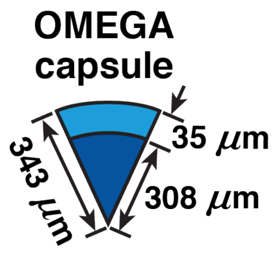
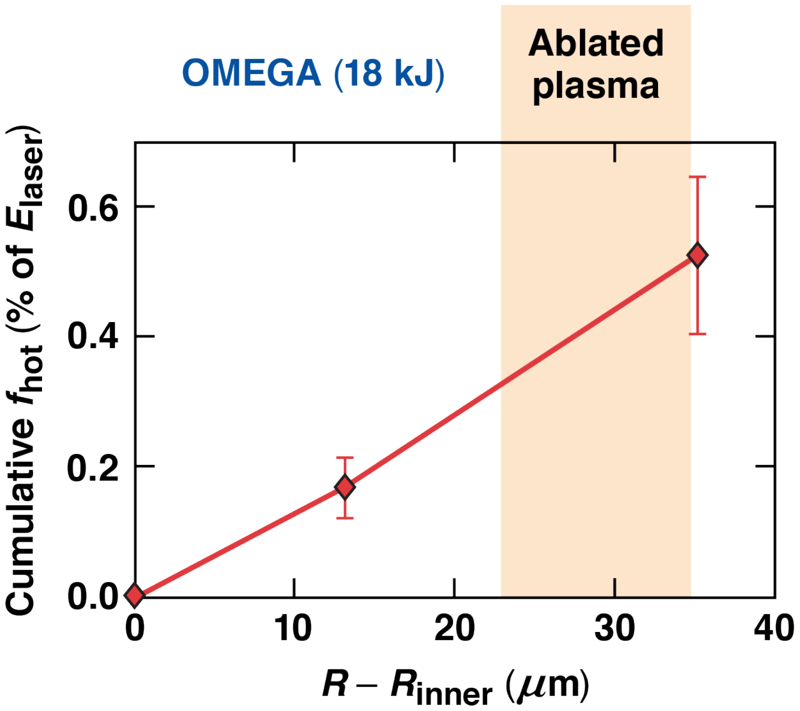
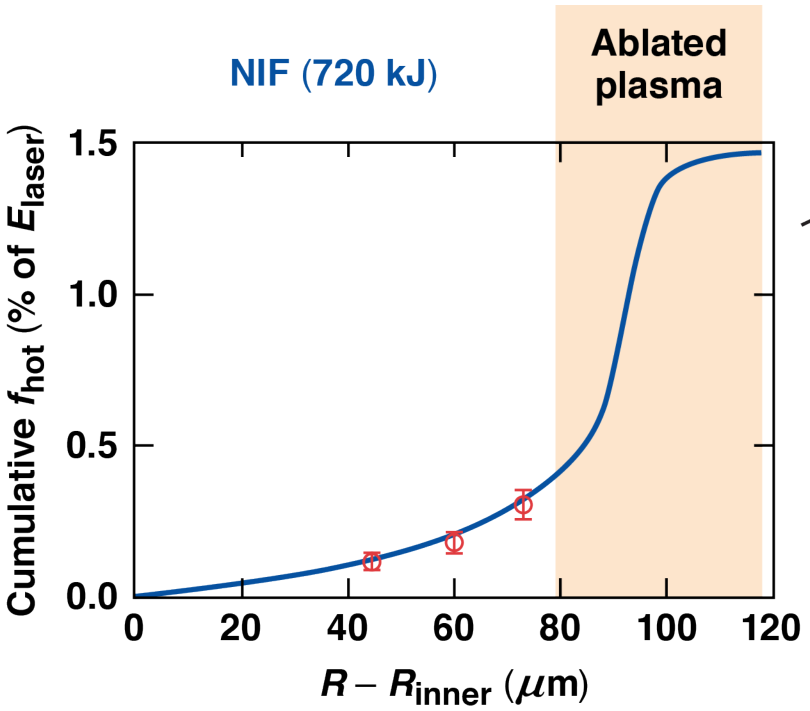
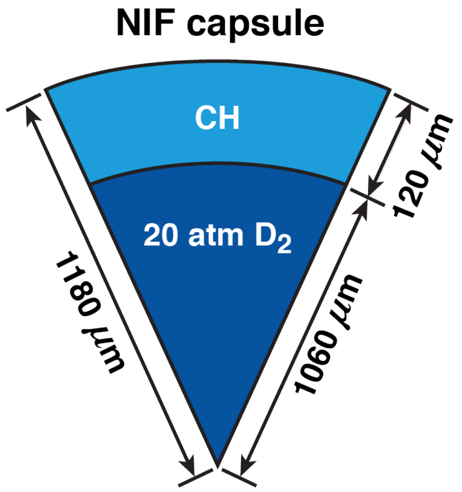
Hydrodynamic Scaling and Hot Electron Preheat in NIF and OMEGA Direct-Drive ICF Implosions









M. J. Rosenberg
University of Rochester
Laboratory for Laser Energetics

64th Annual Meeting of the
APS Division of Plasma Physics
Spokane, WA
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Summary

Hot electron preheat and implosion trajectory data support the hydrodynamic equivalence of scaled direct-drive implosions between NIF and OMEGA

- **Hydrodynamic scaling underpins extrapolation of direct-drive implosion performance from OMEGA to NIF energies**
  - **Scaling of both hydrodynamics and hot electron preheat have been studied experimentally**

- **Hydro-scaled NIF and OMEGA implosions at 10^{15} W/cm^2 (720 kJ and 18 kJ, respectively) both produce ~0.2% of laser energy deposited as hot electron preheat in the inner ~80% of unablated shell**
  - **1.3 MJ experiments generate more preheat (up to ~0.4%)**

- **Implosion trajectories approximately follow the hydro-scaling relations between 720 kJ (NIF) and 18 kJ (OMEGA) implosions**

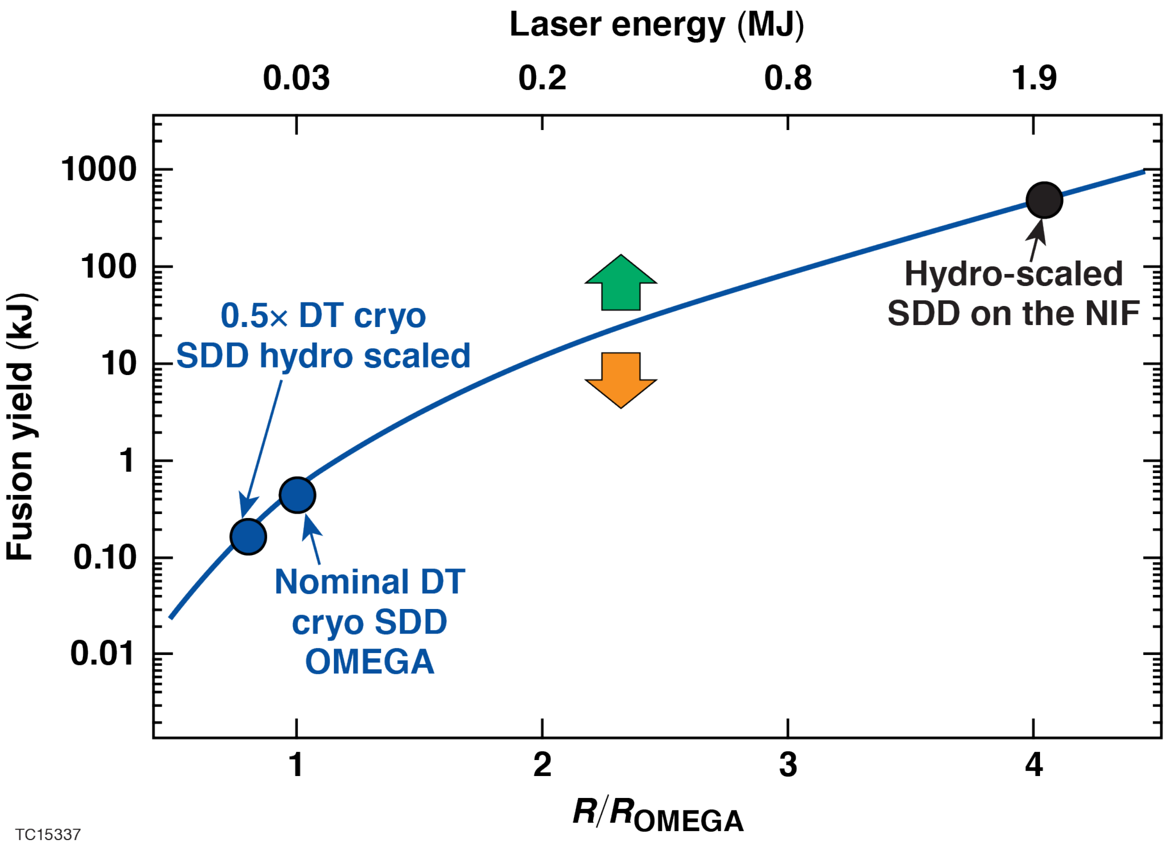
Collaborators

A. A. Solodov, R. Betti, P. B. Radha, S. Kostick, C. Stoeckl, C. J. Forrest, V. Yu. Glebov, F. J. Marshall, S. P. Regan, W. Theobald, T. J. B. Collins, D. H. Froula, J. P. Palastro, and V. N. Goncharov
University of Rochester
Laboratory for Laser Energetics

M. Hohenberger, B. Bachmann, G. N. Hall, A. R. Christopherson, P. Michel
Lawrence Livermore National Laboratory

C. Krauland
General Atomics

Hydrodynamic scaling is used to extrapolate performance of direct-drive cryogenic implosions from OMEGA to NIF energies



TC15337

Hydro-scaling relations for how parameters vary with laser energy

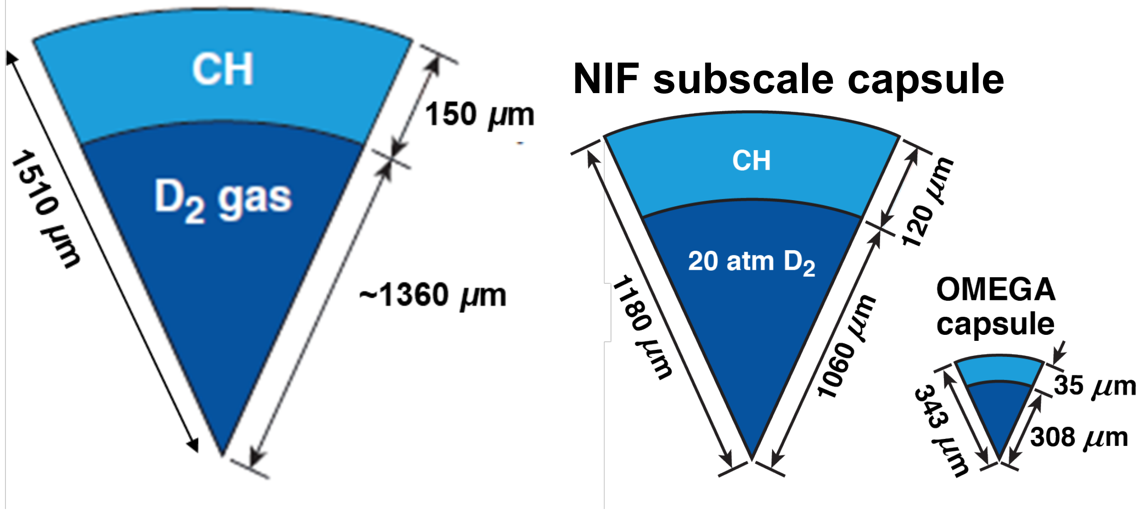
- All intrinsic properties (temperature, density, pressure, velocity) = fixed
- $M \propto E$
- $R \propto E^{1/3}$
- $t \propto E^{1/3}$
- $P \propto E^{2/3}$

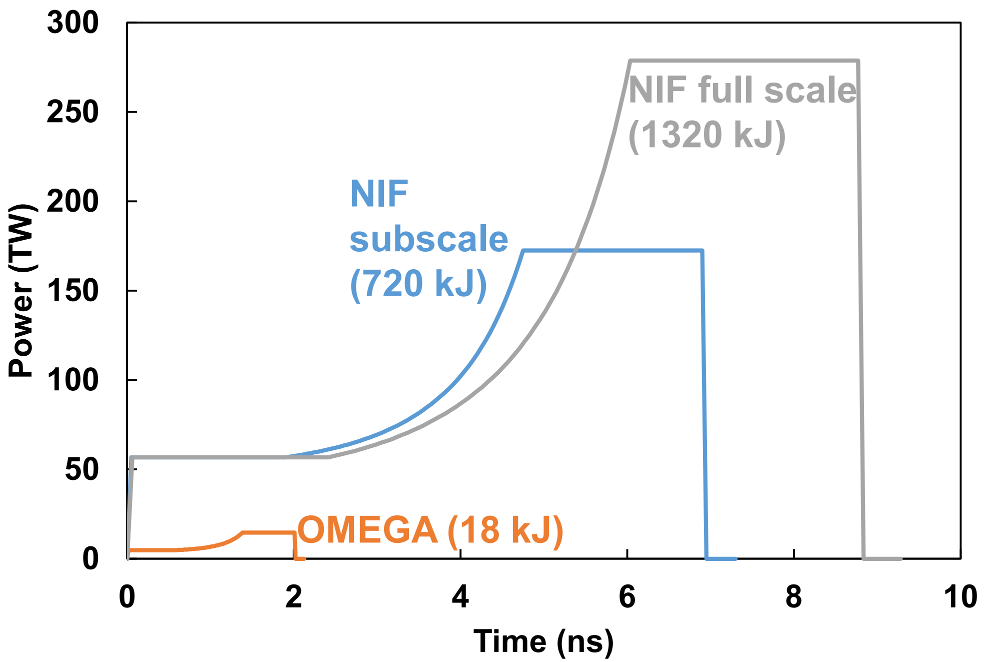
ICF observables

- $\text{Yield} \propto E^{4/3}$ (R^4)

Hydrodynamic scaling, as well as aspects of physics (e.g. hot electron preheat) that do not follow this scaling, need to be studied and verified experimentally

To study hydrodynamic and preheat scaling, hydro-equivalent polar direct drive (PDD) implosions were designed for NIF and OMEGA, spanning 70x in laser energy



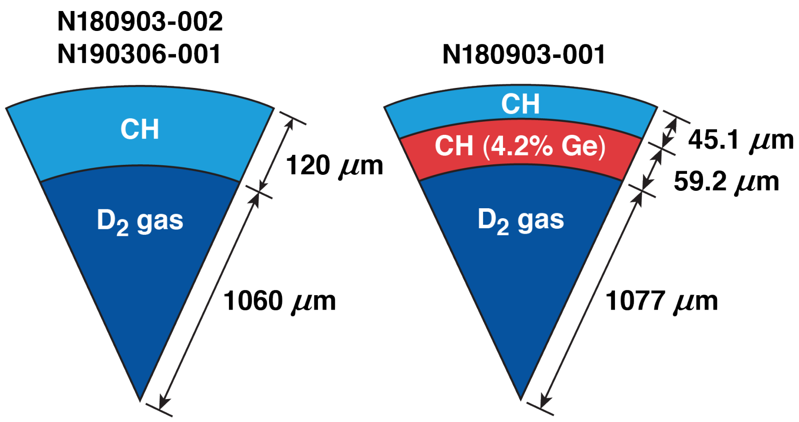


NIF full scale pulse not perfectly scaled to minimize optics damage

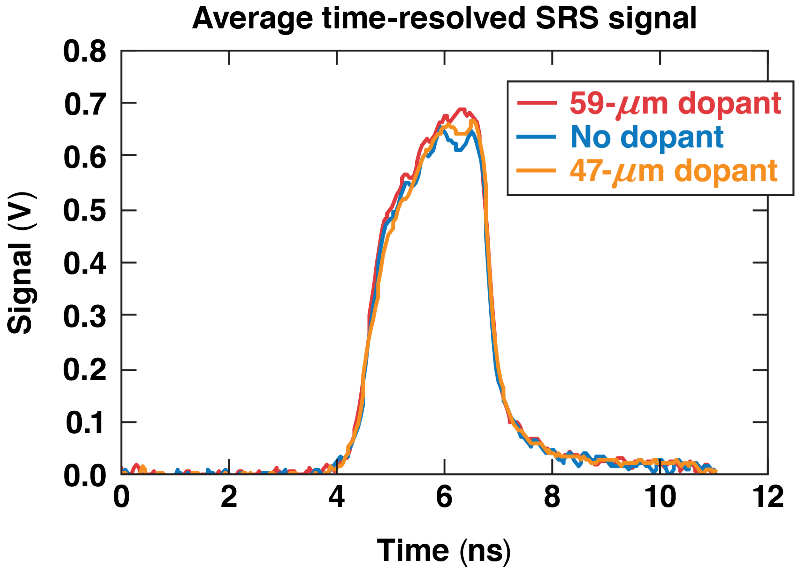
Incident laser intensity 10^{15} W/cm^2 preserved across all 3 scales

Hot electron preheat deposited into the inner layer of the shell is diagnosed using hard x-ray measurements in implosions with or without a Ge-doped layer

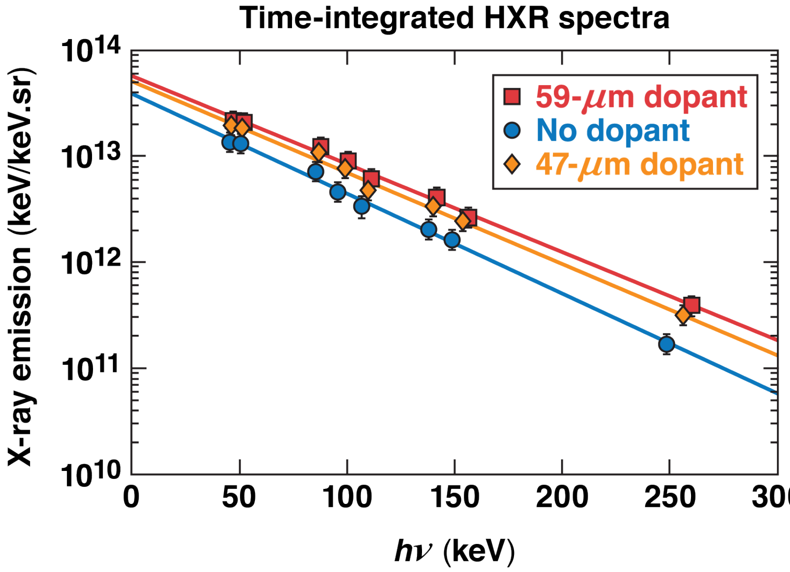
NIF target designs



Scattered light



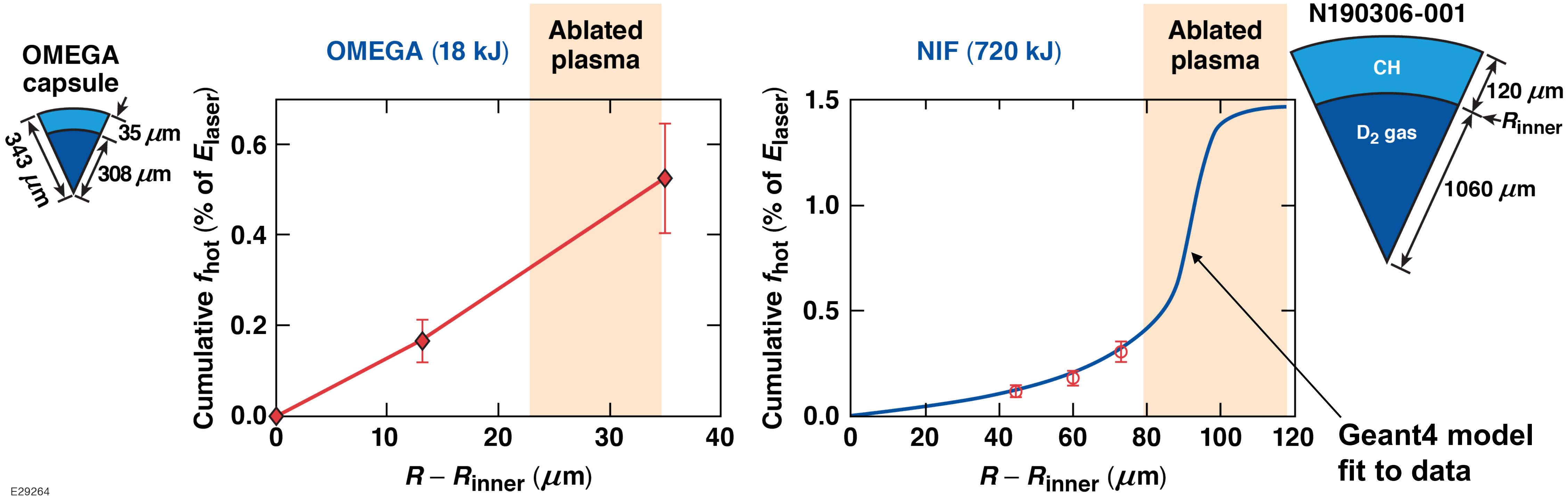
Hard x rays



The laser drive and hot electron source (SRS) is identical
→ difference in hard x-rays ∝ hot electron energy deposited in Ge-doped layer

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

OMEGA and subscale NIF experiments show 0.2% of hot electron energy deposited in the inner 80% of unablated shell, despite more hot e⁻ generation on NIF



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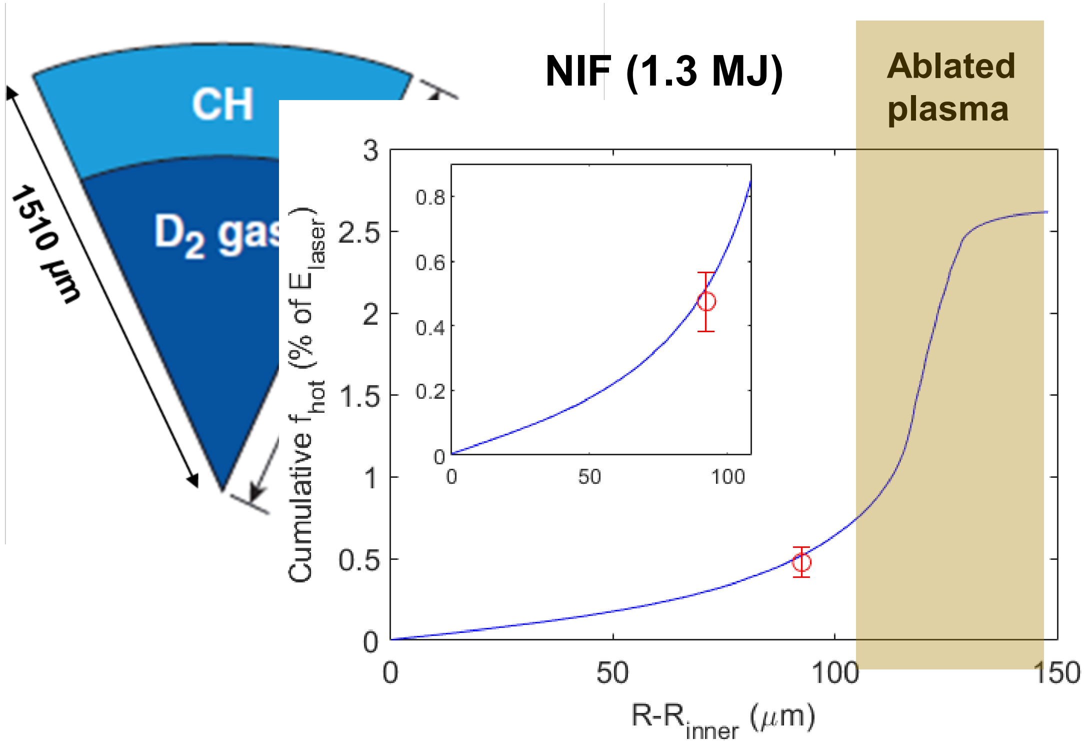
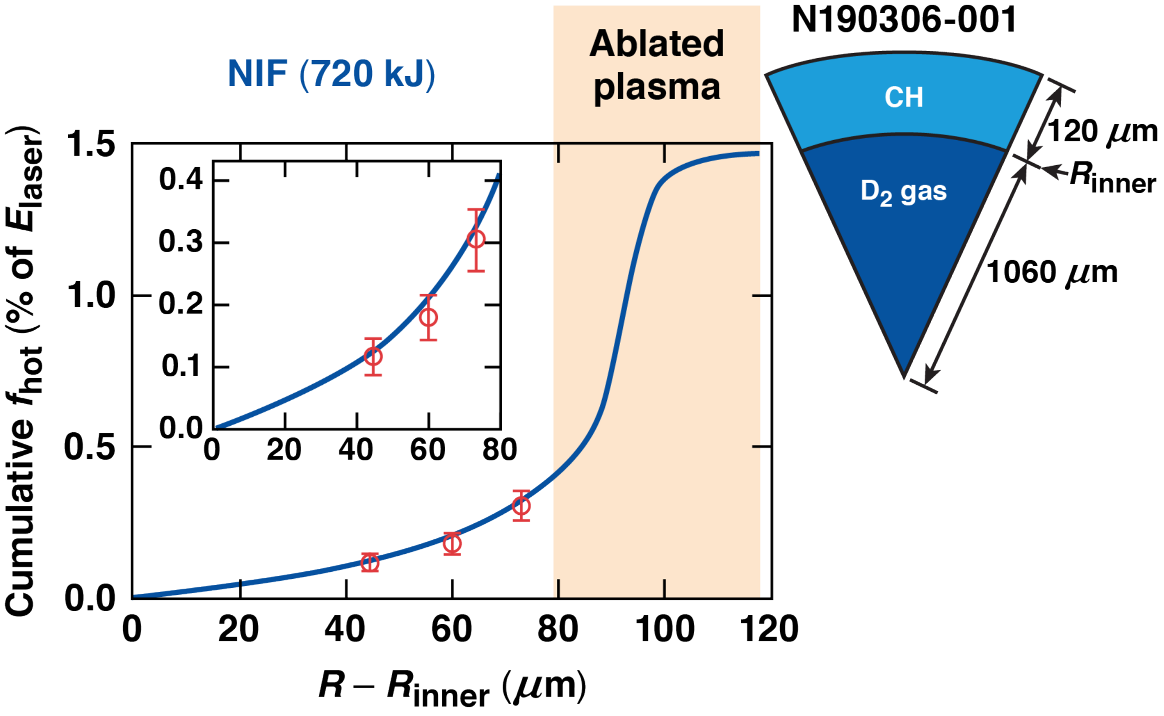
Results show that hot electron preheat does not invalidate hydrodynamic scaling between OMEGA and NIF warm implosions

See also A. A. Solodov *et al.* NI02.00005 (Wednesday am)

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





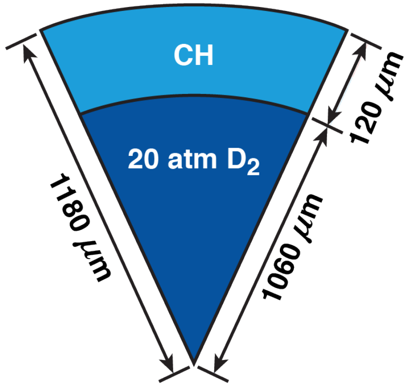
<u>Caveat: difference is less than the apparent factor of 2 because full scale pulse shape not exactly hydrodynamically scaled</u>

1) **Implosion convergence is lower during the pulse: hydro-scaled pulse would have lower preheat, by up to ~27%**
2) **E_{laser} lower than pure hydro-scale: hydro-scaled pulse would have lower $f_{hot} = E_{hot}/E_{laser}$ by definition, by ~13%**

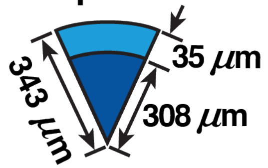
→ Hydro-scaled 3-mm NIF implosions would have <u>~30-50% more preheat than 2.3-mm experiments</u>

Implosion trajectories inferred from x-ray self-emission imaging show similar energetics in hydro-equivalent NIF and OMEGA PDD implosions

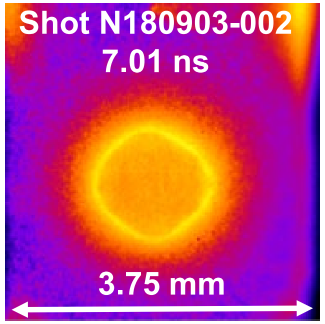
NIF capsule

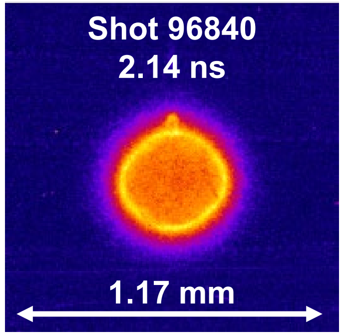


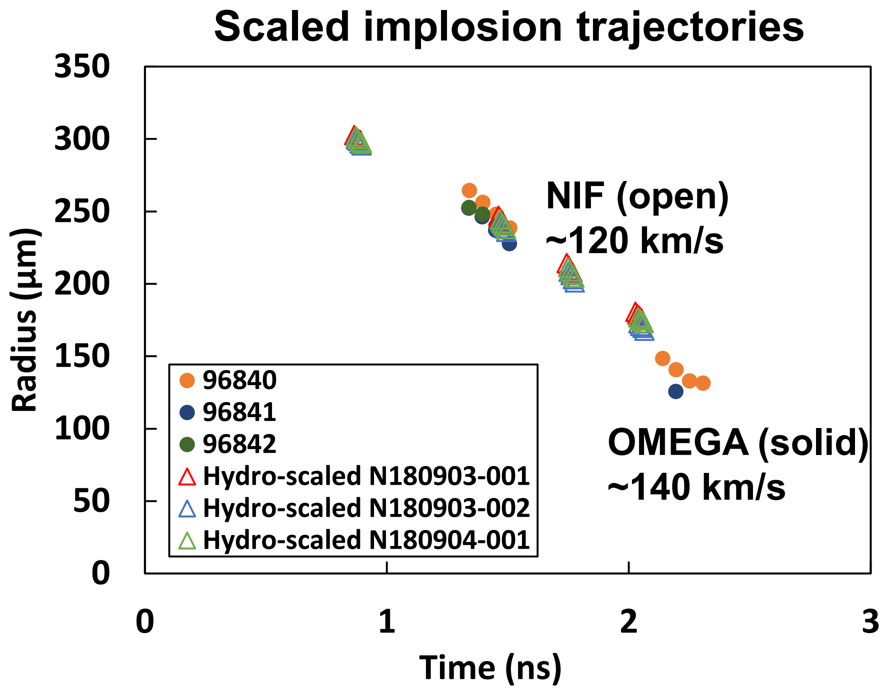
OMEGA capsule



X-ray self-emission images near equator







NIF time and radius hydro-scaled

$t_{NIF\_scaled} = t_{NIF} * (E_{L\_OMEGA}/E_{L\_NIF})^{1/3}$

$R_{NIF\_scaled} = R_{NIF} * (E_{L\_OMEGA}/E_{L\_NIF})^{1/3}$

E_{L_OMEGA} = 18 kJ

Near-overlap of scaled implosion trajectories supports validity of hydrodynamic scaling between OMEGA and NIF implosions

These results contribute to extrapolation of preheat in ignition-scale cryogenic direct drive implosions of around 0.15% of laser energy at 10^{15} W/cm^2

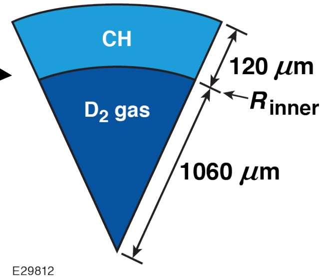
UR LLE

	Multiplier	Preheat (% of laser)
Preheat into inner 80% of unablated shell in warm subscale NIF implosion		~0.2%
Increase scale length to full scale	~1.5-2†	
Increase convergence ratio at end of pulse	~0.4-0.8†	
DT shell and some DT in ablator	~1-1.8‡	
Improve beam smoothing	~0.8†	
Si layer or dopant*	~0.5†	
Total	**~0.5-1**	**~0.1-0.2%**

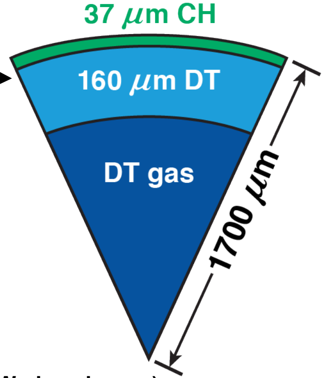
† Based on NIF and/or OMEGA data
‡ Based on hot electron transport modeling

Subscale NIF warm implosion

N190306-001



Notional NIF ignition design



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

* See A. A. Solodov *et al.* NI02.00005 (Wednesday am)
** J. Delettrez et al. Phys. Plasmas 26, 062705 (2019)

UNIVERSITY of ROCHESTER

Hot electron preheat and implosion trajectory data support the hydrodynamic equivalence of scaled direct-drive implosions between NIF and OMEGA

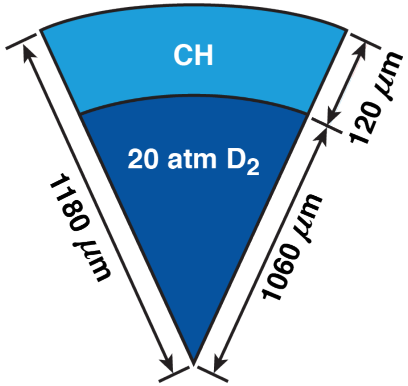
- **Hydrodynamic scaling underpins extrapolation of direct-drive implosion performance from OMEGA to NIF energies**
  - **Scaling of both hydrodynamics and hot electron preheat have been studied experimentally**
- **Hydro-scaled NIF and OMEGA implosions at 10^{15} W/cm^2 (720 kJ and 18 kJ, respectively) both produce ~0.2% of laser energy deposited as hot electron preheat in the inner ~80% of unablated shell**
  - **1.3 MJ experiments generate more preheat (up to ~0.4%)**
- **Implosion trajectories approximately follow the hydro-scaling relations between 720 kJ (NIF) and 18 kJ (OMEGA) implosions**

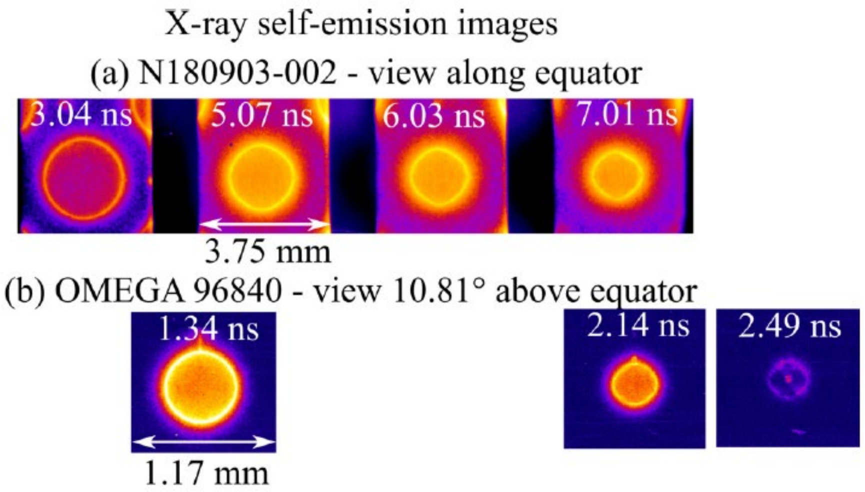
Extrapolation of these results to MJ-scale cryogenic PDD implosions indicates acceptable preheat around 0.1-0.2% of laser energy at 10^{15} W/cm^2 intensity, with scalable implosion properties

APPENDIX AND OLD SLIDES

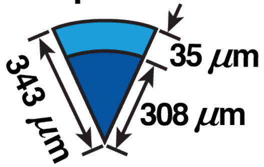
Implosion trajectories inferred from x-ray self-emission imaging show similar energetics in hydro-equivalent NIF and OMEGA PDD implosions

NIF capsule

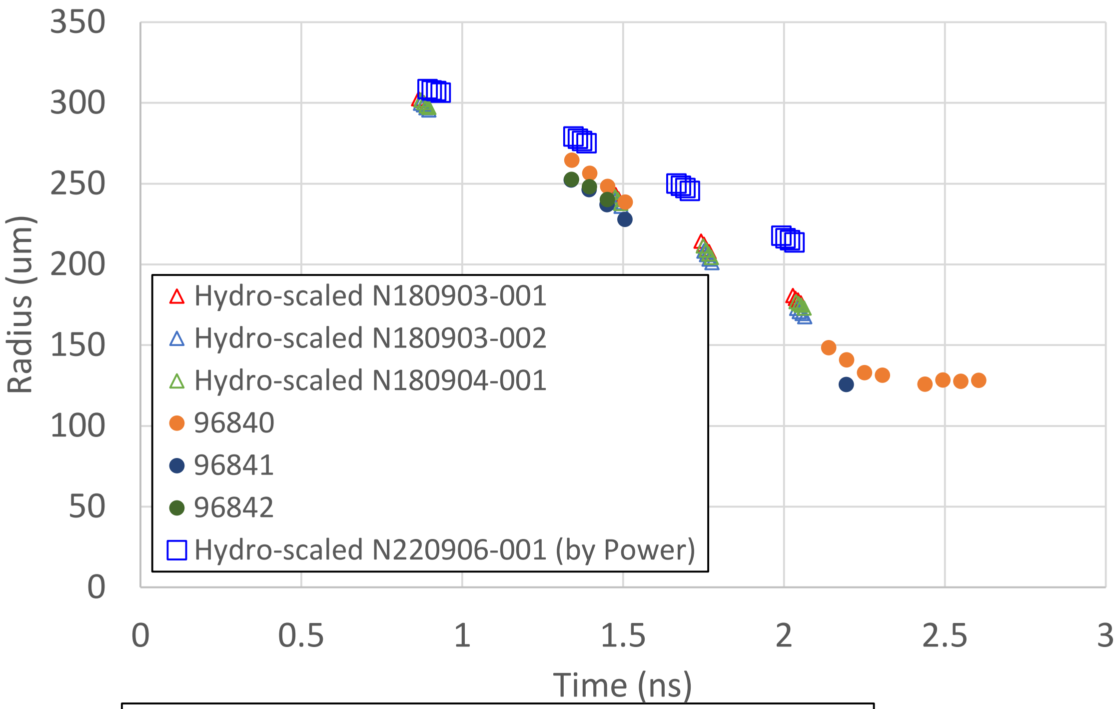




OMEGA capsule



Scaled implosion trajectories



NIF time and radius hydro-scaled

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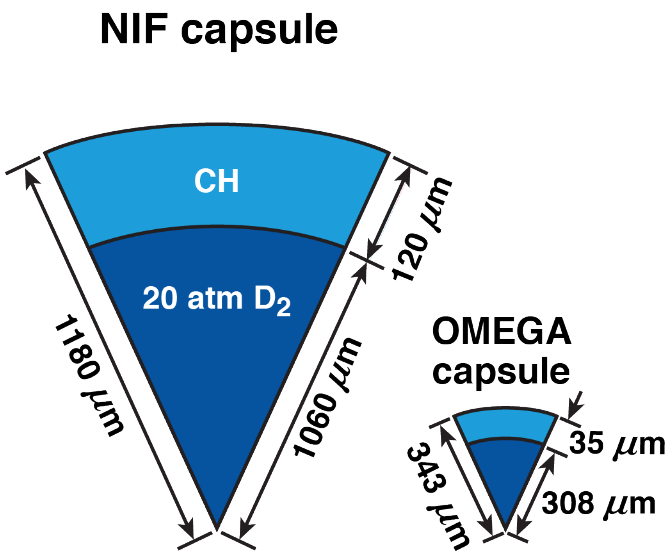
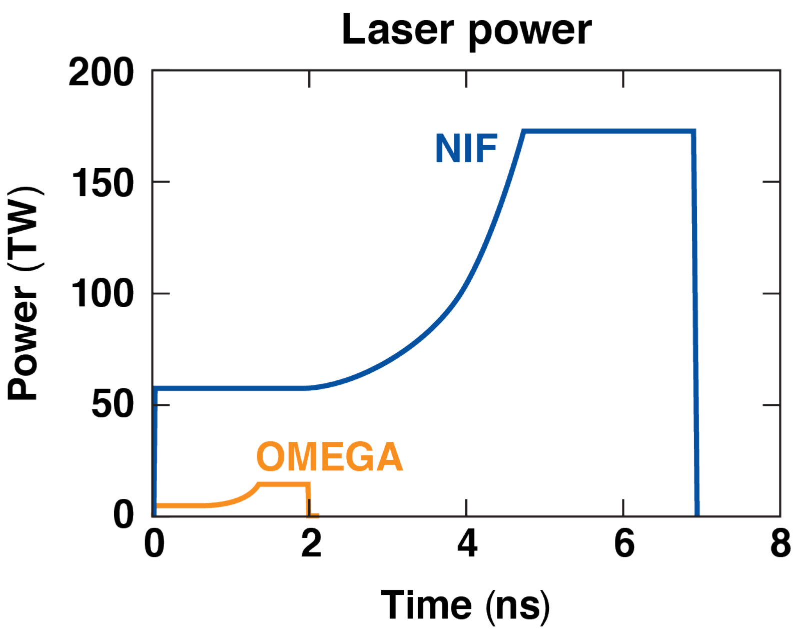
E_{L_OMEGA} = 18 kJ

Near-overlap of scaled implosion trajectories supports validity of hydrodynamic scaling between OMEGA and NIF implosions

To study preheat scaling, hydrodynamically equivalent polar direct drive (PDD) implosions were designed for NIF and OMEGA, spanning 40x in laser energy



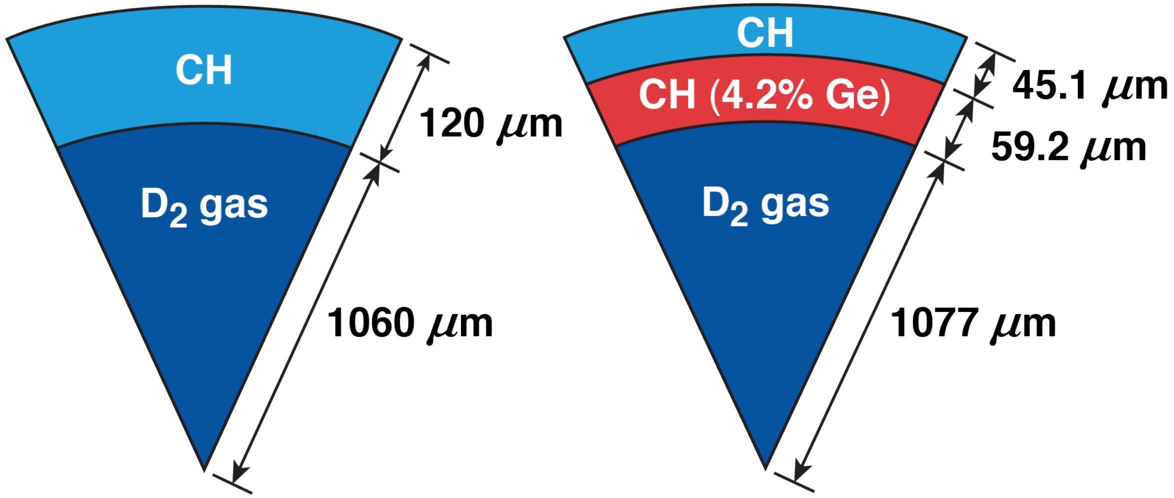


Parameter	NIF	OMEGA
E_L	720 kJ	18 kJ
P_L	172 TW	15 TW
$\langle I_L \rangle$ (W/cm^2)*	1.0×10^{15}	1.0×10^{15}
Pulse length	6.9 ns	2.0 ns
Capsule OD	2360 μm	690 μm
Shell thickness	120 μm	35 μm

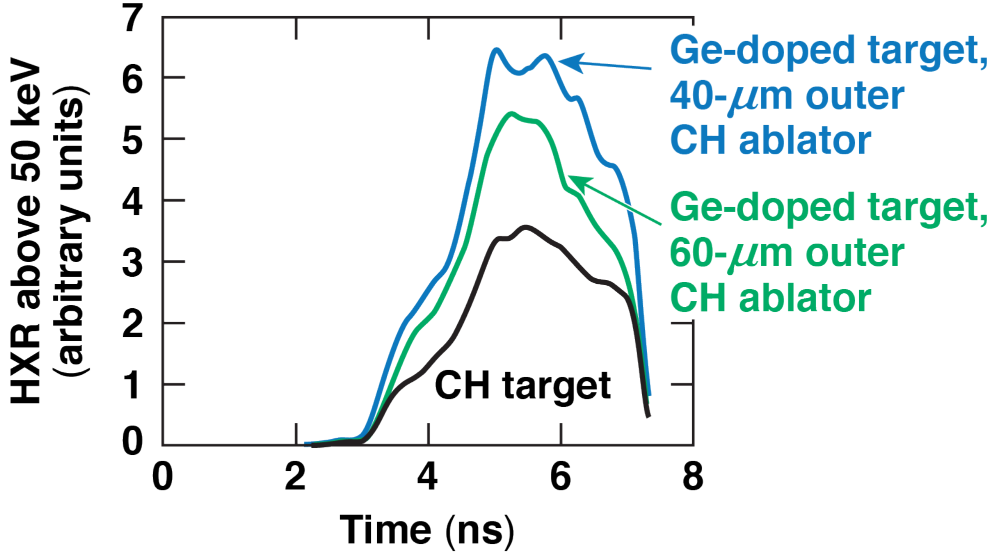
*Average on-target laser intensity

Hot electron preheat deposited into the inner layer of the shell is diagnosed using implosions with or without a Ge-doped layer

NIF target designs



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



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For an identical laser drive and identical hot electron source, the difference in hard x-rays ∝ hot electron energy deposited in Ge-doped layer

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