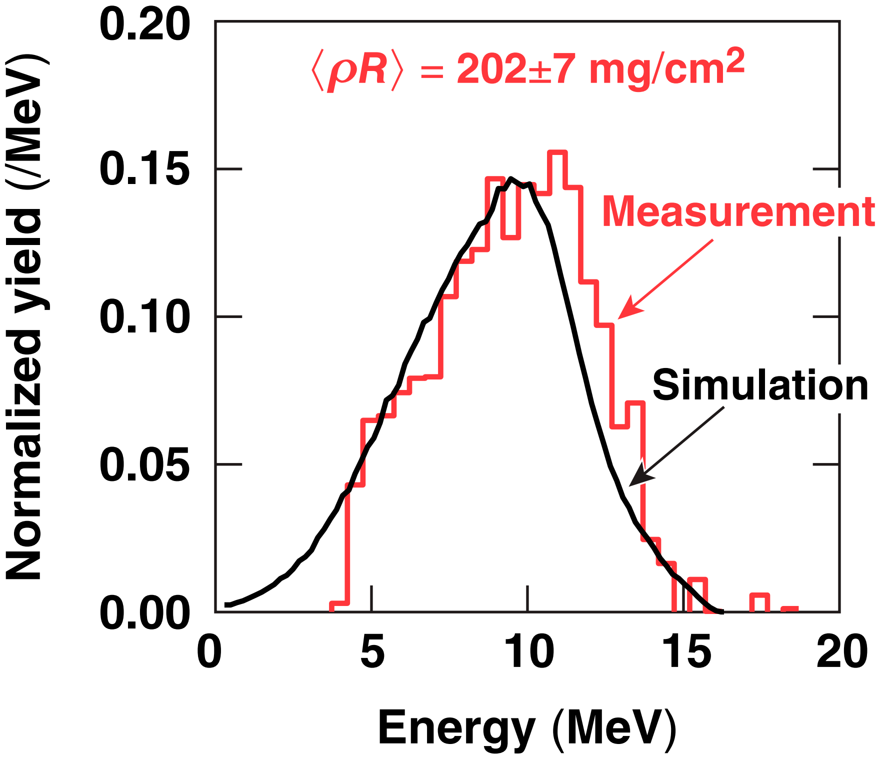
Performance of Direct-Drive Cryogenic Targets on OMEGA



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49th Annual Meeting of the
American Physical Society
Division of Plasma Physics
Orlando, FL
12–16 November 2007

Summary

High-areal-density ($\rho R > 200$ mg/cm^2), low-adiabat cryogenic-fuel assembly has been achieved on OMEGA

- ICF ignition designs rely on low-adiabat fuel assembly
- Maintaining the low level of fuel adiabat during the implosion requires an accurate account for all sources of shell heating, including
  - shock heating
  - preheat due to radiation and suprathermal electrons
  - short-wavelength perturbation growth
- Effects of nonlocal thermal transport are important to model the shock heating
- Areal-density close to 1-D prediction is achieved when the shocks are accurately timed and the suprathermal-electron preheat source is mitigated

Collaborators

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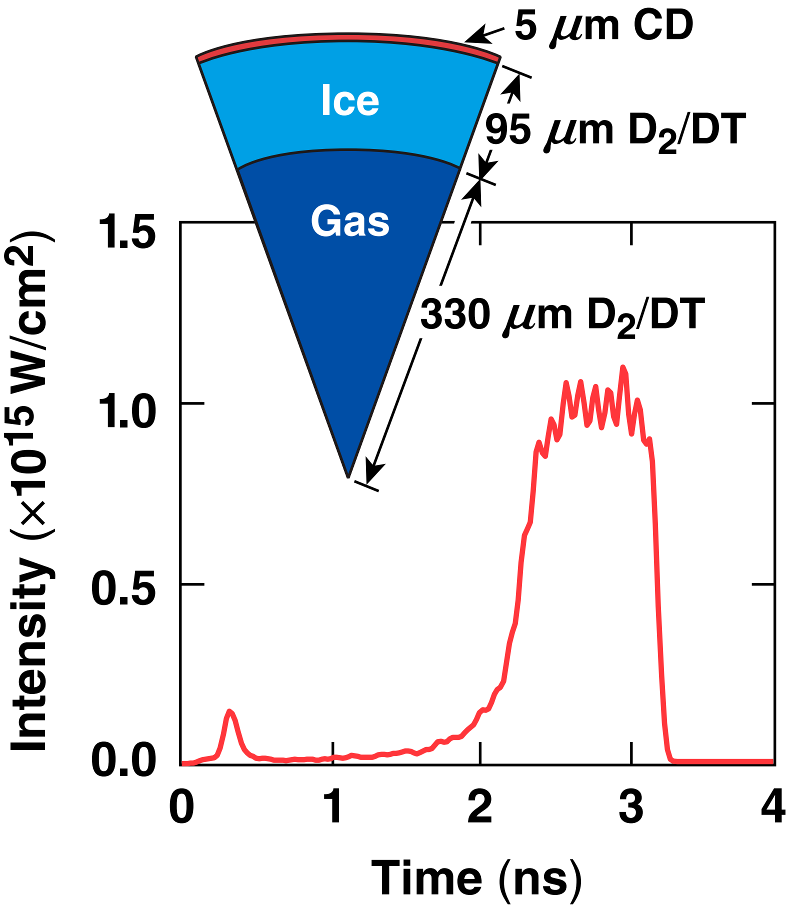
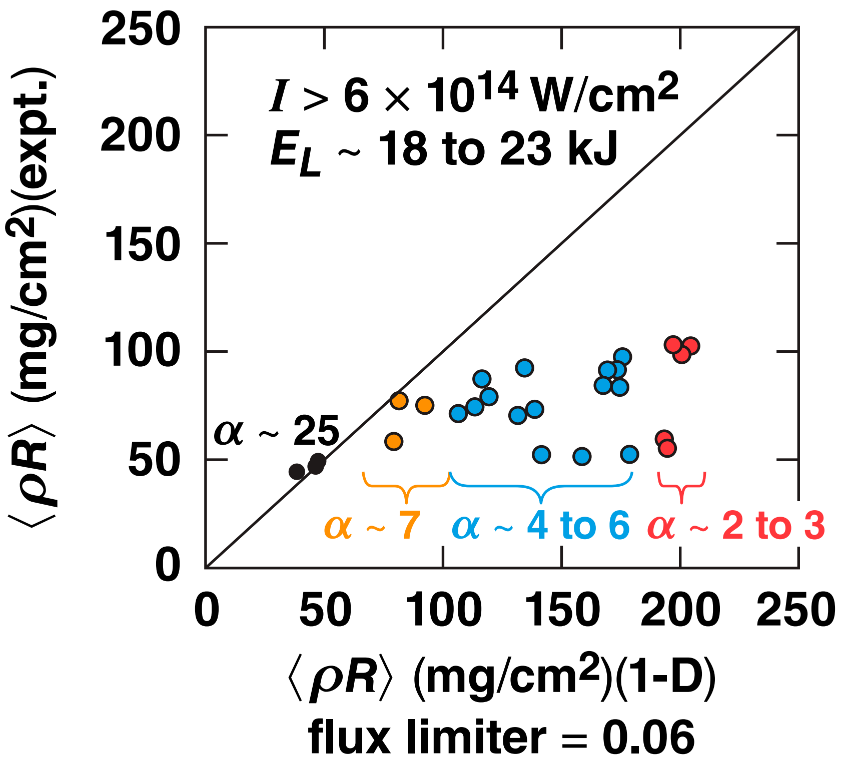
To study physics of low-adiabat fuel compression, a series of cryogenic experiments has been performed on OMEGA



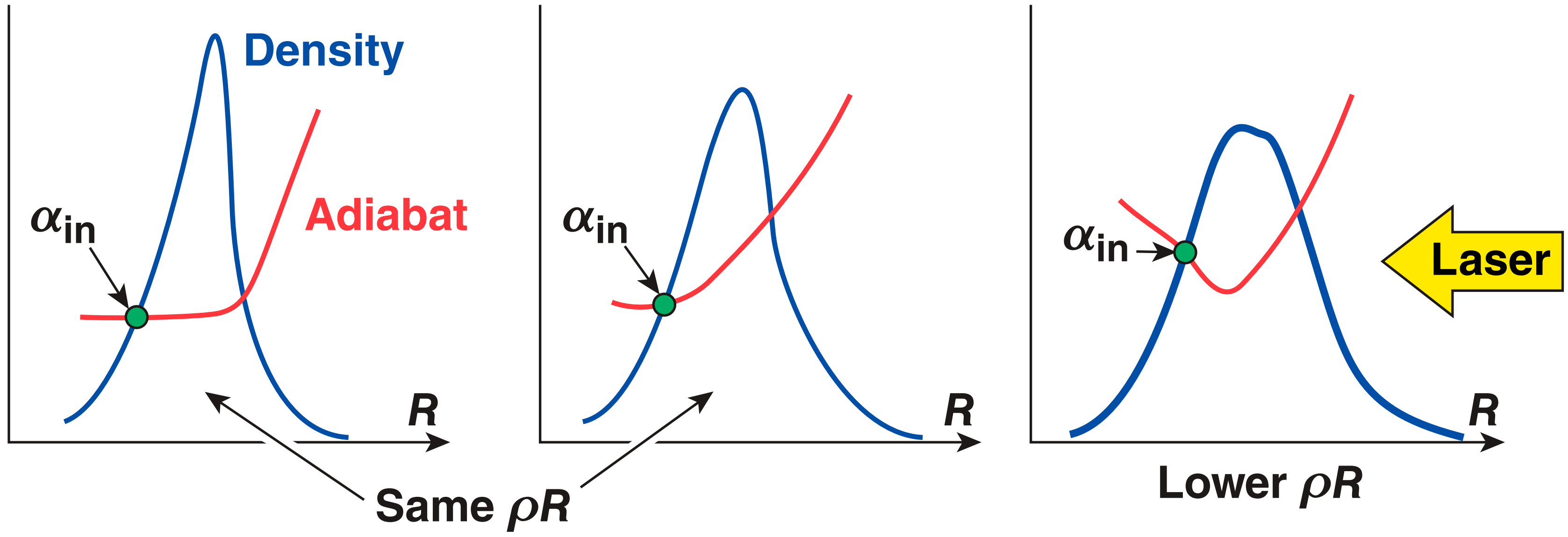
$$\alpha = \frac{P}{P_{\mathrm{Fermi}}}$$



F.J. Marshall *et al*., Phys. Plasmas 12, 056302 (2005).
T.C. Sangster *et al*., Phys. Plasmas 14, 058101 (2007).

For a given laser energy, areal density is sensitive only to the shell adiabat*

- $\rho R = \dfrac{2.6}{\alpha_{\text{in}}^{0.54}} E_{\text{MJ}}^{1/3}$
- Degradation in ρR can be due only to the excessive adiabat increase (extra shell heating).



Same ρR

Lower ρR

TC7808a

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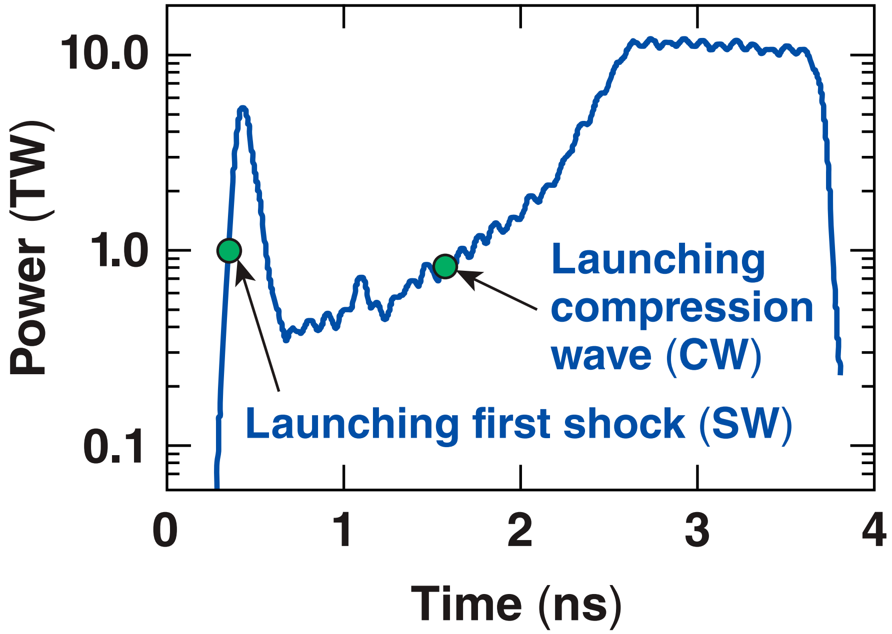
*R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005).

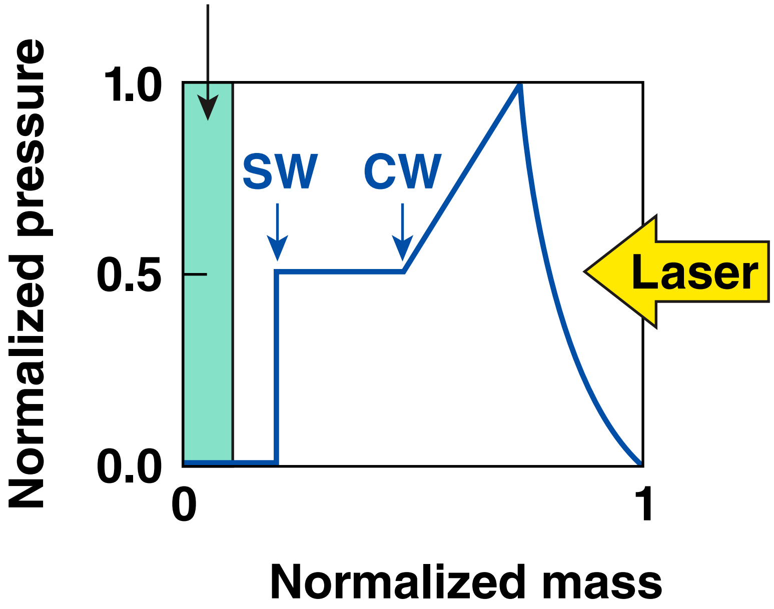
Shock Timing

The main sources contributing to the adiabat degradation include hydrodynamics, radiation and electron preheat, and small-scale nonuniformity growth

- Timing of hydrodynamic waves



CW and SW/RW must coalesce inside 10% initial mass region

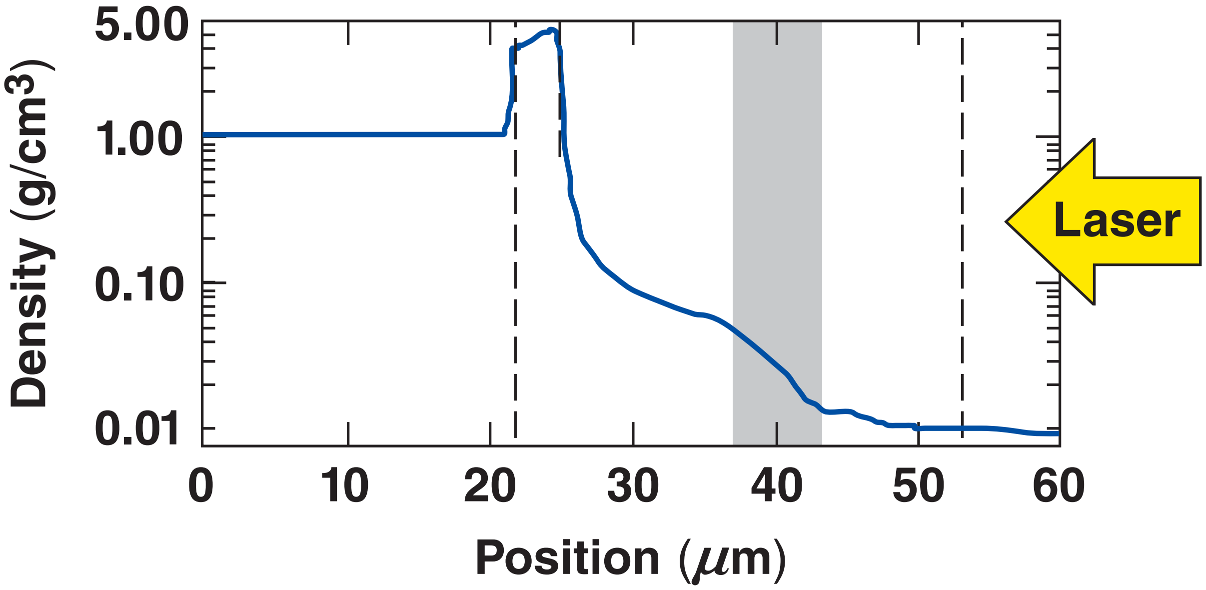


$$\frac{\Delta t_{\text{shock}}}{t_{\text{shock}}} < 5\%,\ t_{\text{shock}} \sim E_p^{-1/2} \Rightarrow \boxed{\frac{\Delta E_p}{E_p} < 10\%}$$

TC7809

A flux-limited thermal transport model* produces sharp density near critical surface

- $q_{SH} = -\kappa \nabla T \qquad q_{FS} = nTV_T$
- $q = \min(q_{SH}, fq_{FS})$
- $0.04 < f < 0.1$



A sharp gradient leads to low laser absorption at the beginning of the pulse

TC6949c

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*R. C. Malone, R. L. McCrory, and R. L. Morse, Phys. Rev. Lett. 34, 721 (1975).

Laser coupling depends on thermal conduction modeling

- Flux-limited Spitzer conduction model with constant flux limiter is not sufficiently accurate

- New nonlocal model solves Boltzmann equation with Krook's collision operator*

$$v\frac{\partial f}{\partial x}+\frac{eE}{m}\frac{\partial f_0}{\partial v_x}=-\nu(v)(f-f_0),\quad f=f_0-\int^{x}\left(\frac{\partial f_0}{\partial x}+\frac{eE}{T}\frac{\partial f_0}{\partial \in}\right)e^{-\int_{x'}^{x}\frac{dx''}{\lambda_{ei}\cos\theta}}\,dx'$$

- To conserve the number of particles and thermal energy, the coefficients in f_0 are renormalized

$$n'=n+\delta n,\quad T'=T+\delta T$$

$$\text{in the limit } \frac{\lambda_{ei}}{L_T}\ll 1,\quad \delta n\sim O\left[\left(\frac{\lambda_{ei}}{L_T}\right)^2\right]$$

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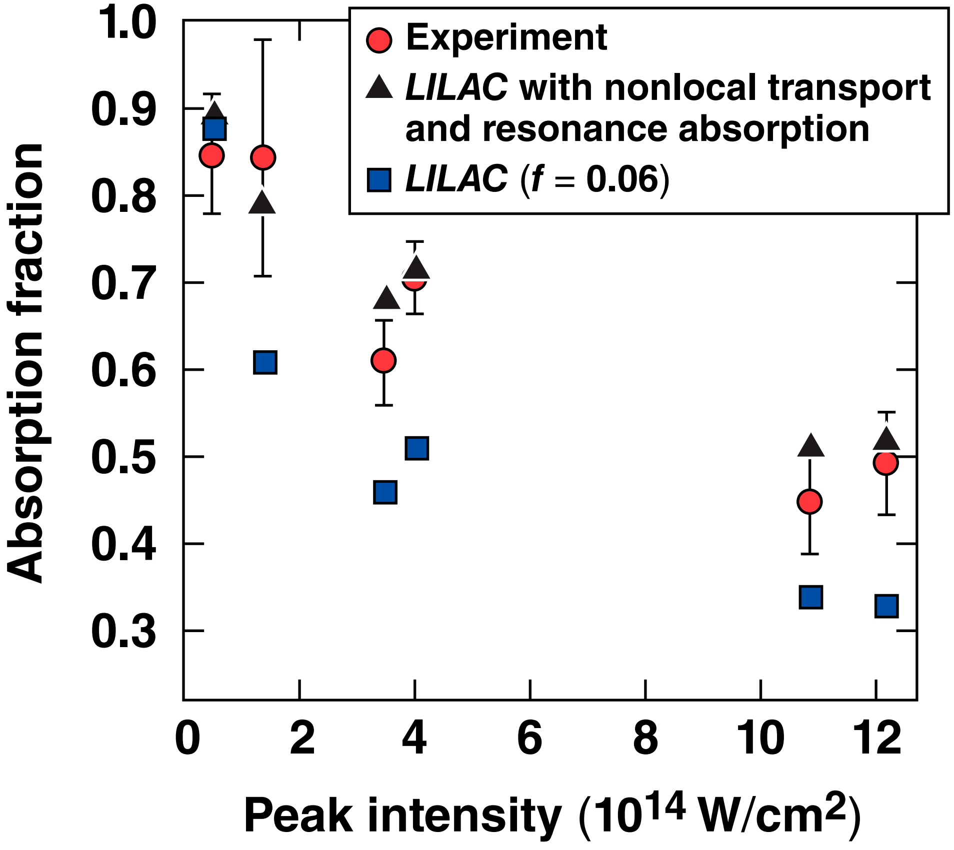
*V. N. Goncharov *et al*., Phys. Plasmas 13, 012702 (2006).

Simulations using the resonance absorption and new nonlocal transport model agree well with a experimental data*

- 200 ps Gaussian pulse



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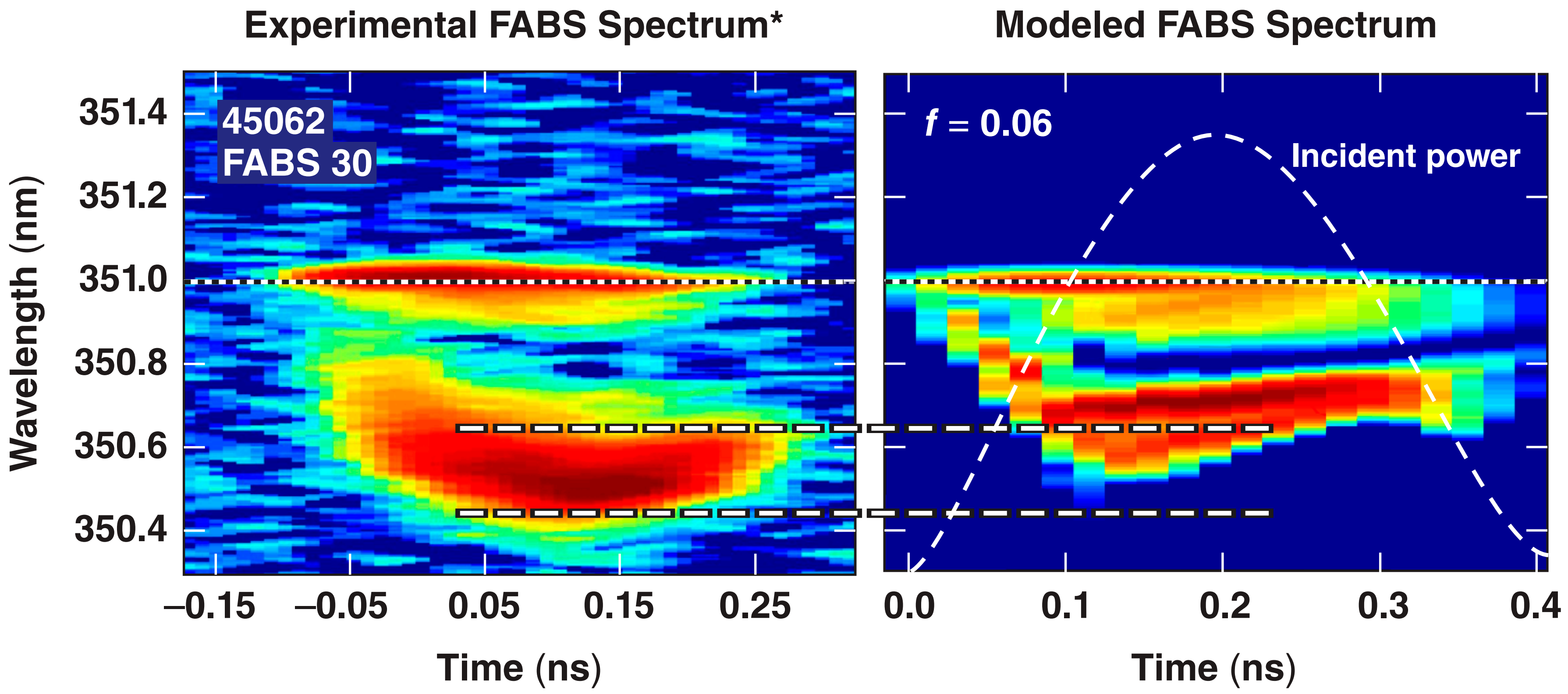
* W. Seka (GI1.00003)

Shock Timing

The nonlocal model is required to explain observed spectral shifts in scattered light

$$\text{Spectral shift}^{1}\ \Delta\omega = \frac{\omega_0}{2c}\int\left(1-\frac{n_e}{n_c}\right)^{-1/2}\frac{\partial}{\partial t}\left(\frac{n_e}{n_c}\right)ds$$



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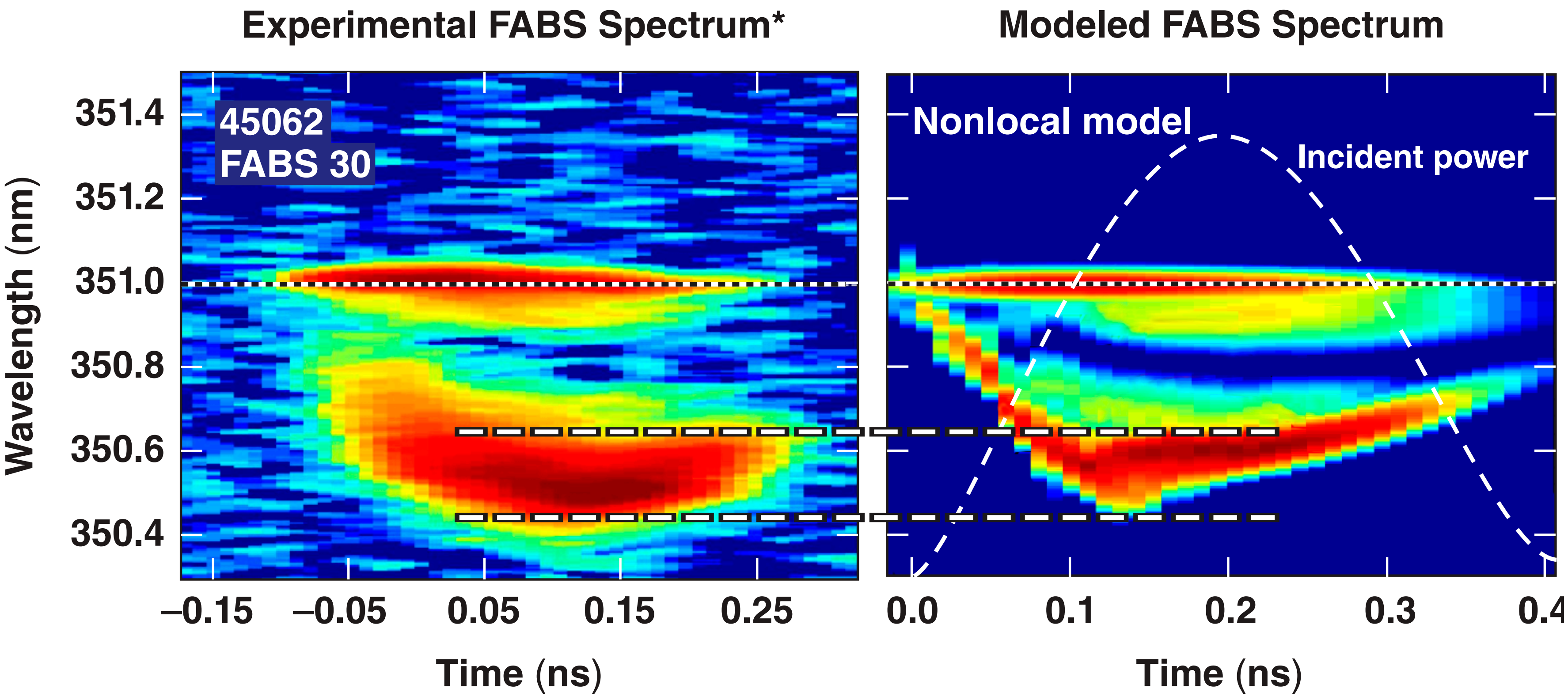
[1] T. Dewandre, J. R. Albritton, and E. A. Williams, Phys. Fluids 24, 528 (1981).
[2] D. Edgell, NO6.00009, this conference

Shock Timing

The nonlocal model is required to explain observed spectral shifts in scattered light



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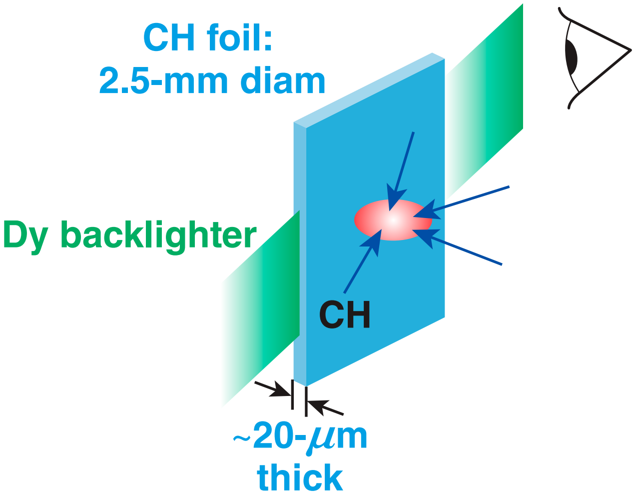
*D. Edgell (NO6.00009)

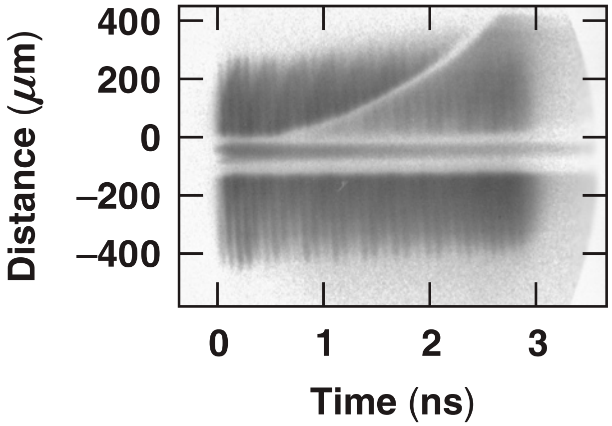
Shock Timing

Measured foil trajectory is in agreement with the results of simulations[1] using the nonlocal transport model

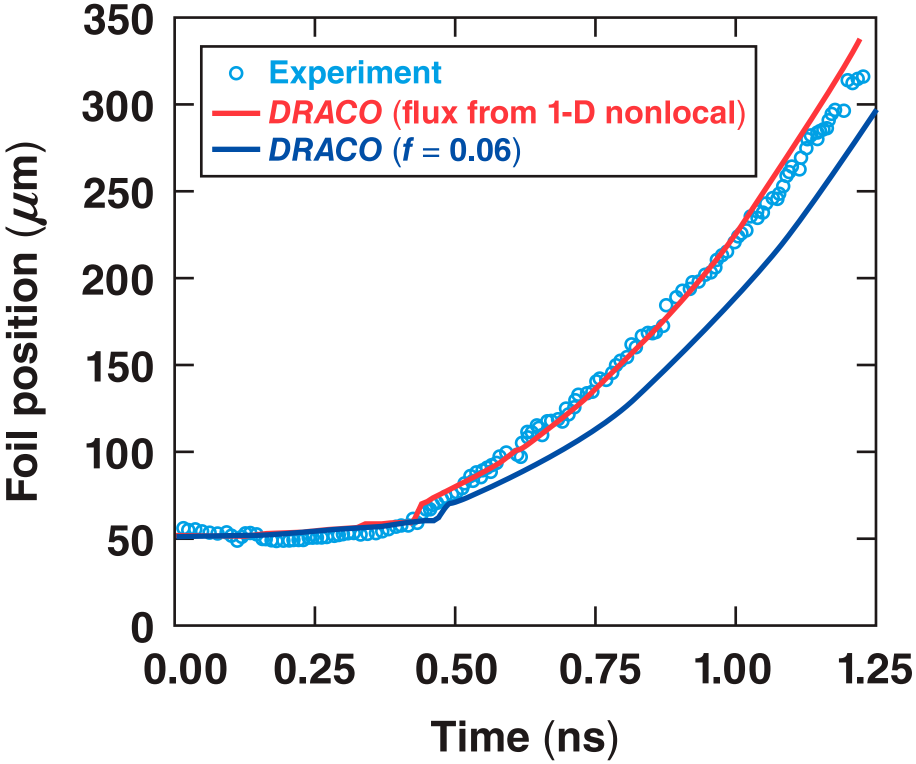
Experimental setup



Measured target trajectory[2]



Shot 46373 (10^{15} W/cm^2, 1-ns pulse)



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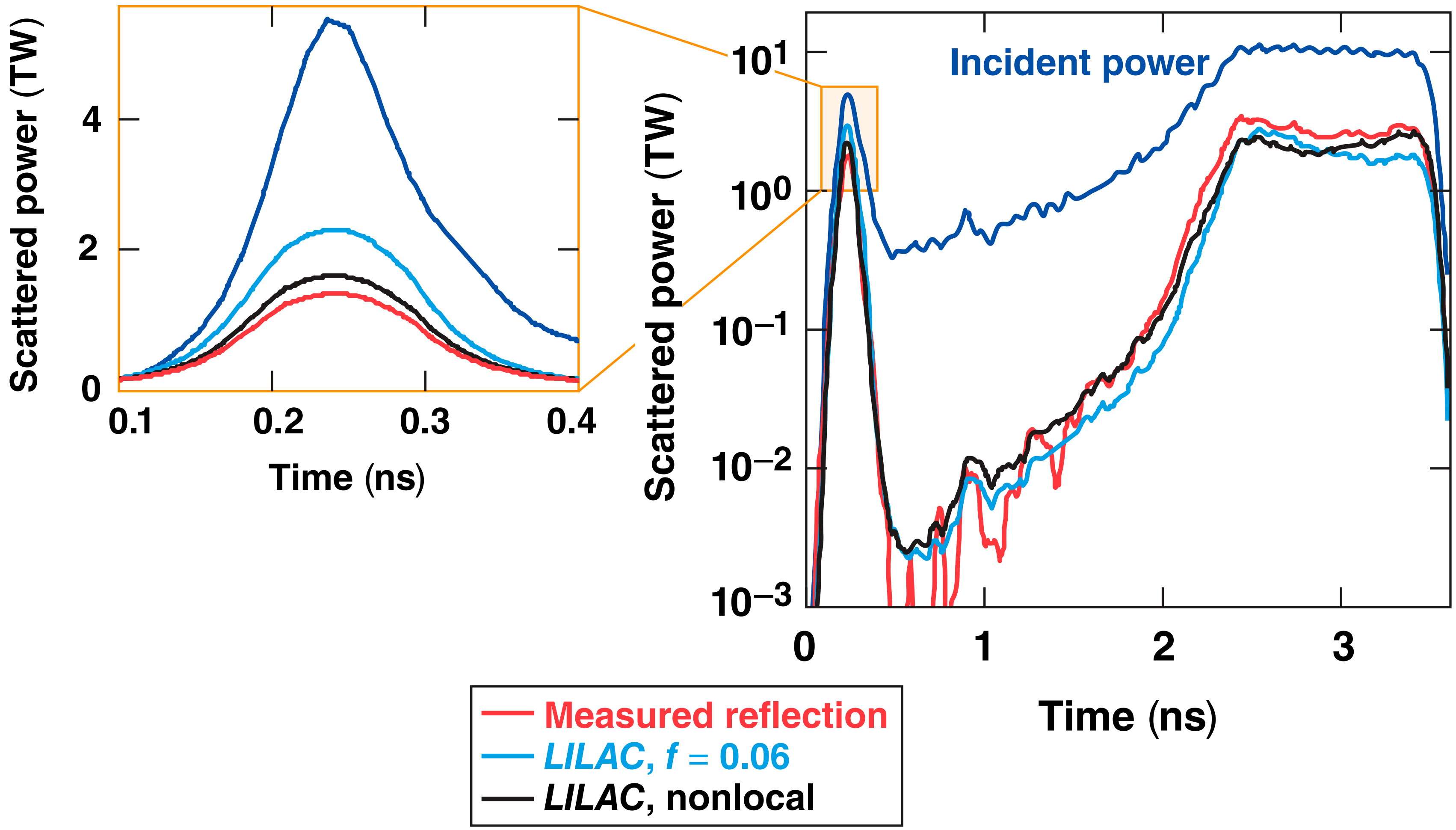
[1] S. Hu (PO6.00014)

[2] V. Smalyuk *et al.*, presented at the 37th Anamolous Absorption Conference, Maui, HI, 27–31 August 2007

Shock Timing

Time-resolved laser-absorption measurements* are in good agreement with the results of the nonlocal model

UR LLE



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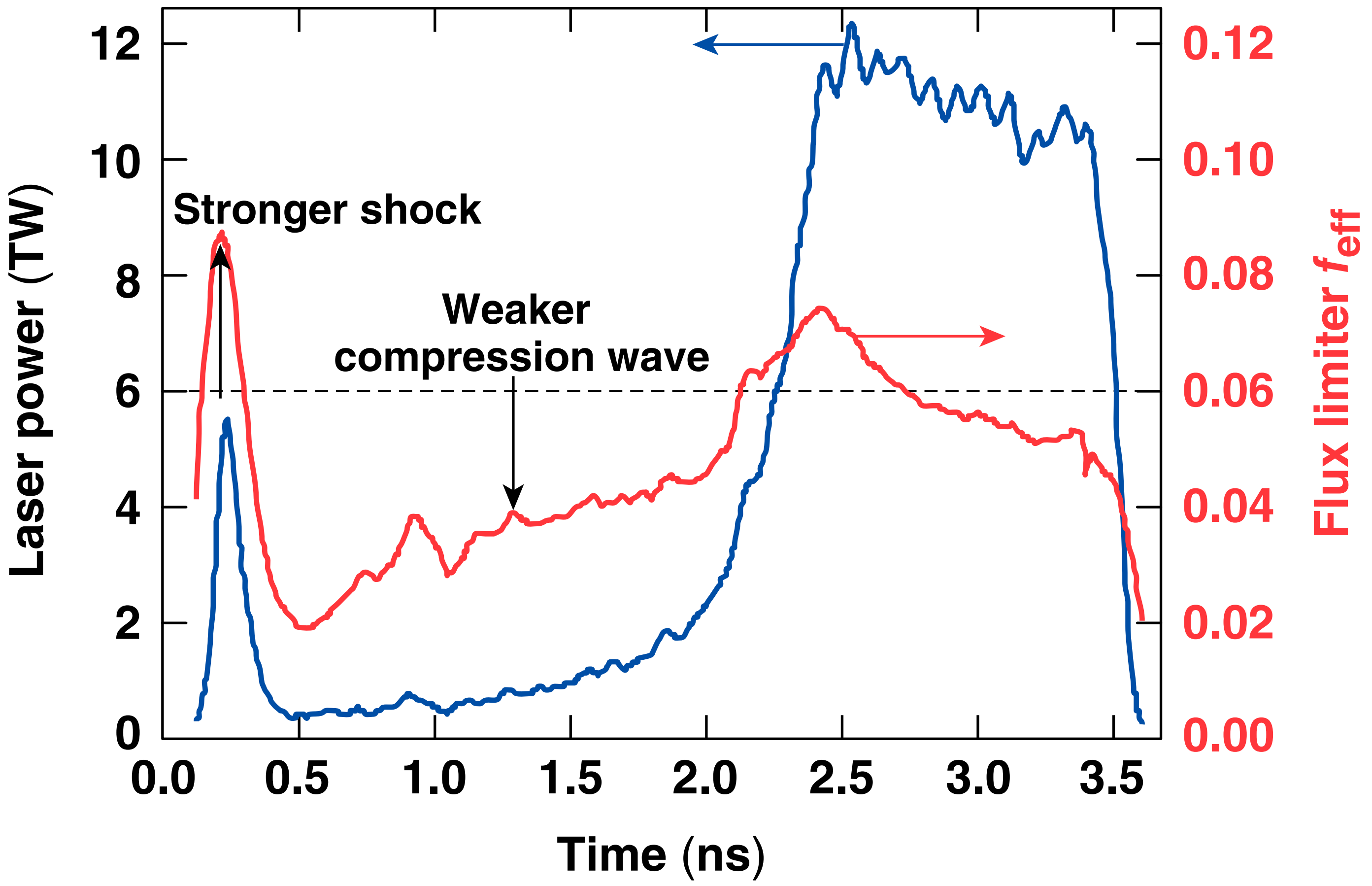
* W. Seka (GI1.00003)

The effective flux limiter is calculated using the results of the nonlocal model

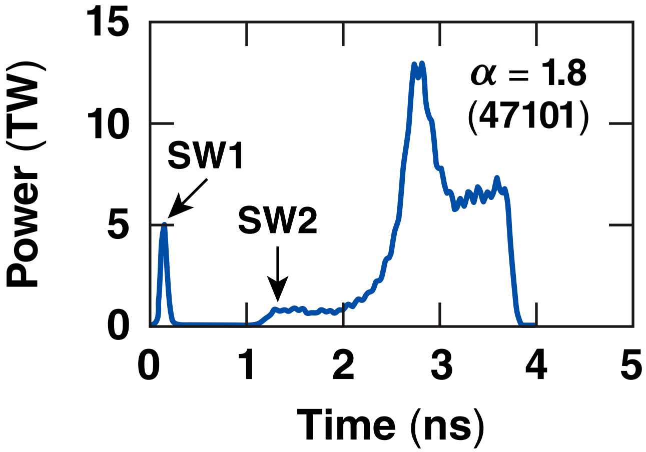
$$f_{\mathrm{eff}} = \max\left(\frac{q_{\mathrm{NL}}}{q_{\mathrm{FS}}}\right)$$

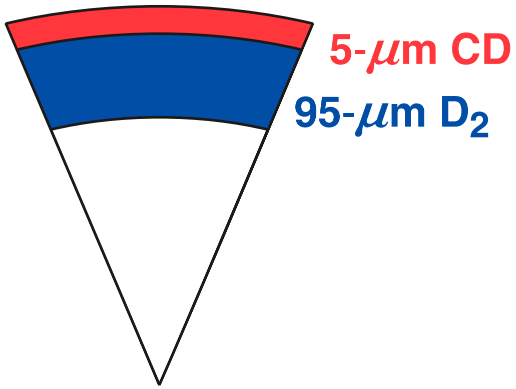
q_{NL} = nonlocal flux
q_{FS} = free-stream flux

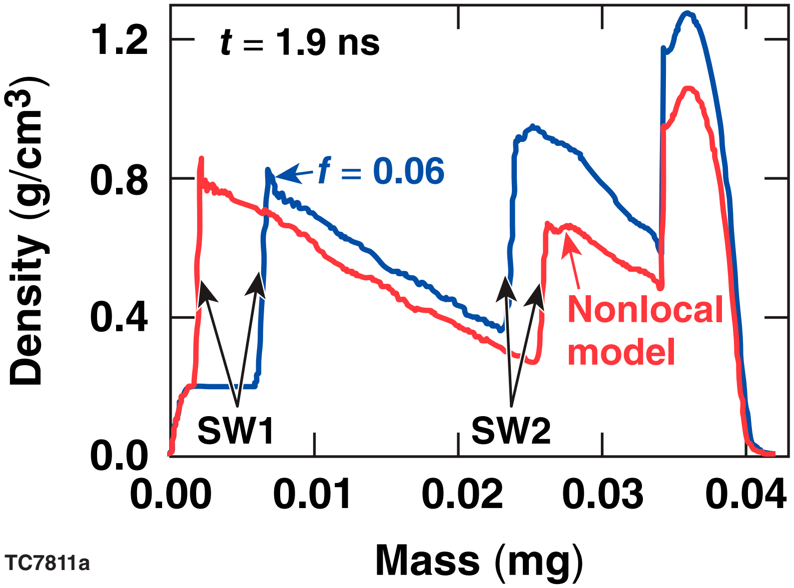


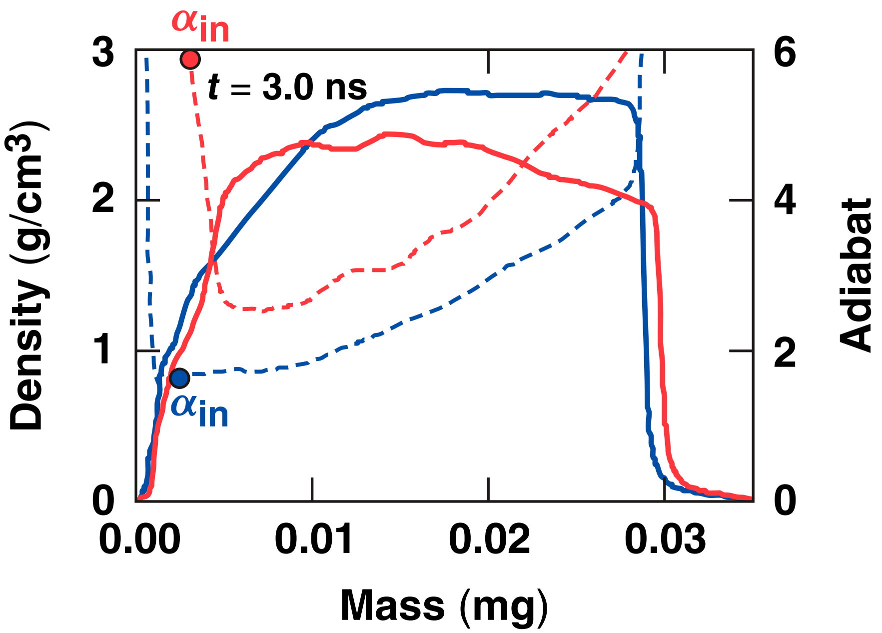
Shock Timing

A correct thermal conduction model is essential for designing low-adiabat targets



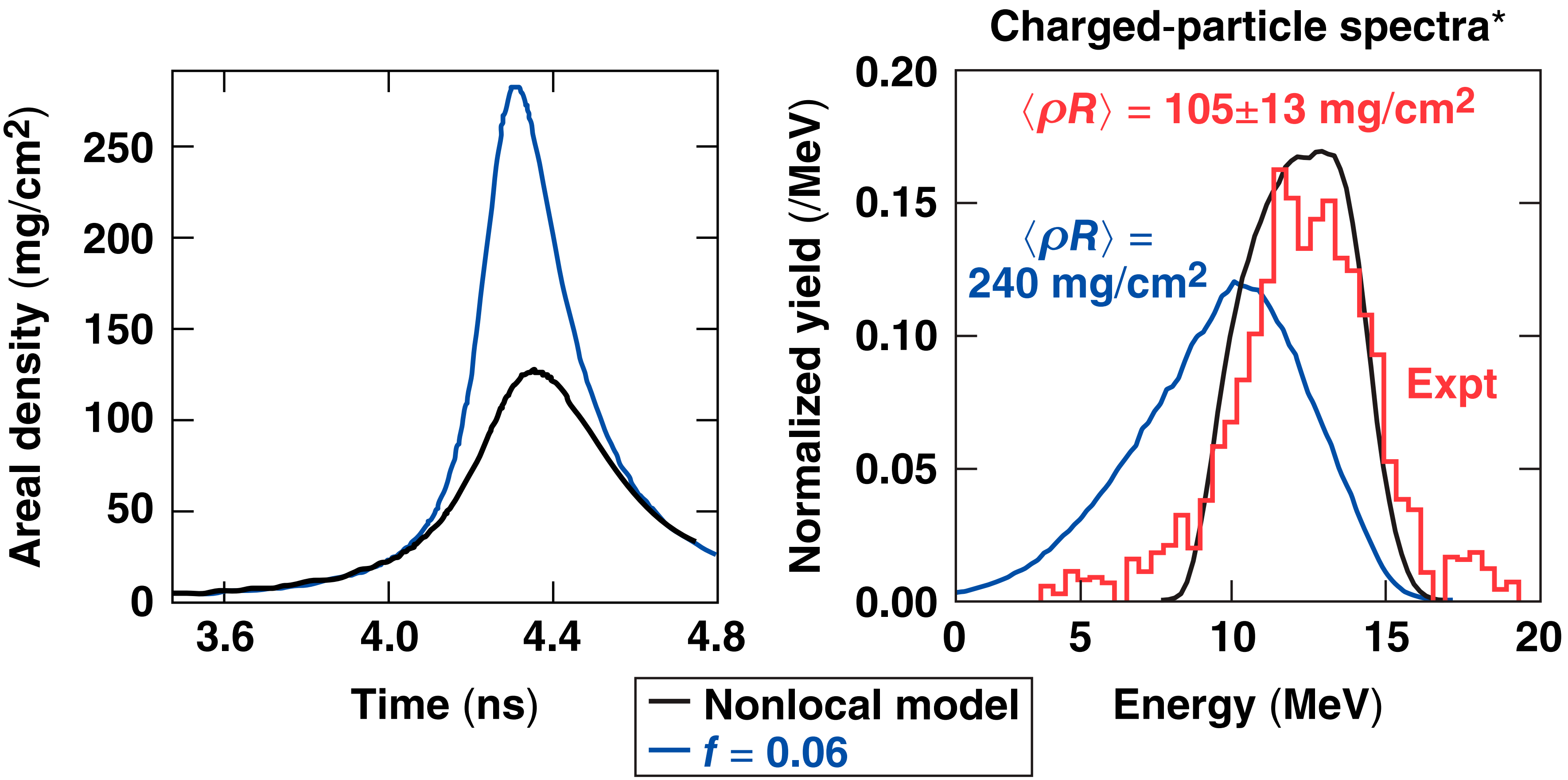






TC7811a

The areal density can be significantly changed depending on the thermal conduction model


Charged-particle spectra*

Shock timing must be adjusted using the nonlocal model.

TC7864a

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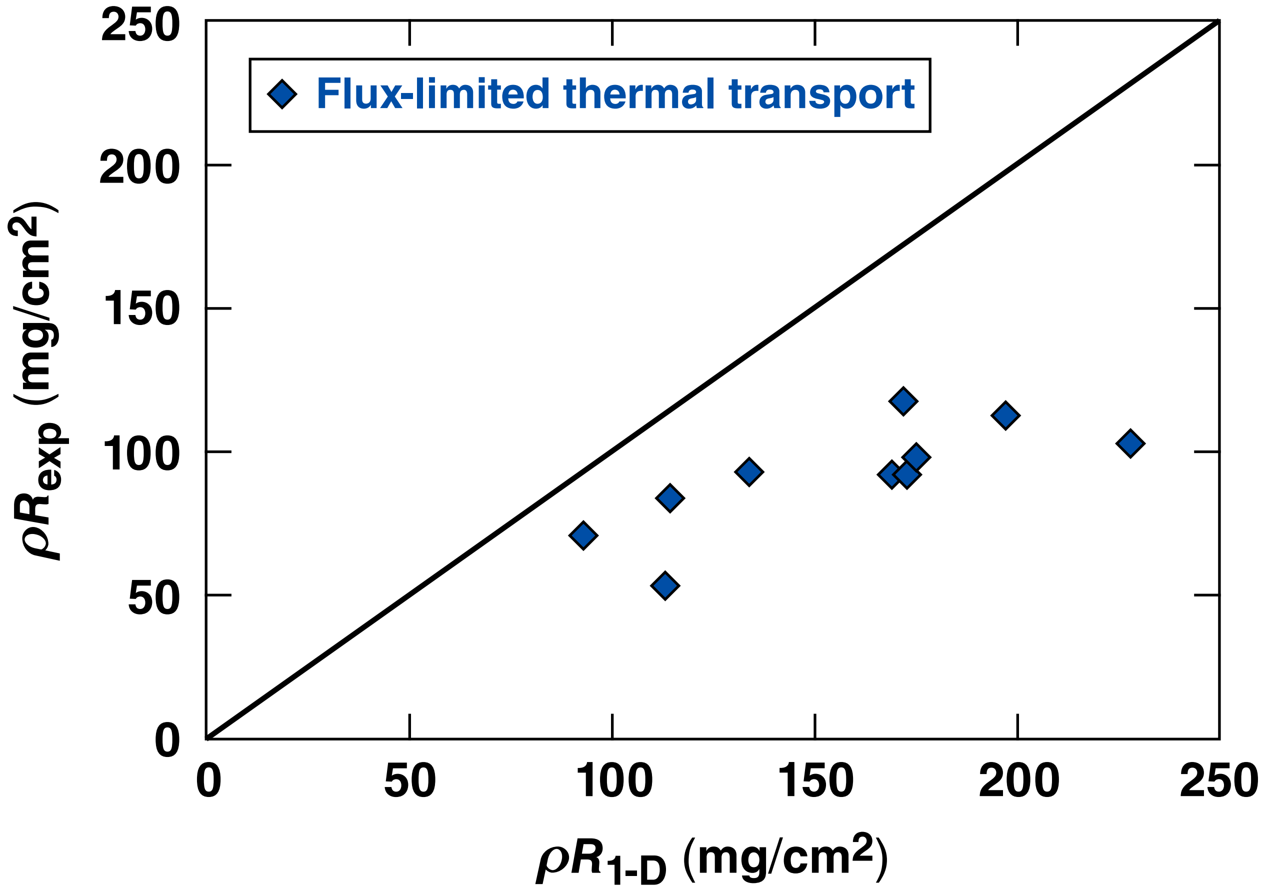
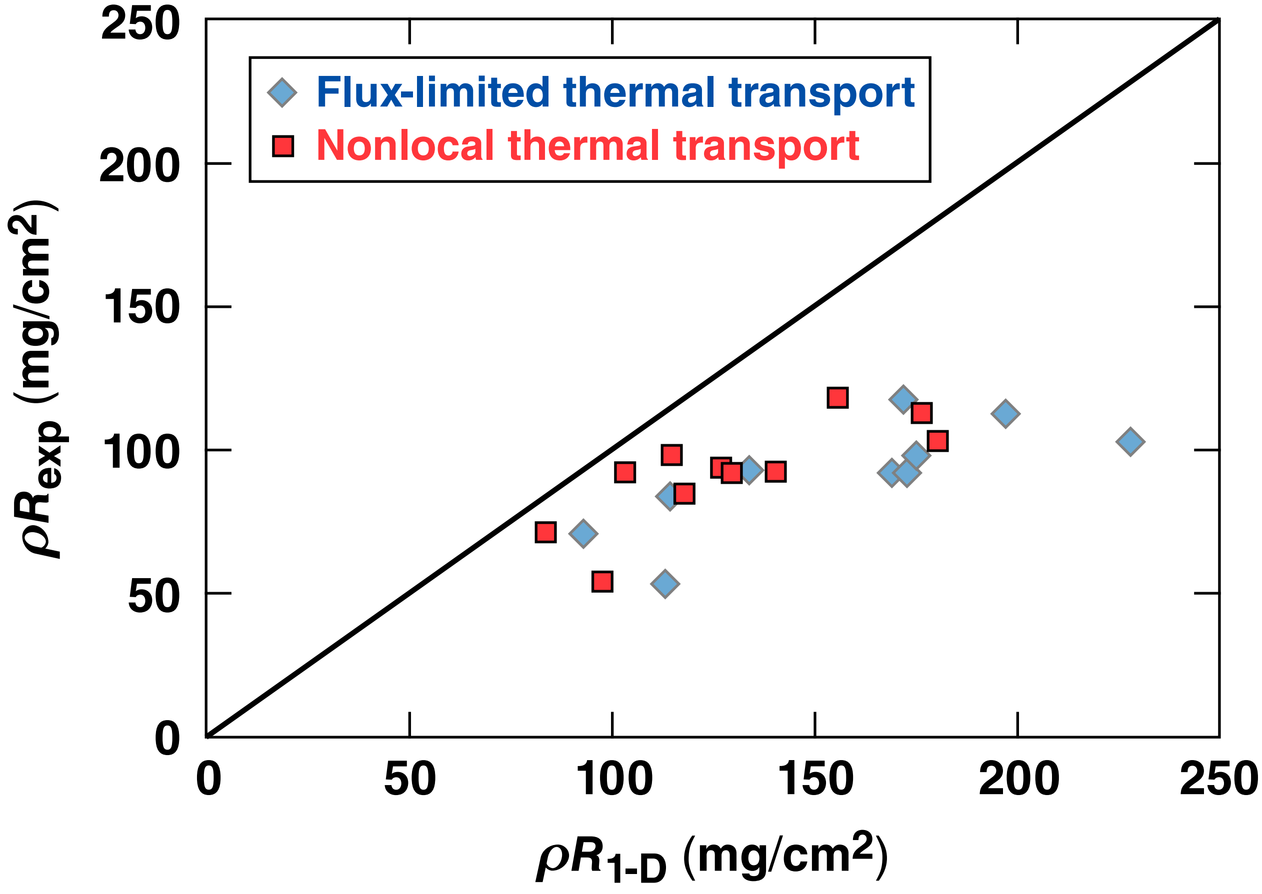
*F. Séguin *et al.*, Phys. Plasmas 9, 2725 (2002).

The agreement between experimental data and code predictions improves when the nonlocal model is used



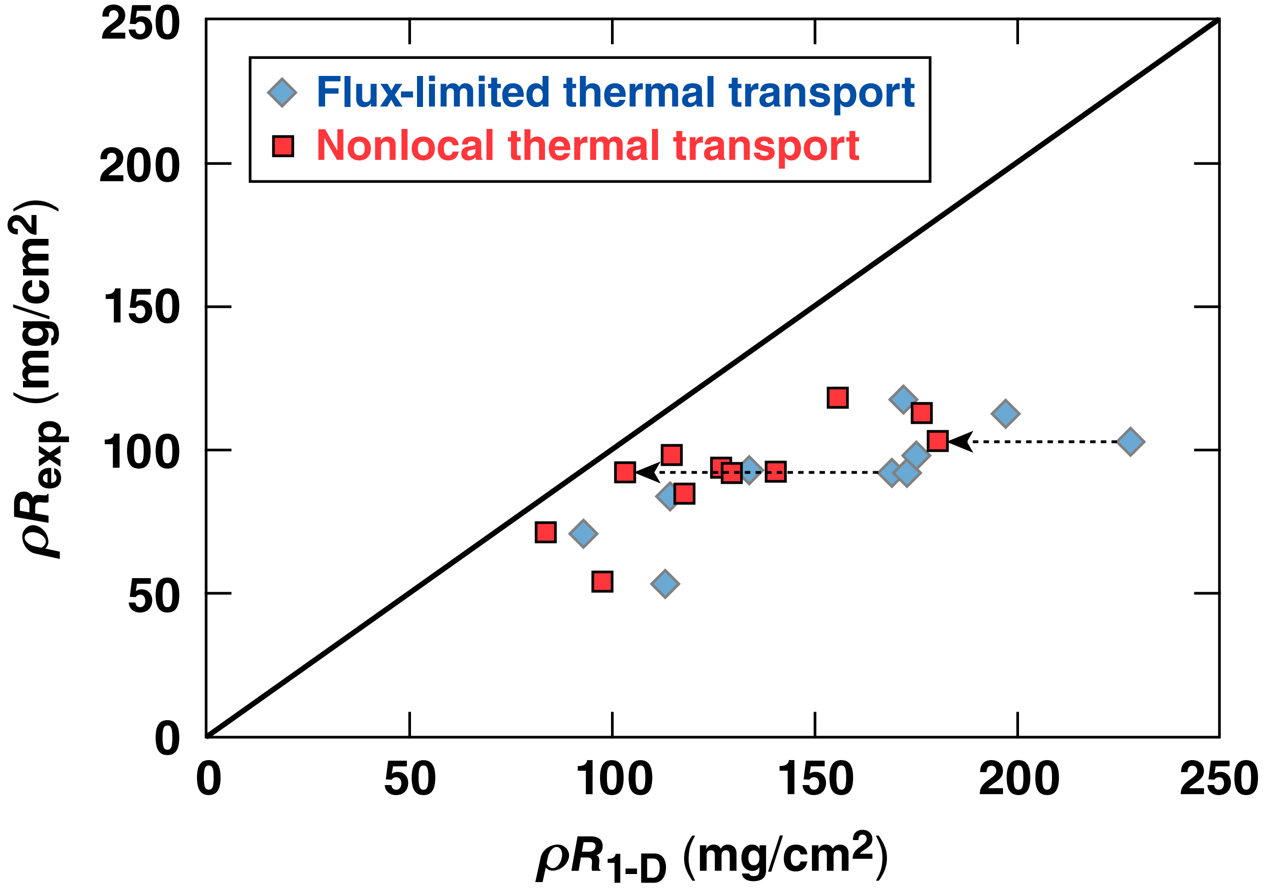
TC8037-1

The agreement between experimental data and code predictions improves when the nonlocal model is used



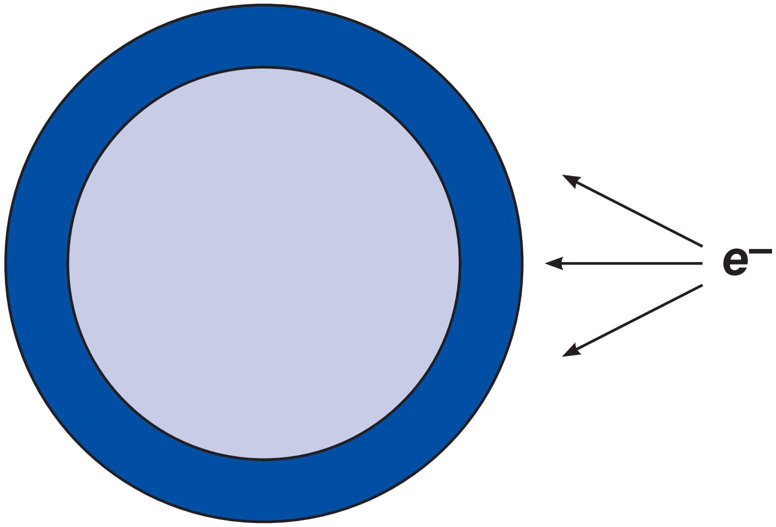
TC8037-2

The agreement between experimental data and code predictions improves when the nonlocal model is used



Preheat

Hot-electron preheat generated by laser–plasma interaction can contribute to the final areal density degradation



$$p \sim \alpha\rho^{5/3} \Rightarrow \alpha \sim \frac{T^{5/3}}{p^{2/3}}$$

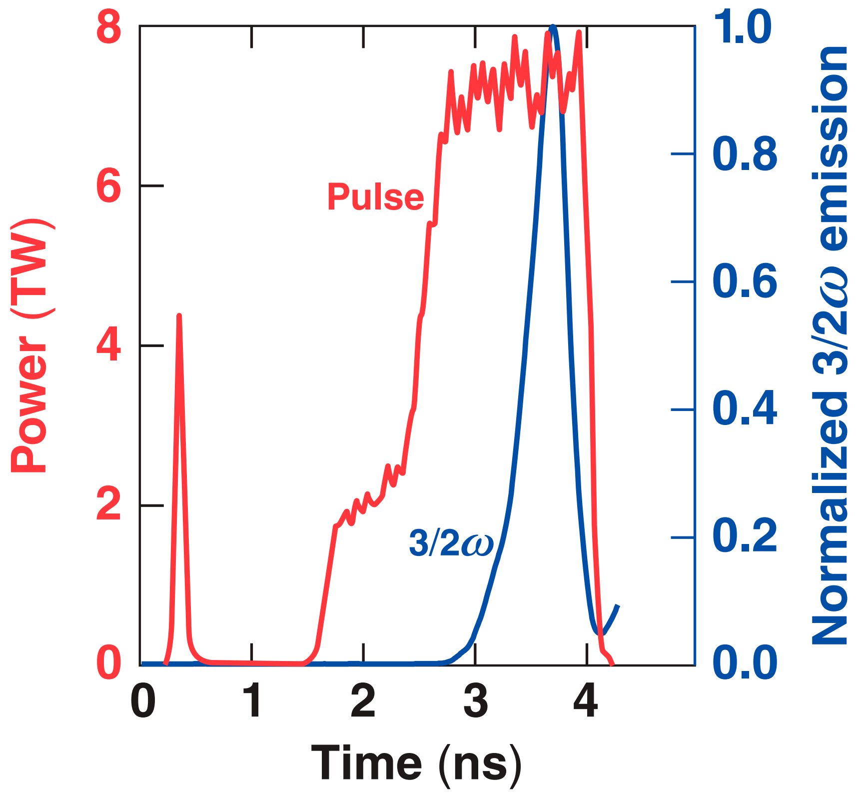
$$\rho R \sim \alpha^{-0.54} \Rightarrow \rho R = \frac{\rho R_0}{\left(1 + \Delta T_{\text{preheat}}/T_0\right)^{0.9}}$$

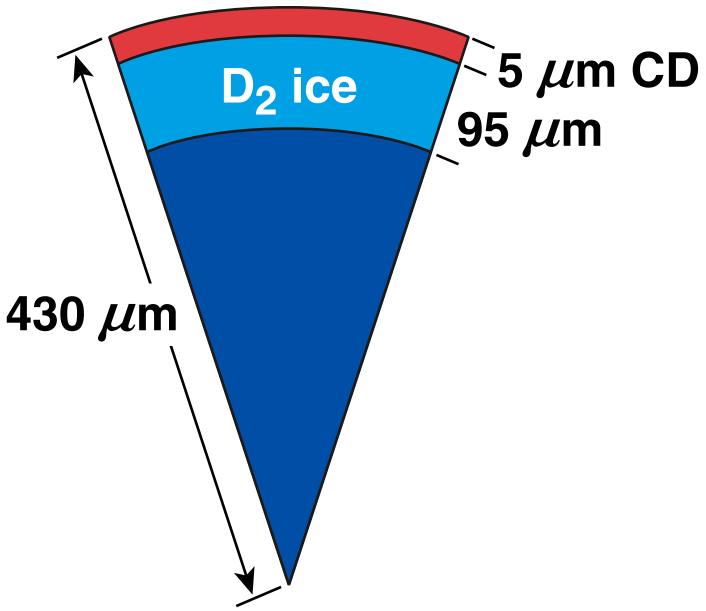
- Low-α designs $T_0 \sim 20$ eV
- 20% ρR reduction for $\Delta T_{\text{preheat}} \approxeq 6$ eV
- For OMEGA designs $\frac{\rho R}{\rho R_0} \sim 0.8$ if $E_{\text{preheat}} \sim 10$ J ($<0.1\%$ E_L)

Preheat

3/2ω light indicates the presence of two-plasmon-decay instability

3/2ω emission for shot 46520



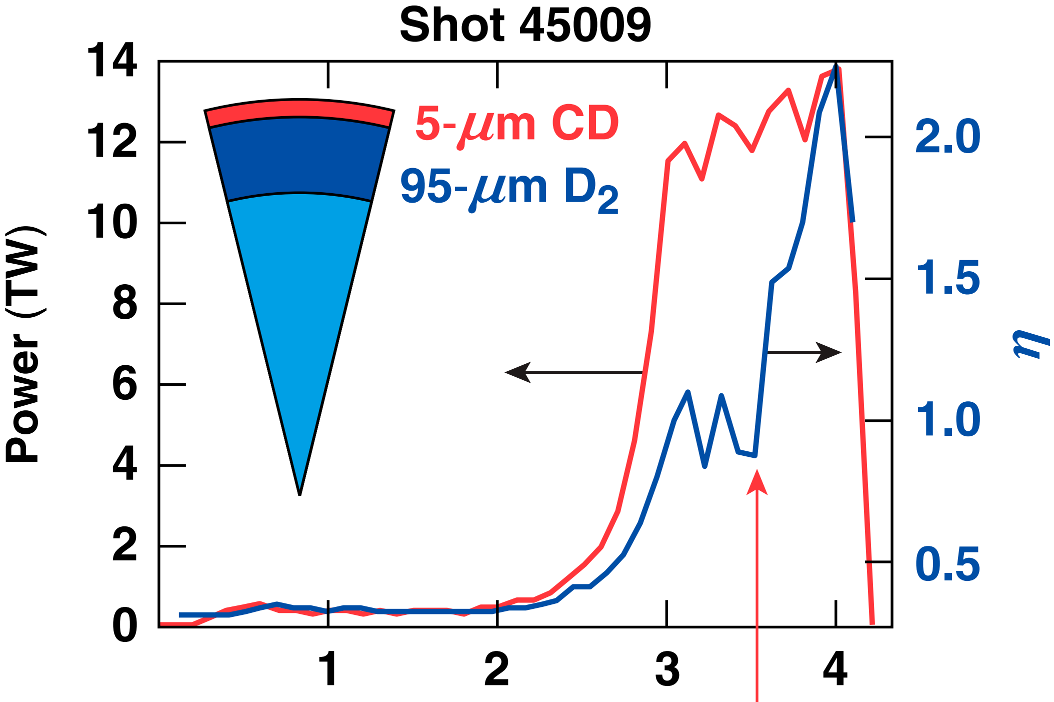


W. Seka (GI00003)

Preheat

Onset of 3/2ω signal correlates with CD burnthrough time

- Above-threshold parameter* for 2 ω_p instability $\eta = \dfrac{I_{14} L_{\mu m}}{230\, T_{keV}}$
- Instability develops when $\eta > 1$



CD burnthrough
Absorption is reduced
T is reduced, I is increased

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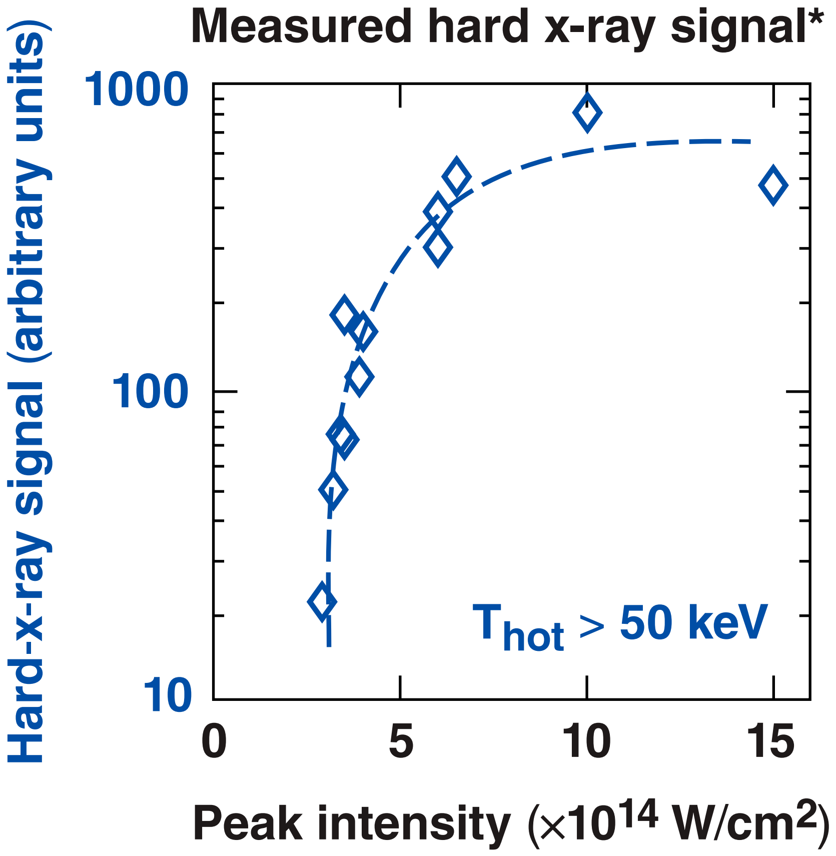
*A. Simon *et al.*, Phys. Fluids 26, 3107 (1983).
J. A. Delettrez (JO3.00003)

Preheat

The measured hard x-ray signal is correlated with laser intensity

Cryogenic low-α D_2 targets with thin ($\leq 5\ \mu m$) CD ablator



TC7839a

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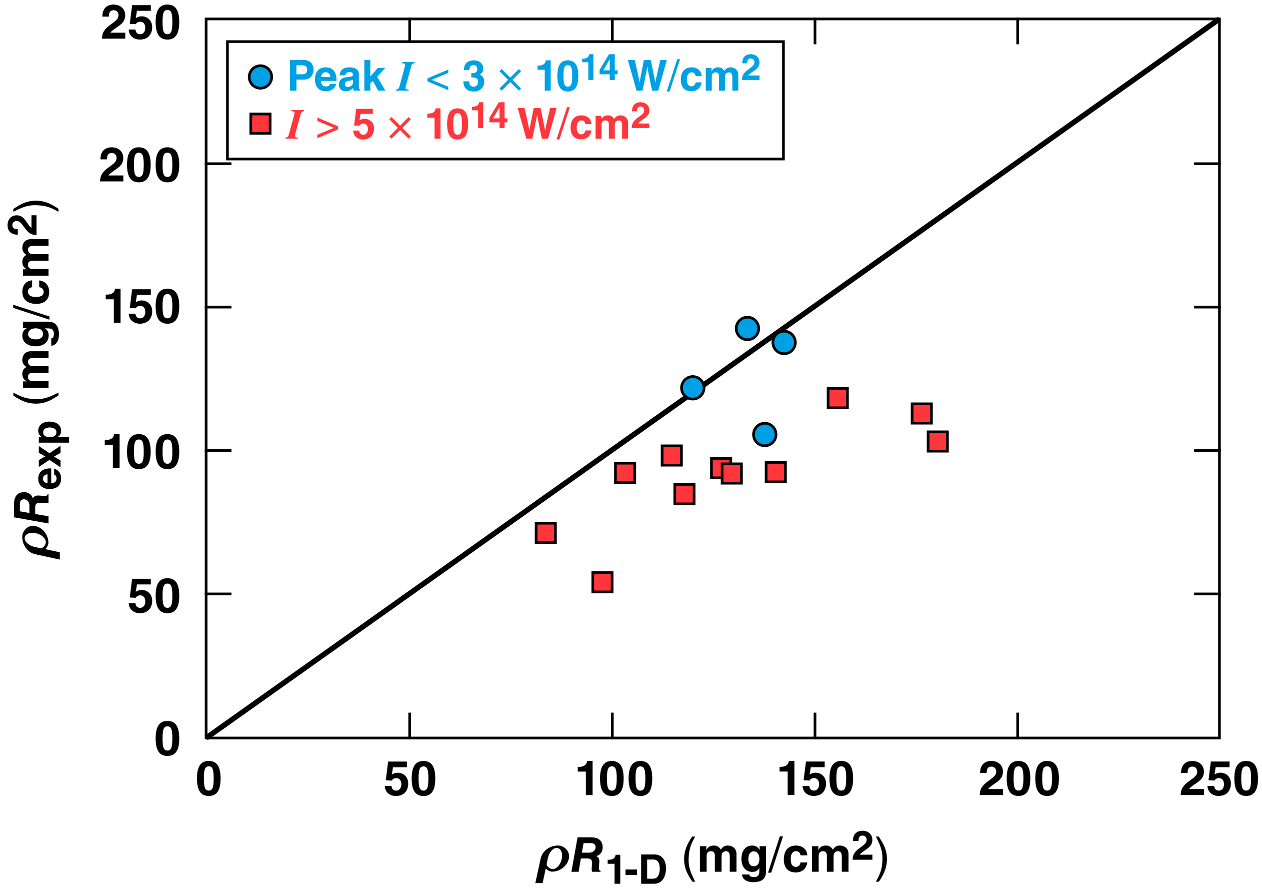
*C. Stoeckl *et al.*, Rev. Sci. Instrum. 72, 1197 (2001).

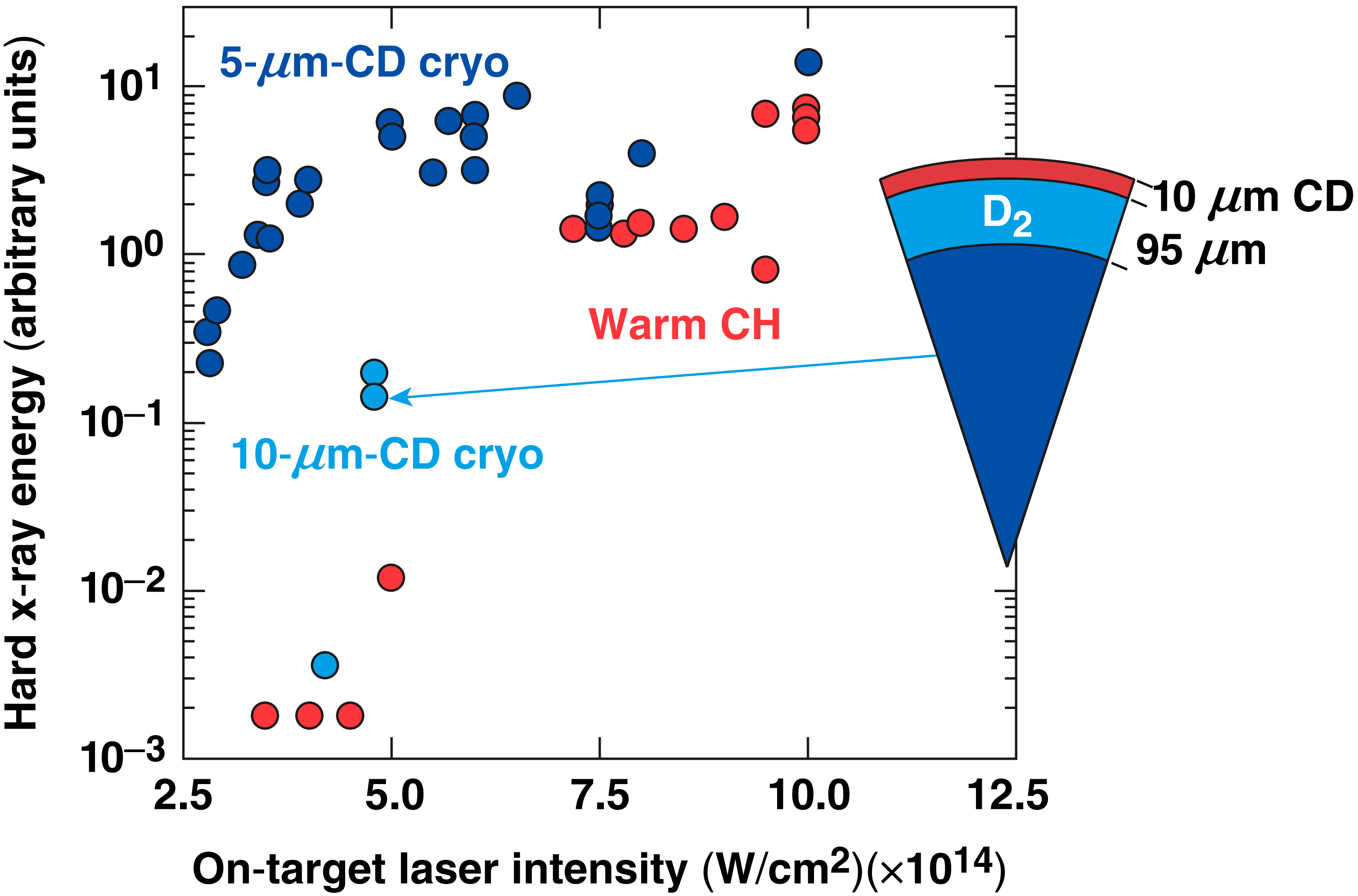
An improved agreement between simulated and measured ρR is observed for low intensity implosions



TC8037a

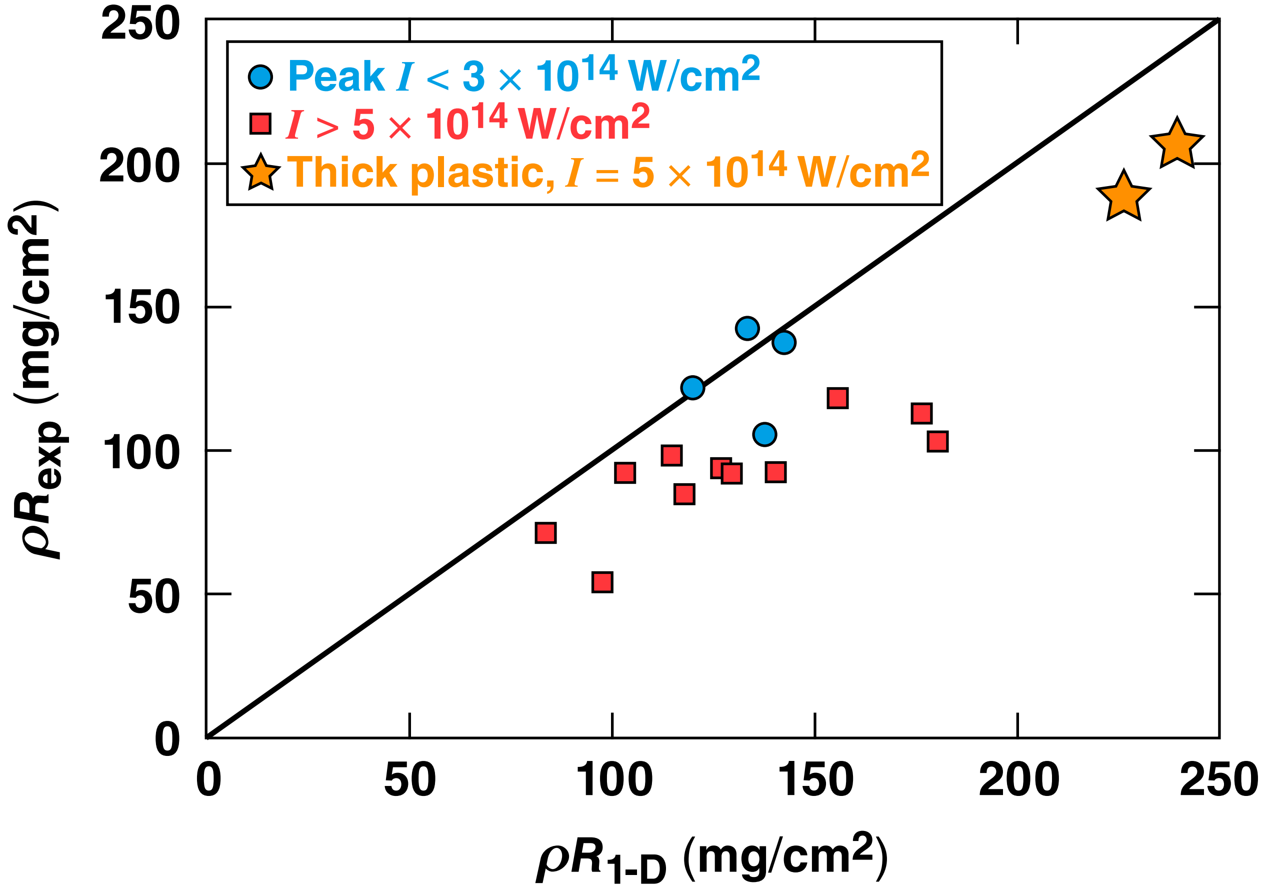
Preheat

Suprathermal-electron preheat at higher intensities was mitigated by thickening the CD-overcoat layer



TC7813a

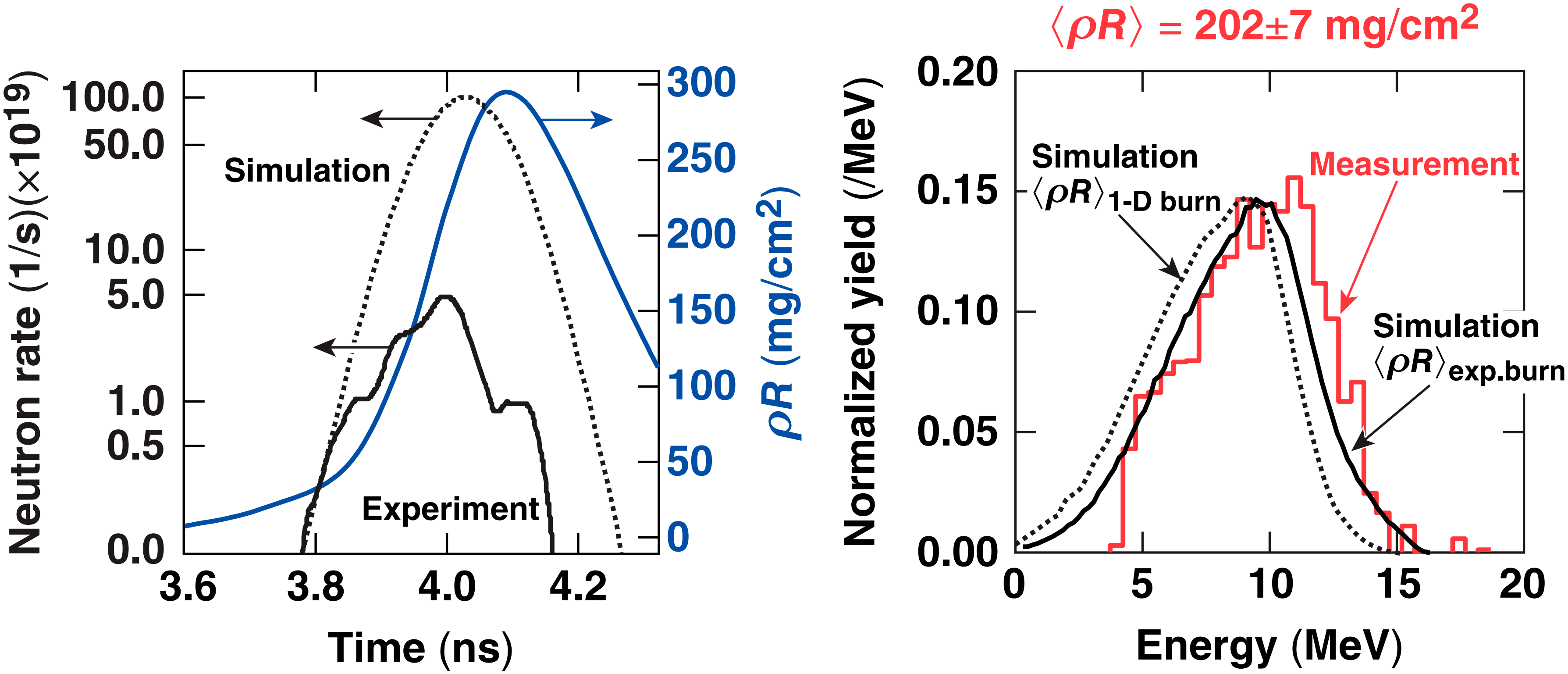
Areal density above 200 mg/cm^2 was achieved using 10-μm-thick CD ablators



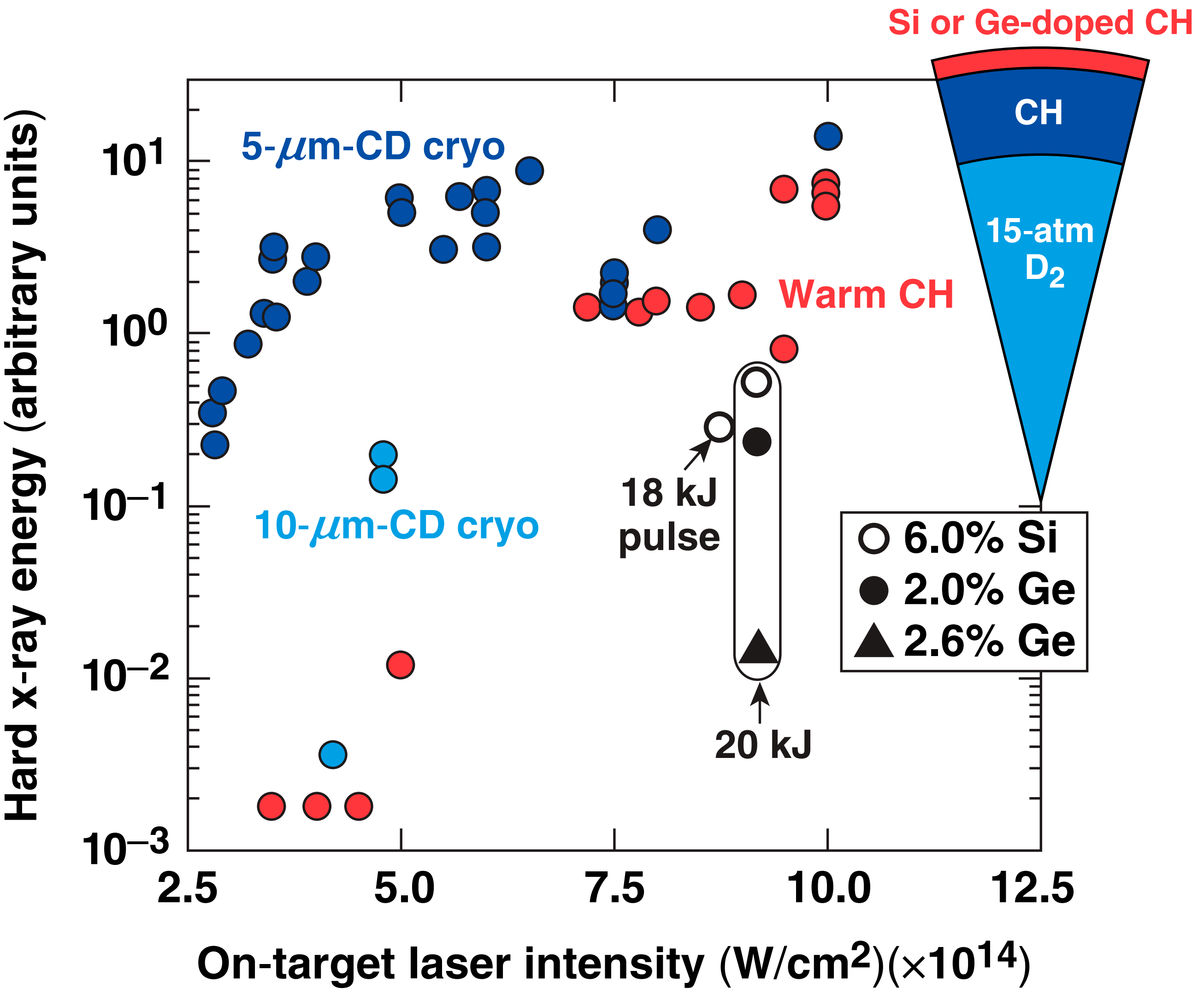
TC8037b

Agreement with charge particle spectrum is improved when predicted ρR is averaged over the experimental burn history

- $\alpha = 2$ design



If required for future designs, the hot electron generation can be further reduced by using high-Z dopants

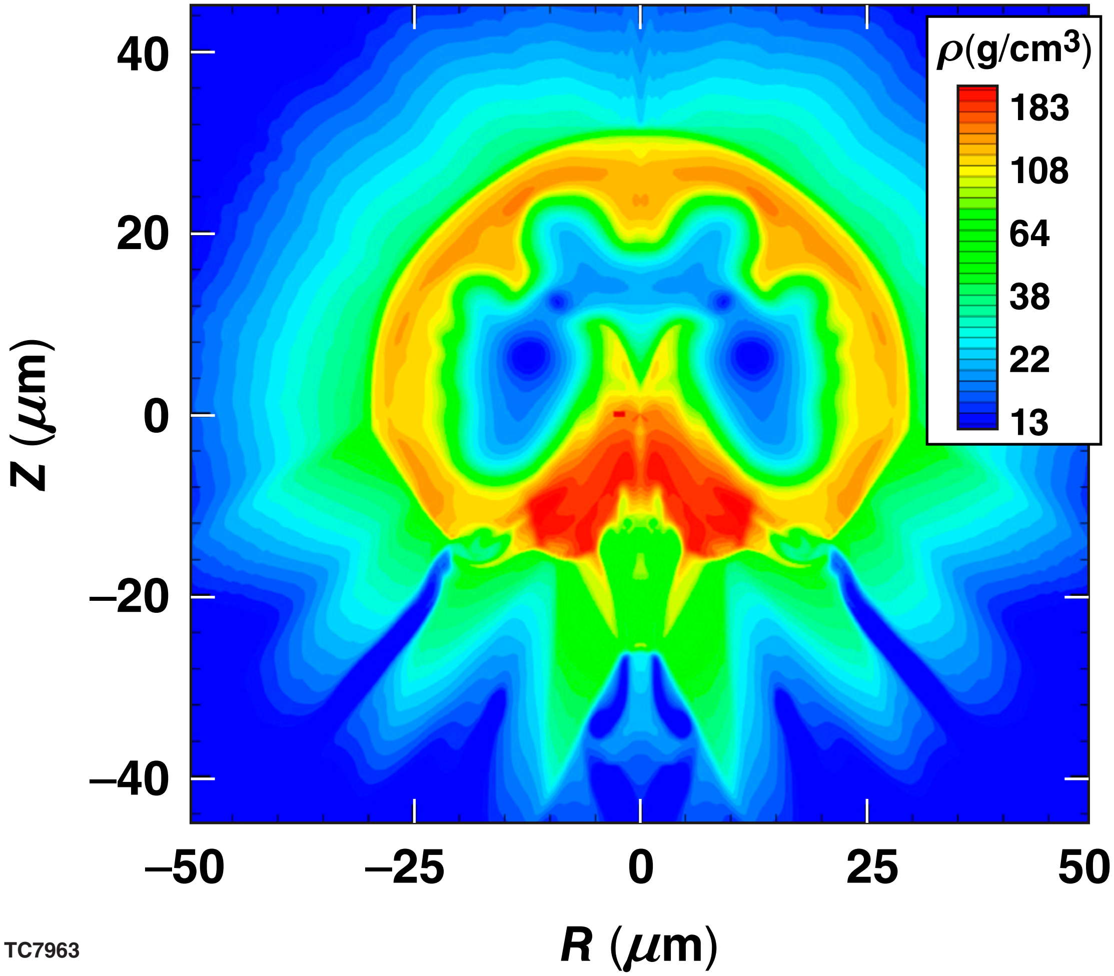


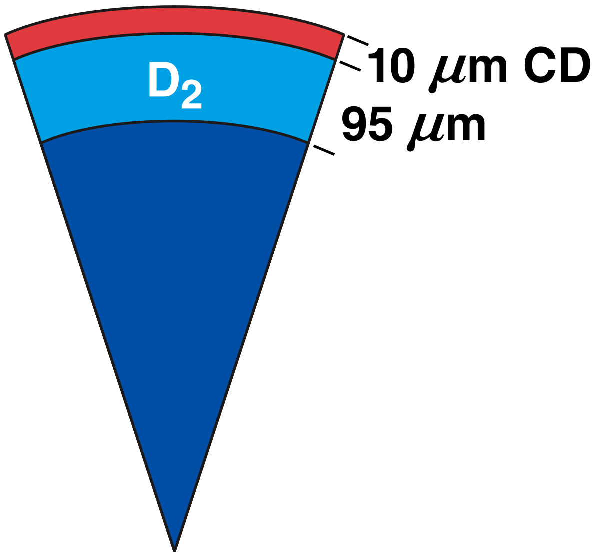
TC7813b

P. B. Radha (JO3.00002)

DRACO simulations predict significant shell deformation in low-adiabat, thick-CD cryogenic implosions

- **Thick-CD designs have lower ablation velocity and increased RT growth factors**

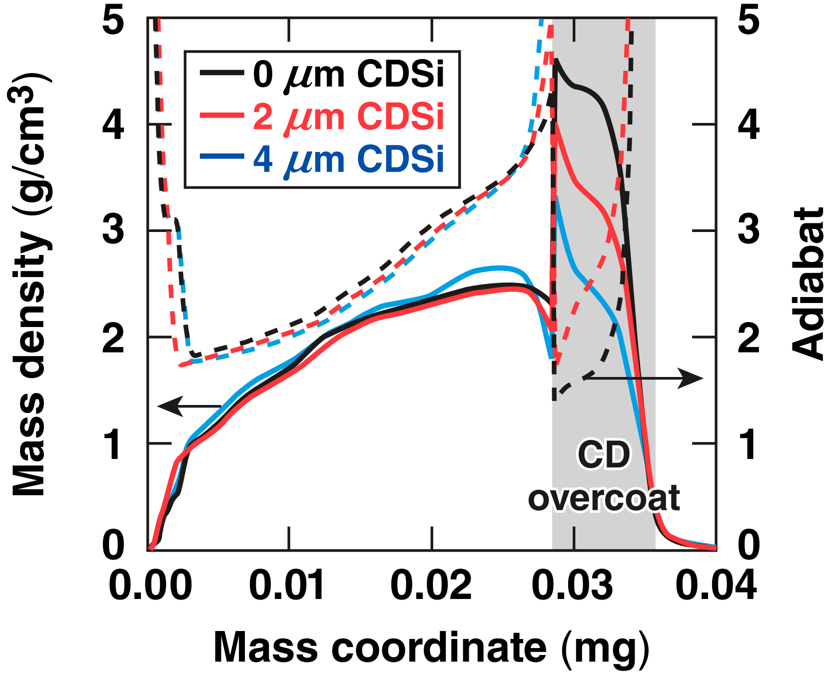




α = 2 cryogenic implosions at peak neutron production

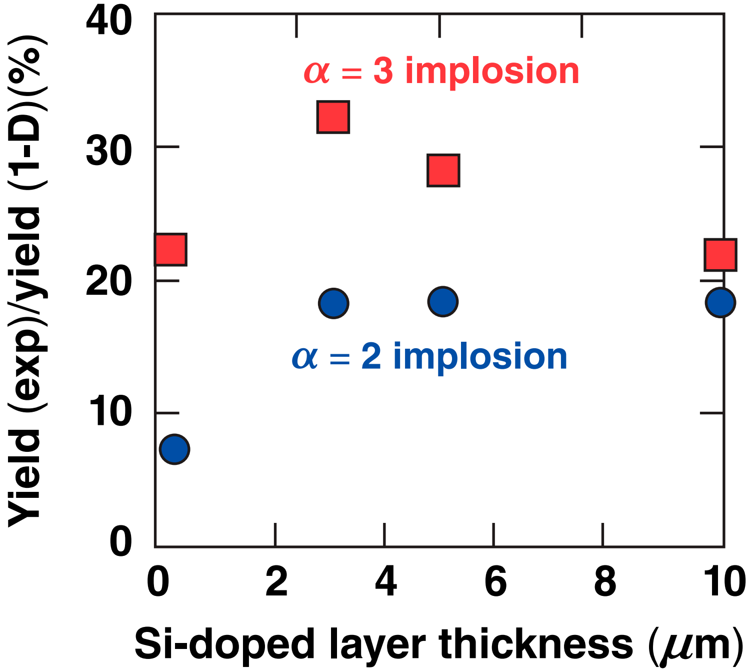
High-Z-doped ablators help reducing the laser imprint[1,2] and Rayleigh-Taylor instability growth[3]

Cryogenic implosion, simulation



Warm implosion, experimental data

$I_{max} = 8 \times 10^{14}$ W/cm^2



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[1] M. Karasik *et al.*, Bull. Am. Phys. Soc. 49, 276 (2004).

[2] A. Mostovich *et al.*, "Enhanced Direct-drive implosion with thin high-*Z* ablation layers," submitted to Phys. Rev. Lett.

[3] J. P. Knauer (PO6.00010)

Summary/Conclusions

High-areal-density ($\rho R > 200$ mg/cm^2), low-adiabat cryogenic-fuel assembly has been achieved on OMEGA

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LLE

- ICF ignition designs rely on low-adiabat fuel assembly
- Maintaining the low level of fuel adiabat during the implosion requires an accurate account for all sources of shell heating, including
  - shock heating
  - preheat due to radiation and suprathermal electrons
  - short-wavelength perturbation growth
- Effects of nonlocal thermal transport are important to model the shock heating
- Areal-density close to 1-D prediction is achieved when the shocks are accurately timed and the suprathermal-electron preheat source is mitigated