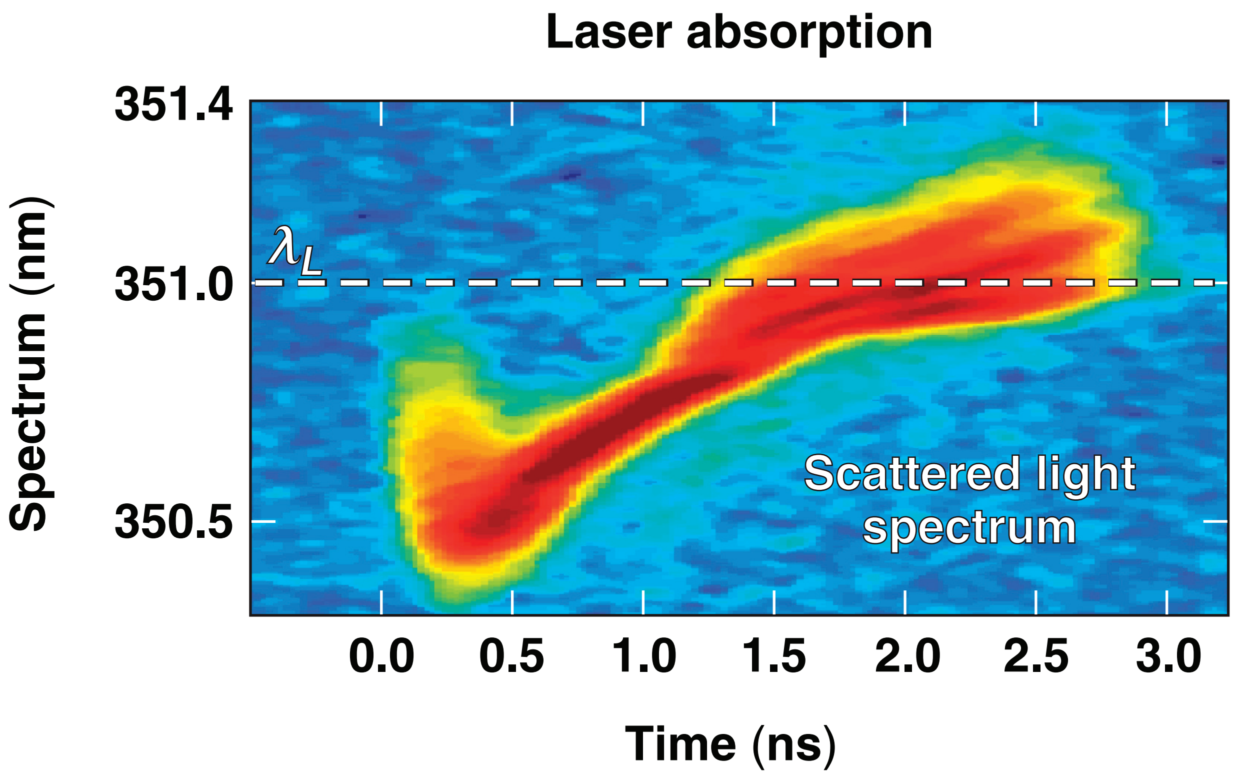
Laser-Energy Coupling, Mass Ablation Rate, and Shock-Heating in Direct-Drive ICF

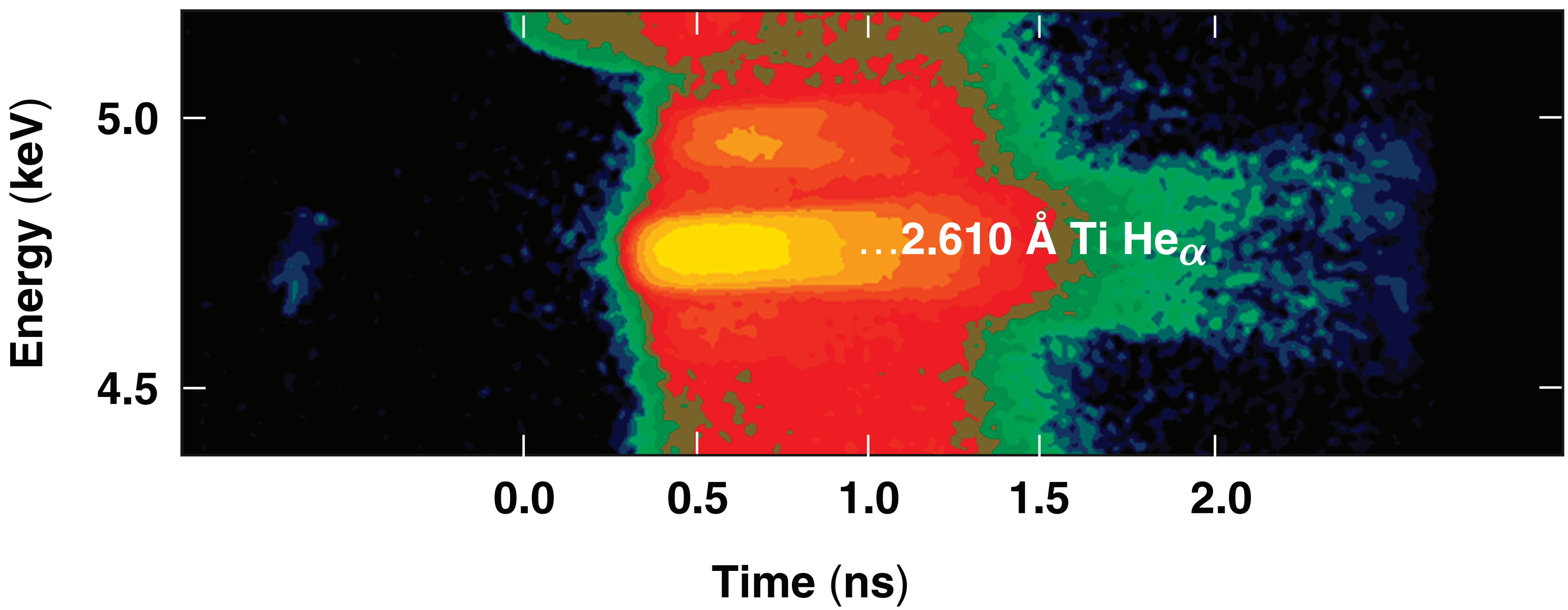


S. P. Regan *et al.*
University of Rochester
Laboratory for Laser Energetics

48th Annual Meeting of the
American Physical Society
Division of Plasma Physics
Philadelphia, PA
30 October–3 November 2006

Laser-Energy Coupling, Mass Ablation Rate, and Shock-Heating in Direct-Drive ICF

Mass Ablation Rate



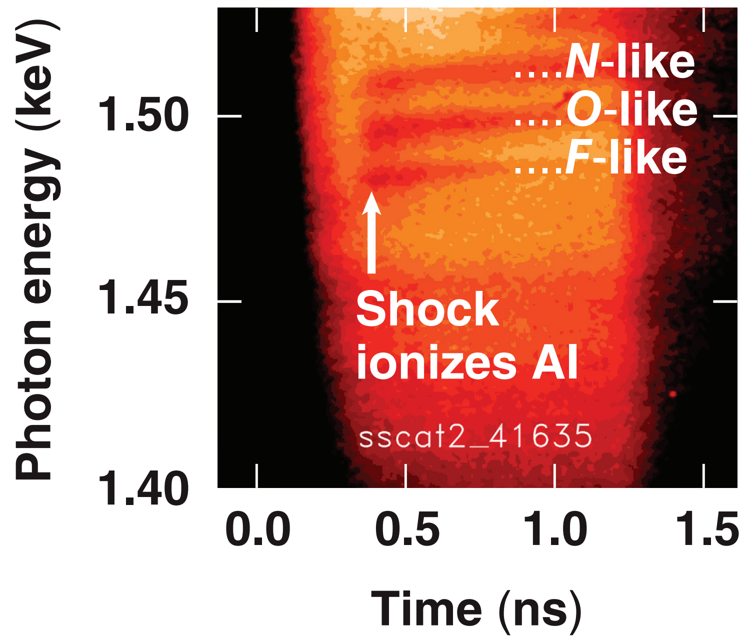
S. P. Regan *et al.*
University of Rochester
Laboratory for Laser Energetics

48th Annual Meeting of the
American Physical Society
Division of Plasma Physics
Philadelphia, PA
30 October–3 November 2006

Laser-Energy Coupling, Mass Ablation Rate, and Shock-Heating in Direct-Drive ICF

UR LLE

Shell conditions



S. P. Regan *et al.*
University of Rochester
Laboratory for Laser Energetics

48th Annual Meeting of the
American Physical Society
Division of Plasma Physics
Philadelphia, PA
30 October–3 November 2006

Summary

Detailed investigation of direct-drive coupling is being used to tune physics models

UR LLE

- A wide variety of experiments have been used to study direct-drive laser coupling.
- The measurements are compared with predictions of hydrodynamics codes.
- Integrated laser absorption is in good agreement with the models; however, some details are inconsistent.
- A nonlocal thermal-transport model is being developed.

These measurements have the accuracy required to design ignition targets.

Collaborators

R. Epstein, V. N. Goncharov, I. Igumenshchev, D. Li, P. B. Radha,
H. Sawada, W. Seka, T. R. Boehly, J. A. Delettrez, O. Gotchev, J. P. Knauer,
J. A. Marozas, F. J. Marshall, R. L. McCrory, P. W. McKenty, D. D. Meyerhofer,
T. C. Sangster, S. Skupsky, V. A. Smalyuk, and B. Yaakobi

Laboratory for Laser Energetics
University of Rochester

R. C. Mancini

University of Nevada

S. H. Glenzer and O. L. Landen

Lawrence Livermore National Laboratory

G. Gregori

Rutherford Appleton Laboratory

Related talks:

Wednesday morning: G02.03, G02.04
Friday: Z01.02, Z01.03, Z01.05, Z01.12, and Z01.13

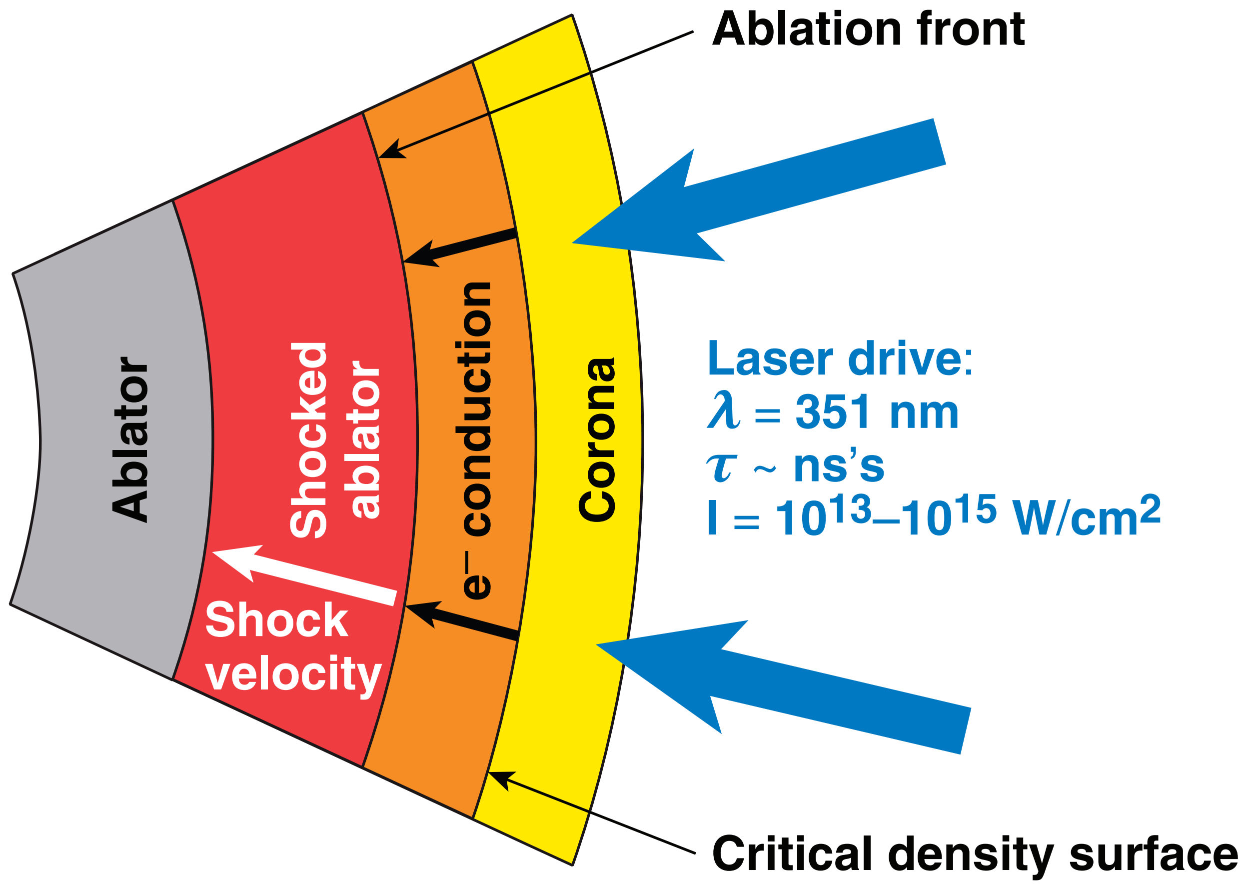
Outline

Laser-Energy Coupling, Mass Ablation Rate, and Shock-Heating in Direct-Drive ICF

UR LLE

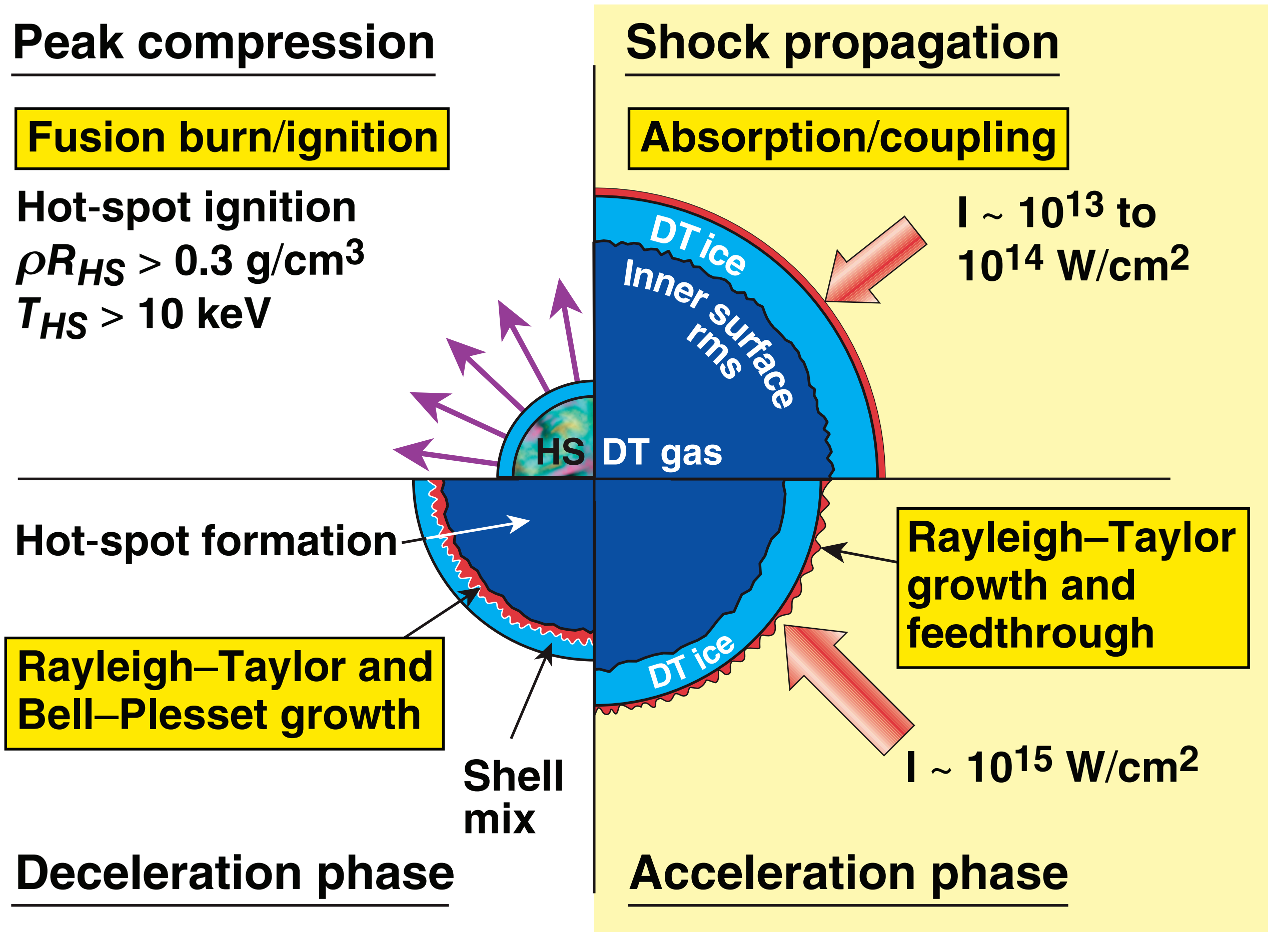
- Direct-drive ICF
- Laser absorption
- Mass ablation rate
- Shell conditions
- Conclusions

Laser energy is deposited in the corona and transported to the ablation surface by electron thermal conduction



The shell is heated primarily by the shock-wave, and to a lesser extent by x-ray radiation and energetic electrons from the corona.

The implosion is initiated by the ablation of material from the outer shell surface with intense laser beams



E14874a

Ignition depends on the implosion velocity, the shell areal density, and the adiabat of the shell

Direct-Drive Energetics vs. Rayleigh–Taylor hydrodynamic instability

$$E_{min} \propto \frac{\alpha^{1.8}}{V_{imp}^{5.8}}$$ [*,†]

vs.

$$\gamma_{RT} = \alpha_{RT}\sqrt{kg} - \beta_{RT} V_a; \; V_a \sim \alpha^{3/5}$$ [**]

$$\alpha = P_{fuel}/P_{Fermi}$$

Shell conditions
Shock timing

$$V_{imp} \propto \frac{P}{\dot{m}}; \quad P \propto \left(f_{abs}\eta_{hydro} I\right)^{2/3} \quad \text{and} \quad \dot{m} \propto \left(f_{abs}\eta_{hydro} I\right)^{1/3}$$ [††]

Absorption fraction

Mass ablation rate

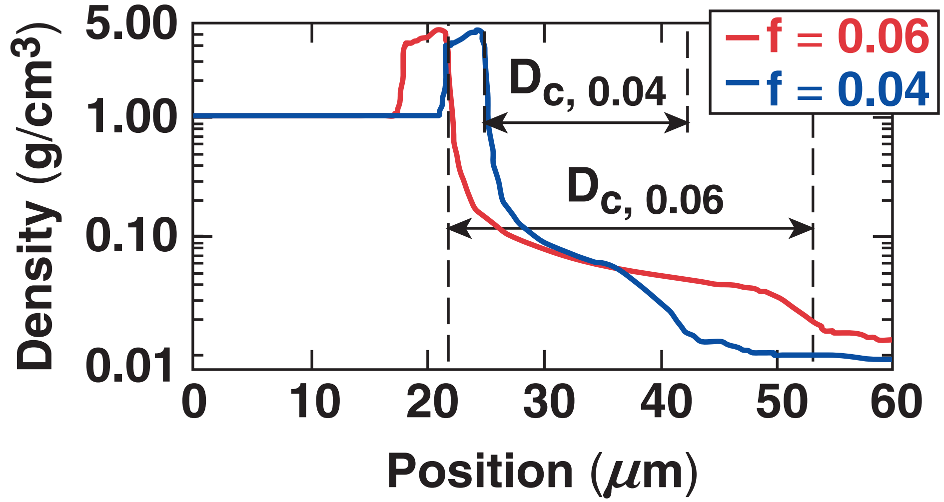
The shell adiabat is mainly controlled by the shock-wave strength.

* Herrmann *et al.*, Nuc. Fus. 41, 99 (2001).
† Betti *et al.*, Phys. Plasmas 9, 2277 (2002).
** Betti *et al.*, Phys. Plasmas 5, 1446 (1998).
†† Lindl, Phys. Plasmas 2, 3933 (1995).

1-D hydrodynamics code *LILAC* has been used routinely to simulate implosions for direct-drive ICF

LILAC (1-D hydrodynamics code)*

- Laser absorption with ray trace and Maxwell solvers
- Radiative transport
- Thermal transport**
  - $q_{SH} = -\kappa \nabla T \quad q_{FS} = nTV_T$
  - sharp cutoff
    $q_{eff} = \min(q_{SH}, fq_{FS})$
  - $0.04 < f < 0.1$

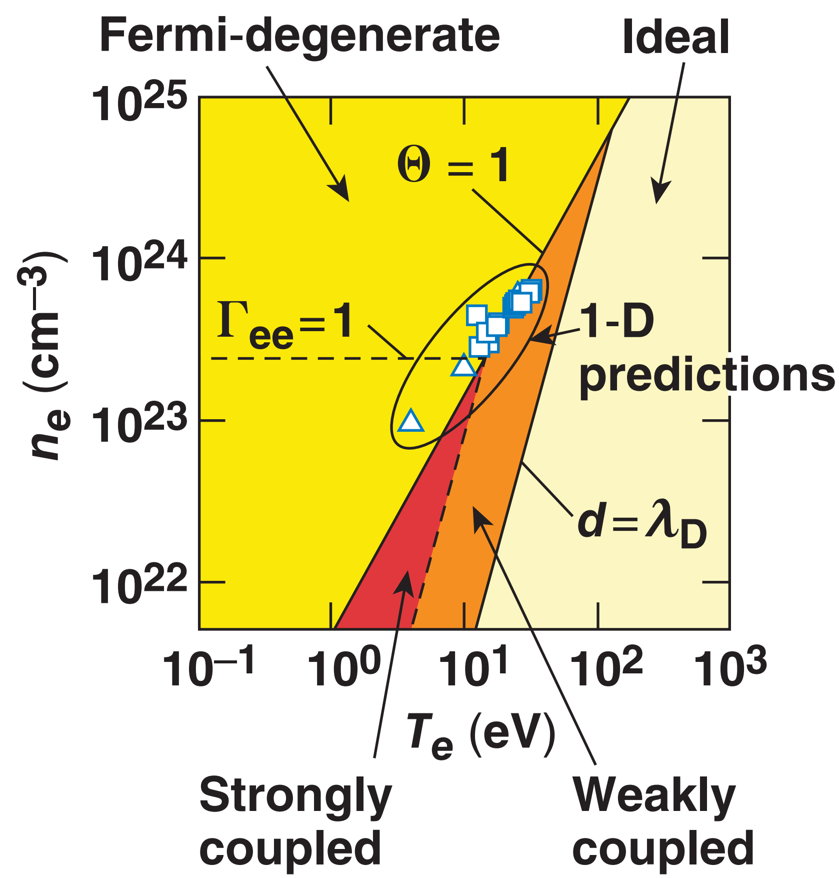


- Nonlocal model using a simplified Boltzmann equation (Krook model)†
  - mean-free path of electron is comparable to temperature-scale length

* J. Delettrez *et al.*, Phys. Rev. A, 3926 (1987).
** R. C. Malone, R. L. McCrory, and R. L. Morse, Phys. Rev. Lett. 34, 721 (1975).
† V. N. Goncharov, Phys. Plasmas 13, 012702 (2006).

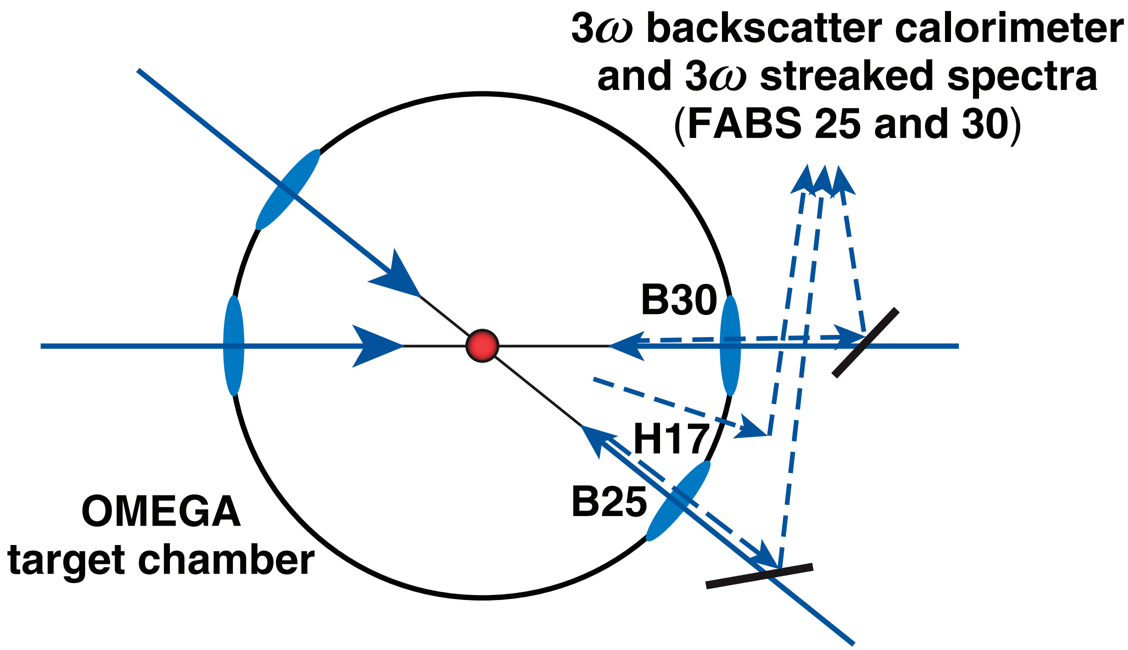
A wide variety of experiments is being used to study direct-drive laser coupling

- Laser absorption
  - Measure power of scattered-laser light
- Mass ablation rate
  - Measure the ablation time vs. ablator thickness
    - burnthrough experiments of non-accelerating targets
- Shell Conditions
  - Measure time-resolved T_e of shell using:
    - x-ray absorption spectroscopy
    - spectrally resolved x-ray scattering



E15066

Scattered light is detected behind two focusing lenses (FABS 25 and 30) and between focusing lenses (H17)

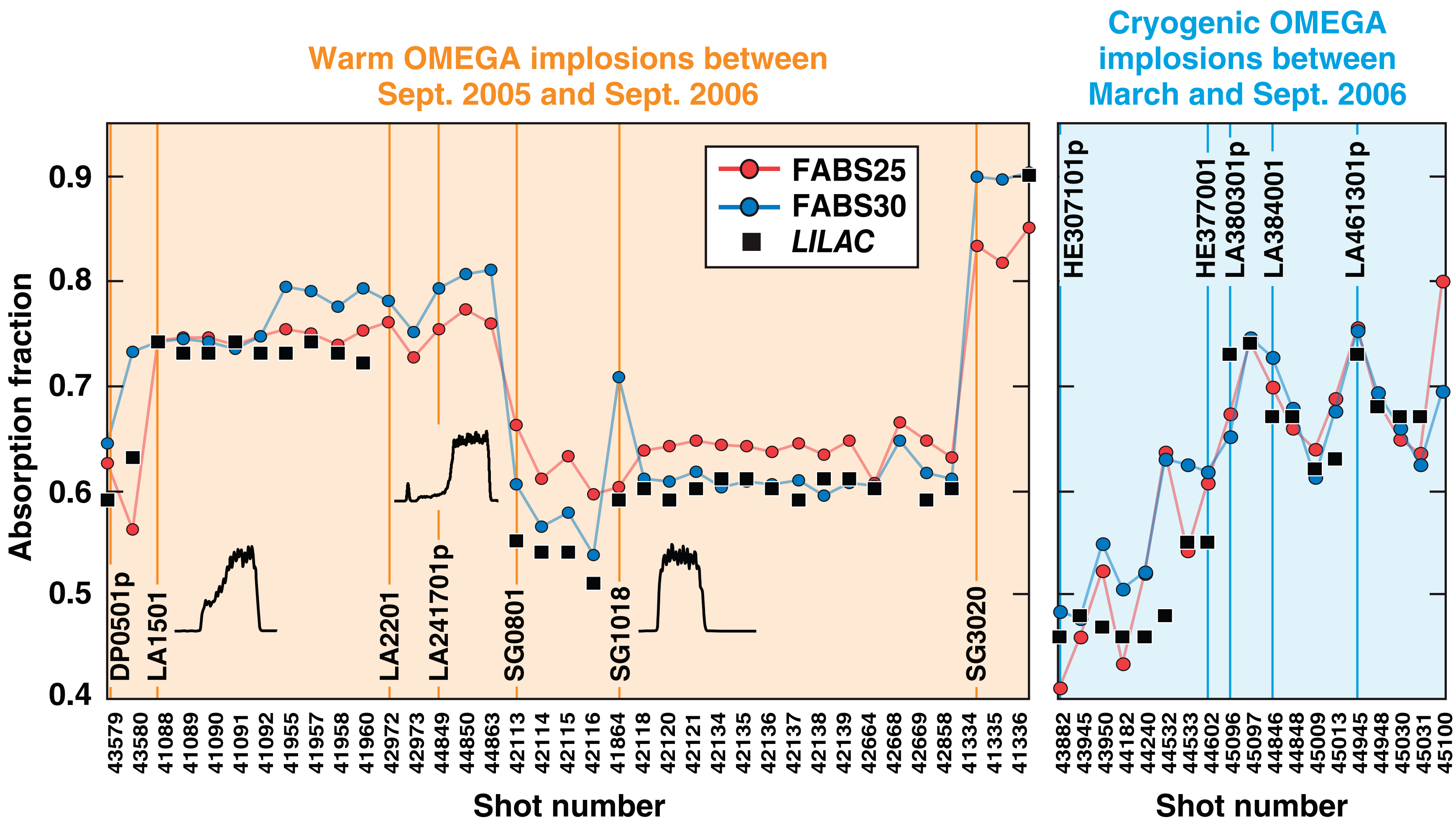


- Measurement: scattered light extrapolated to 4π (E_{scatt})
  - Absorption fraction = $(E_{tot} - E_{scatt})/E_{tot}$
  - Calculated deviations from isotropy are in percent range.

Laser Absorption

Time-integrated absorption data agree quite well with *LILAC* predictions for a wide variety of targets, pulse shapes, and irradiation energies

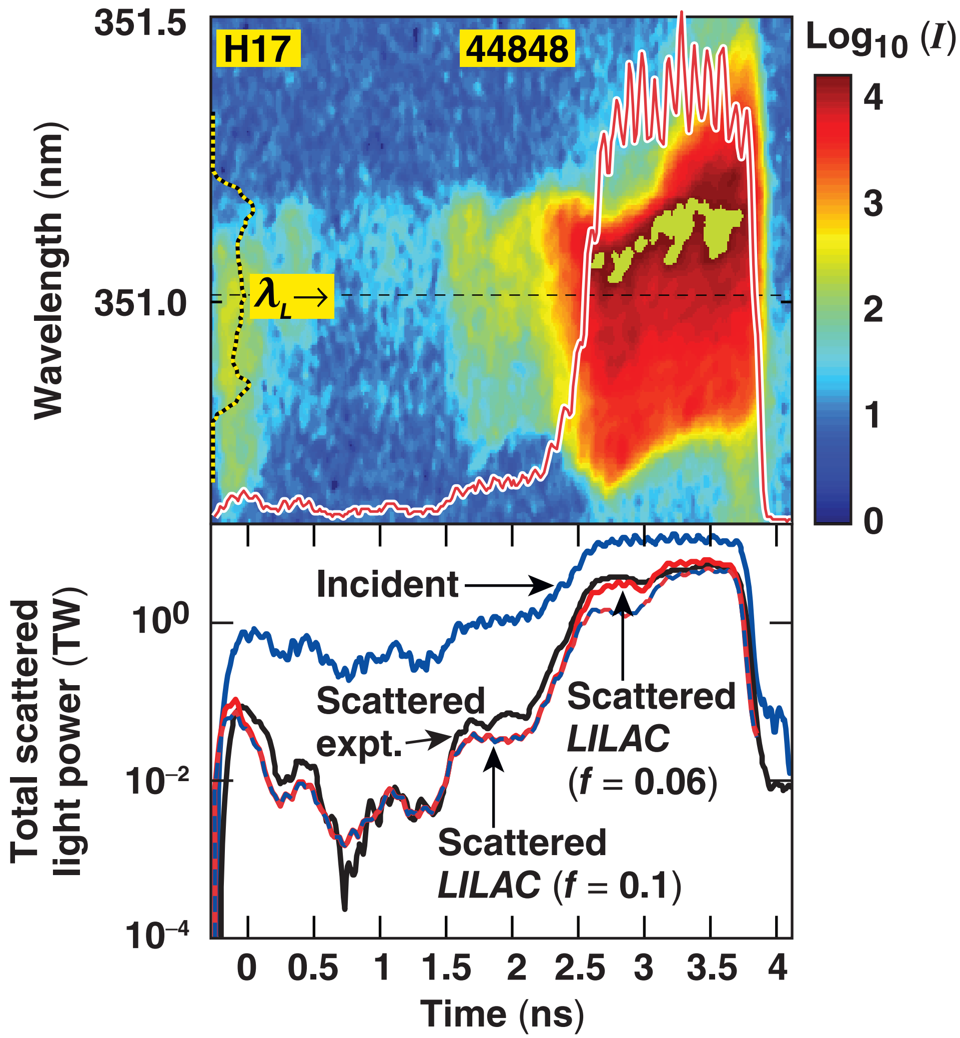
UR LLE



E14627b

Some differences are observed between the scattered-light power measurements and the *LILAC* simulation

Measured absorption fraction = 67%
LILAC (*f* = 0.06) = 67%
LILAC (*f* = 0.1) = 77%

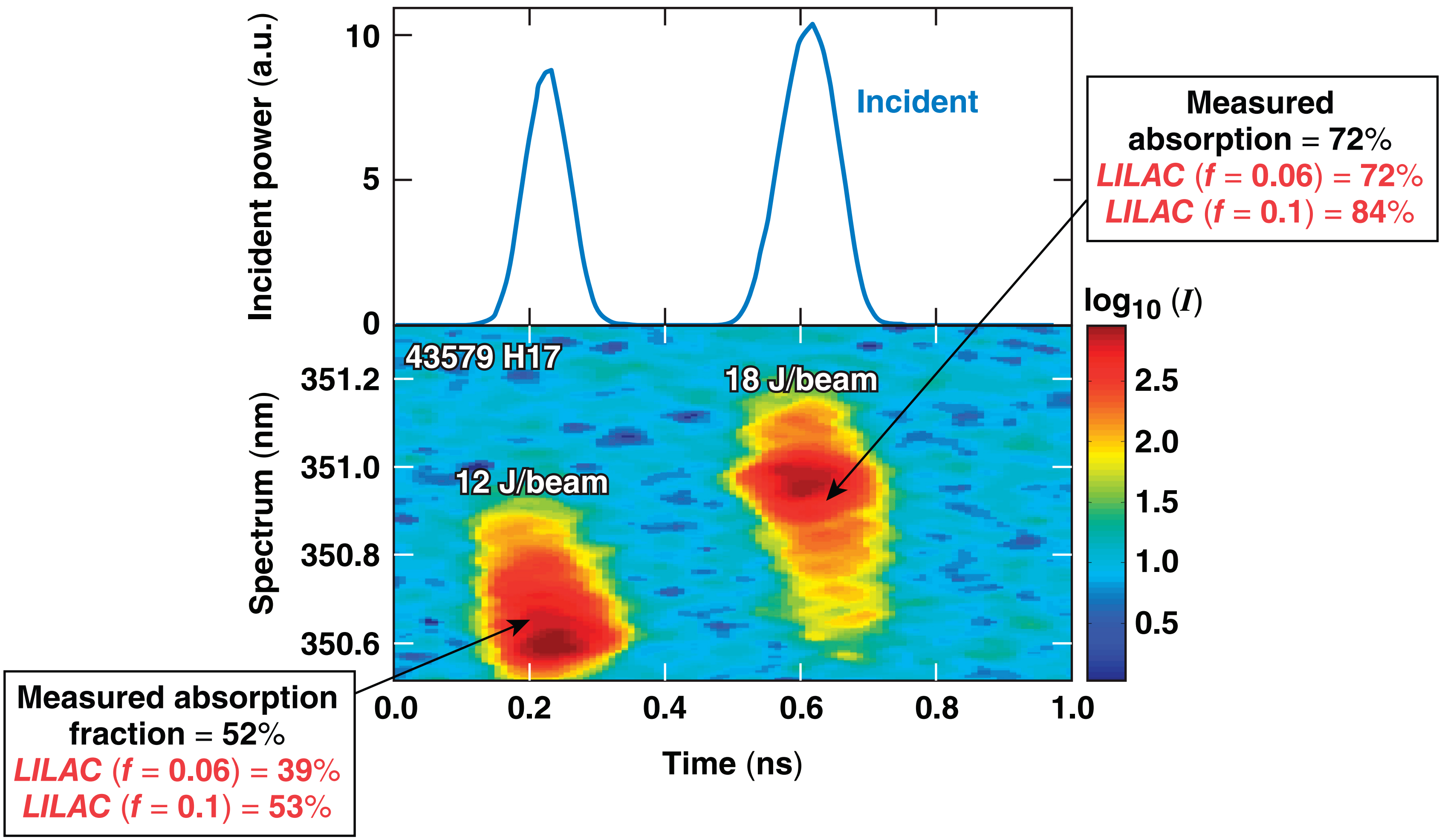


Target: cryogenic DT (95 μm), 5.4-μm CD shell

E15205a

Laser Absorption

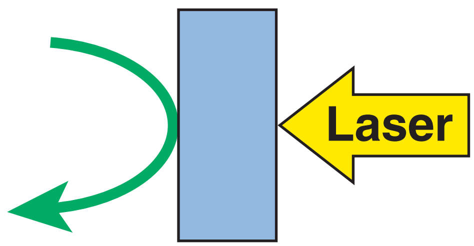
Double-picket pulses are well suited for investigating higher absorption at early times



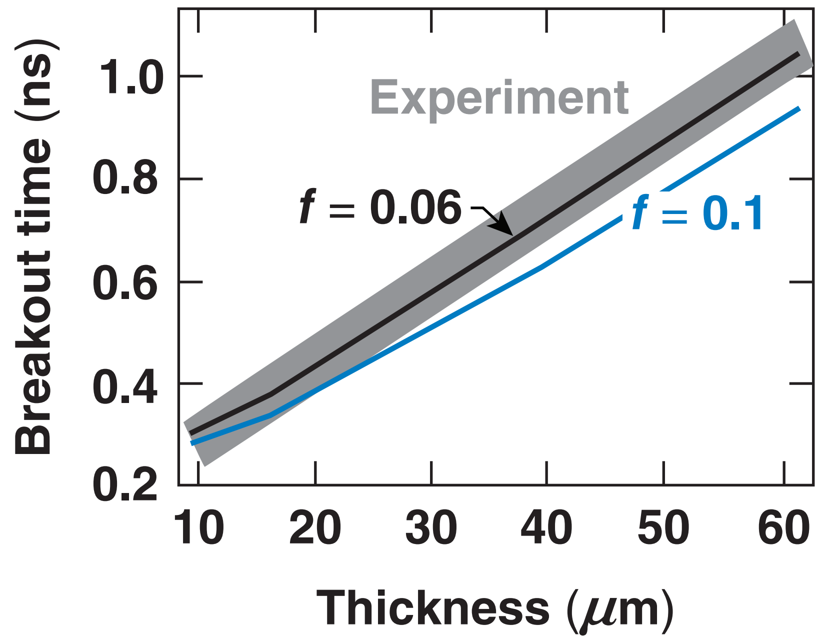
E14630a

The discrepancy revealed with the scattered-light power is not evident in shock-velocity measurements

Velocity interferometer system for any reflector (VISAR)

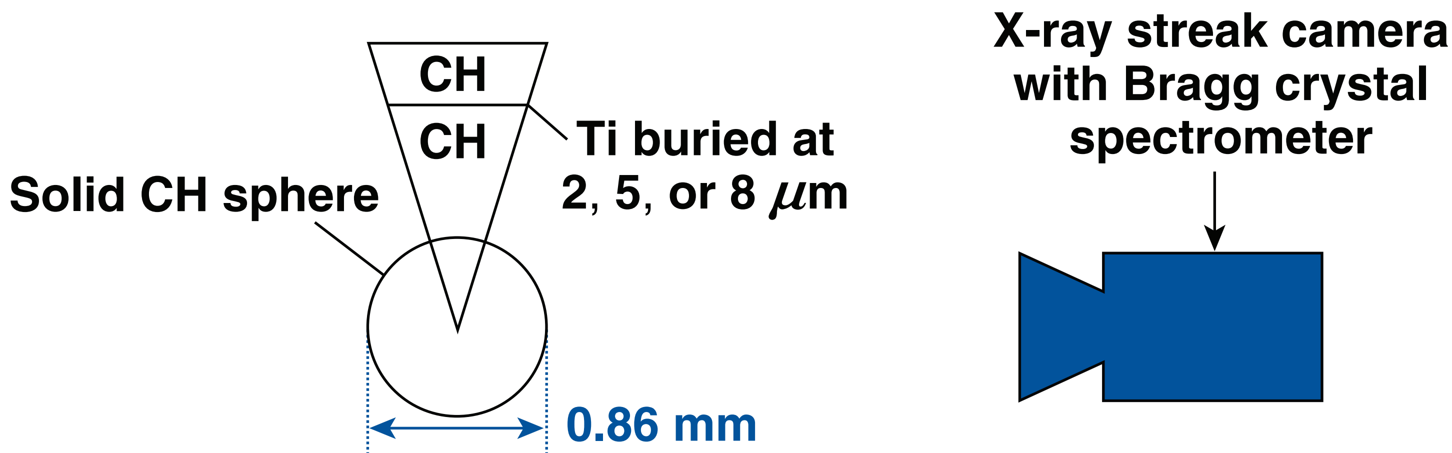


Shock breakout measurements



Boehly *et al.*, Phys. Plasmas 13, 056303 (2006).
Goncharov *et al.*, Phys. Plasmas 13, 012702 (2006).

Laser-driven burnthrough experiments were performed with non-accelerating spherical targets

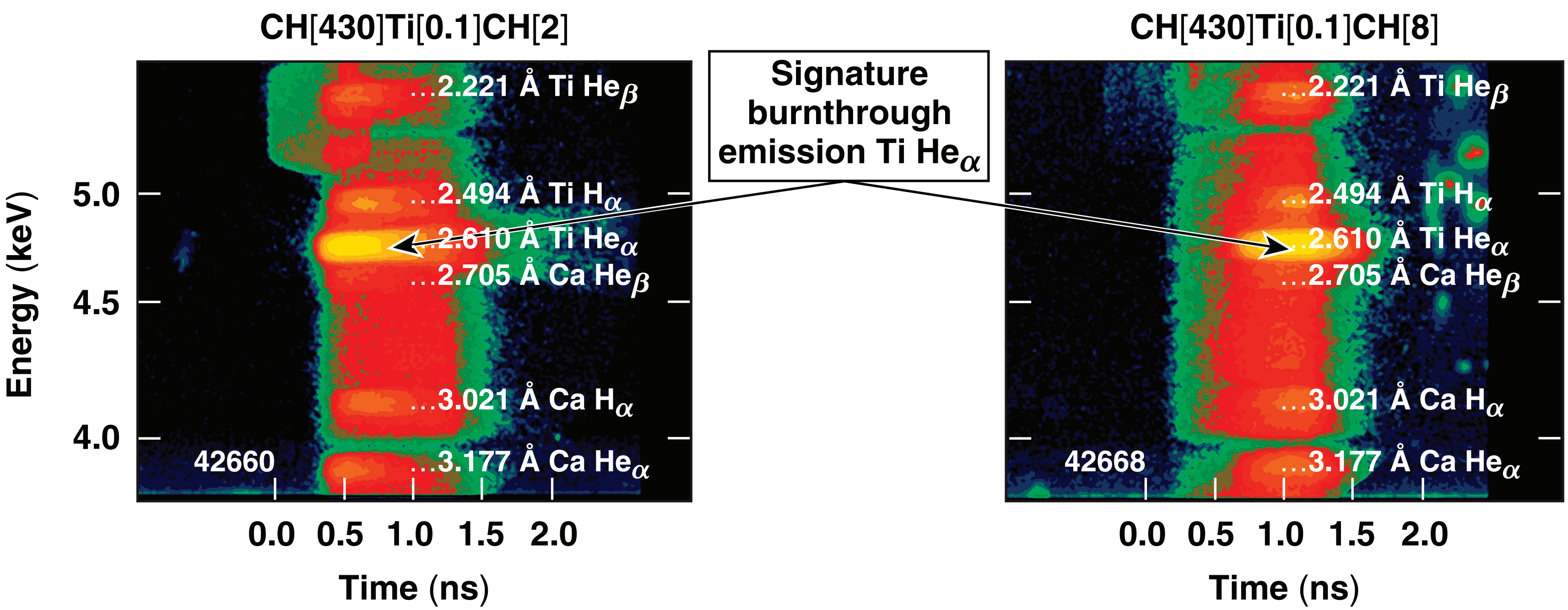


Drive Intensity: 1×10^{15} W/cm^2

Drive: 23-kJ, 1 ns square laser pulse

Hydrodynamic instabilities are negligible with solid CH target.

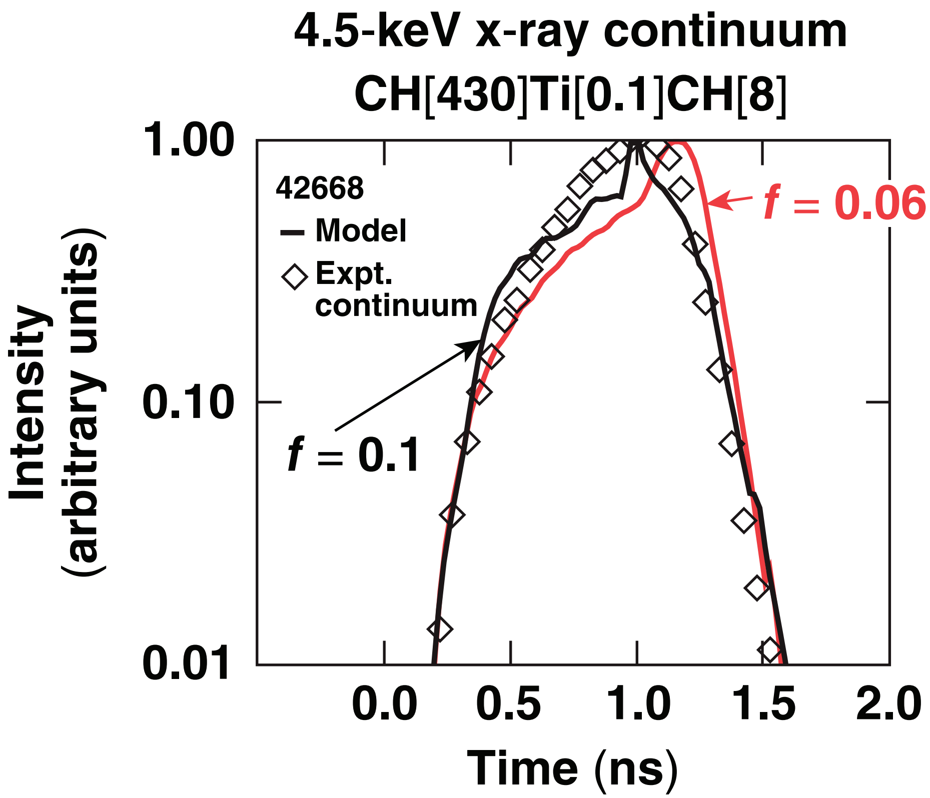
Mass ablation rate is inferred from onset of K-shell emission of ablated Ti tracer layer

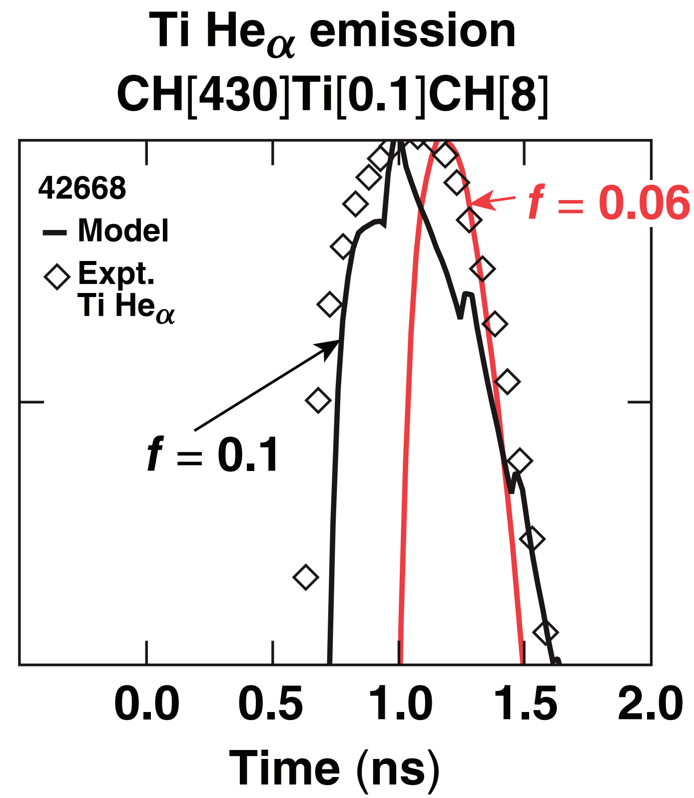


The timing is set by synchronizing the predicted and measured 4.5-keV x-ray continuum emission.

Mass Ablation Rate

LILAC/Spect3D* time-dependent model is synchronized to experiment using x-ray continuum in the 4.5-keV range





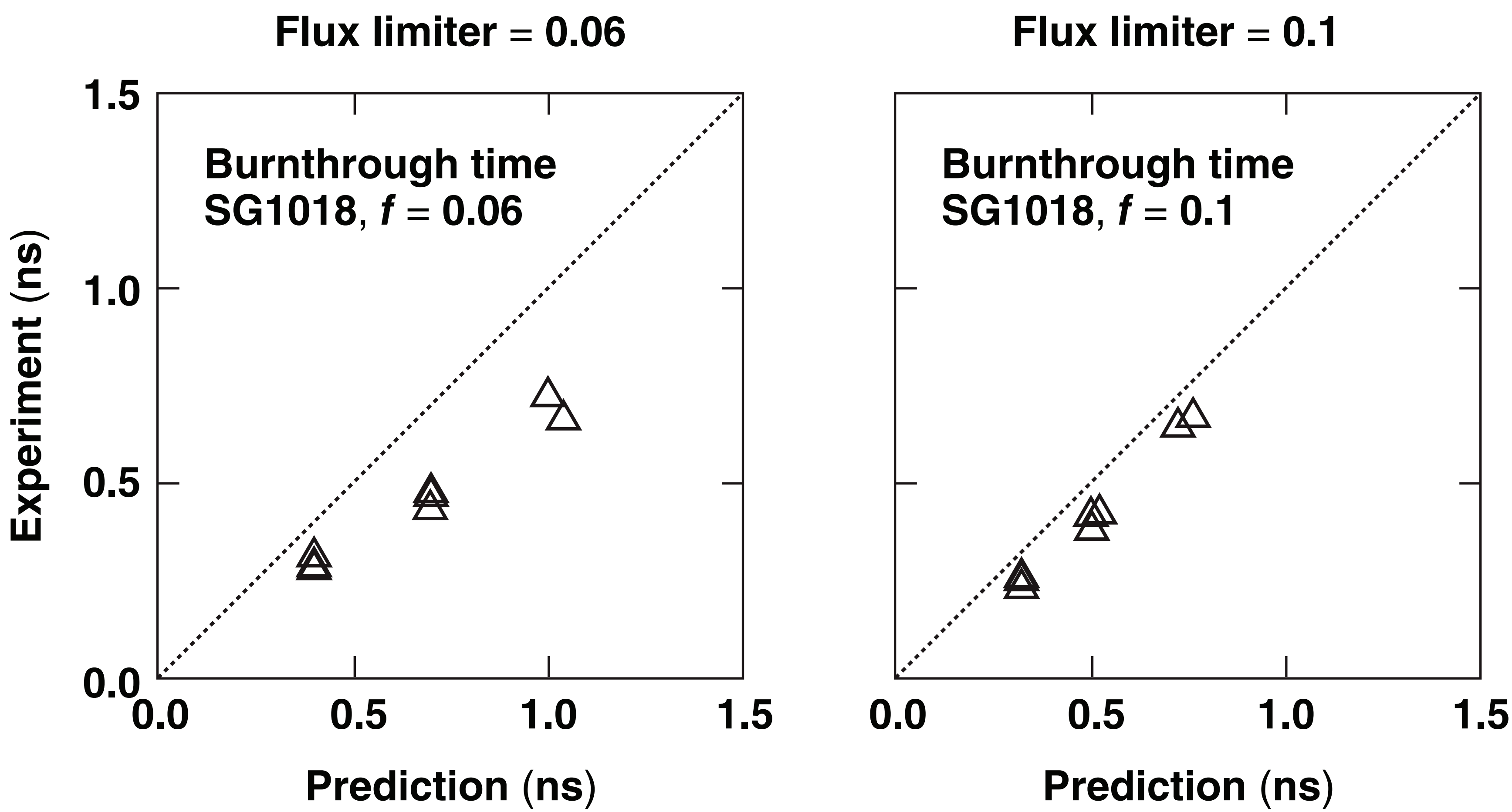
Burnthrough time: Ti He_α intensity reaches 10% of its peak intensity.

E15068

*Prism Computational Sciences Inc., Madison, WI 53711

Mass Ablation Rate

Burnthrough experiment is consistent with higher mass ablation rate of the 1-D prediction with f = 0.1



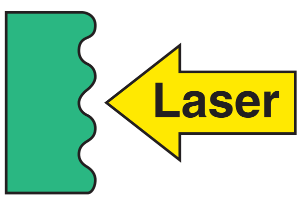
Lower drive intensities will be investigated.

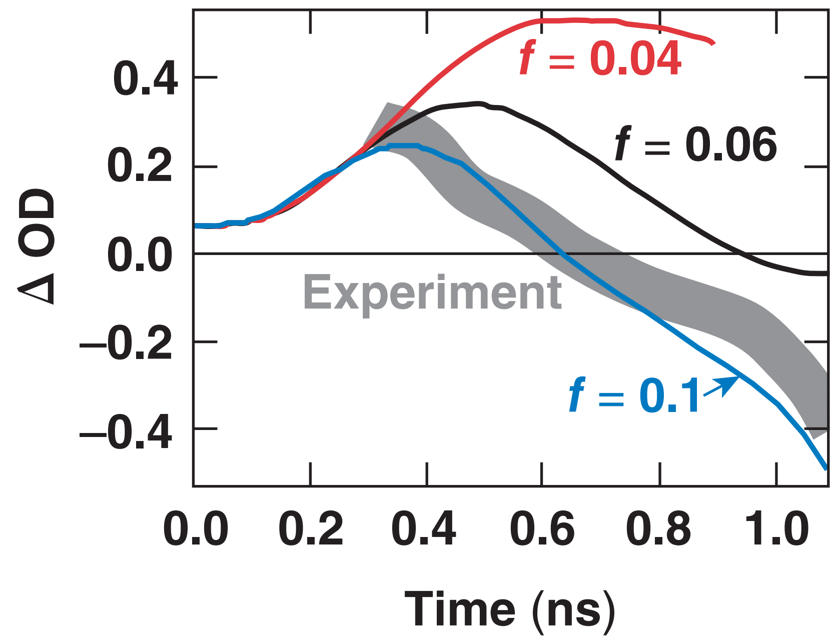
E15069

A flux limiter of 0.1 is also needed to model Richtmyer Meshkov (RM) experiments

RM Experiment

- 2-ns square pulse, $I = 4 \times 10^{14}$ W/cm^2
- CH foil d = 40 μm, λ = 20 μm

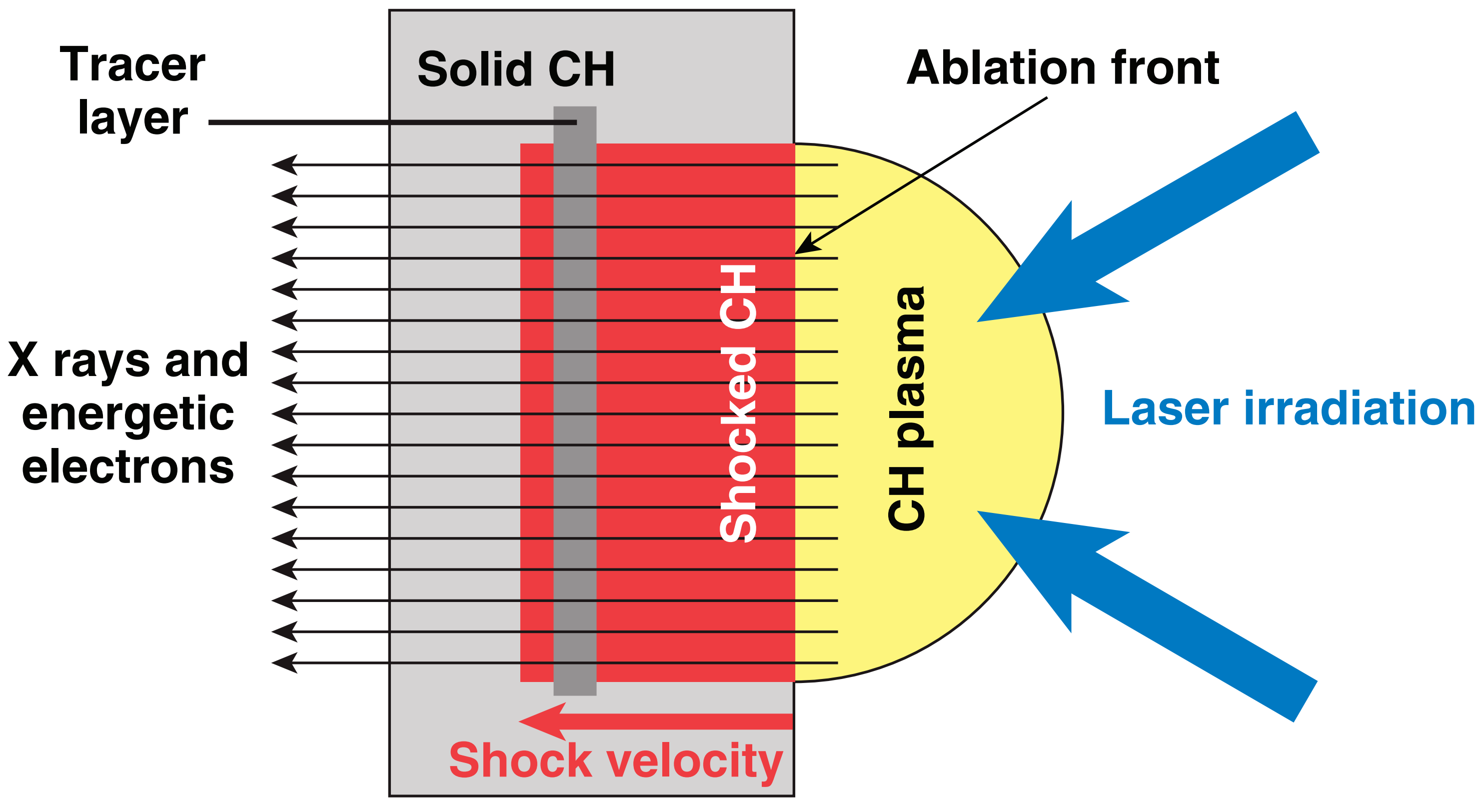




Gotchev *et al.*, Phys. Rev. Lett. 96, 115005 (2006).
Goncharov *et al.*, Phys. Plasmas 13, 012702 (2006).

Shell Conditions

Local shell conditions were measured with time-resolved x-ray absorption spectroscopy

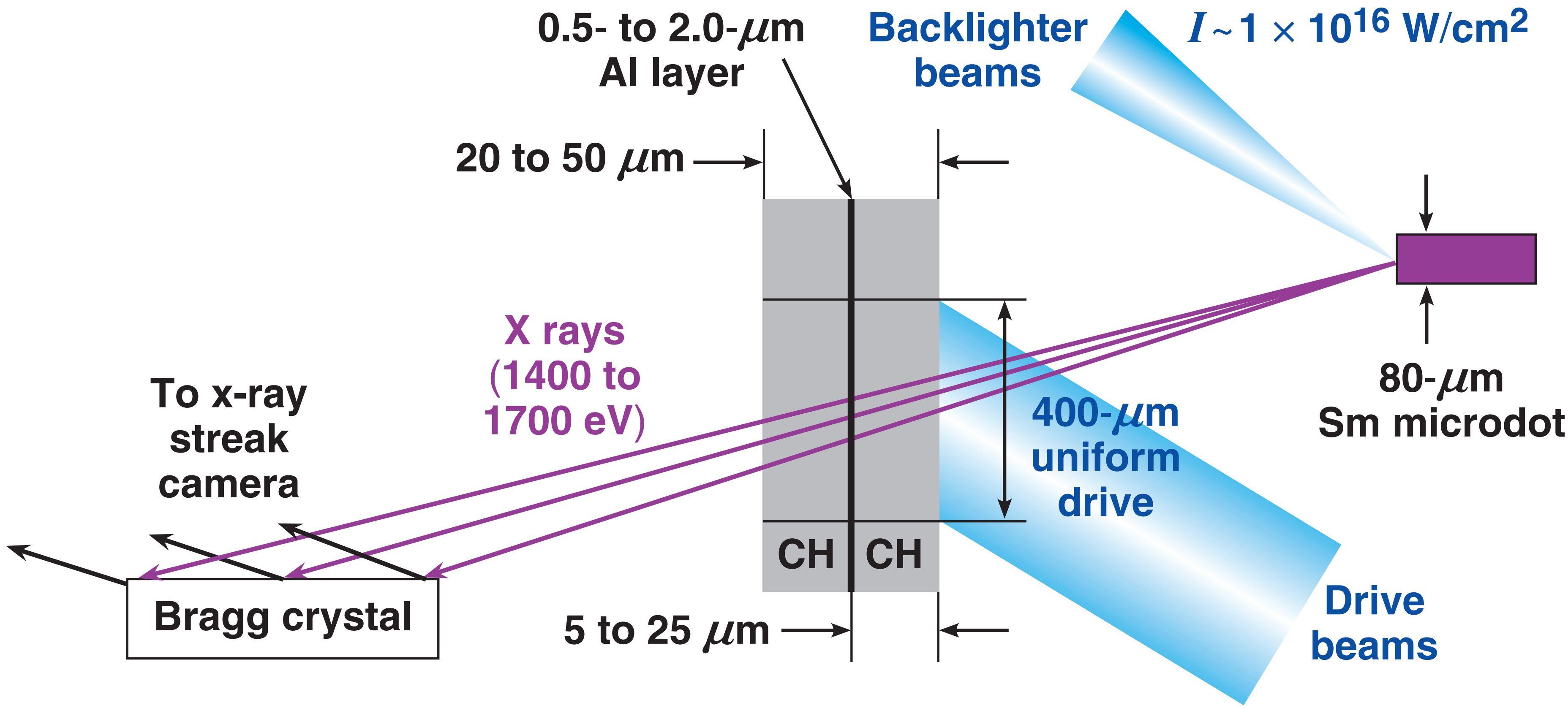


The buried depth of the tracer layer is varied to probe different parts of the shell.

E14883a

Shell Conditions

X-ray absorption spectroscopy of a CH planar target with a buried Al tracer layer was performed with a Sm backlighter

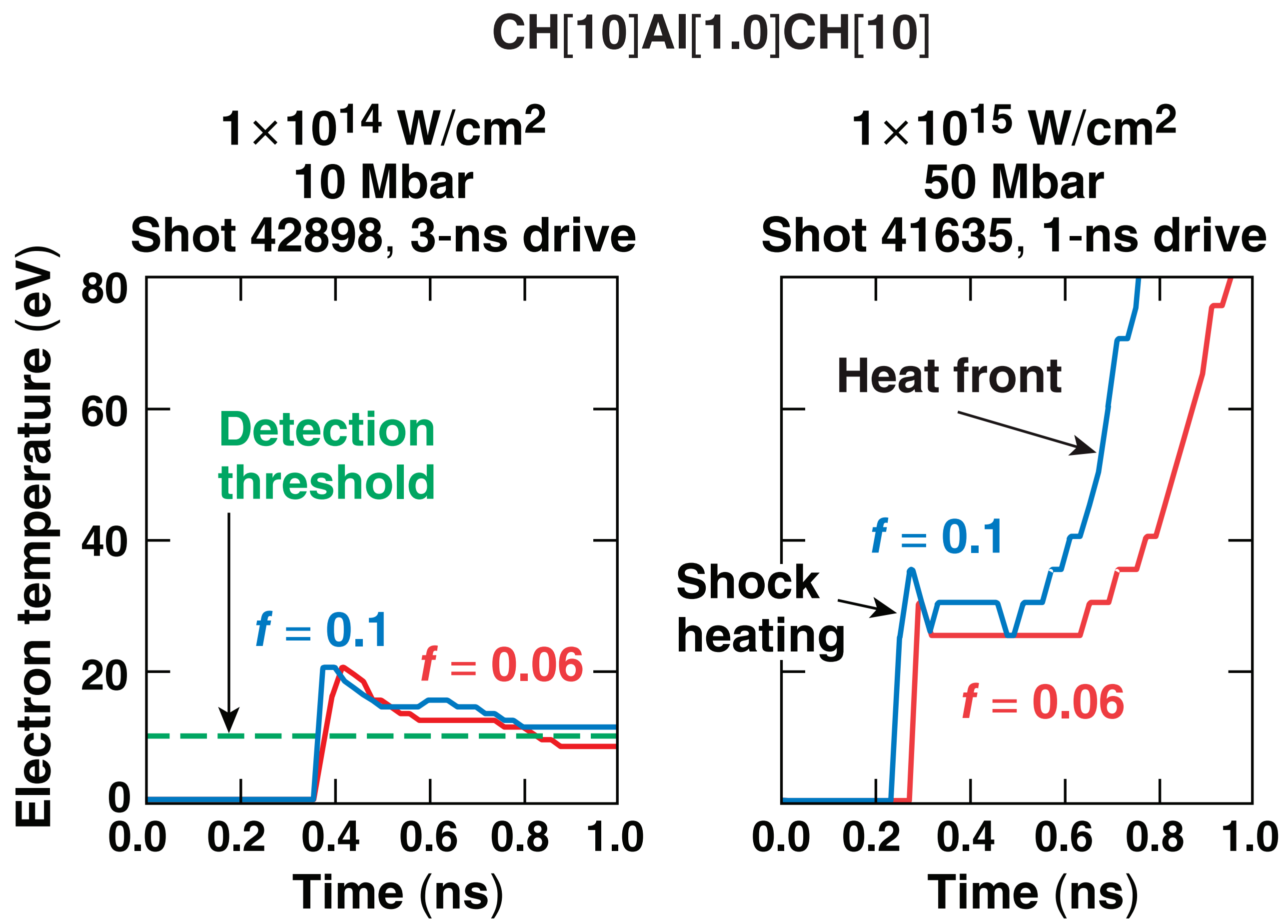


$\Delta E = 3.5$ eV
$\Delta t < 100$ ps

E14880a

Boehly *et al.*, Phys. Rev. Lett. 87, 145003 (2001).

LILAC predictions show T_e in the Al layer rises as the drive intensity is increased



The timing of the shock and the arrival of the heat front can be measured with absorption spectroscopy.

E14885a

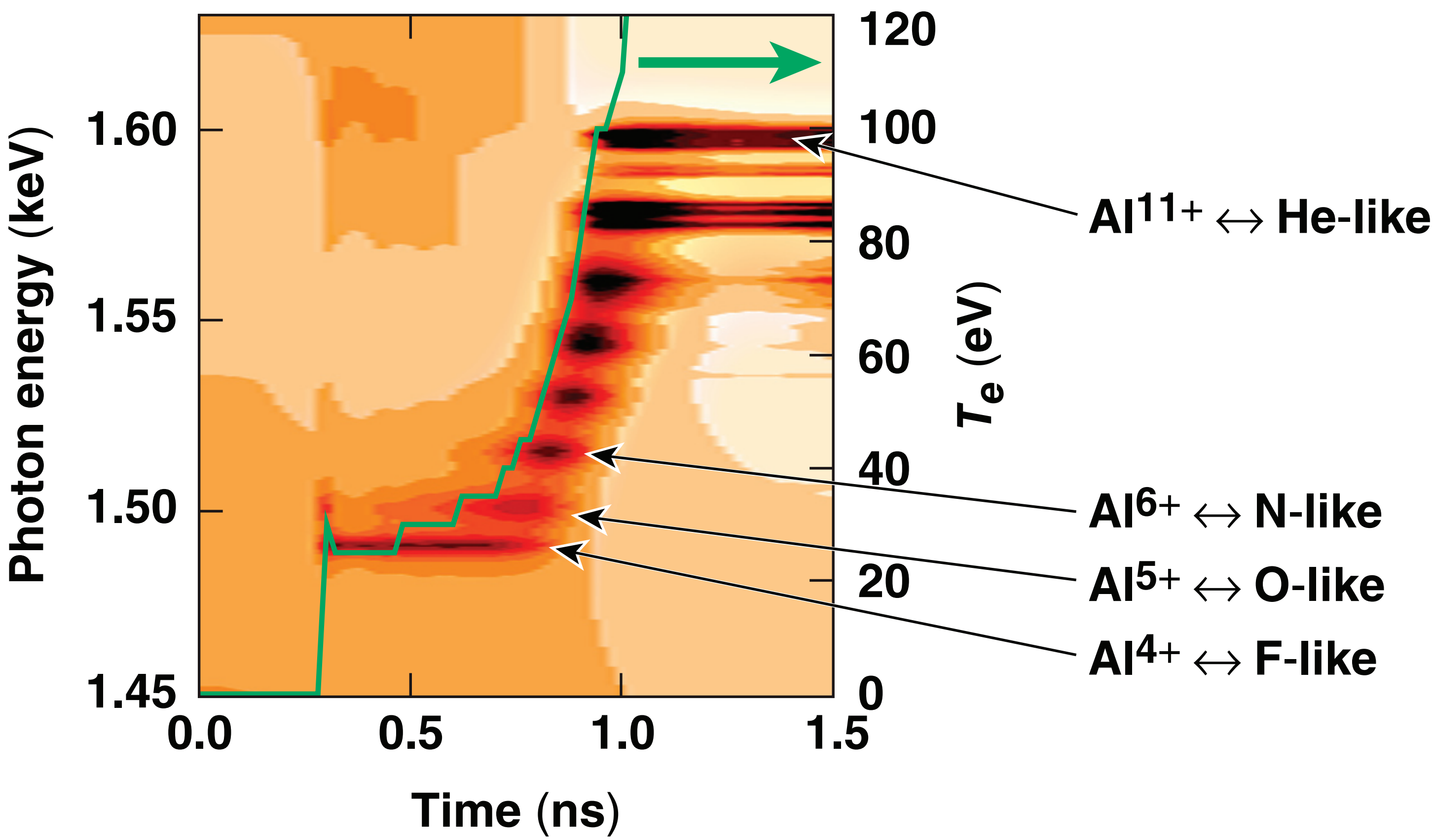
Shell Conditions

Higher charge states of Al are ionized in succession and absorb in 1*s*-2*p* transitions as the shell T_e increases

f = 0.06

LILAC/Spect3D* simulated 1*s*-2*p* absorption spectra

$$I(\nu) = I_0(\nu)e^{(-\kappa(\nu, n_e, T_e)\rho\Delta L)}$$

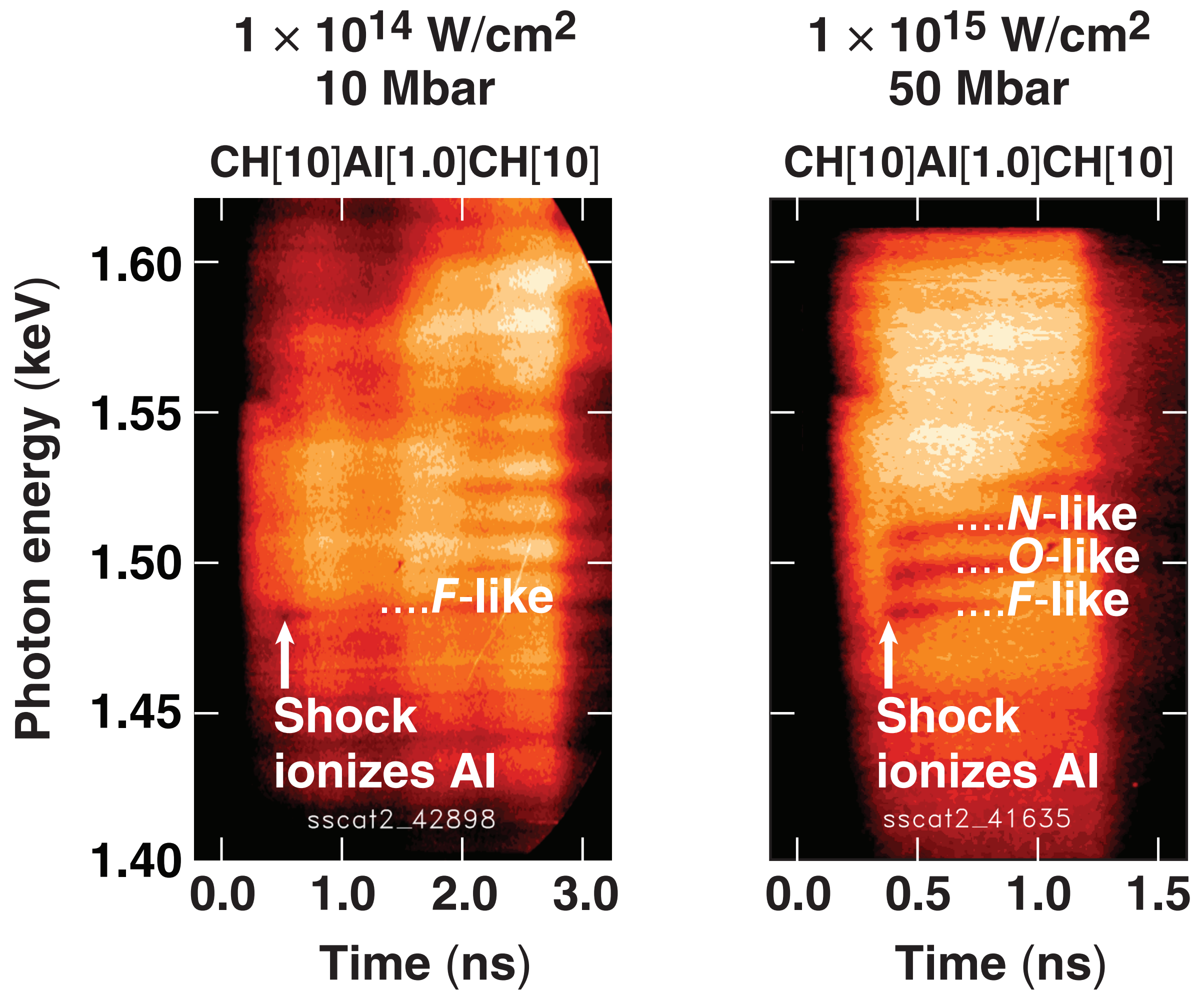


E15228

*Prism Computational Sciences Inc., Madison, WI 53711

Shell Conditions

Significant changes are observed in the Al 1*s*–2*p* absorption spectra as the drive intensity is increased



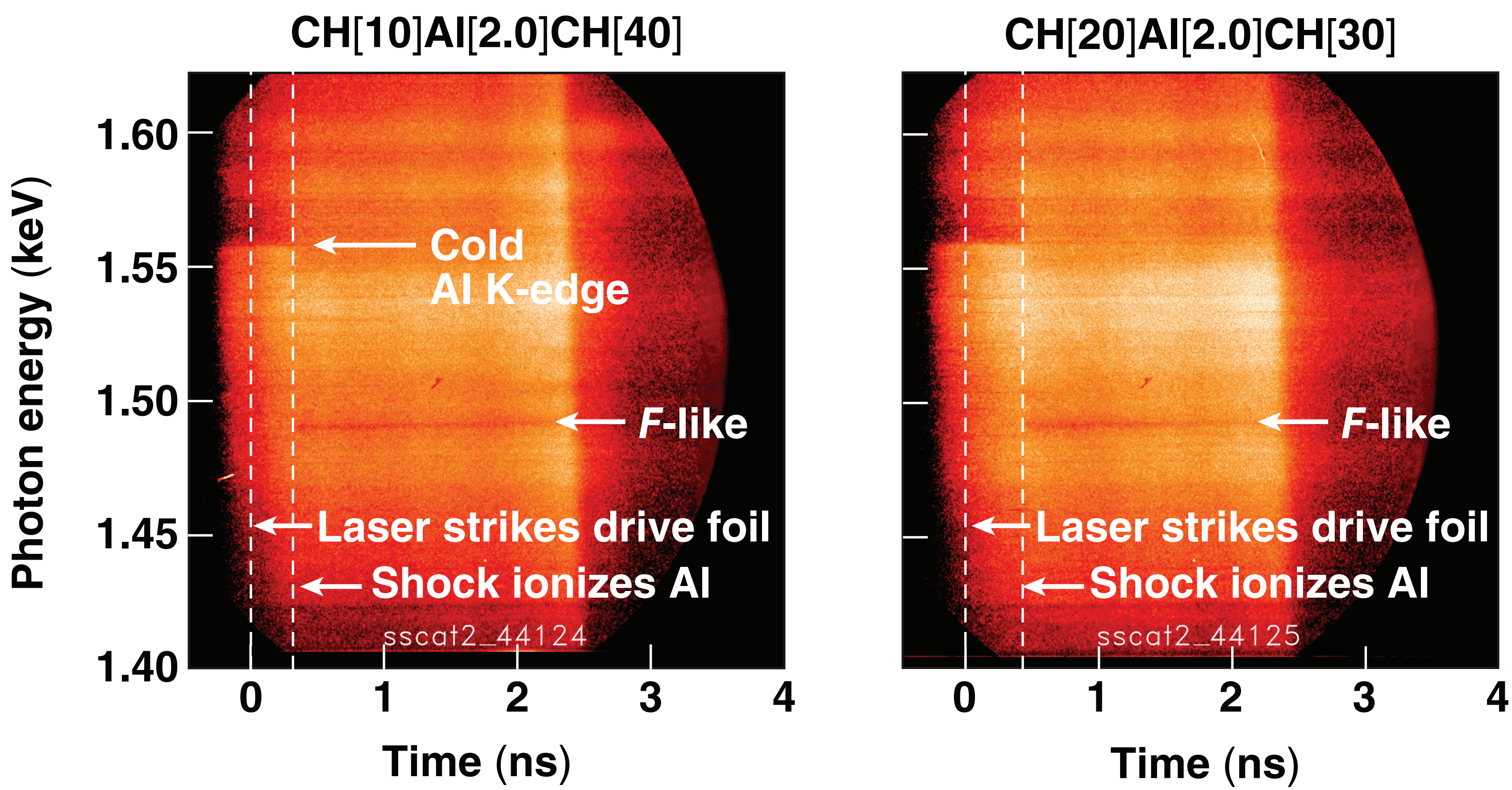
- Laser strikes drive foil at $t = 0$ ns.

E14884a

Shell Conditions

Only the *F*-like Al 1*s*–2*p* absorption feature is observed with a drive intensity of 1×10^{14} W/cm^2

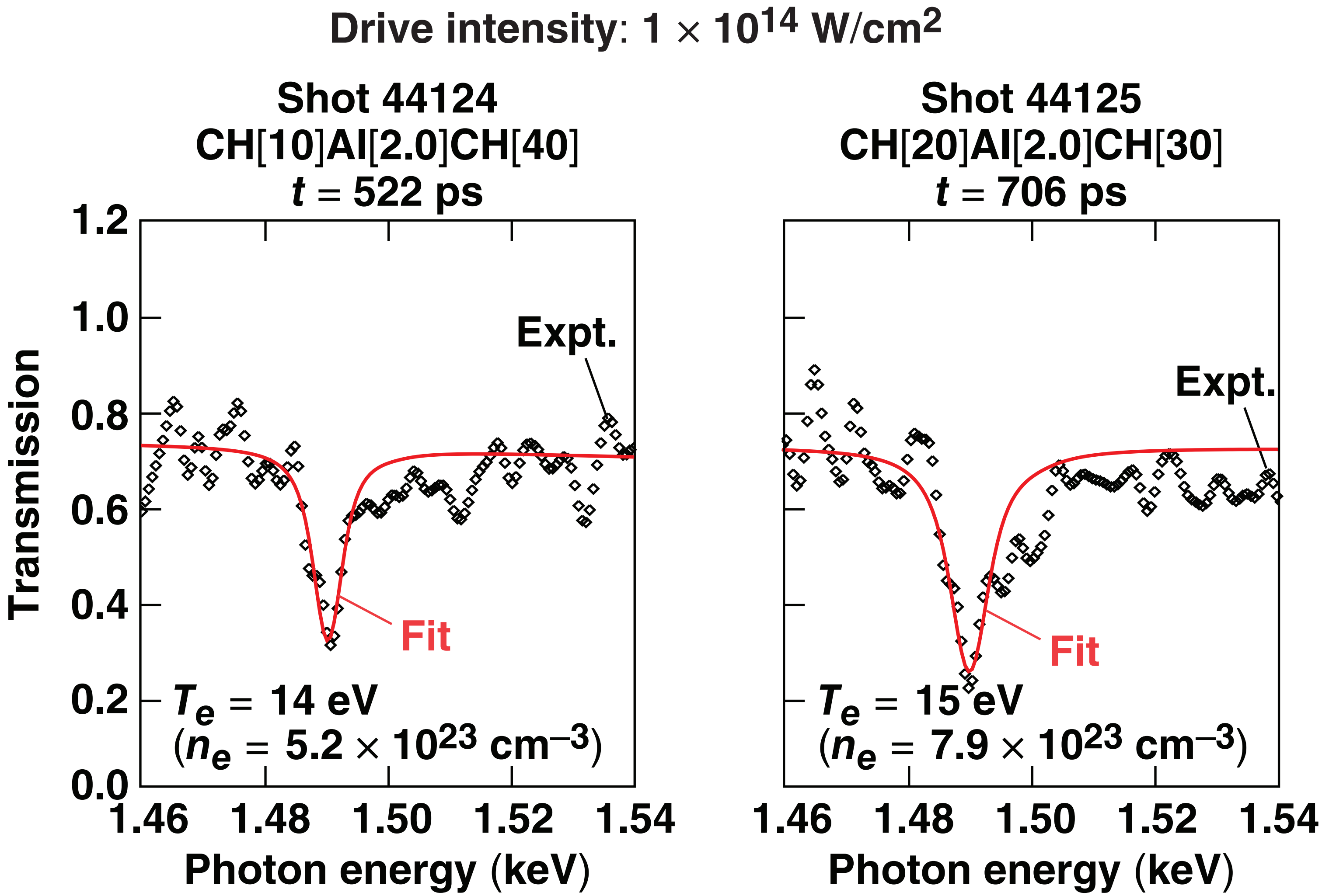
Drive intensity: 1×10^{14} W/cm^2



The onset of the 1*s*–2*p* absorption depends on the buried depth of the Al layer.

E14886a

Measured spectra are fit with PrismSPECT* assuming uniform shell conditions for drive intensity of 1×10^{14} W/cm^2

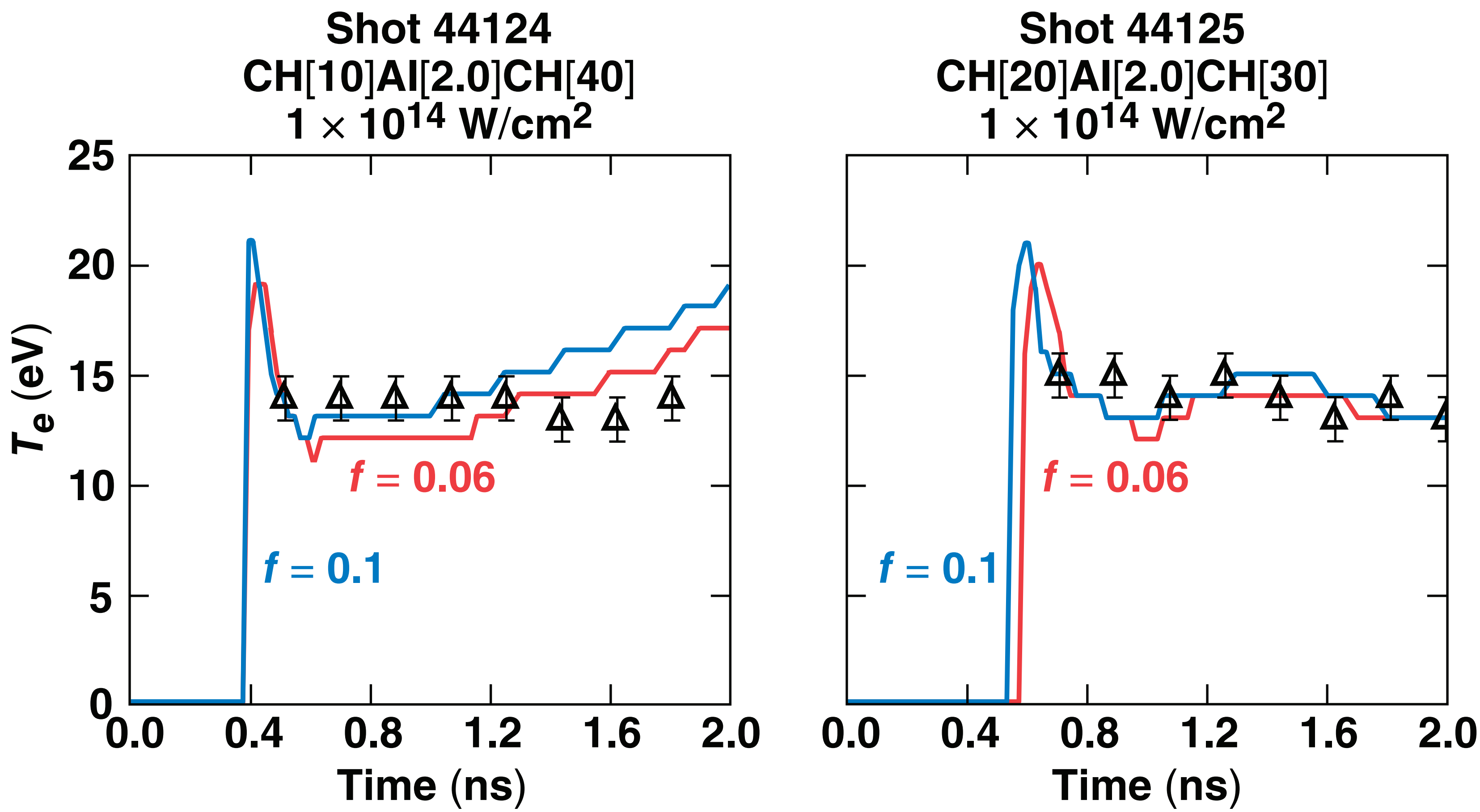


*Prism Computational Sciences Inc., Madison, WI 53711

Shell Conditions

Time-resolved electron temperatures inferred from absorption spectra are close to the *LILAC* predictions for 1×10^{14} W/cm^2

Drive intensity: 1×10^{14} W/cm^2



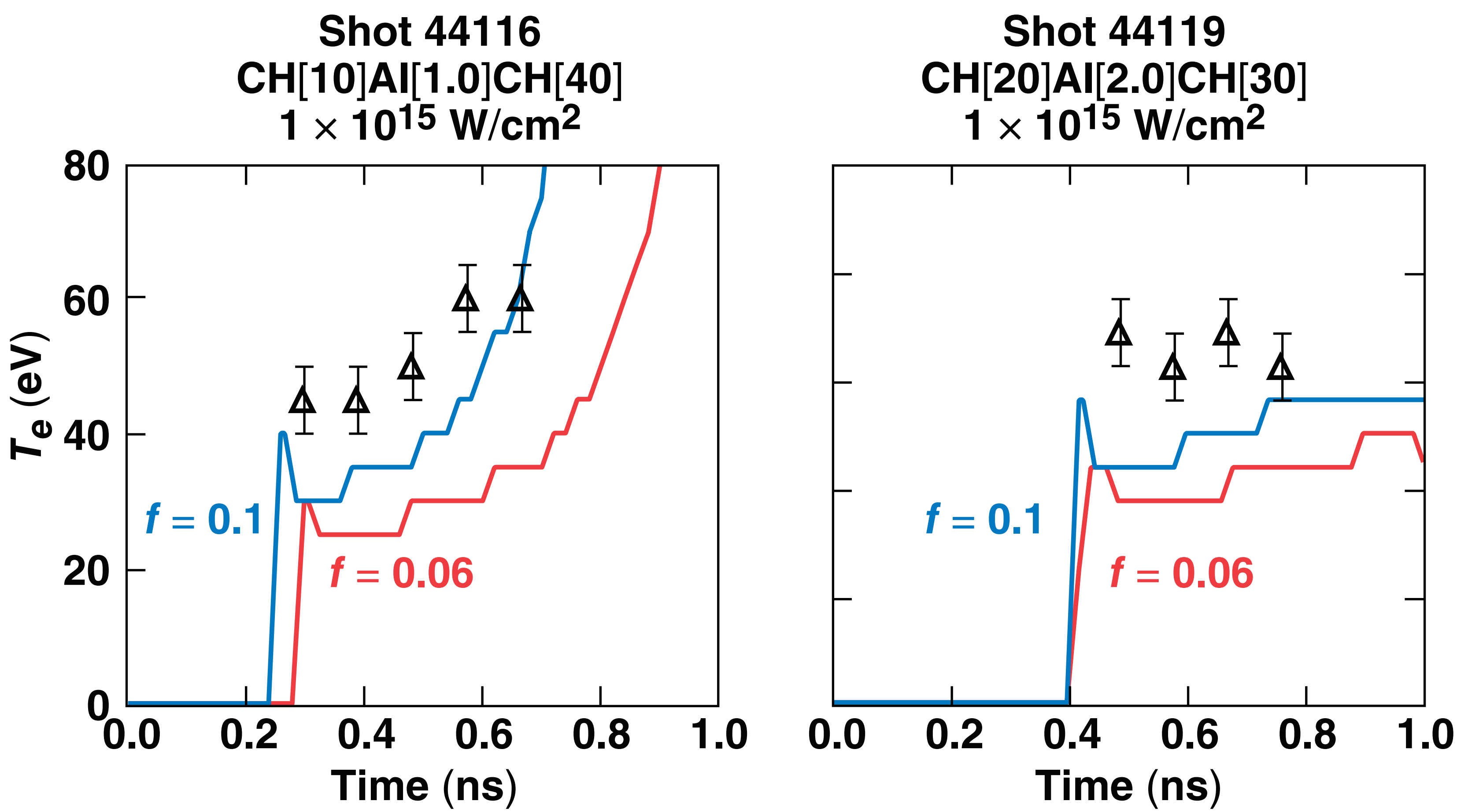
An upper limit of $T_e = 20$ eV was inferred from spectrally resolved x-ray scattering.

E14889b

Shell Conditions

Time-resolved electron temperatures inferred from absorption spectra are higher than *LILAC* for 1×10^{15} W/cm^2

Drive intensity: 1×10^{15} W/cm^2



E14913a

A nonlocal treatment of the thermal transport* is expected to improve agreement between simulation and experiment

1. Laser absorption
   - Early time laser absorption is higher than *LILAC*. Z01.02

   Resonance absorption
   Nonlocal effects

   Z01.13
   Z01.12

2. Mass ablation rate
   - Measured mass ablation rate at 1×10^{15} W/cm^2 is higher than *LILAC*.

   Nonlocal effects

3. Shell Conditions Z01.03, Z01.05
   - Measured shell T_e at 1×10^{14} W/cm^2 is consistent with *LILAC*.
   - Measured shell T_e at 1×10^{15} W/cm^2 is higher than *LILAC*.

   Nonlocal effects
   Accuracy of modeling T_e in buried Al-tracer layer

E15070

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

Summary/Conclusions

Detailed investigation of direct-drive coupling is being used to tune physics models

- A wide variety of experiments have been used to study direct-drive laser coupling.
- The measurements are compared with predictions of hydrodynamics codes.
- Integrated laser absorption is in good agreement with the models; however, some details are inconsistent.
- A nonlocal thermal-transport model is being developed.

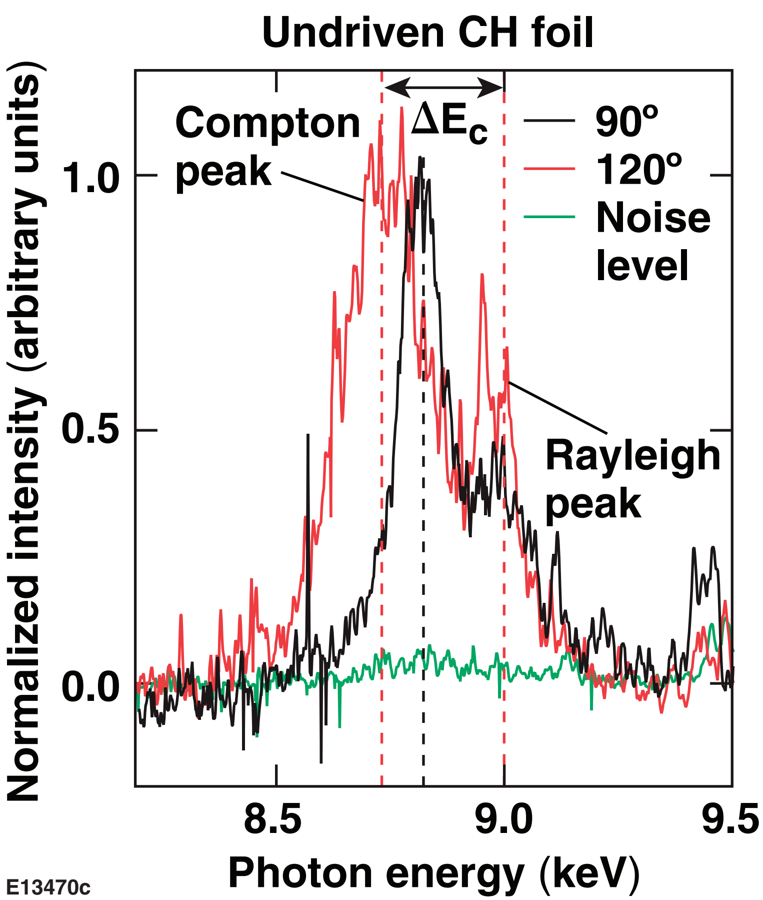
These measurements have the accuracy required to design ignition targets.

Extra slides

X-ray scattering

Plasma conditions of shock-heated matter are diagnosed with spectrally resolved x-ray scattering

- The spectral line shapes of the elastic Rayleigh and the inelastic Compton components are fitted to infer T_e and Z.*
- The Doppler-broadened Compton feature is sensitive to T_e for $T_e > T_F$.
- The ratio of Rayleigh and Compton intensities is sensitive to Z.



Compton downshifted energy (eV)

$$\Delta E_C = \frac{\hbar^2 k^2}{2m_e} \qquad k = \frac{4\pi}{\lambda_0} \sin\left(\frac{\theta}{2}\right)$$

θ: scattering angle
λ_0: wavelength of probe

(Zn Heα ~ 1.3 Å ~ 9.0 keV)

ΔE_C = 178 eV (for 90°)
= 267 eV (for 120°)

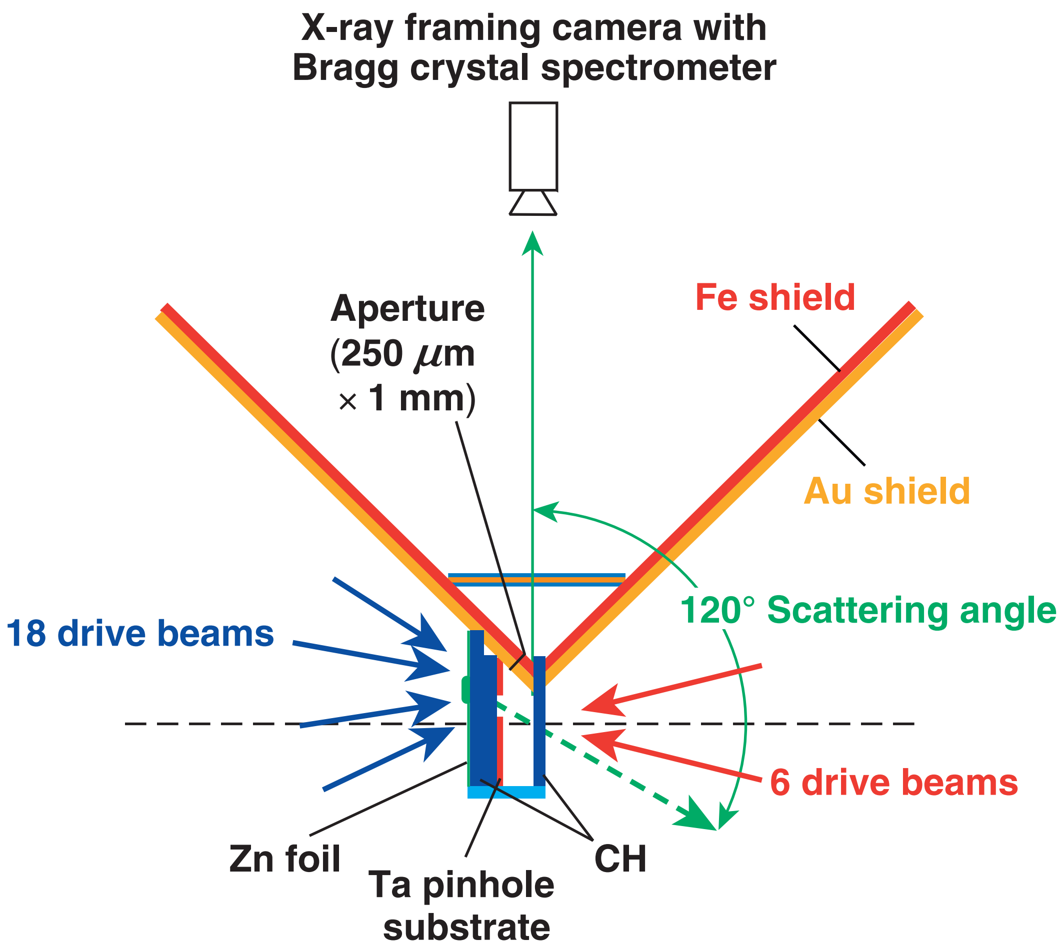
*S. H. Glenzer *et al.*, Phys. Rev. Lett. 90, 175002 (2003)
G. Gregori *et al.*, Phys. Rev. E 67, 026412 (2003).

E13470c

X-ray scattering

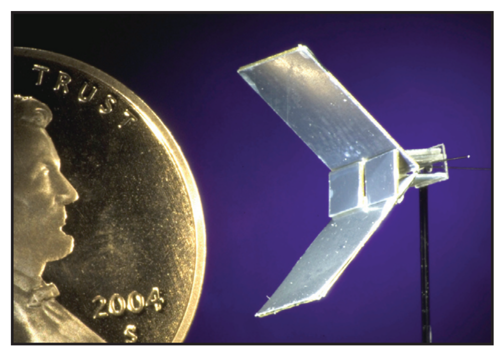
Scattered Zn He$_\alpha$ emission was recorded from a direct-drive, shock-heated CH foil

UR LLE



Zn He$_\alpha$ at 9 keV

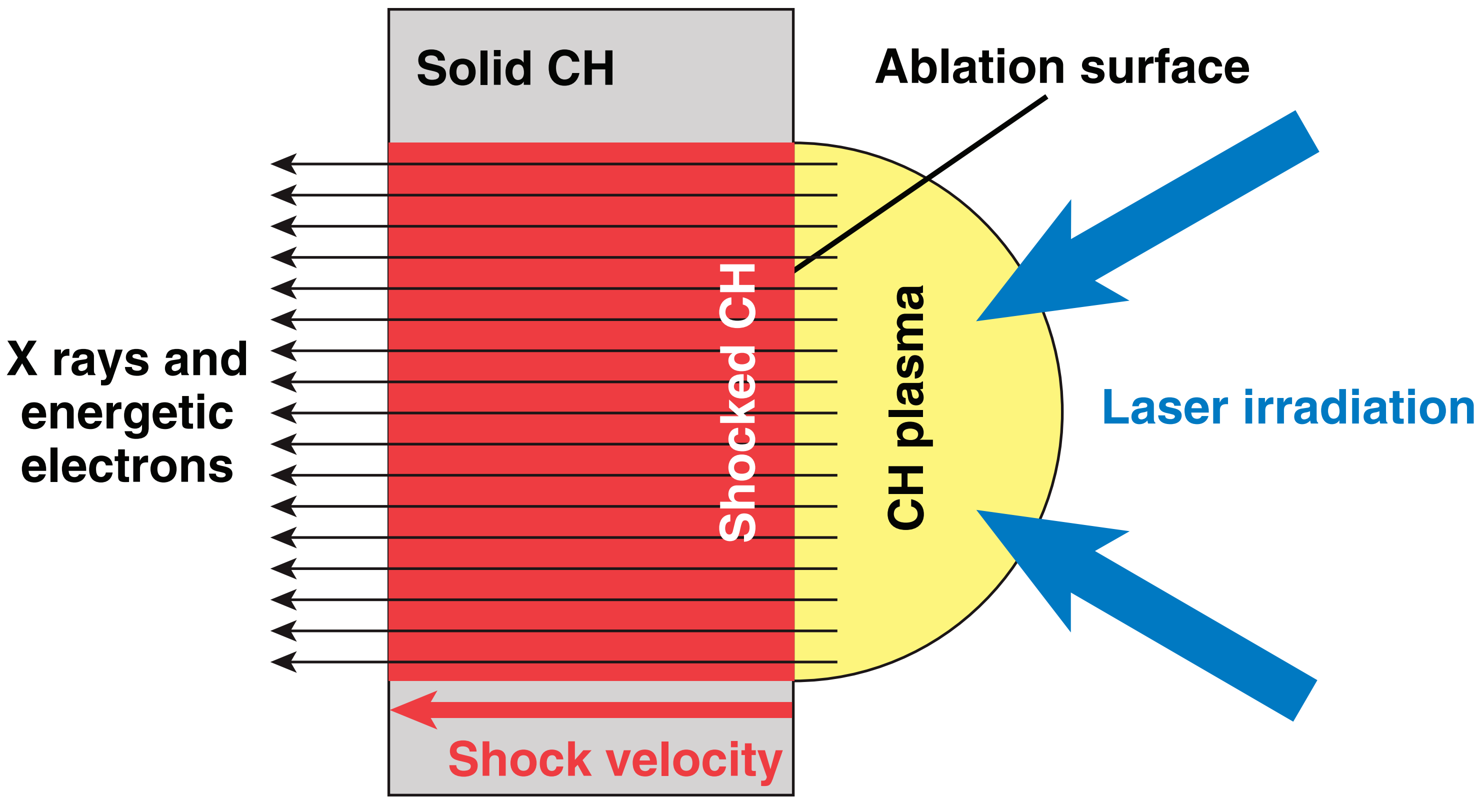
- Target
  - 125-μm CH (2.25 × 3 mm)
  - 6 × 8 mm Au/Fe shields (100-μm Au, 50-μm Fe in thickness)
  - 250-μm viewing slit
  - 400-μm pinhole size
  - 5-μm Zn foil
- Laser conditions
  - 3-ns square pulse
  - 280 J/beam
  - 400-μm flattop drive for drive foil
  - 100-μm spot for backlighters



E14878

X-ray scattering

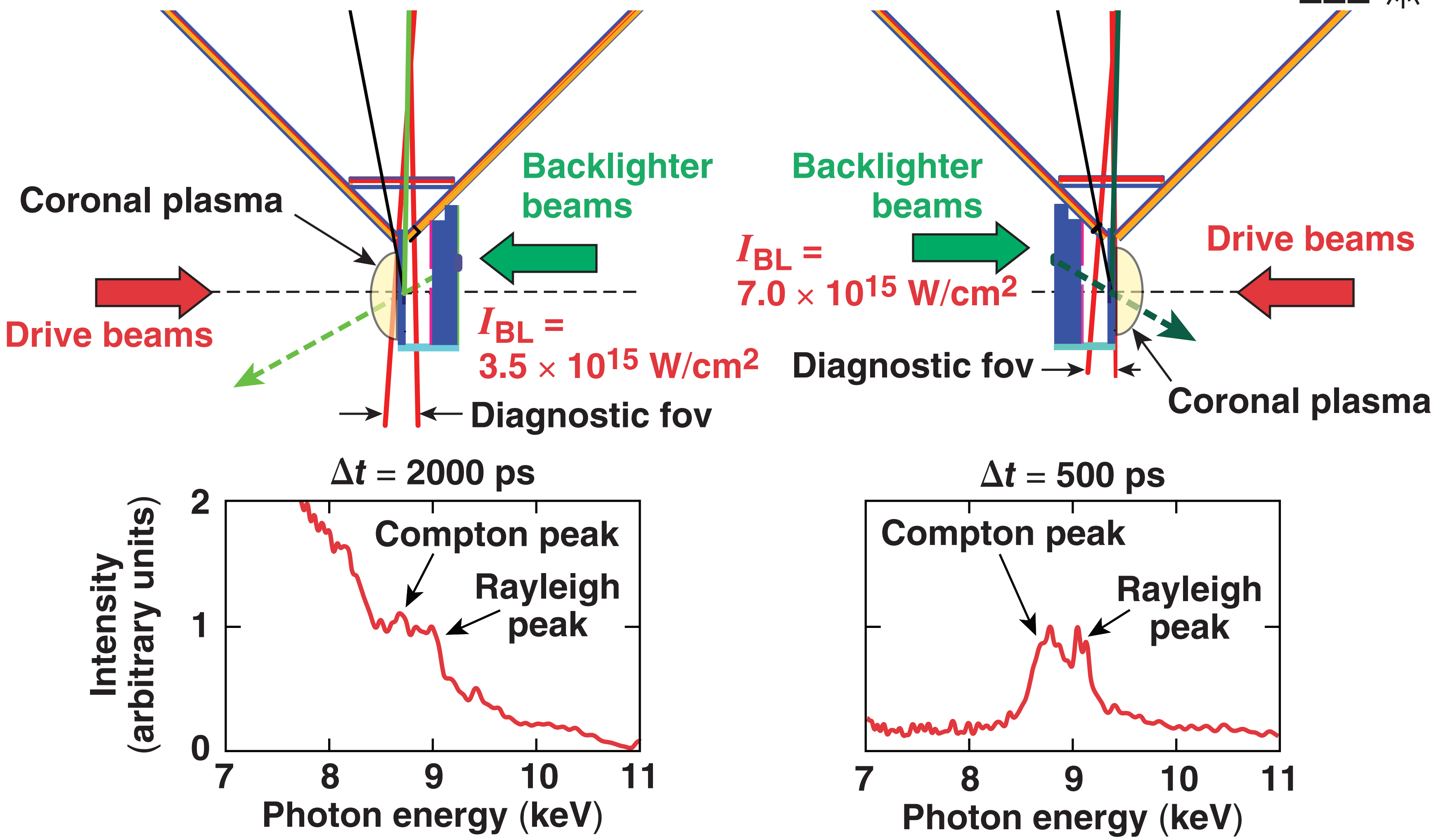
Spatially averaged shell conditions were measured with non-collective spectrally resolved x-ray scattering



The scattering is recorded just as the shock has propagated through the target.

E14879

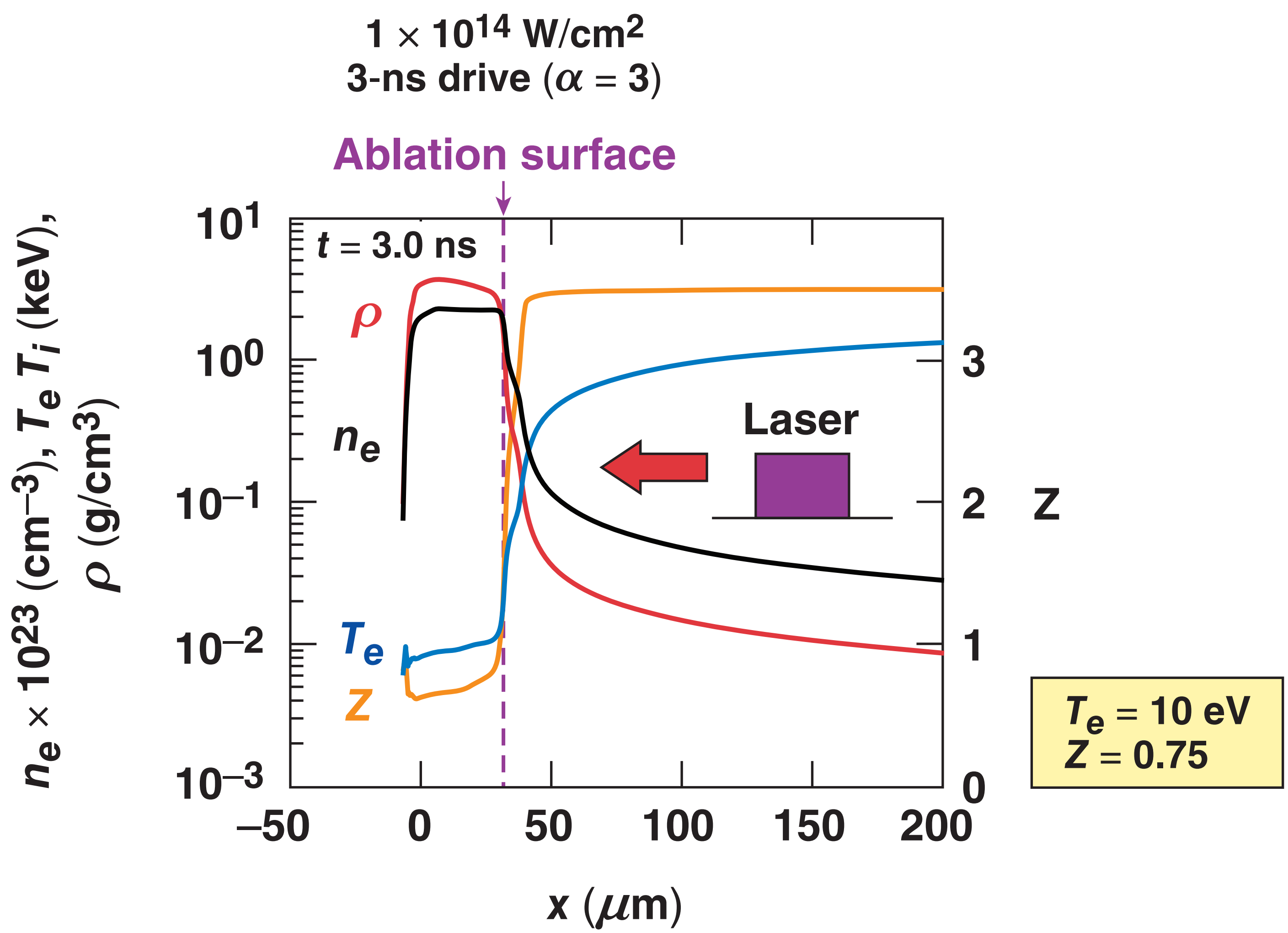
X-ray radiation from the coronal plasma must be shielded from the spectrometer



Drive intensity of 1 × 10^{15} W/cm^2: X-ray background overwhelmed scattered signal.

E14210a

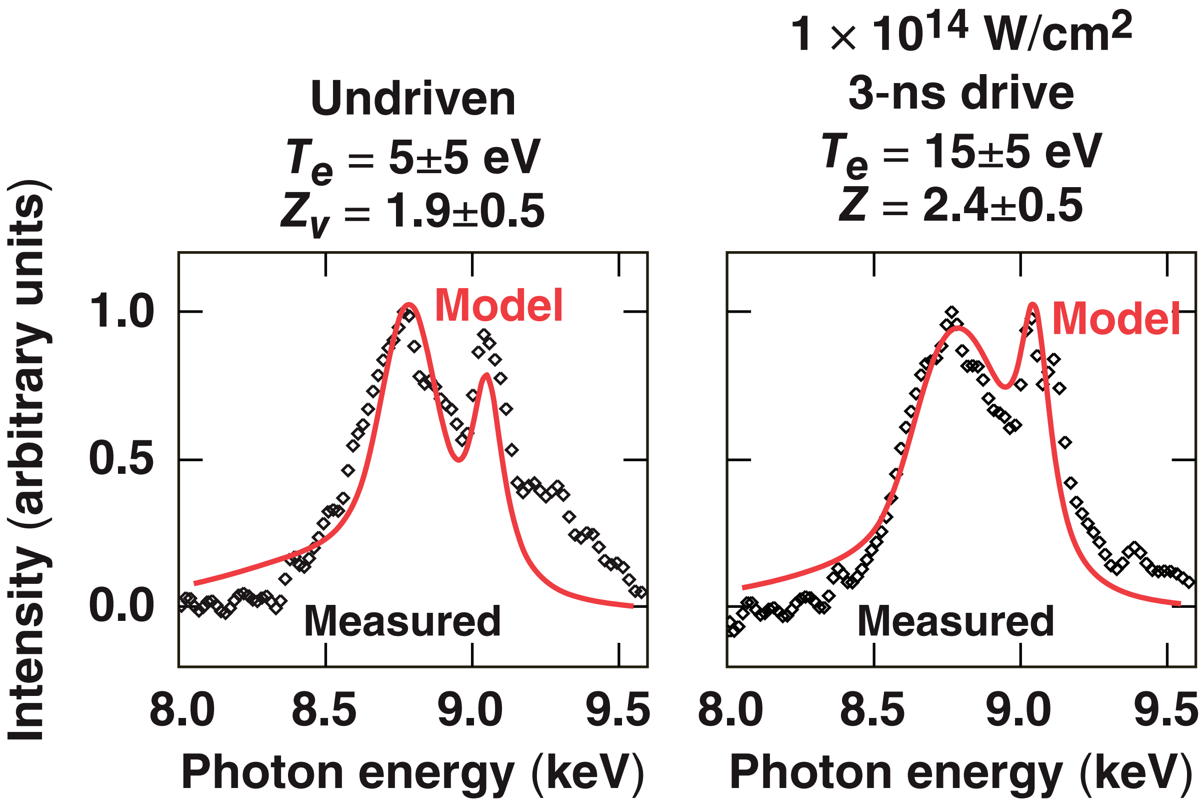
The 1-D hydrodynamics code *LILAC* predicted plasma conditions at shock breakout



- The compressed foil has nearly uniform conditions

X-ray scattering

An upper limit of the electron temperature can be inferred from the x-ray scattering of about 20 eV



1-D prediction
T_e = 10 eV
Z = 0.75

Scattered x-ray spectra from driven and undriven CH targets look similar.

E14211a