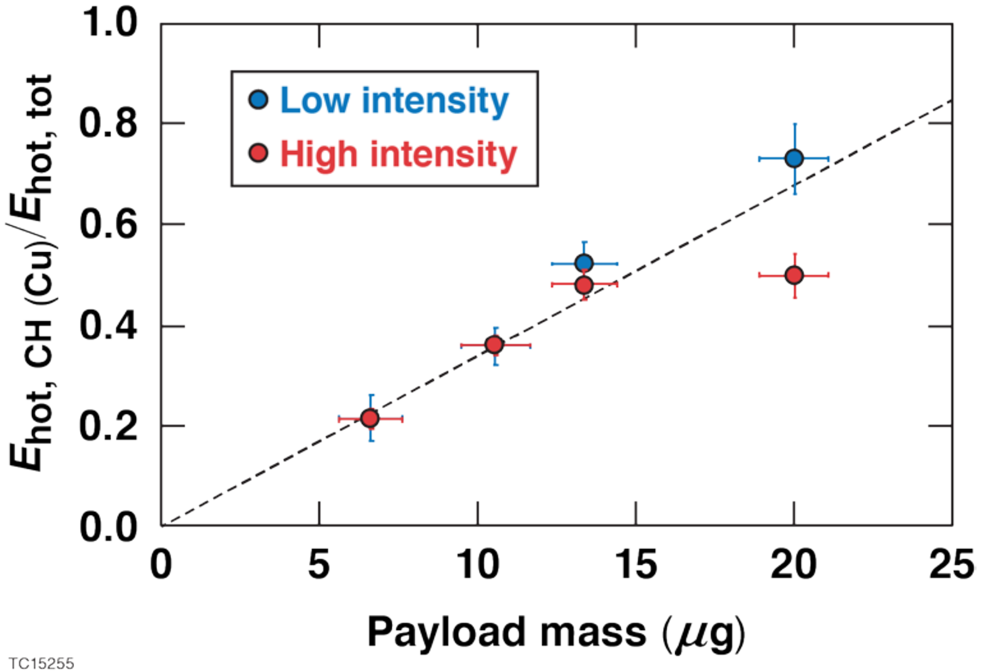
$\omega/2$ images indicate that the TPD activity in the corona is identical between the all-CH and CH (Cu) payload implosions





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



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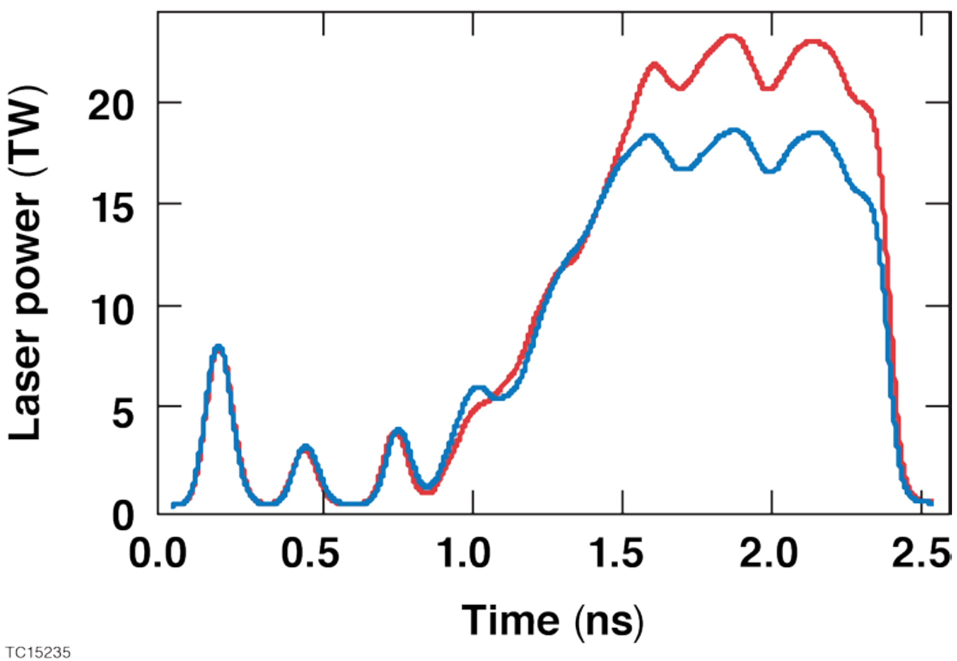

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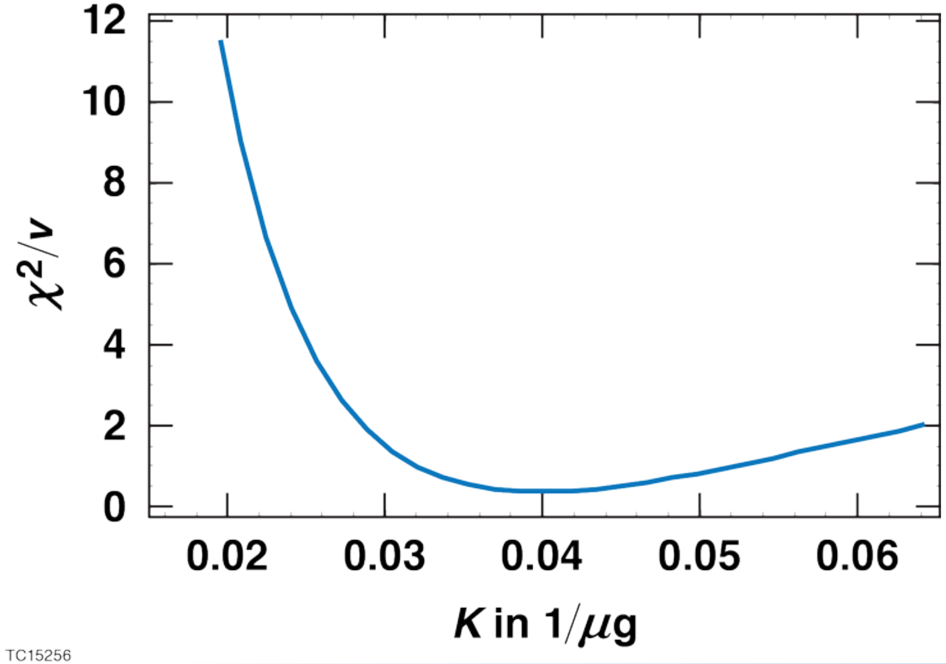
A simple model based on uniform deposition per unit mass was developed to describe the multilayered experiments

$$K \equiv \frac{1}{E_{\mathrm{hot,tot}}}\frac{\mathrm{d}E_{\mathrm{dep}}}{\mathrm{d}M} = \mathrm{const}$$

$$E_{\mathrm{hot,CH(Cu)}} = \mathrm{KE}_{\mathrm{tot}} M_{\mathrm{payload}}$$

$$E_{\mathrm{hot,tot}} = \frac{\mathrm{HXRD}_{\mathrm{All\ CH}}}{\left[E_{\mathrm{rad}}/E_{\mathrm{dep}}\right]_{\mathrm{CH}}}$$

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



M_{payload} = payload mass

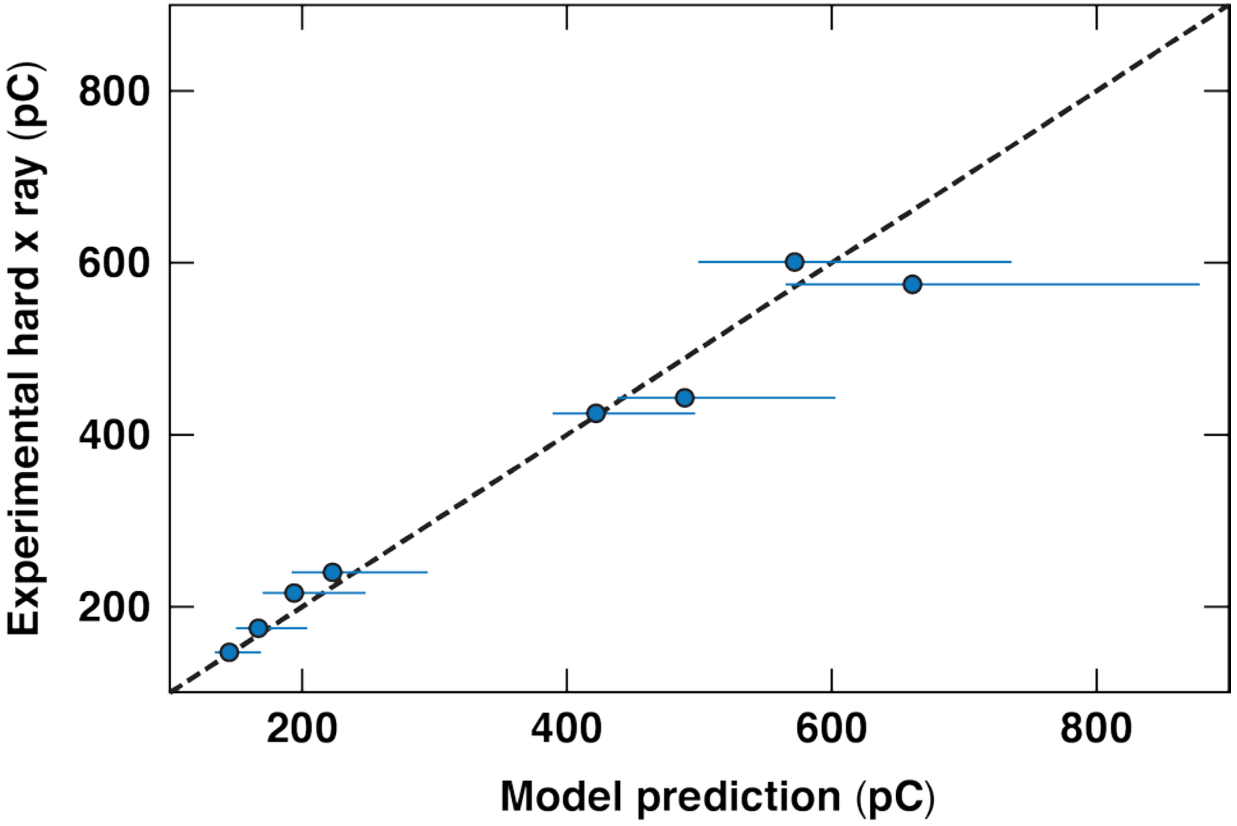
$E_{\mathrm{hot,CH(Cu)}}$ = energy deposited into CH (Cu)

$E_{\mathrm{hot,tot}}$ = total hot-electron energy

$\frac{\mathrm{d}E_{\mathrm{dep}}}{\mathrm{d}M}$ = electron energy deposited per unit mass

TC15256

The good agreement between the model and data confirms the hypothesis that hot-electron deposition is approximately uniform with respect to mass

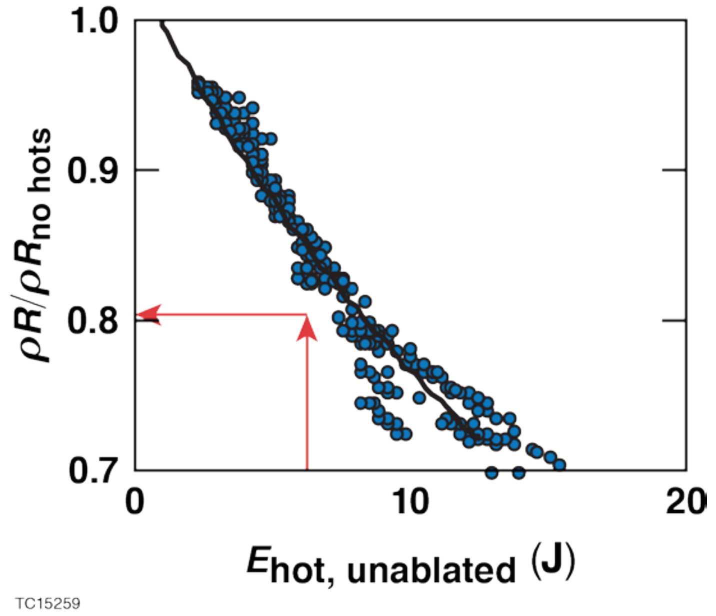


TC15257

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

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

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



Shot number	$E_{\text{hot, DT}}$	$E_{\text{hot, unablated}}$	$\rho R_{\text{experiment}}$	$\rho R_{LILAC\text{, no hots}}$	$\rho R_{LILAC\text{, hots}}$
77064	14±3 J	5±1 J	195±17 mg/cm^2	230 mg/cm^2	198±5 mg/cm^2
85784	22±4 J	8±2 J	160±14 mg/cm^2	210 mg/cm^2	170±9 mg/cm^2

*S. P. Regan *et al.*, Phys. Rev. Lett. 117, 025001 (2016); 117, 059903(E) (2016).

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- **Hot-electron transport experiments on the NIF**

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

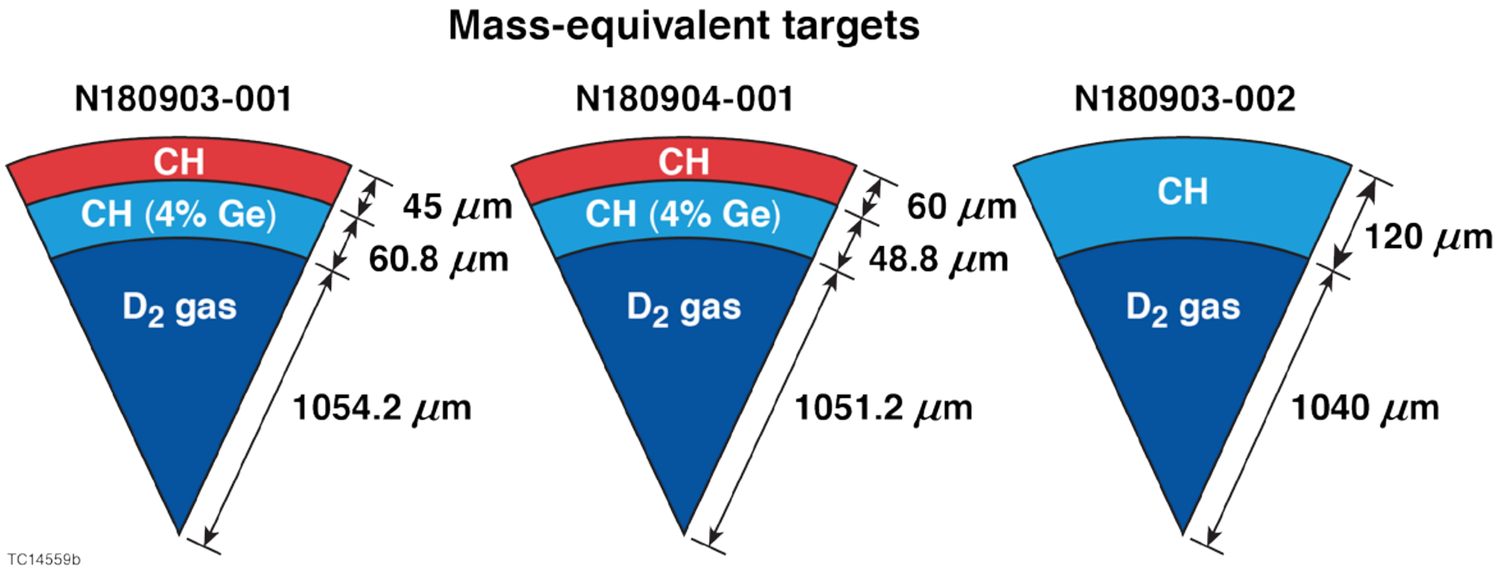
	NIF	OMEGA
Scale length at quarter-critical $L_{\mu m}$	$\sim$400 μm	$\sim$150 μm
Electron temperature at quarter-critical $T_{e,keV}$	$\sim$3.2 keV	$\sim$2.5 keV
Intensity at quarter-critical I_{14}	$\sim$4 to 8 $\times$ 10^{14} W/cm^2	$\sim$3.5 $\times$ 10^{14} W/cm^2
η_{TPD}	~2 to 5	~1
η_{SRS}	~5 to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

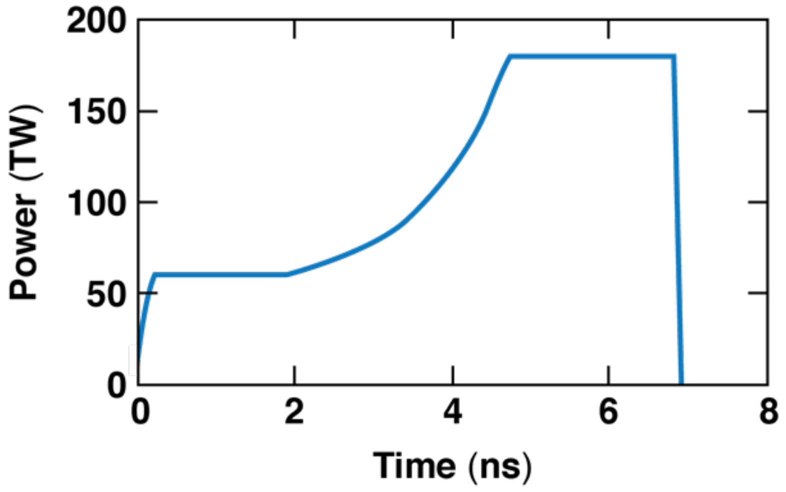
$$\eta_{TPD} = I_{14} L_{\mu m} / 233\ T_{e,keV}$$

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

LPI: laser–plasma interaction
SRS: stimulated Raman scattering

The OMEGA preheat platform is being developed on the NIF to measure the coupling of hot electrons into the target

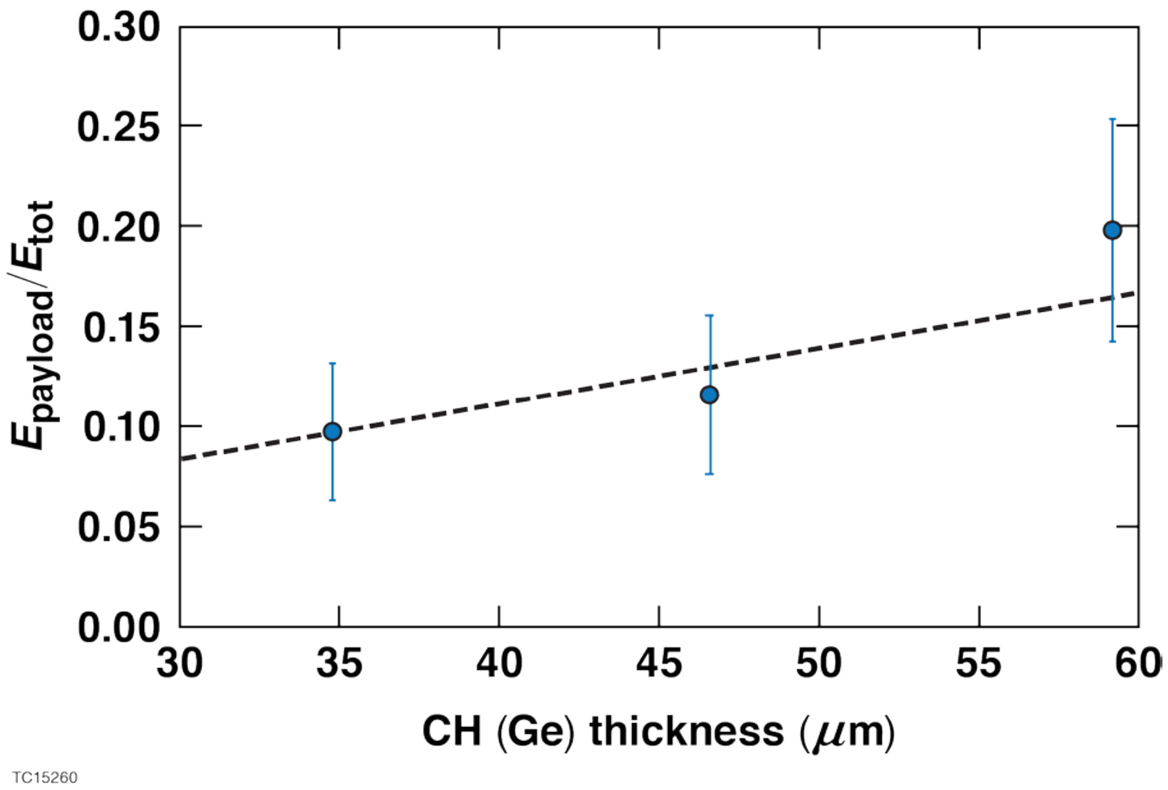




Different buried depths of the Ge-doped layer are examined to diagnose the hot-electron deposition profile in the imploding shell

* A. A. Solodov *et al*., NO5.00011, this conference.

Experiments on the NIF indicate that approximately one quarter of the total hot-electron energy is coupled into the unablated shell*



- More detailed hydro-scaled experiments are still needed to quantify the scaling of preheat with laser energy

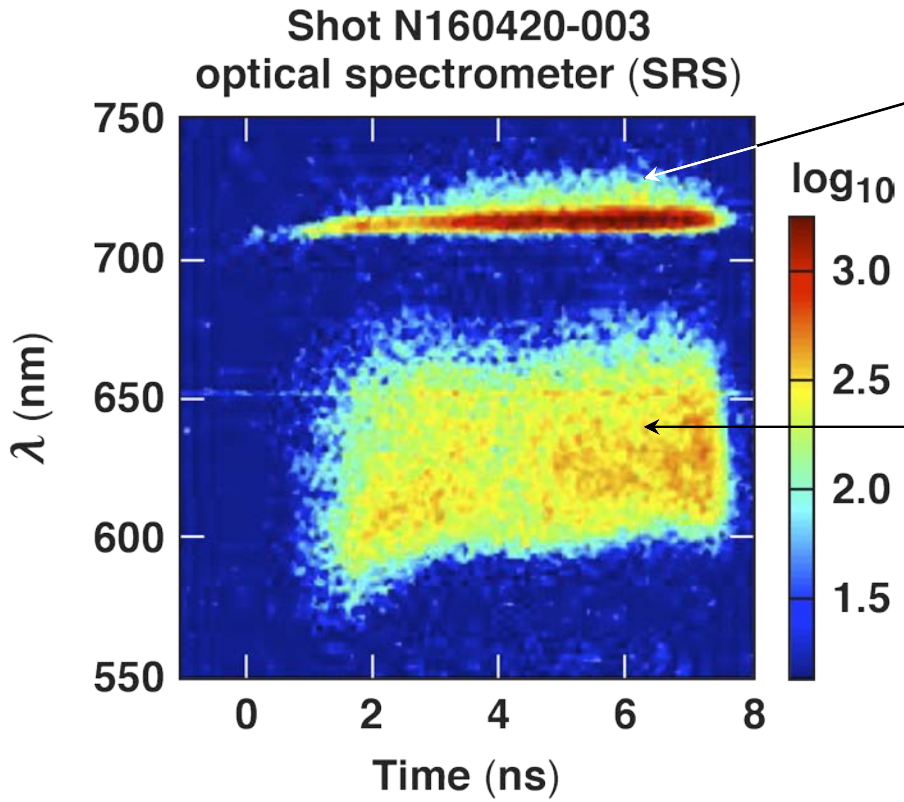
* A. A. Solodov *et al*., NO5.00011, this conference.

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
- Modeling of these experiments indicated an ~10-20% degradation in areal density as a result of hot-electron preheat for typical $\alpha = 4$ designs
- A similar experimental campaign is underway on the NIF to assess the viability of direct drive on the NIF

Backup

On OMEGA, TPD is the dominant hot-electron source, while NIF experiments show significant amounts of SRS



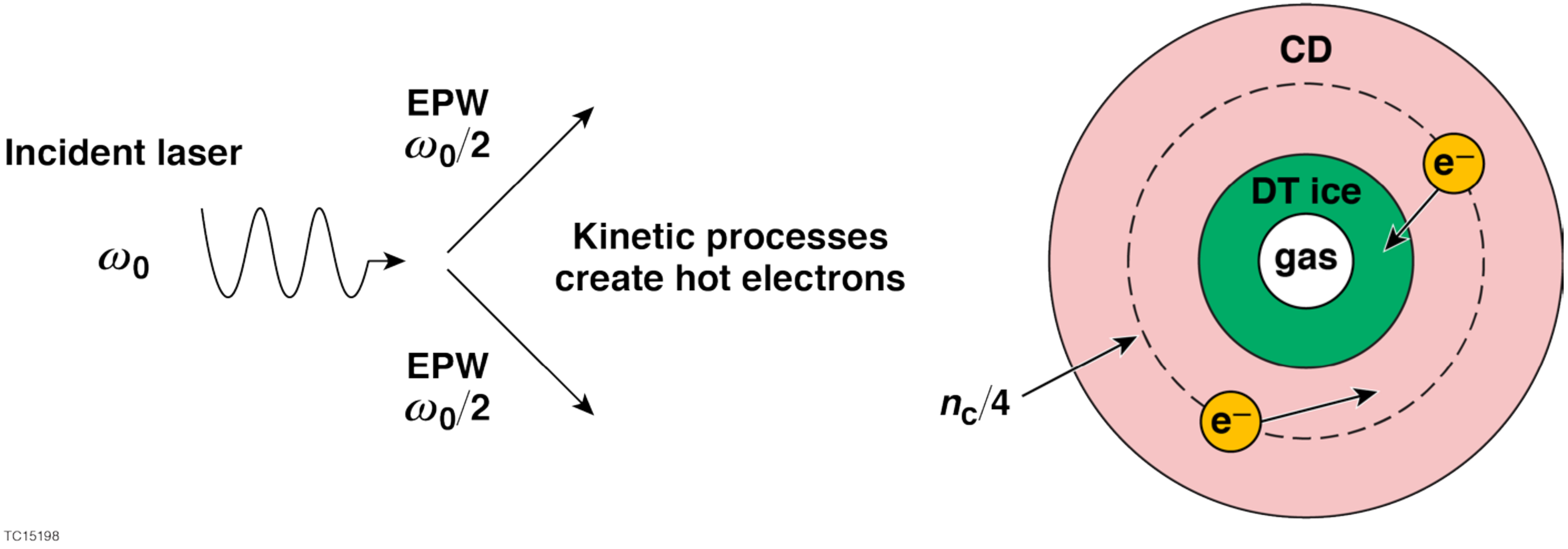
Absolute SRS at $\omega/2$ ($\lambda = 700\ \mu m = 2\lambda_0$)

SRS emission ($700\ \mu m > \lambda > \lambda_0$)

E25567k

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

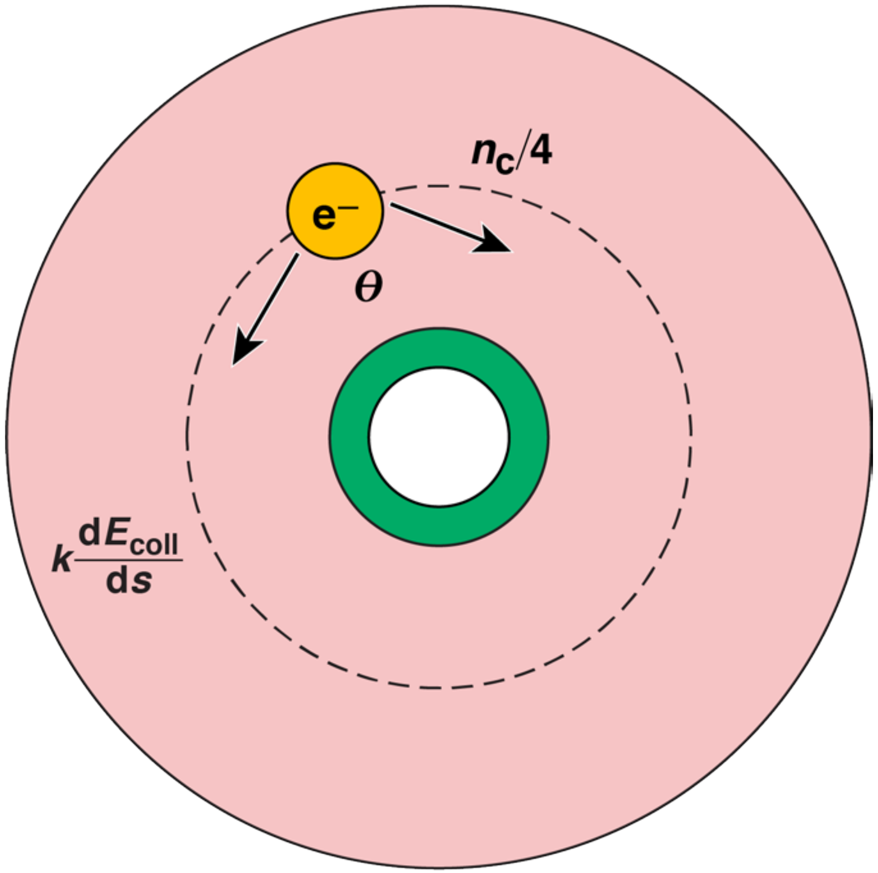
- The TPD instability is thought to be the prevalent source of hot electrons in direct-drive ICF



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

ICF: inertial confinement fusion
EPW: electron plasma wave

Electron transport is described with a two-parameter *ad hoc* model to fit the data where the electron divergence angle and coronal stopping power are varied



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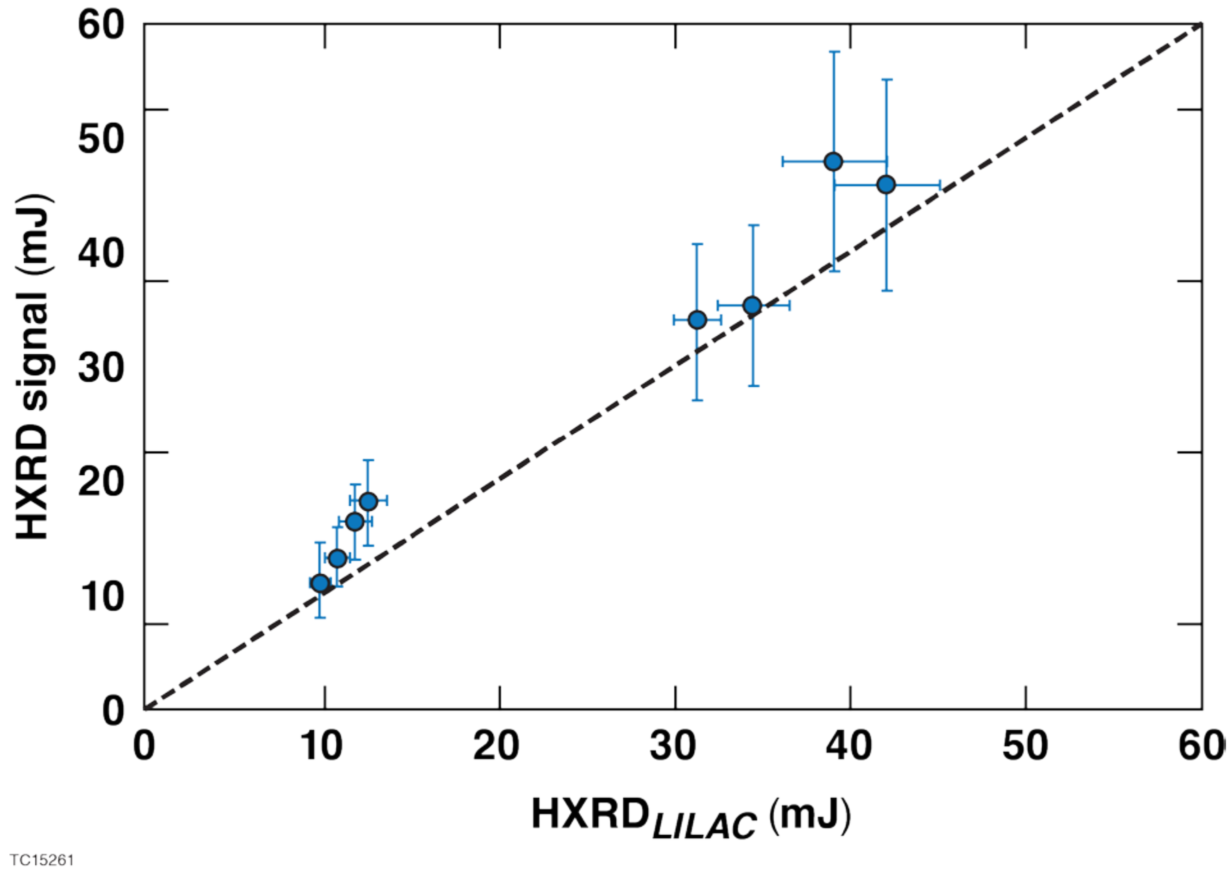
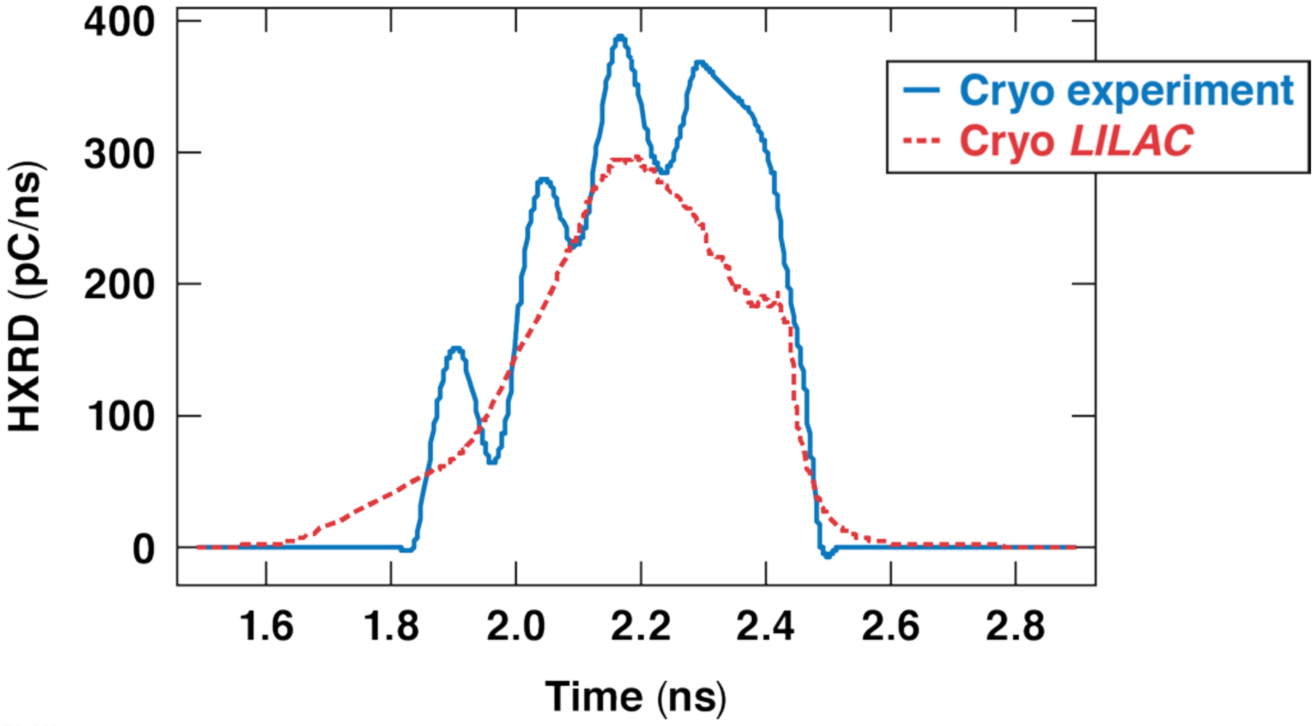
The best fit to the experimental data occurs at a full divergence angle of 40°



The hot-electron model almost captures the measured hard x-ray signal in the cryo experiment and predicts that 9±5 out of 44±10 J of preheat energy is coupled into the unablated DT



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$\rho R_{\text{experiment}}$	$\rho R_{LILAC\text{, no hots}}$	$\rho R_{LILAC\text{, hots}}$
160±14 mg/cm^2	206 mg/cm^2	160±16 mg/cm^2