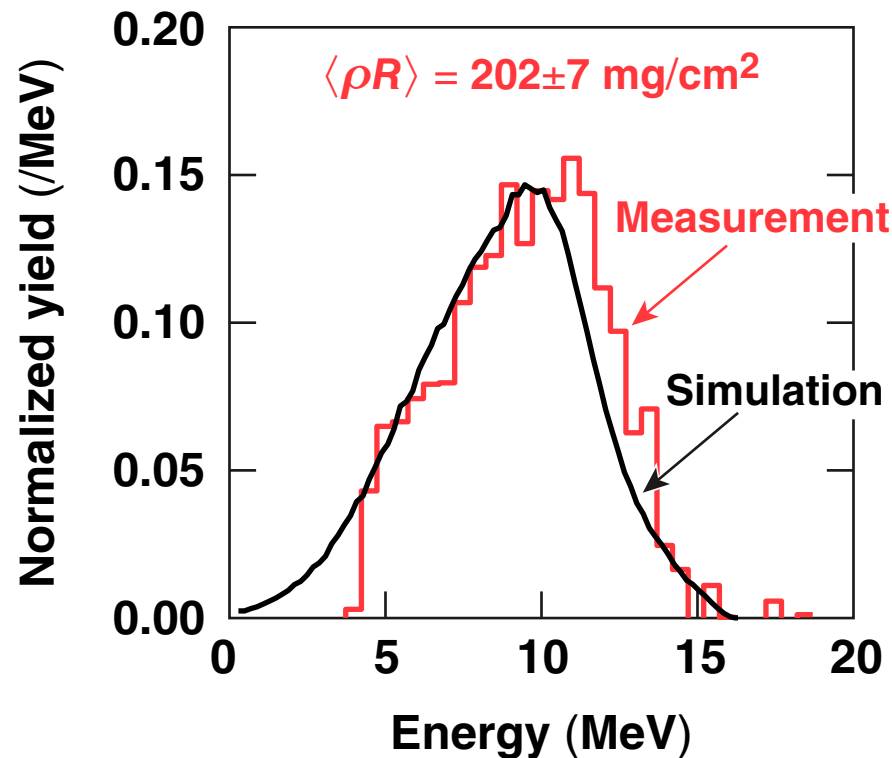


Performance of Direct-Drive Cryogenic Targets on OMEGA



V. N. Goncharov
University of Rochester
Laboratory for Laser Energetics

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

Summary

High-areal-density ($\rho R > 200 \text{ mg/cm}^2$), 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



**T. C. Sangster, P. B. Radha, R. Betti, T. R. Boehly, T. J. B. Collins,
R. S. Craxton, J. A. Delettrez, R. Epstein, V. Yu. Glebov, S. X. Hu,
I. V. Igumenshchev, R. Janezic, J. P. Knauer, S. J. Loucks, J. R. Marciante,
J. A. Marozas, F. J. Marshall, D. N. Maywar, R. L. McCrory, P. W. McKenty,
D. D. Meyerhofer, S. P. Regan, R. Roides, W. Seka, S. Skupsky,
V. A. Smalyuk, J. M. Soures, and C. Stoeckl**

**University of Rochester
Laboratory for Laser Energetics**

D. Shvarts

**Nuclear Research Center
Negev, Israel**

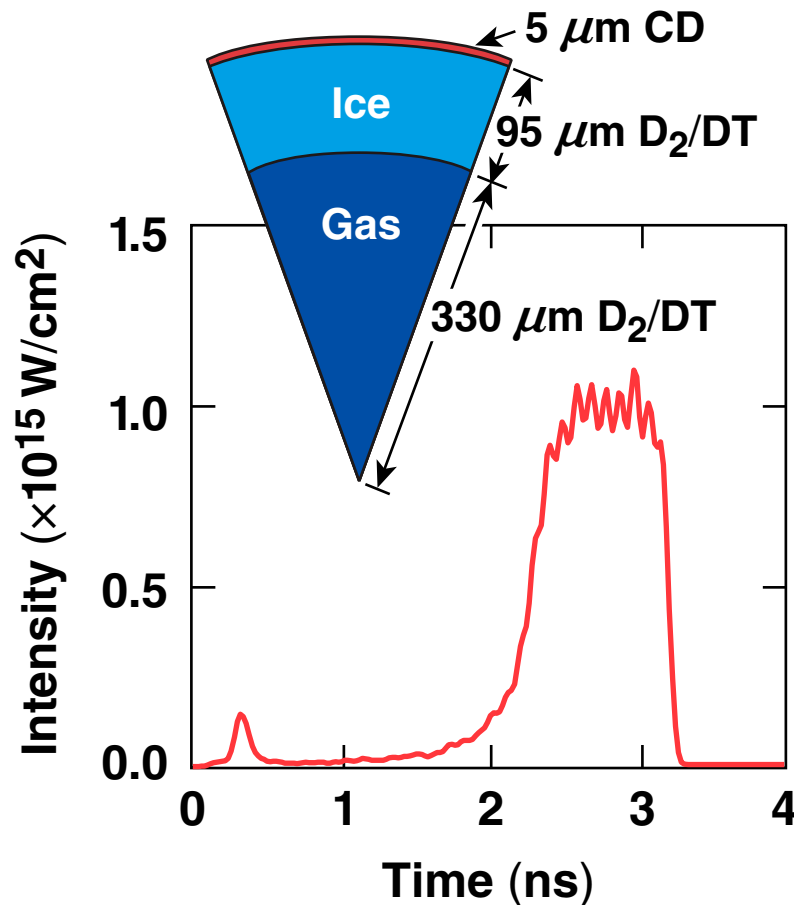
J. A. Frenje, R. D. Petrasso, and C. K. Li

Massachusetts Institute of Technology

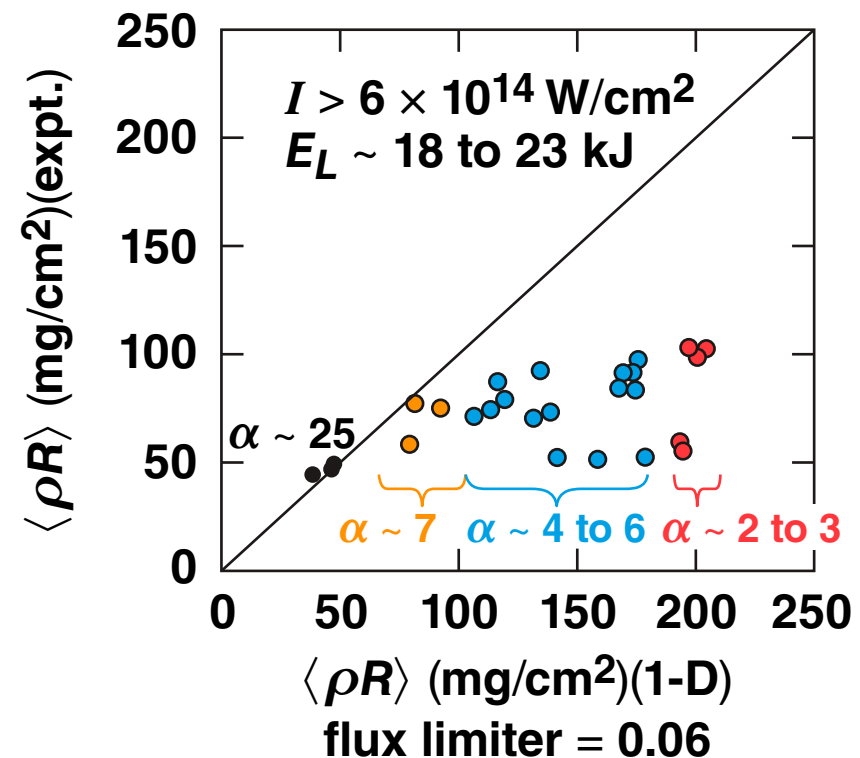
W. Manheimer and D. Colombant

Naval Research Laboratory

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



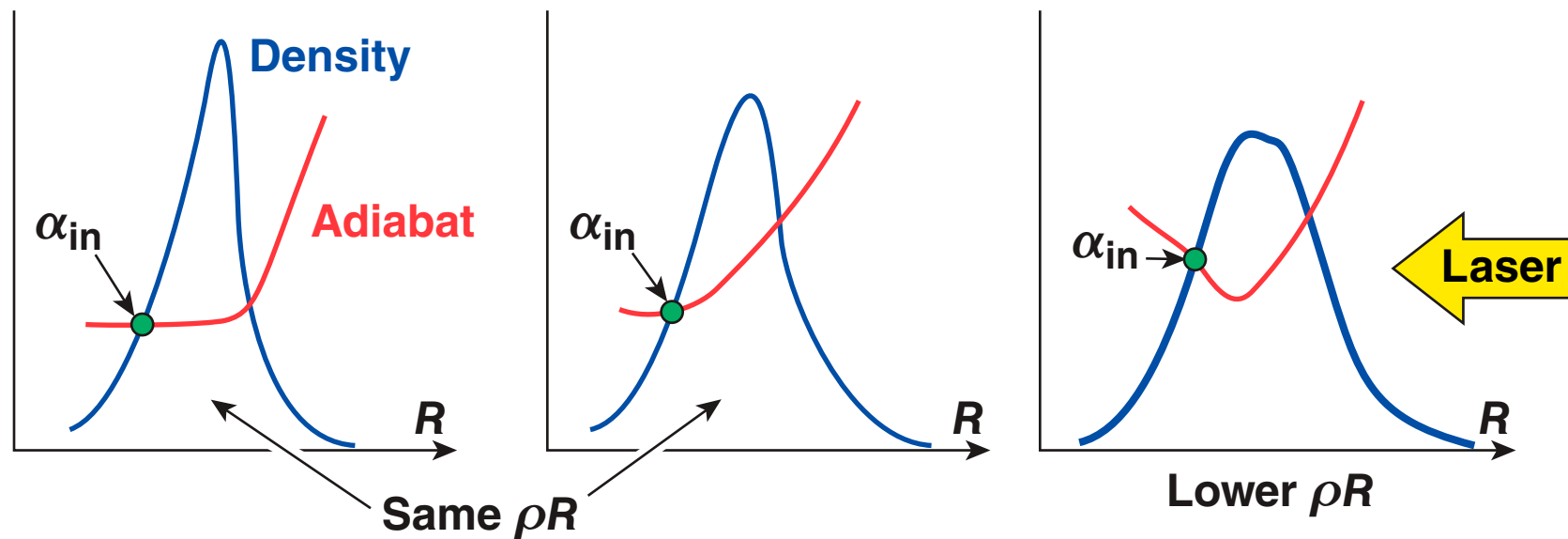
$$\alpha = \frac{P}{P_{\text{Fermi}}}$$



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*

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

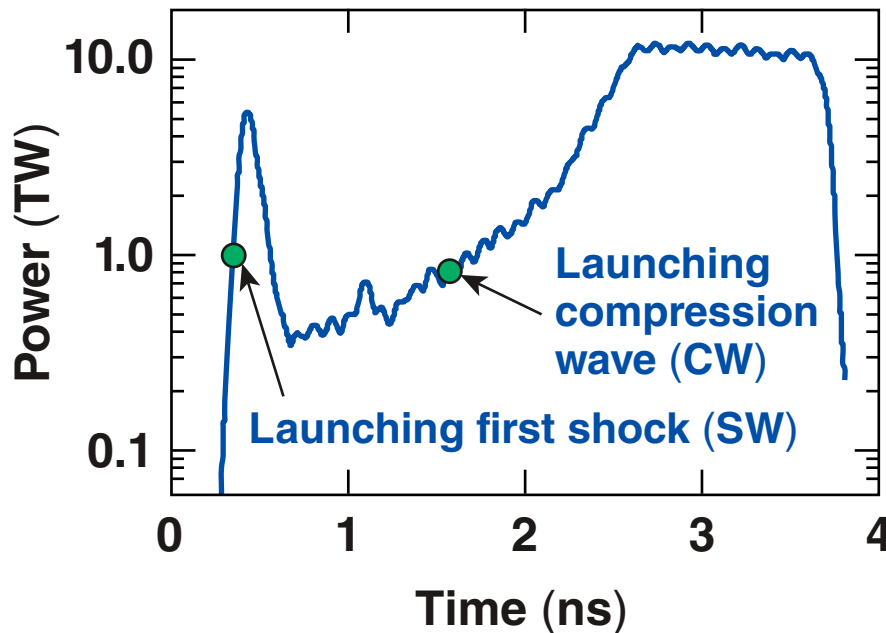


Shock Timing

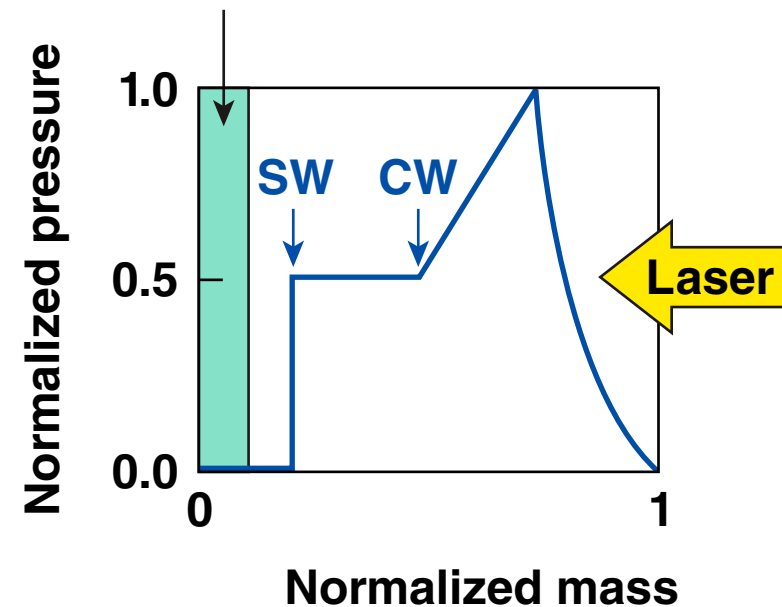
The main sources contributing to the adiabat degradation include hydrodynamics, radiation and electron preheat, and small-scale nonuniformity growth



- Timing of hydrodynamic waves



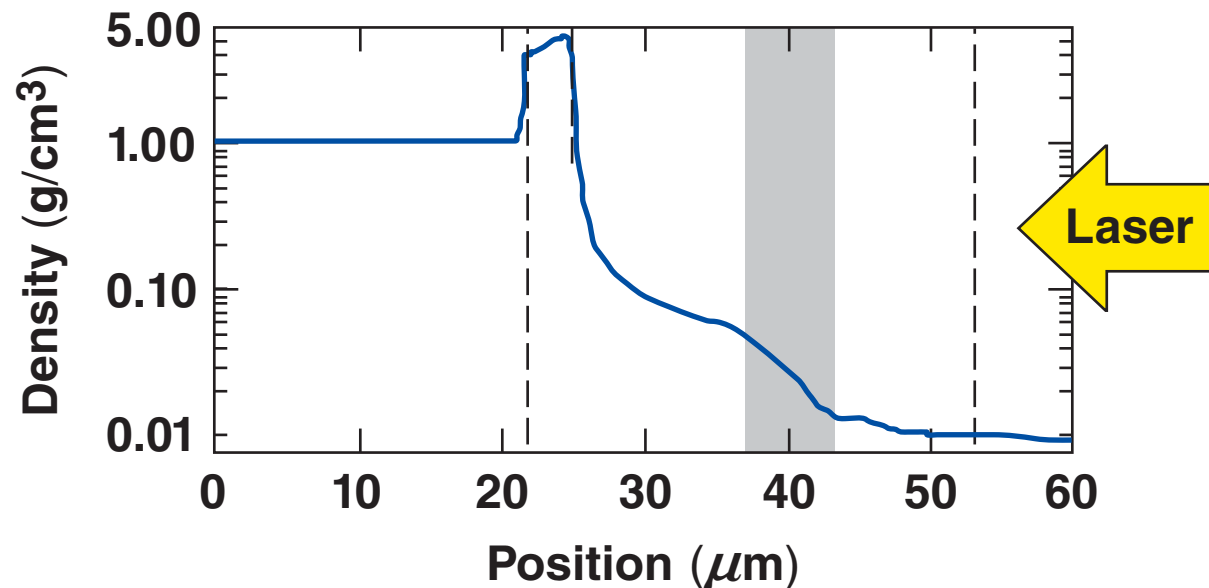
CW and SW/RW must coalesce inside 10% initial mass region



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

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

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



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

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*

$$\mathbf{v} \frac{\partial f}{\partial \mathbf{x}} + \frac{e\mathbf{E}}{m} \frac{\partial f_0}{\partial \mathbf{v}_x} = -\nu(\mathbf{v})(f - f_0), \quad f = f_0 - \int^{\mathbf{x}} \left(\frac{\partial f_0}{\partial \mathbf{x}} + \frac{e\mathbf{E}}{T} \frac{\partial f_0}{\partial \epsilon} \right) e^{-\int_{\mathbf{x}'}^{\mathbf{x}} \frac{d\mathbf{x}''}{\lambda_{ei} \cos \theta}} d\mathbf{x}'$$

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

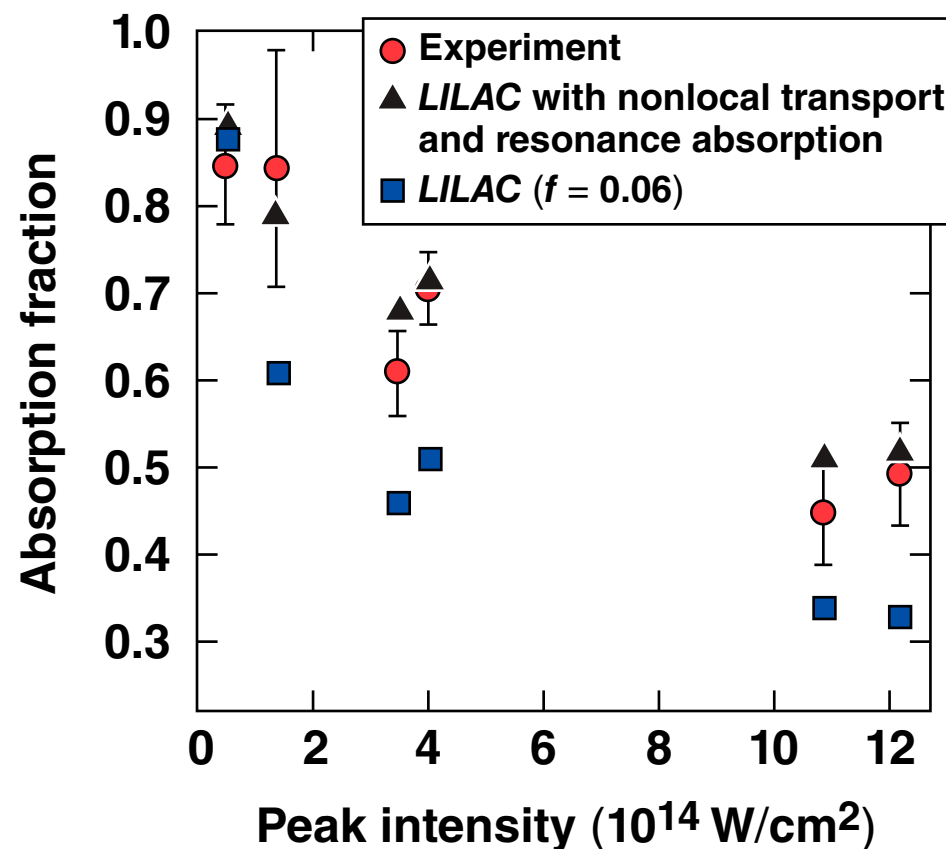
$$n' = n + \delta n, \quad T' = T + \delta T$$

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

Shock Timing

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

- 200 ps Gaussian pulse



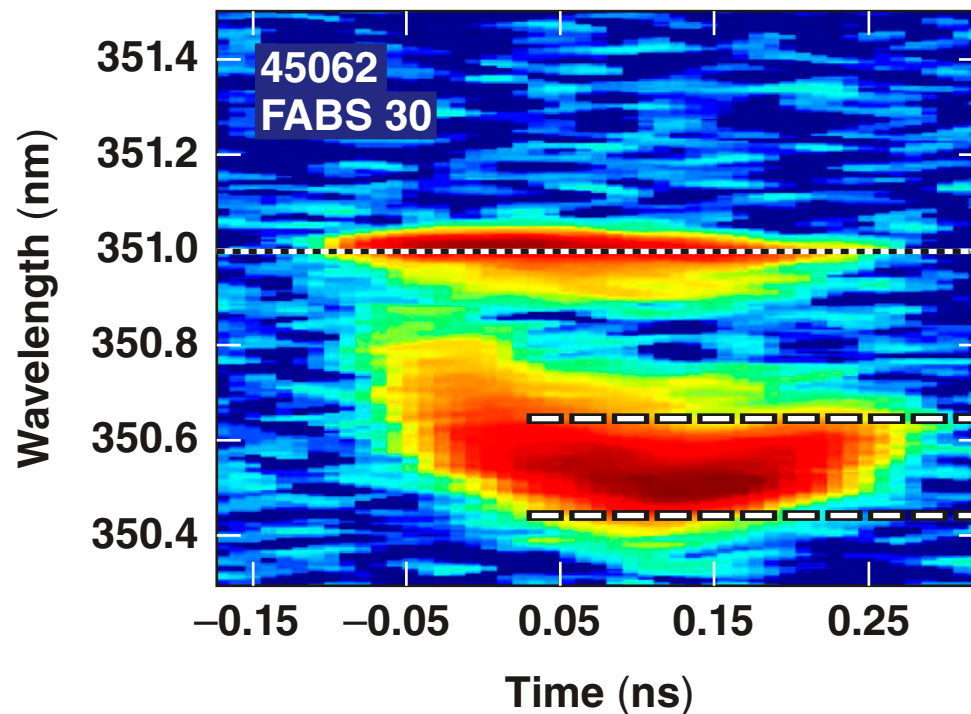
Shock Timing

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

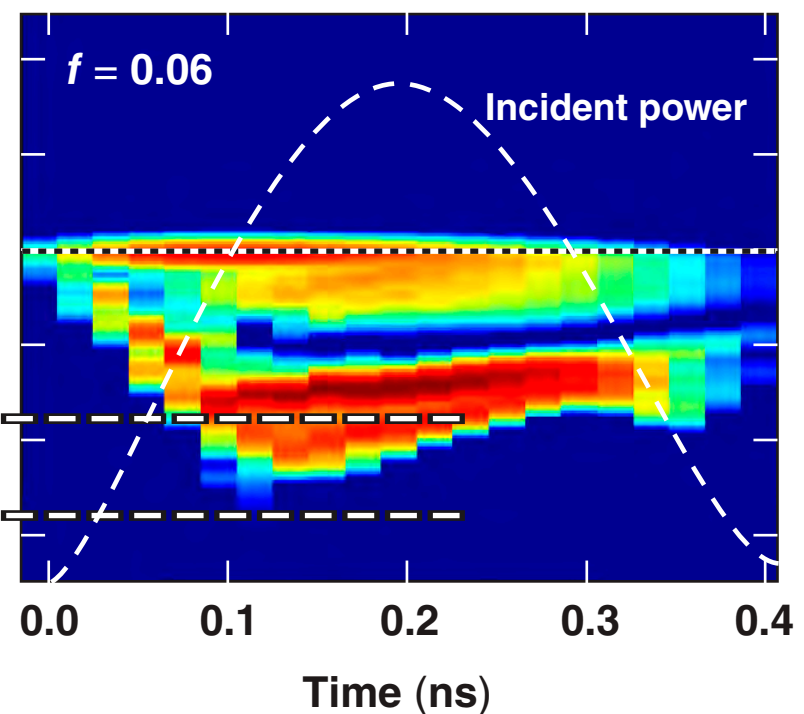


$$\text{Spectral shift}^1 \Delta\omega = \frac{\omega_0}{2c} \int \left(1 - \frac{n_e}{n_c}\right)^{-1/2} \frac{\partial}{\partial t} \left(\frac{n_e}{n_c}\right) ds$$

Experimental FABS Spectrum*



Modeled FABS Spectrum

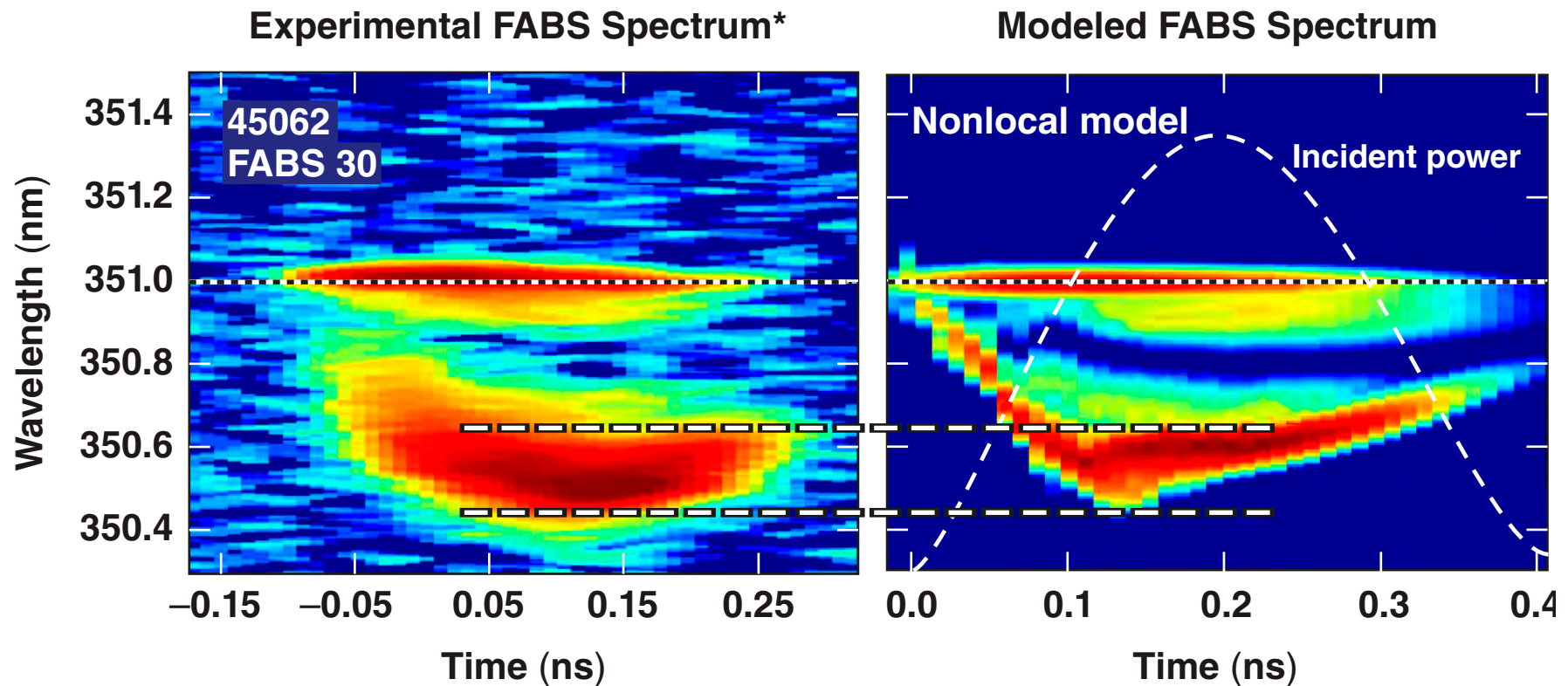


¹T. Dewandre, J. R. Albritton, and E. A. Williams, Phys. Fluids 24, 528 (1981).

²D. Edgell, NO6.00009, this conference

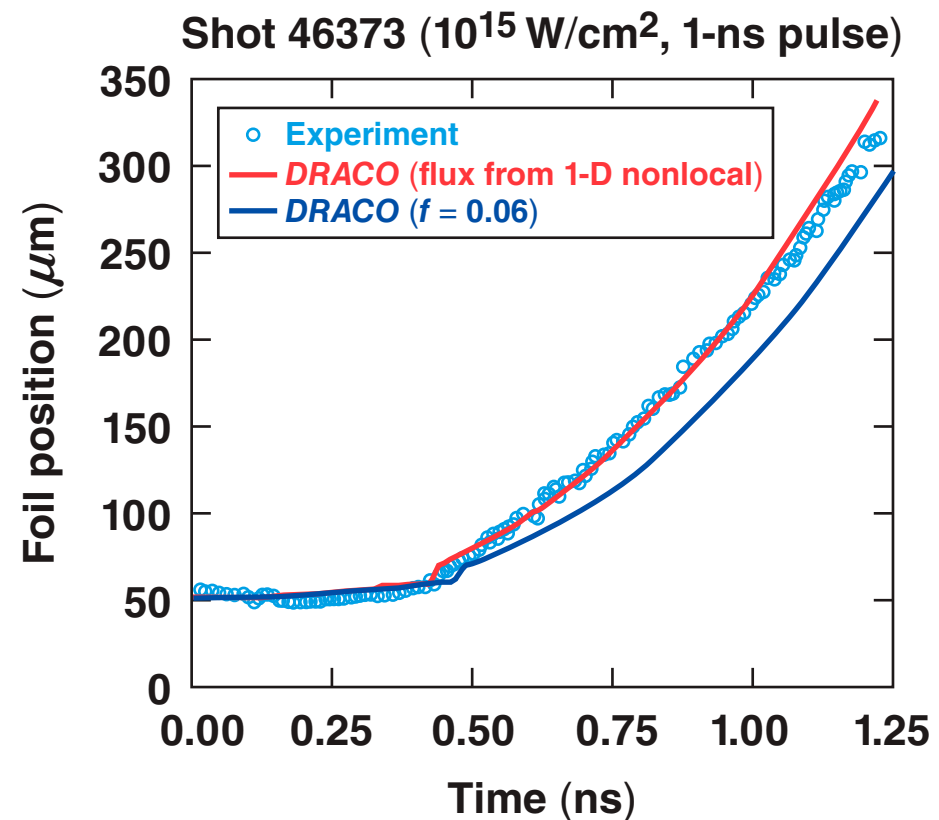
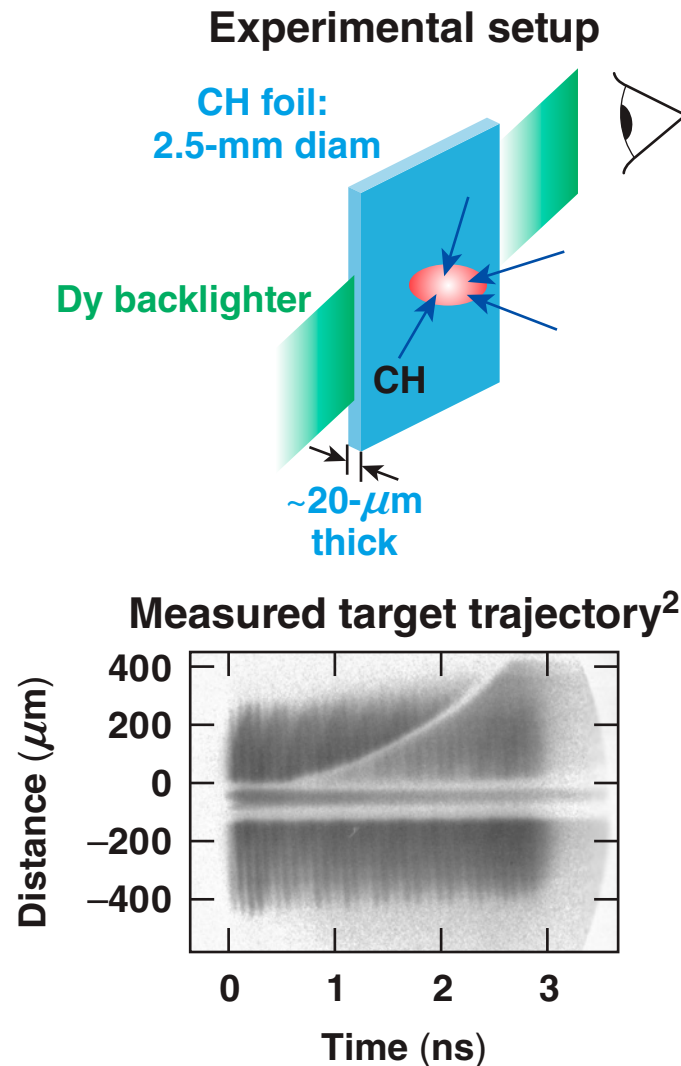
Shock Timing

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



Shock Timing

Measured foil trajectory is in agreement with the results of simulations¹ using the nonlocal transport model

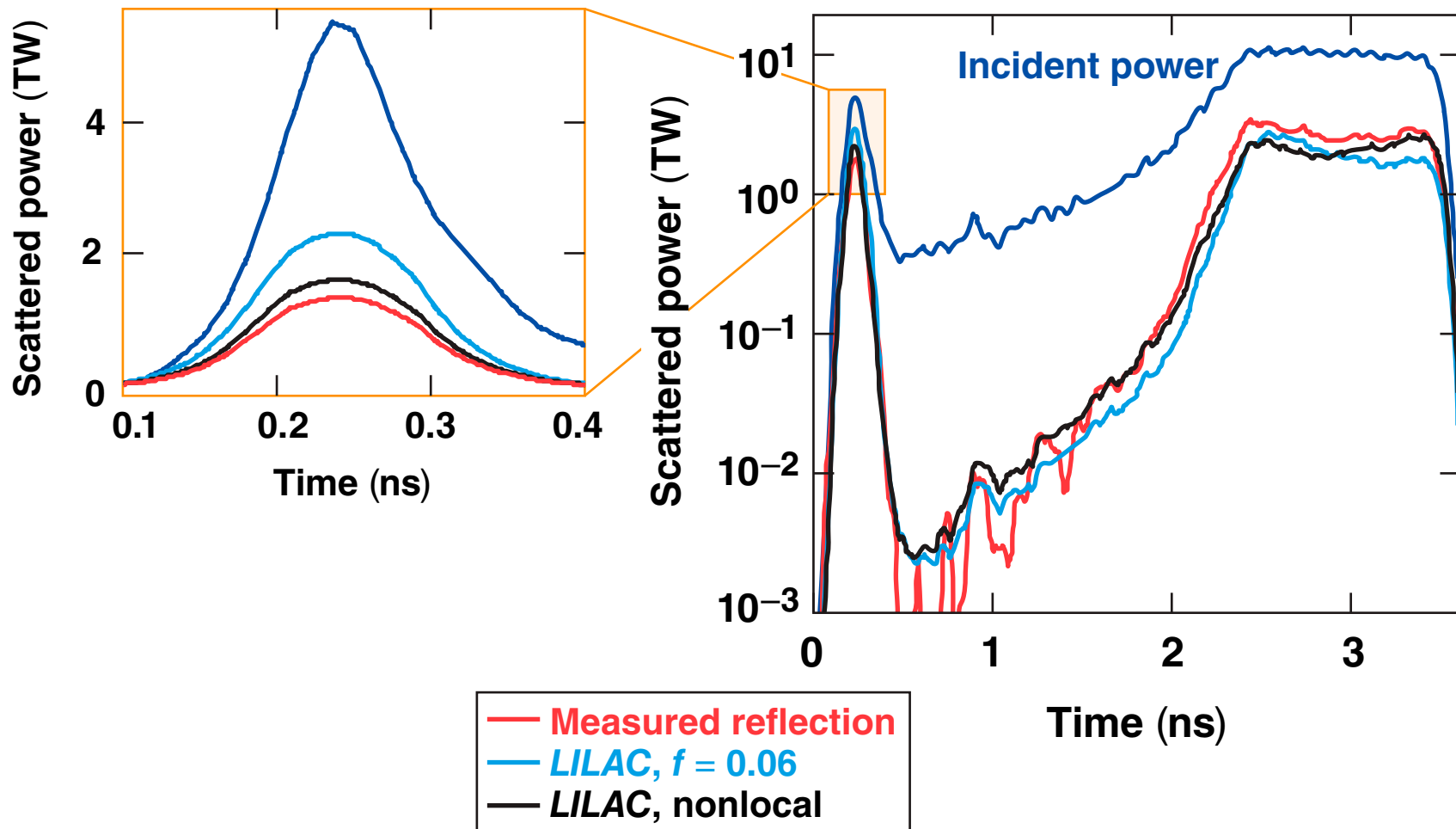


¹S. Hu (PO6.00014)

²V. Smalyuk *et al.*, presented at the 37th Anomalous 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

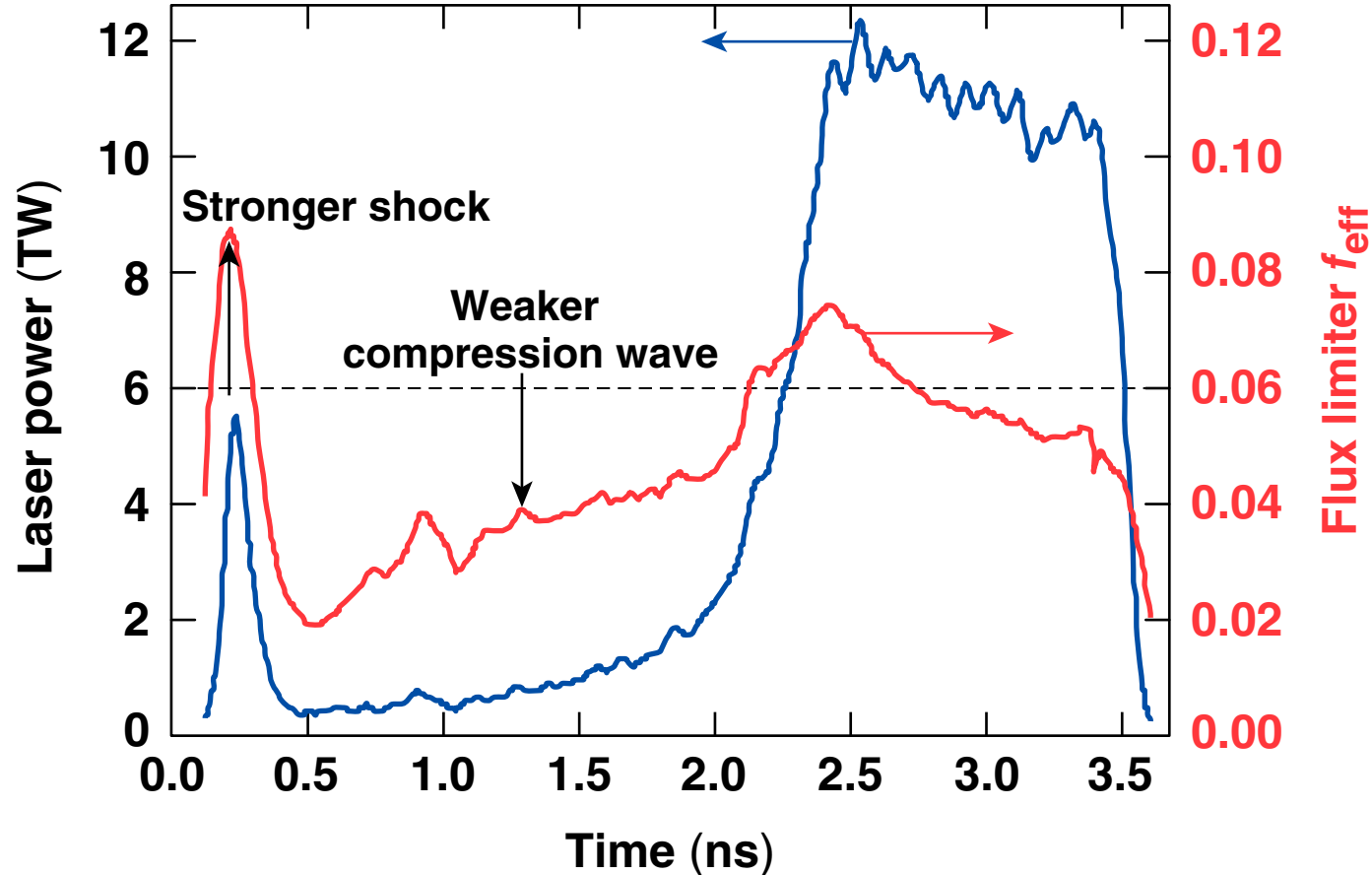


Shock Timing

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

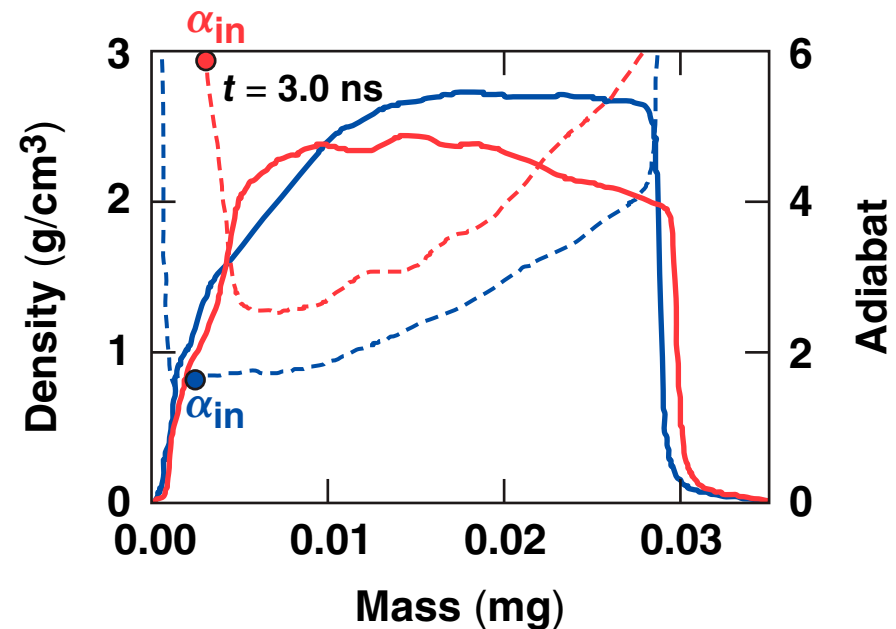
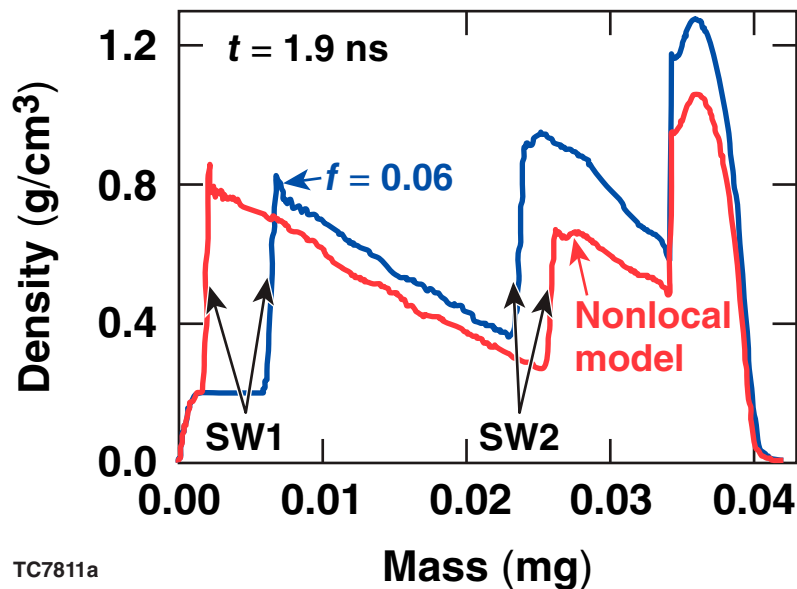
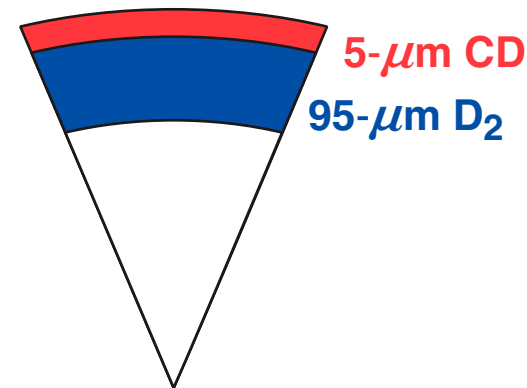
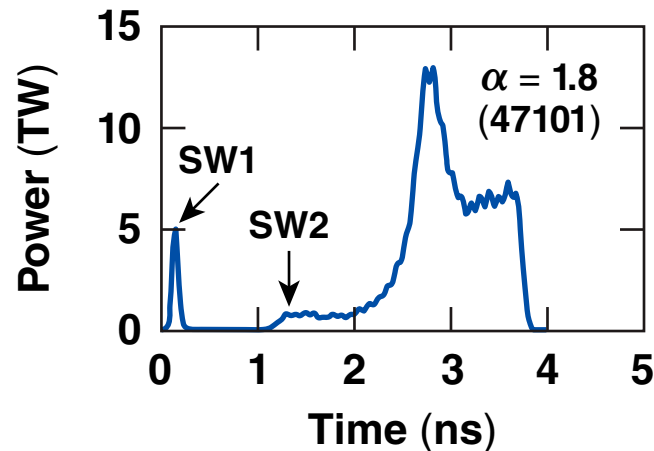


$$f_{\text{eff}} = \max\left(\frac{q_{\text{NL}}}{q_{\text{FS}}}\right) \quad \begin{array}{l} q_{\text{NL}} = \text{nonlocal flux} \\ q_{\text{FS}} = \text{free-stream flux} \end{array}$$



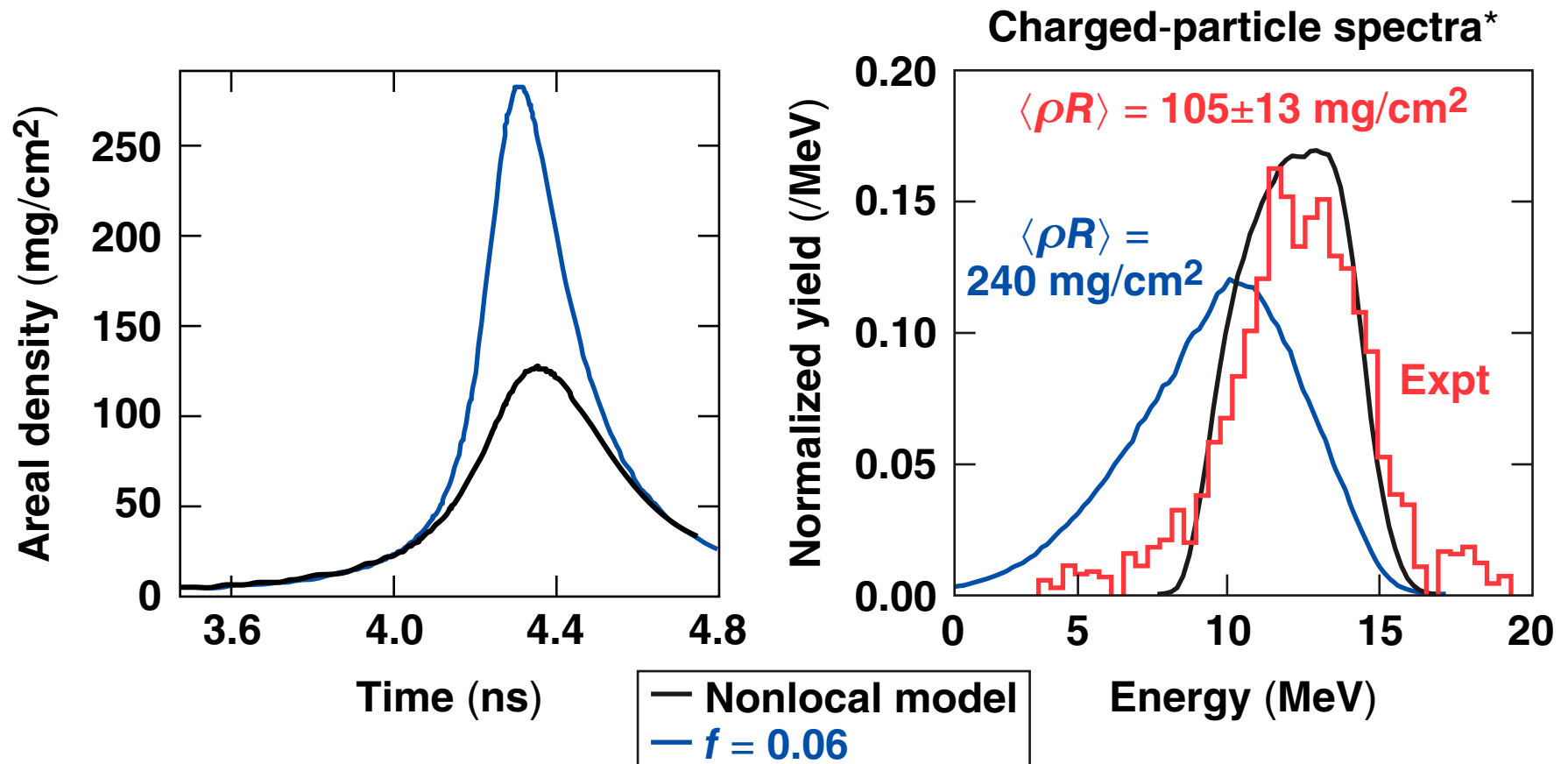
Shock Timing

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



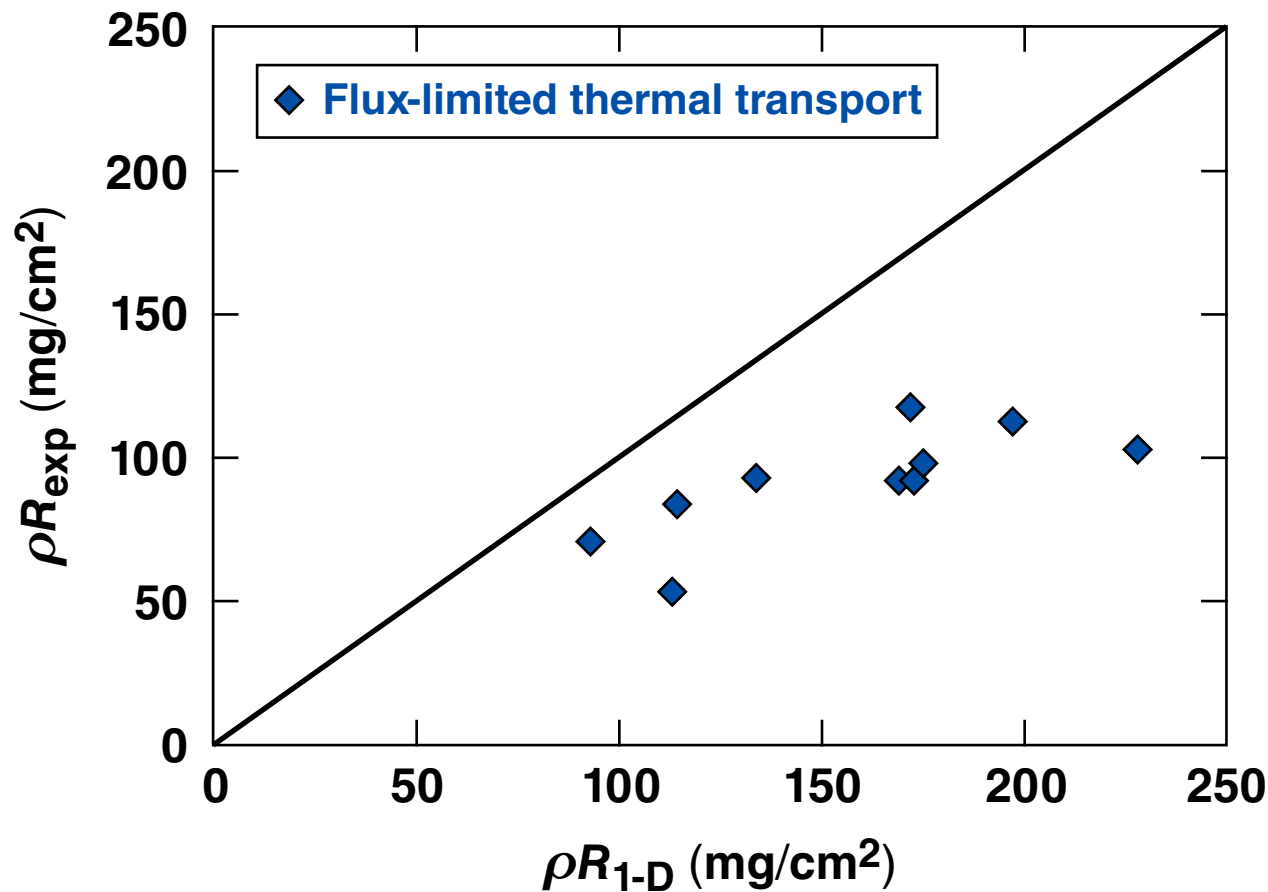
Shock Timing

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

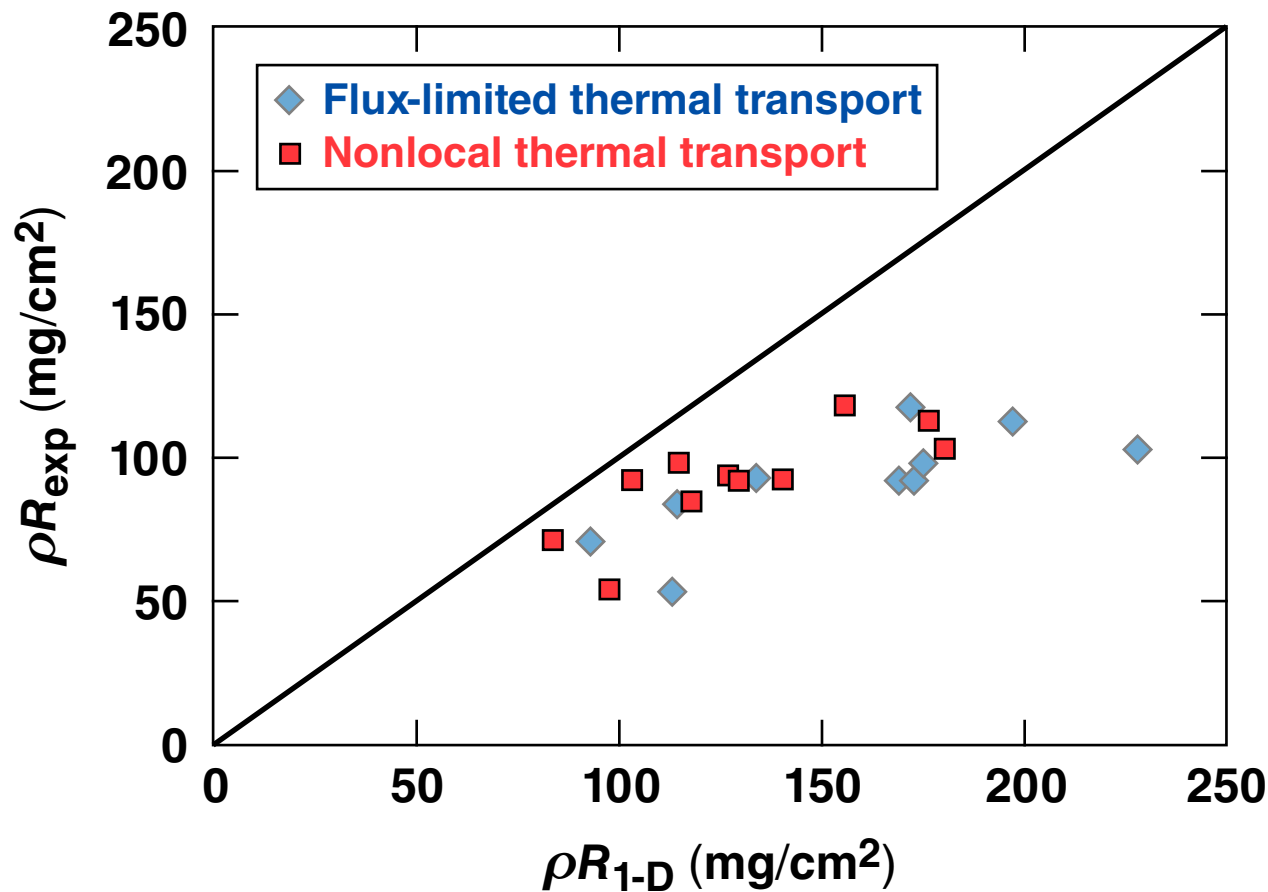


Shock timing must be adjusted using the nonlocal model.

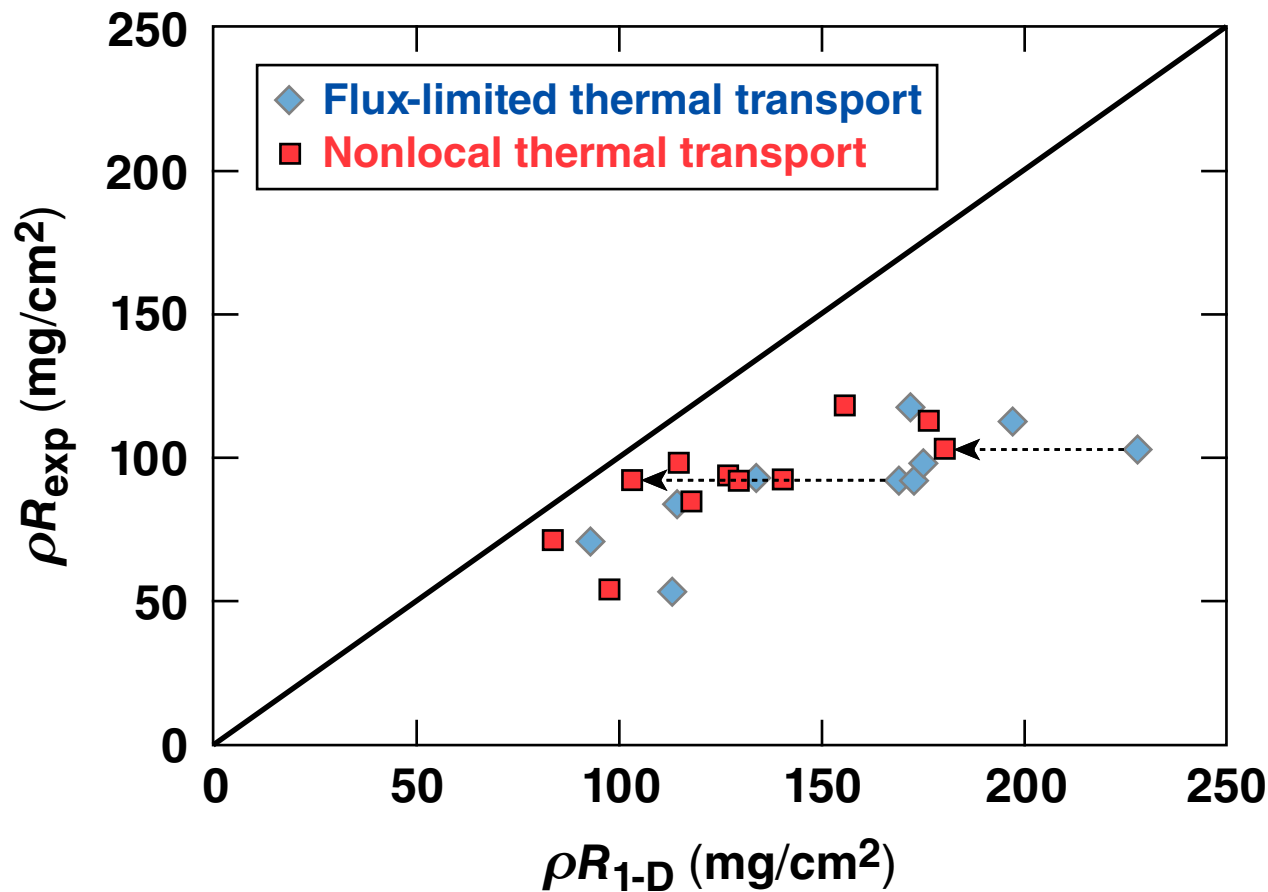
The agreement between experimental data and code predictions improves when the nonlocal model is used



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

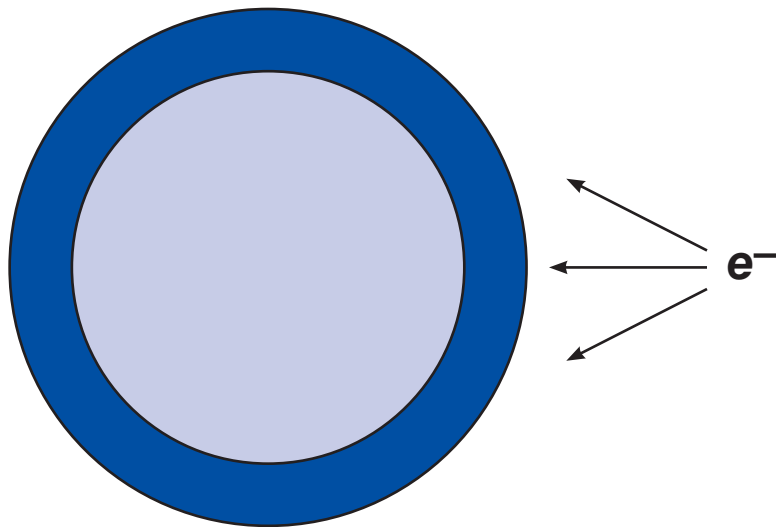


The agreement between experimental data and code predictions improves when the nonlocal model is used



Preheat

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



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

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

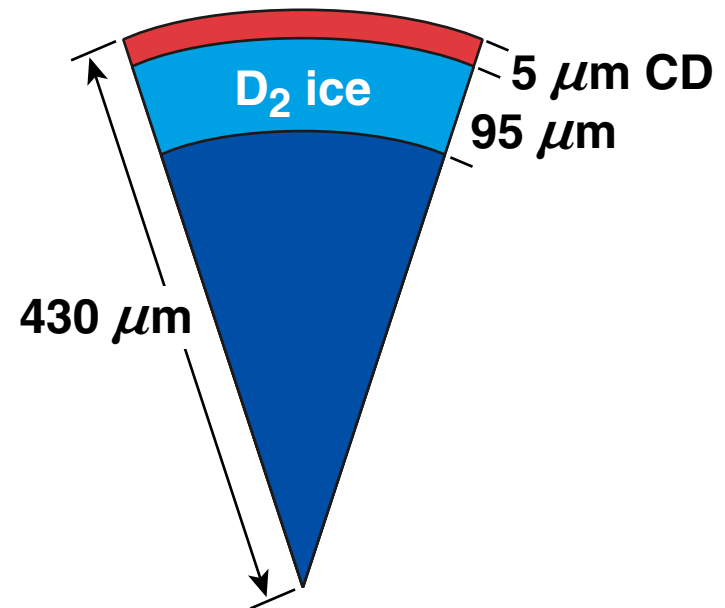
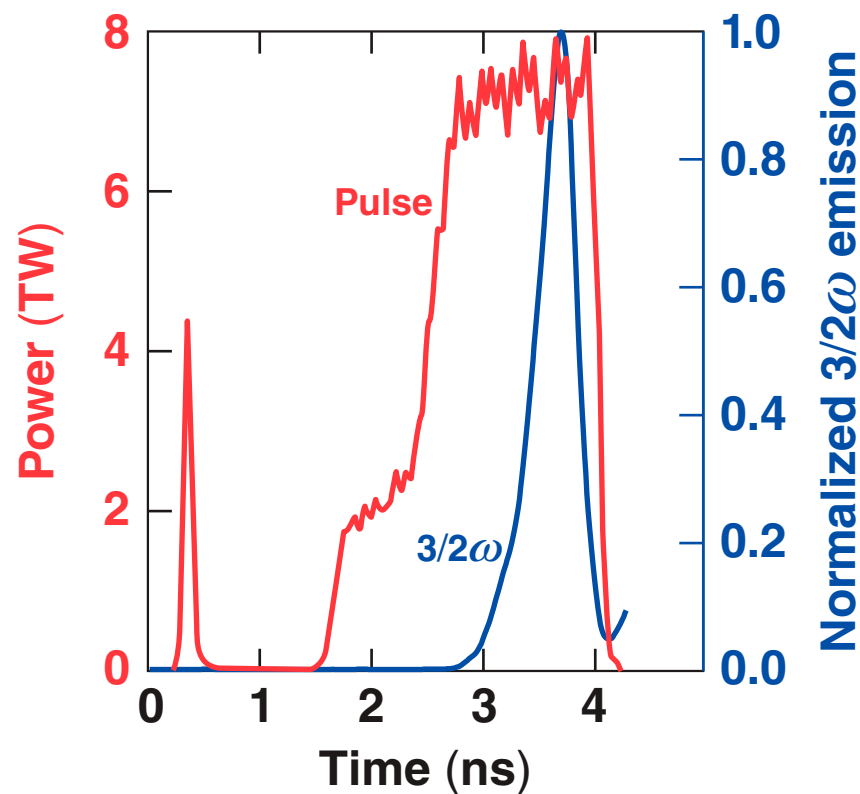
- Low- α designs $T_0 \sim 20$ eV
- 20% ρR reduction for $\Delta T_{\text{preheat}} \approx 6$ eV
- For OMEGA designs $\frac{\rho R}{\rho R_0} \sim 0.8$ if $E_{\text{preheat}} \sim 10$ J ($< 0.1\%$ E_L)

Preheat

$3/2\omega$ light indicates the presence of two-plasmon-decay instability

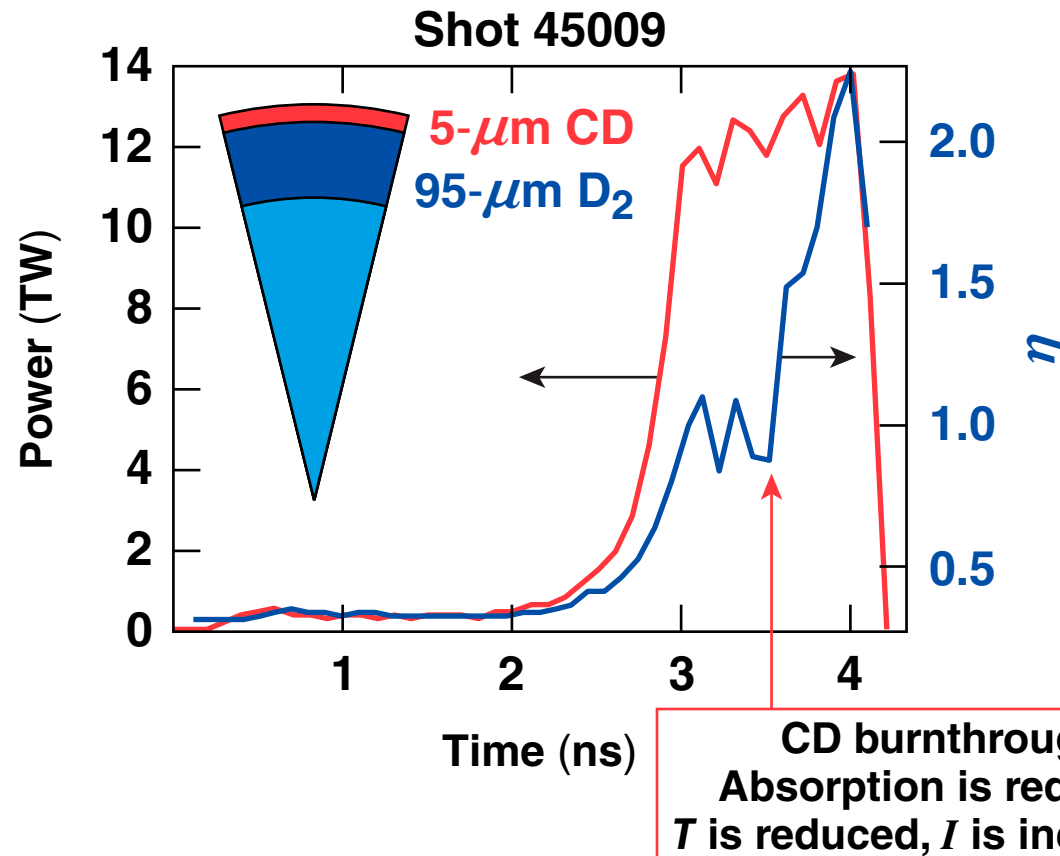


$3/2\omega$ emission for shot 46520



Onset of $3/2\omega$ signal correlates with CD burnthrough time

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



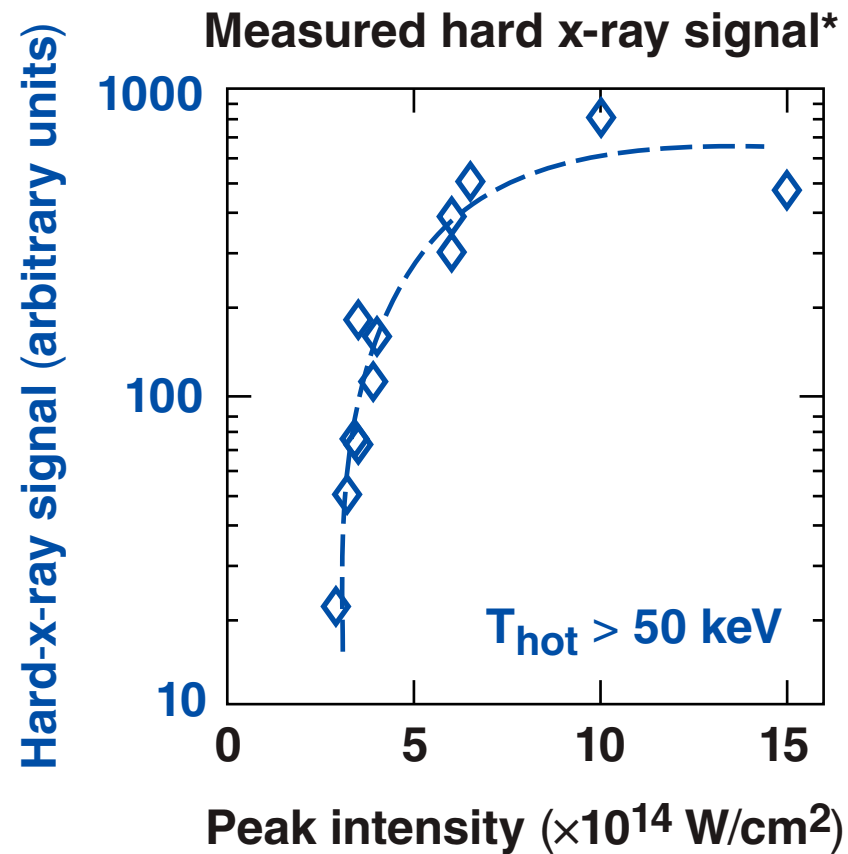
*A. Simon *et al.*, Phys. Fluids **26**, 3107 (1983).
J. A. Delettrez (JO3.00003)

Preheat

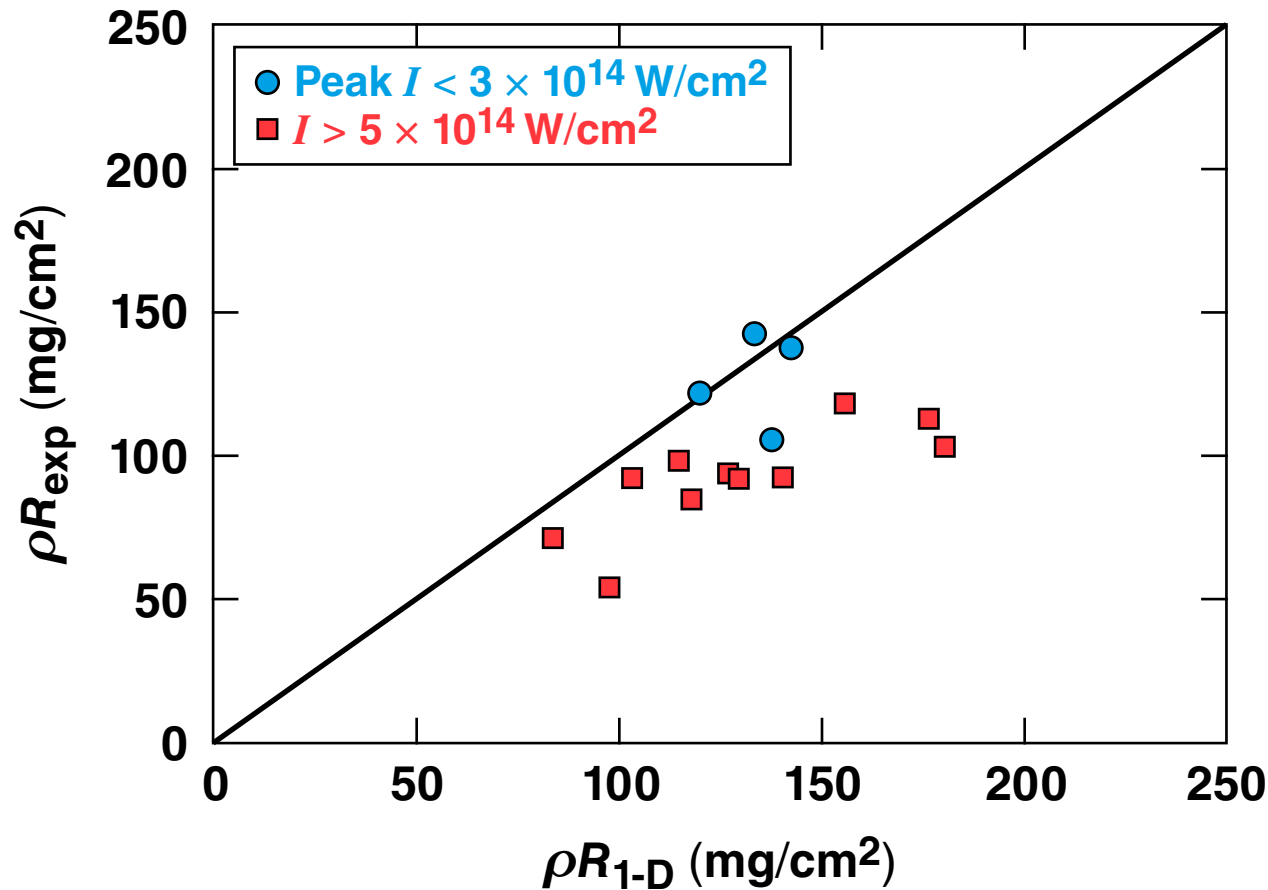
The measured hard x-ray signal is correlated with laser intensity



Cryogenic low- α D₂ targets with thin ($\leq 5 \mu\text{m}$) CD ablator

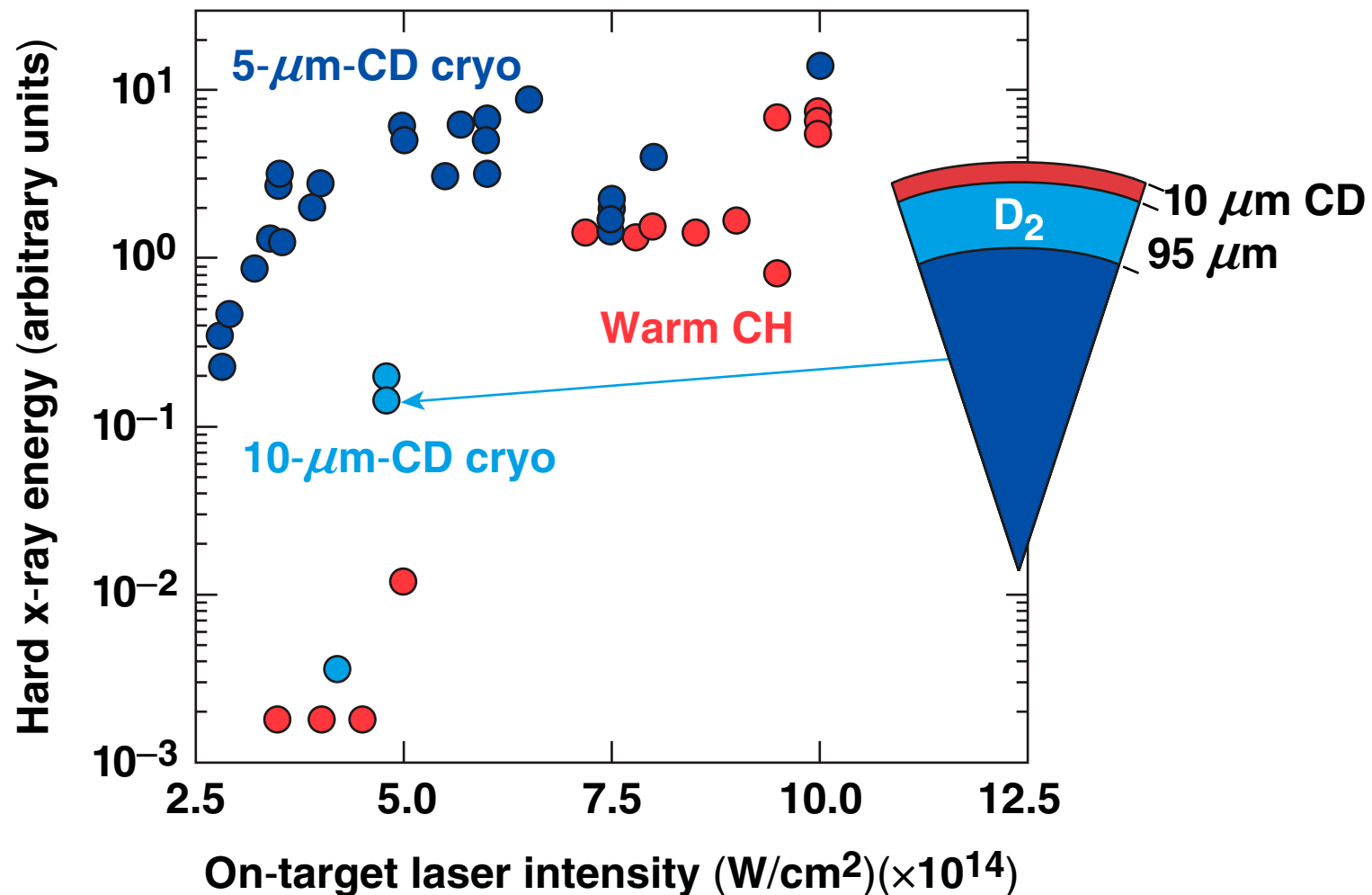


An improved agreement between simulated and measured ρR is observed for low intensity implosions

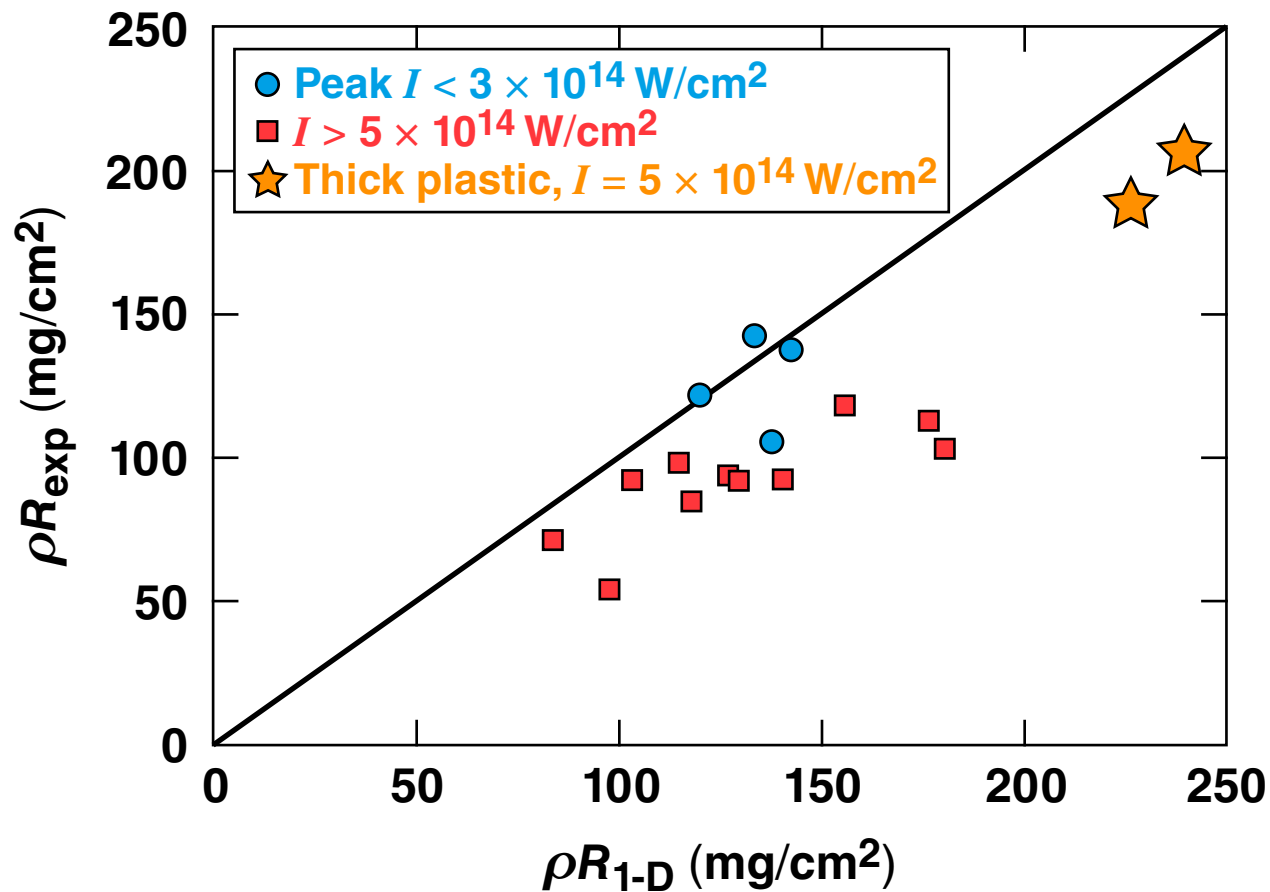


Preheat

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



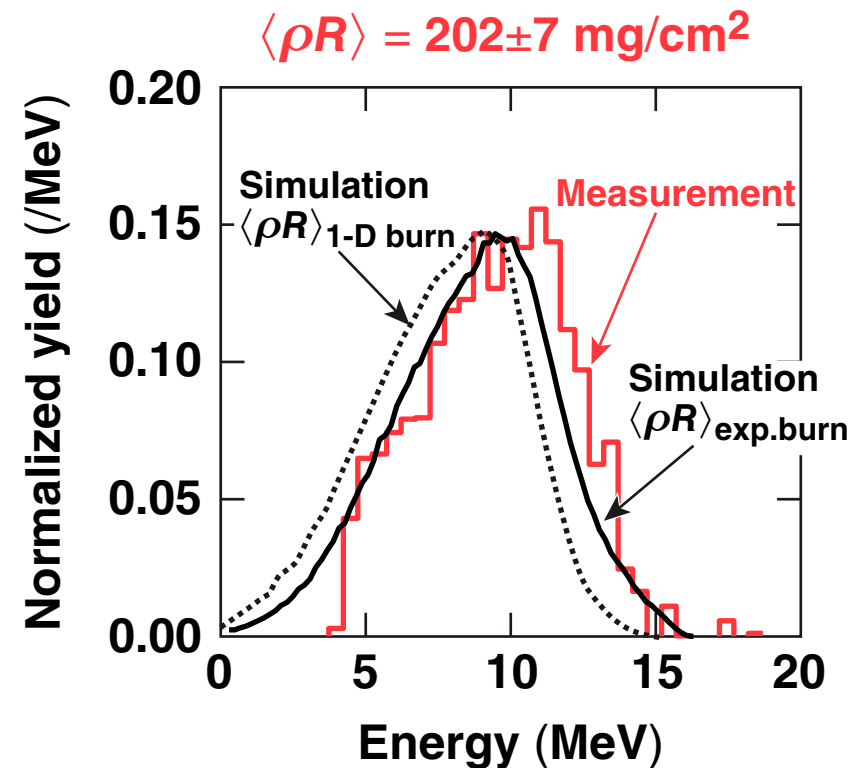
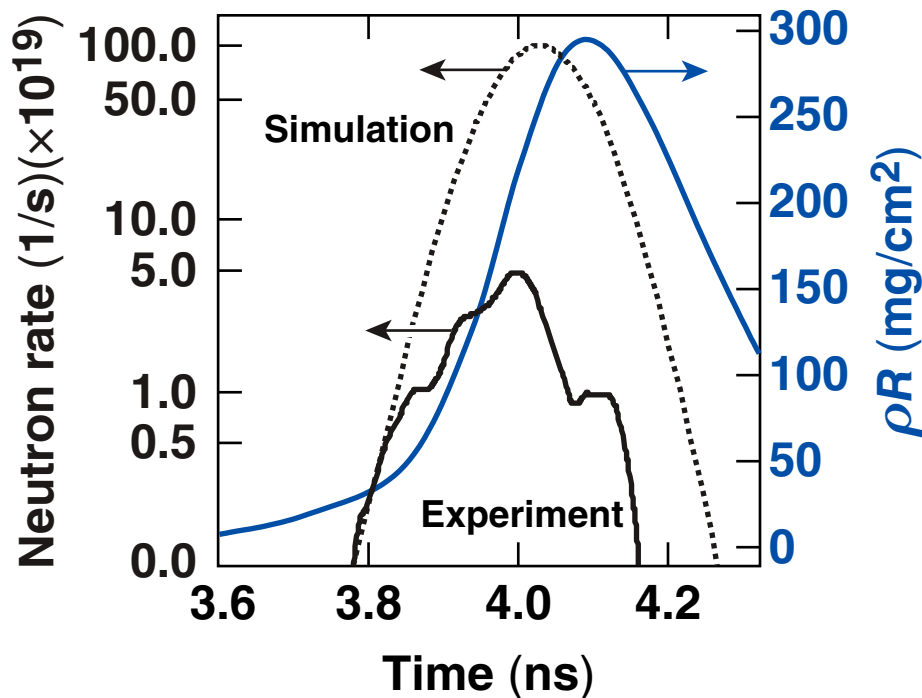
Areal density above 200 mg/cm² was achieved using 10- μ m-thick CD ablators



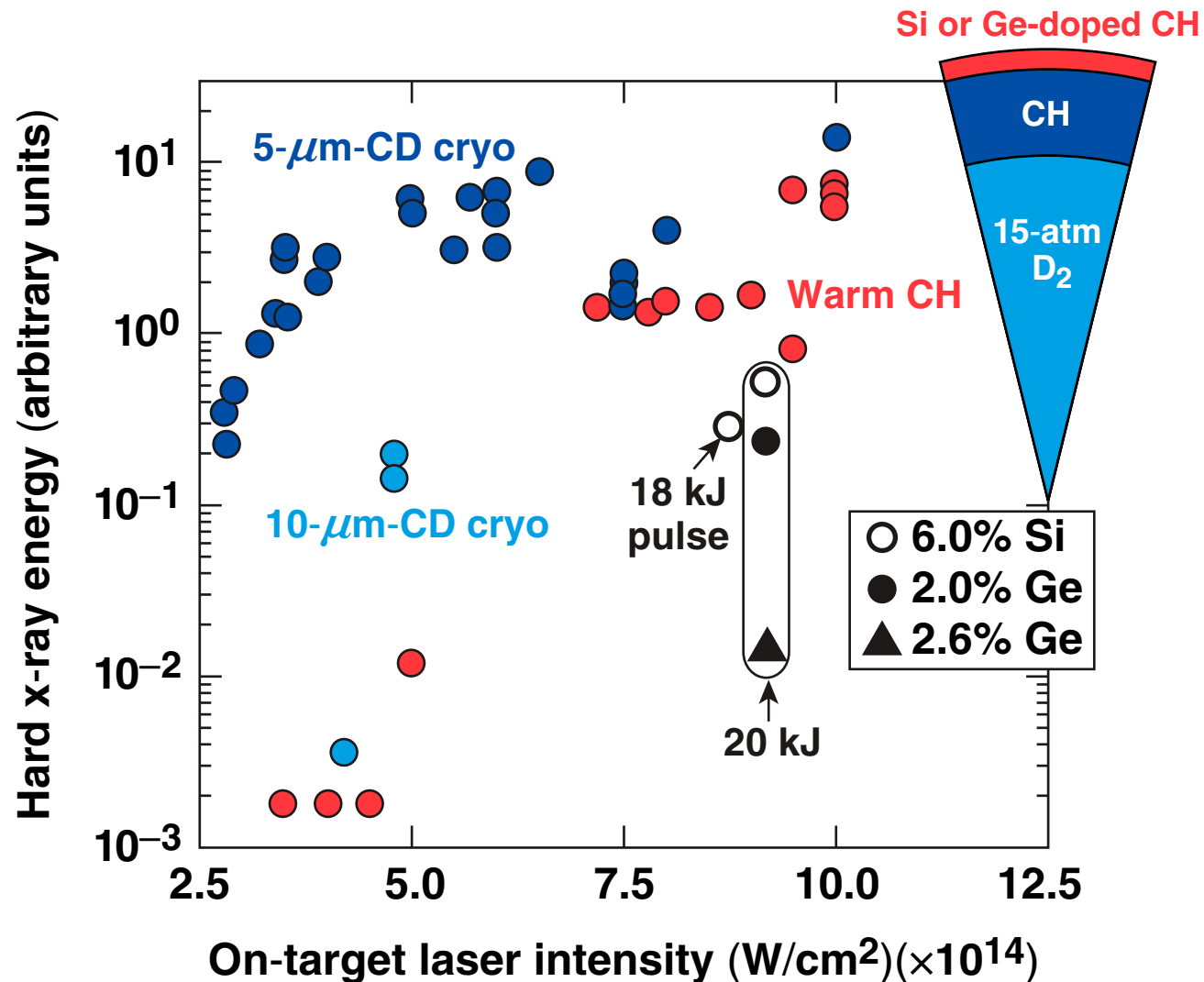
Agreement with charge particle spectrum is improved when predicted ρR is averaged over the experimental burn history



- $\alpha = 2$ design



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

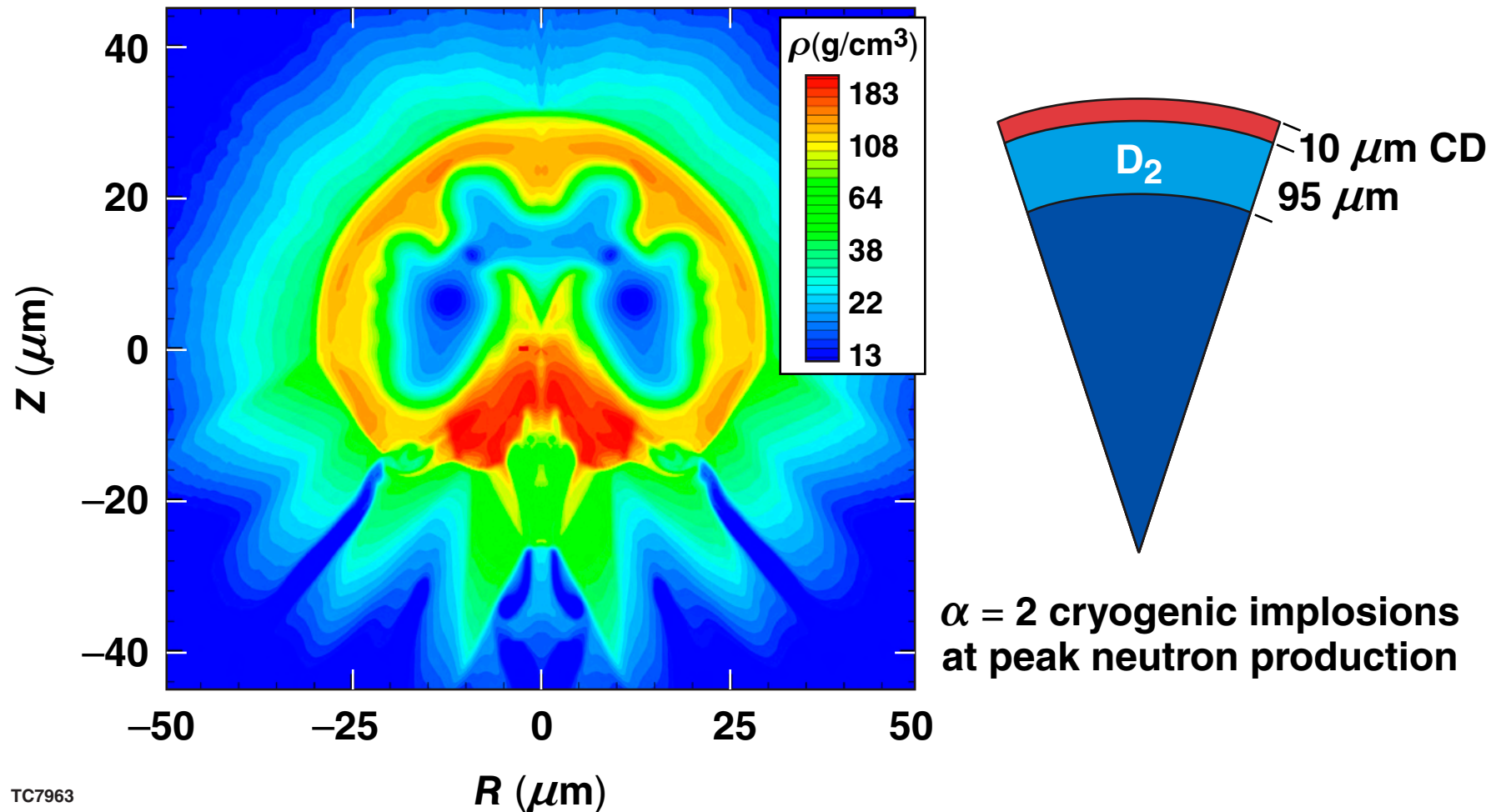


Nonuniformity growth

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

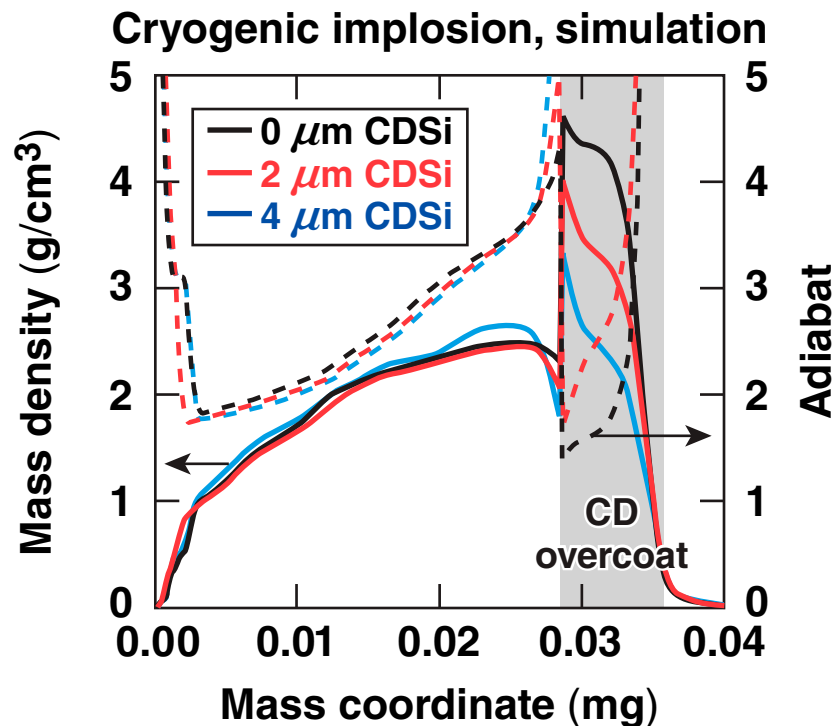


- Thick-CD designs have lower ablation velocity and increased RT growth factors

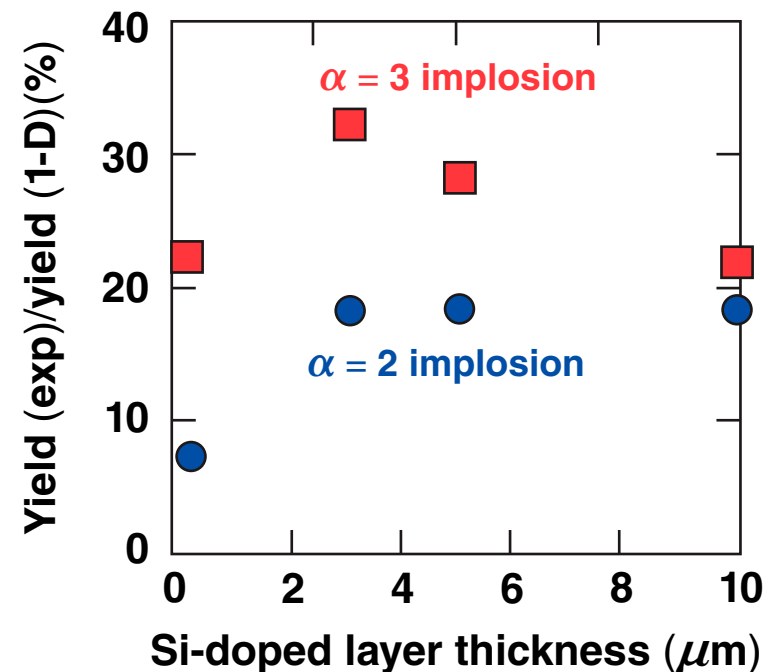


Nonuniformity growth

High-Z-doped ablators help reducing the laser imprint^{1,2} and Rayleigh-Taylor instability growth³



Warm implosion, experimental data
 $I_{\text{max}} = 8 \times 10^{14} \text{ W}/\text{cm}^2$



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 ($\rho R > 200 \text{ mg/cm}^2$), 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