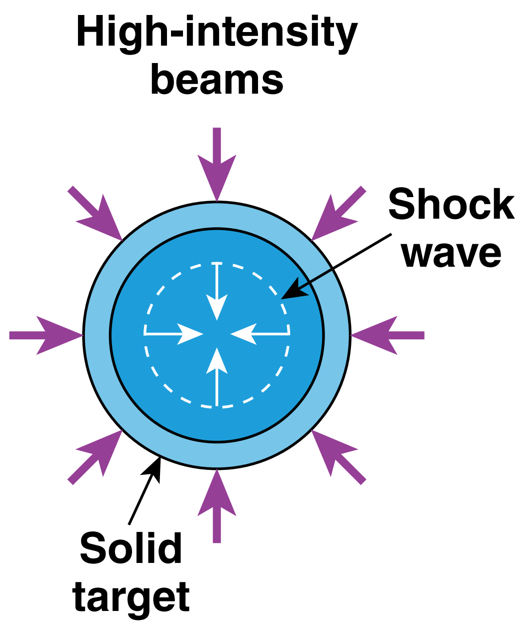
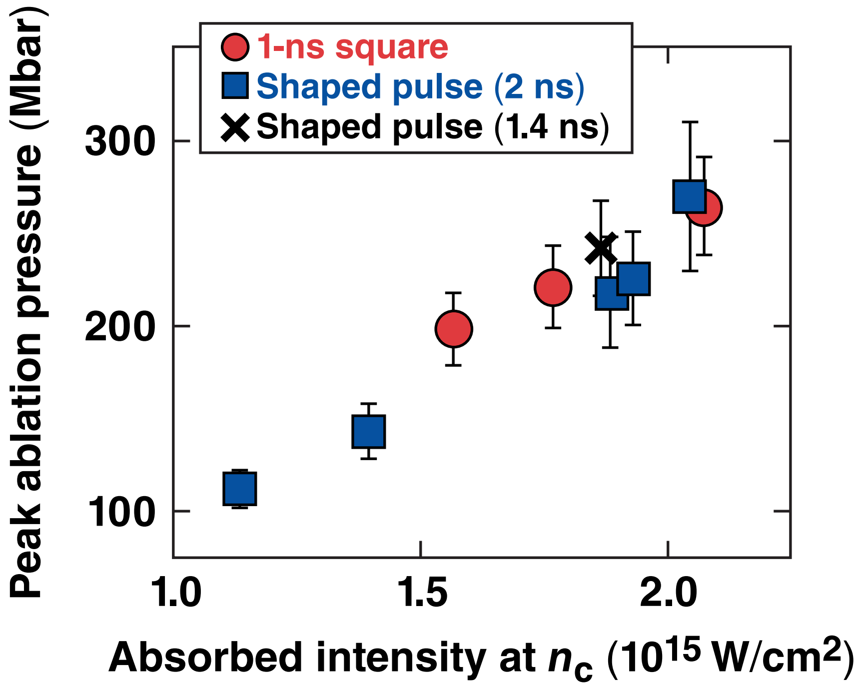
Strong-Shock Generation and Laser–Plasma Interactions for Shock-Ignition Inertial Fusion





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Summary

High-intensity shock-ignition (SI) experiments on OMEGA provide valuable data on hot-electron production and shock ablation pressure

- Multiple overlapping high-intensity beams generate an energetic hot-electron distribution ($<$100 keV) with a conversion efficiency of up to ~10%
- Turning off smoothing by spectral dispersion (SSD) in overlapping high-intensity beam experiments increased the hot-electron fraction and shock strength
- Stimulated Raman scattering (SRS) increases significantly (~5×) when SSD is turned off, while two-plasmon–decay (TPD) is unaffected
- Moderate hot electrons may be beneficial to shock ignition by coupling energy to the outer layer of the imploding capsule

The inferred ablation pressures of 270 Mbar at ~3×10^{15} W/cm^2 approaches the minimum SI requirement of 300 Mbar.

Collaborators

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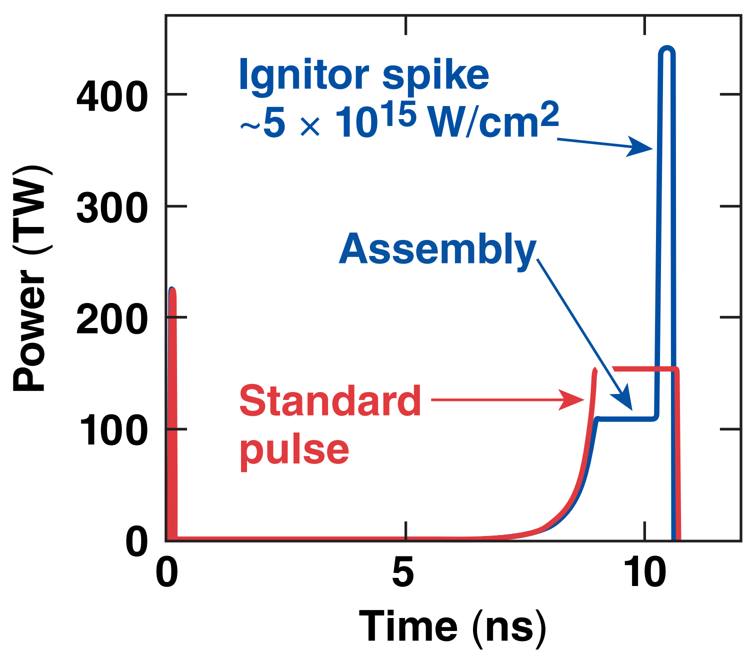
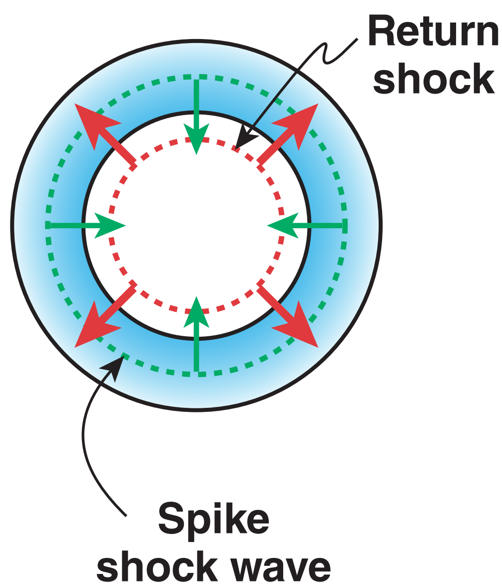
Sufficient ablation pressure and T_{hot} < 150 keV must be demonstrated for shock ignition during the ignitor spike



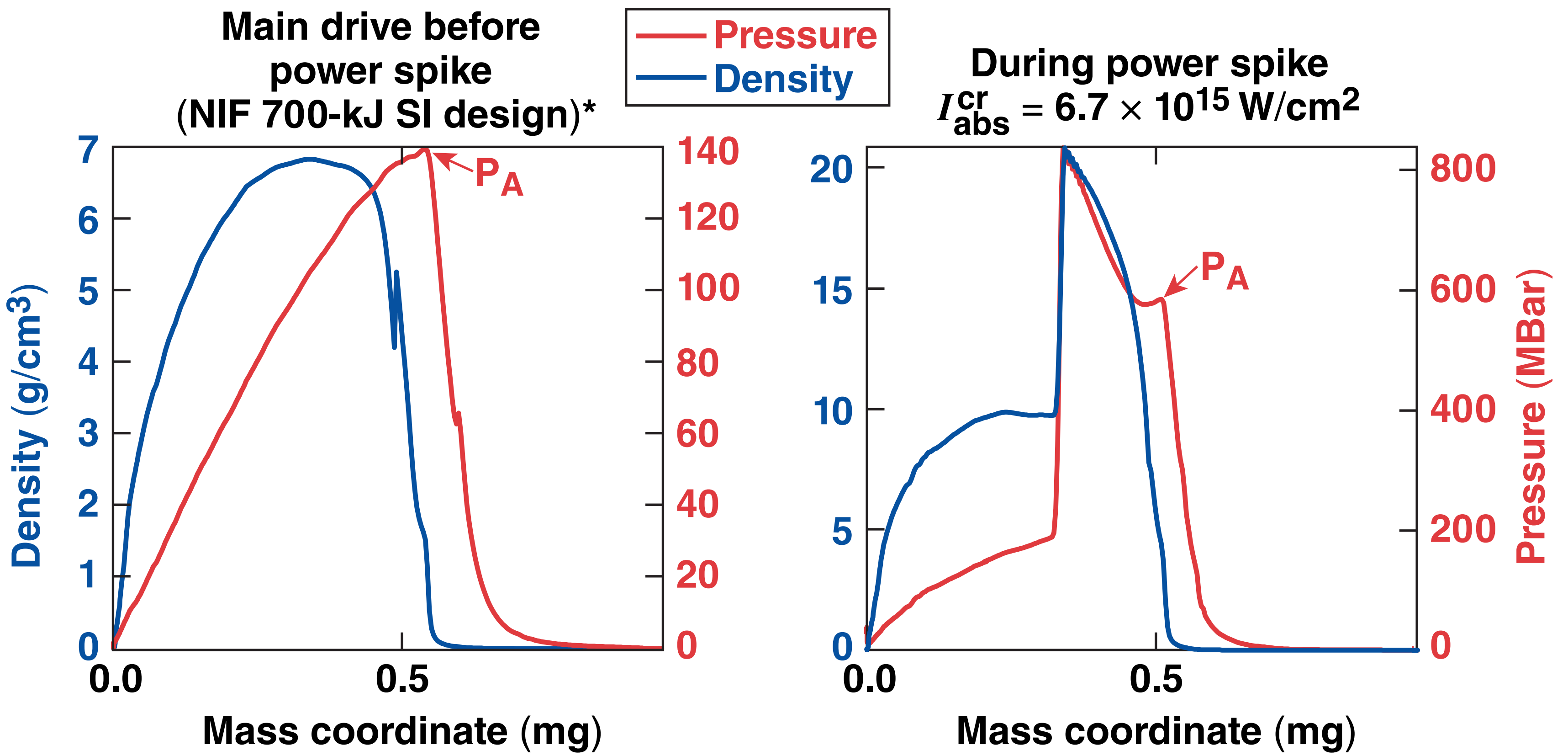


- Critical issues for shock ignition
  - demonstrate ~300- to 400-Mbar spike-generated ablation pressure
  - demonstrate hot-electron temperatures of ≤150 keV generated by spike

TC8918d

*R. Betti *et al.*, Phys. Rev. Lett. 98, 155001 (2007).

SI requires minimum ablation pressures of ~300 Mbar; up to ~600 Mbar is required for large ignition margins

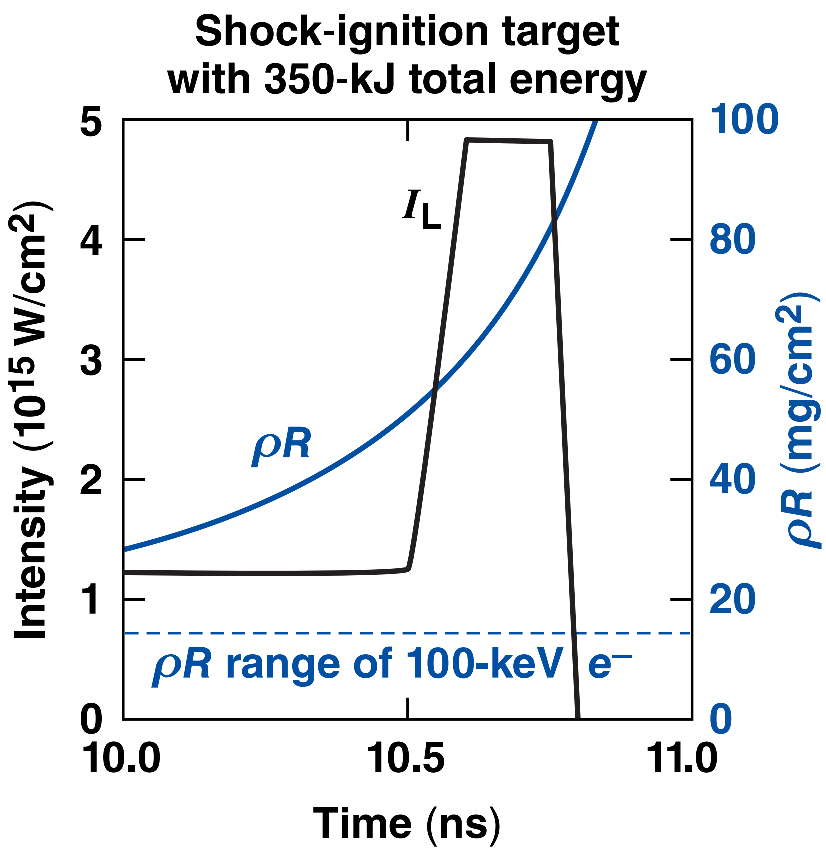


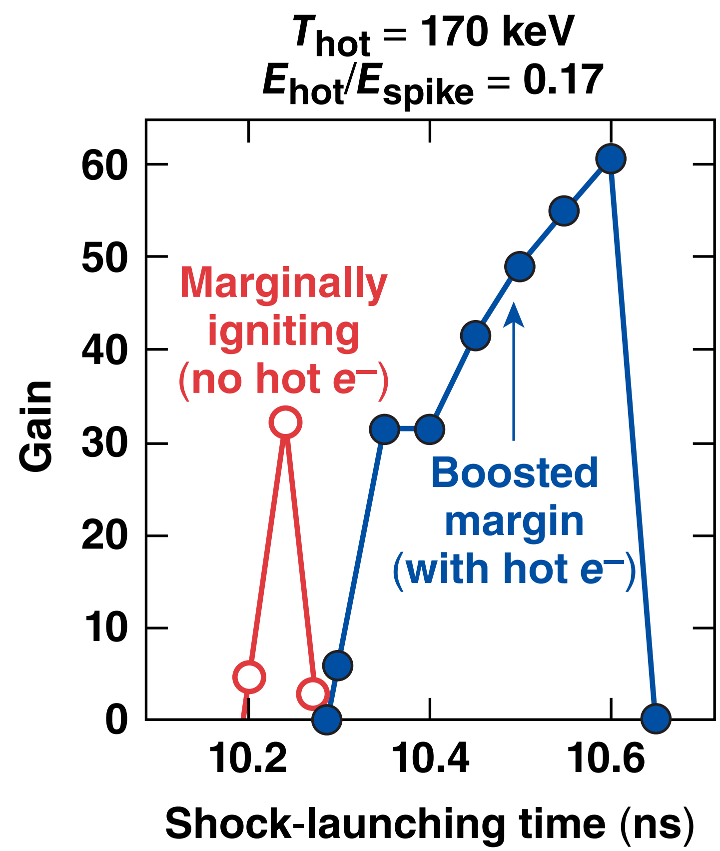
Minimum ablation pressure for SI ~ 2× (P_A main drive) ~300 Mbar.
Ablation pressure for the National Ignition Facility (NIF) 700-kJ polar-drive (PD) SI design with an ignition threshold factor (ITF) = 4 ~ 600 Mbar.

E23176

*K. S. Anderson *et al.*, Phys. Plasmas 20, 056312 (2013).

Laser–plasma interaction during the spike pulse and hot-electron generation are important issues for shock ignition



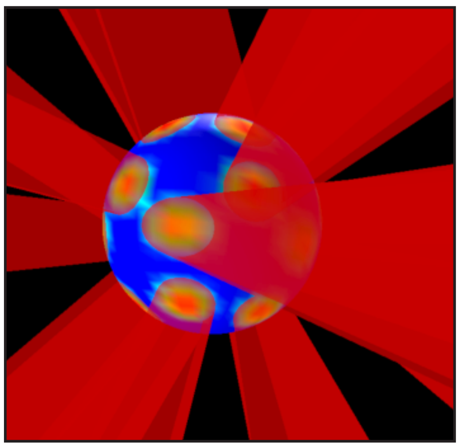


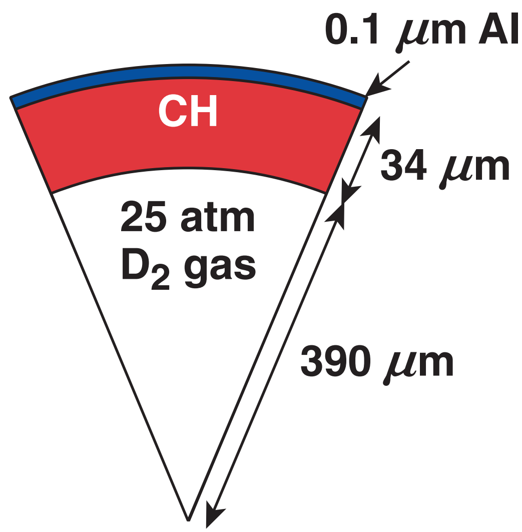
If the ρR is high enough when hot electrons are produced, they will be stopped in the outer regions of the shell.

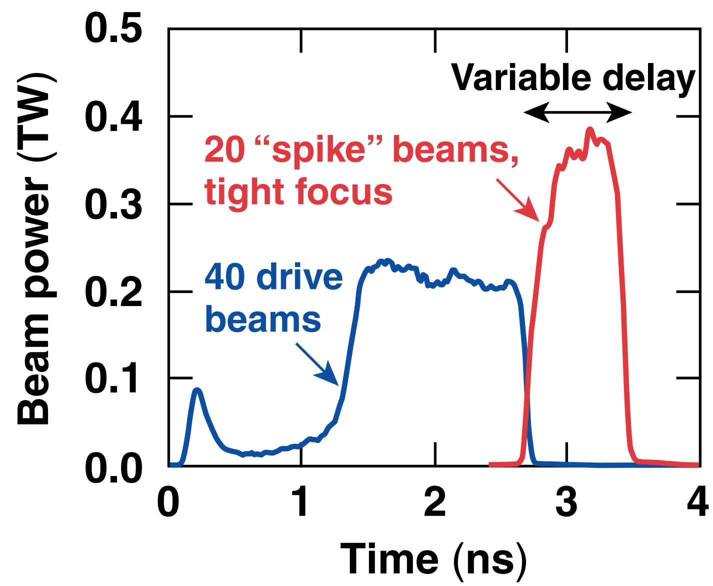
R. Betti *et al.*, J. Phys., Conf. Ser. 112, 022024 (2008);
S. Gus'kov *et al.*, Phys. Rev. Lett. 109, 255004 (2012).

TC7870i

The 40 + 20 configuration was used to study the interaction with single high-intensity beams on OMEGA





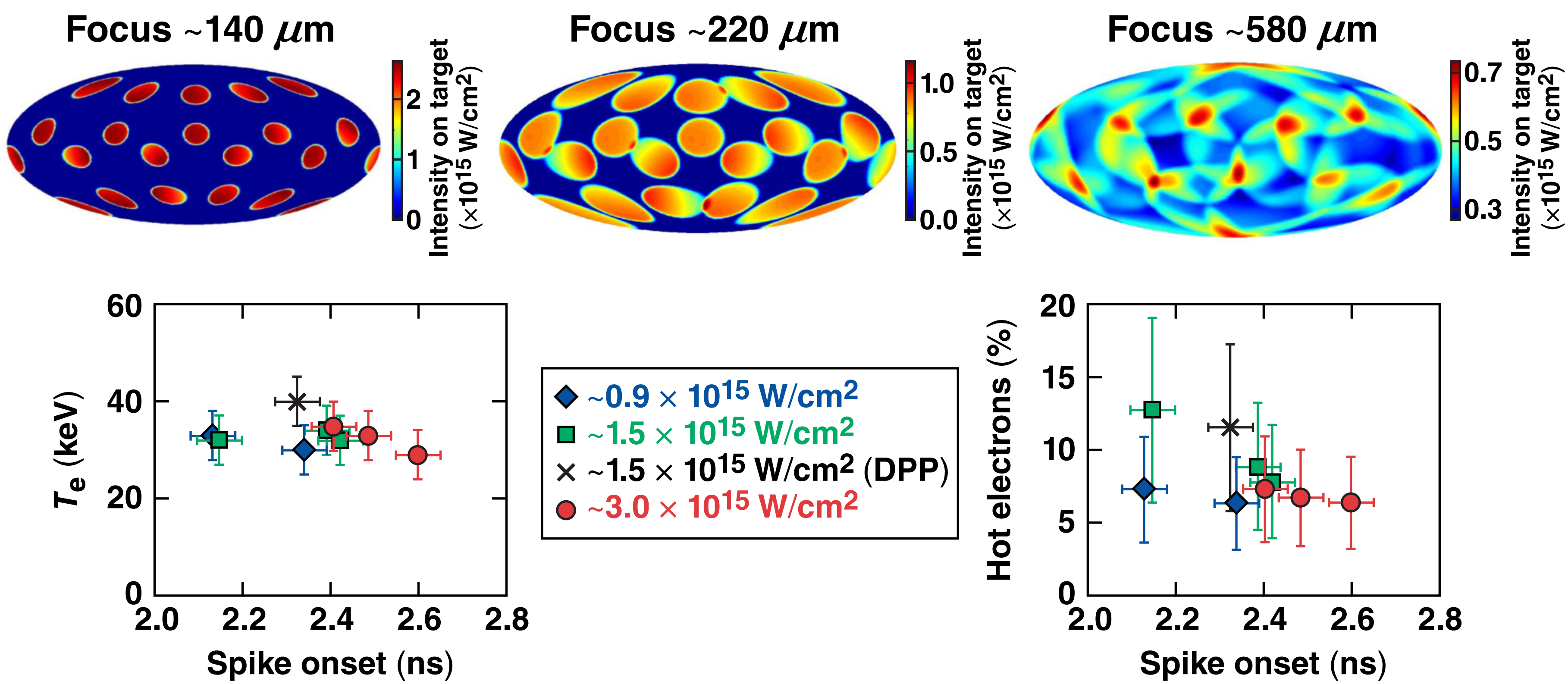


- Single-beam shock-ignition studies in spherical geometry up to ~8 × 10^{15} W/cm^2
- 40 drive beams: distributed phase plate (DPP), distributed phase rotator (DPR) (no SSD), ~14 kJ
- 20 spike beams: no DPP, ~5 kJ

E20035c

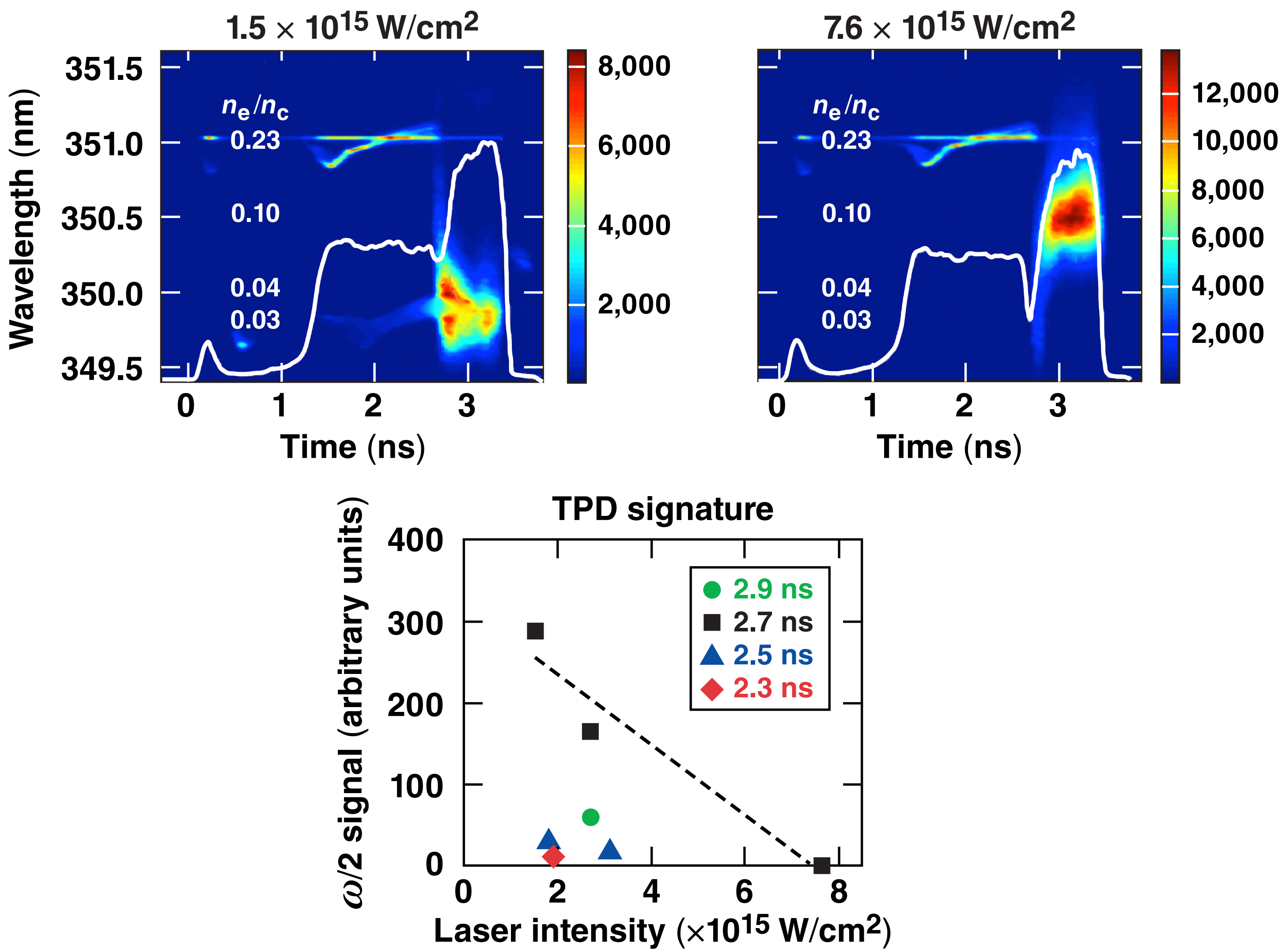
W. Theobald *et al.*, Phys. Plasmas 19, 102706 (2012).

Up to ~12% of the spike energy was converted into a moderate (~30-keV) hot-electron distribution



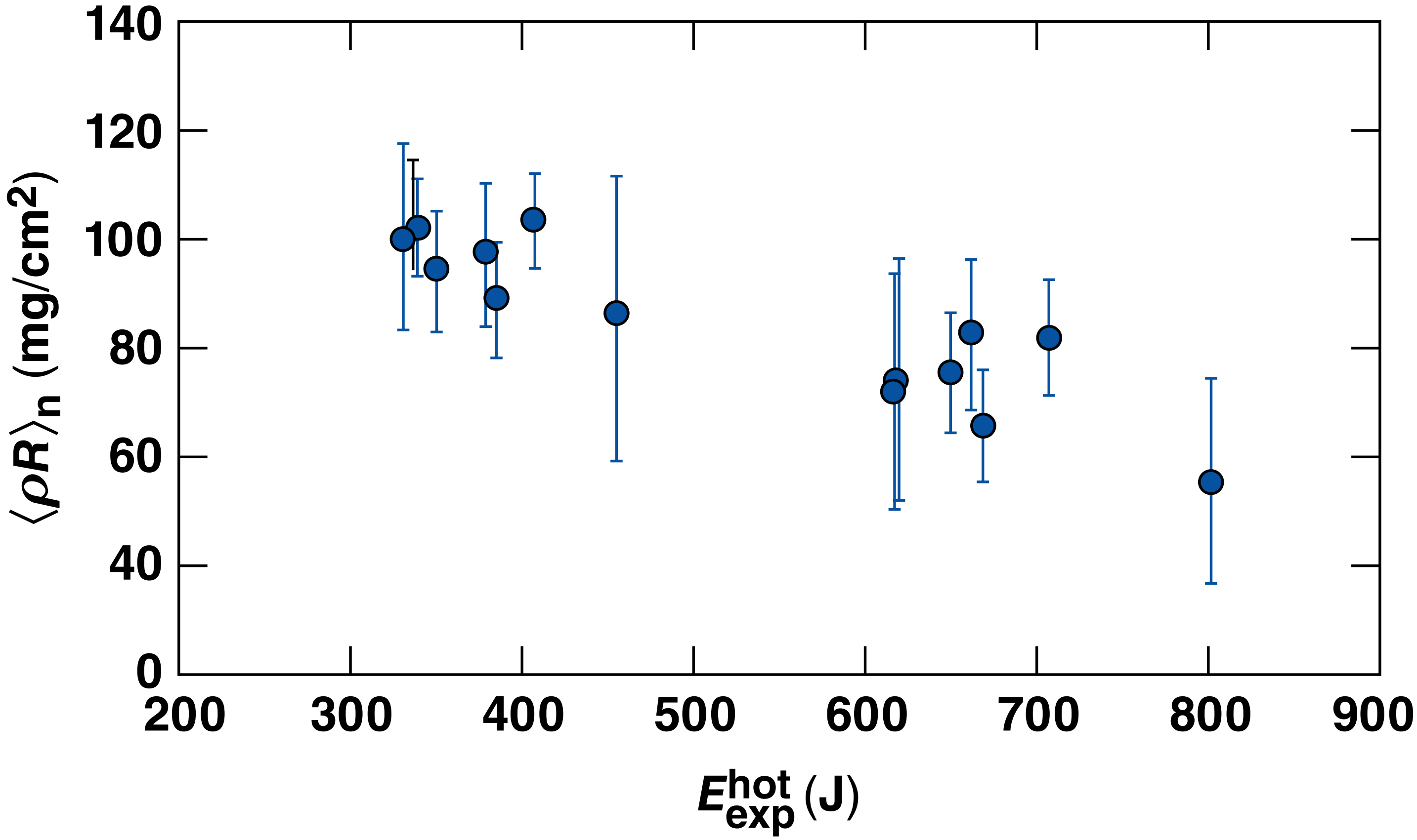
- Hot-electron generation in the 40 + 20 experiment is dominated by SRS
- The TPD instability is strongly suppressed

At high laser intensity, stimulated Brillouin scattering (SBS) signal is emitted near $n_c/4$ and TPD is suppressed



E20064a

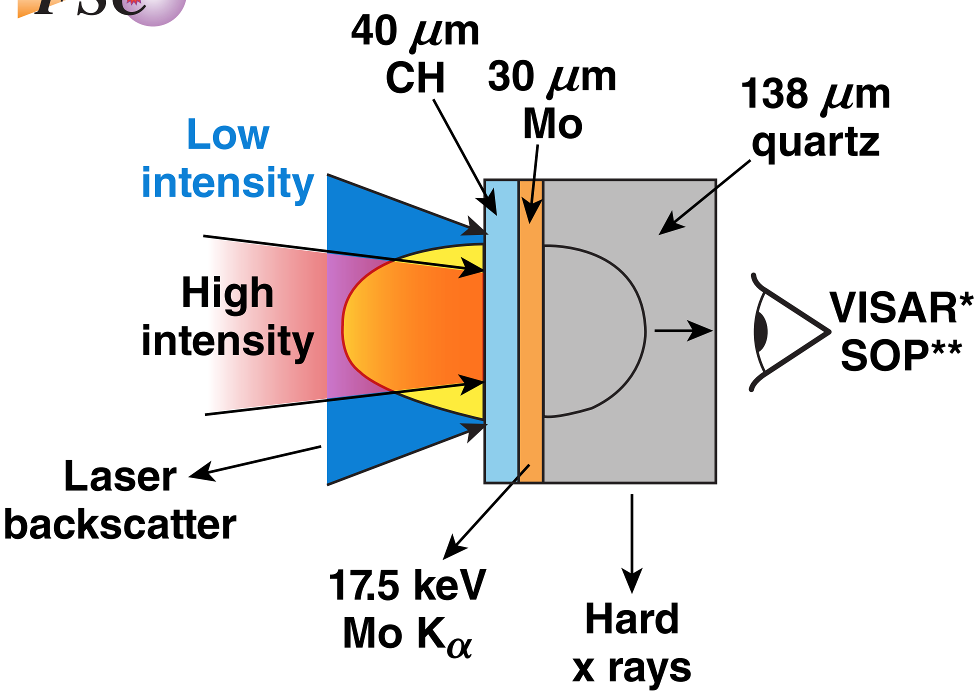
Areal-density measurements show implosion degradation with increasing hot-electron production

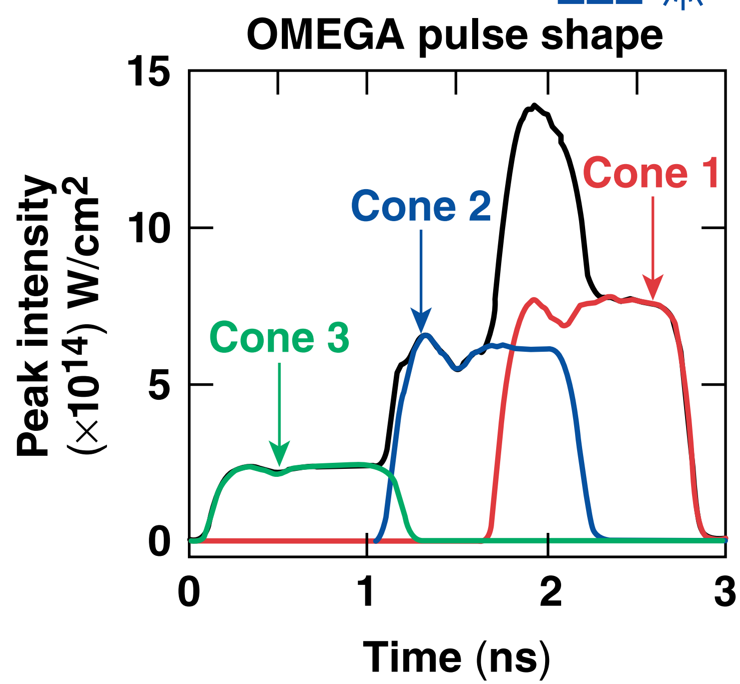


The areal density of OMEGA targets is too low to stop hot electrons on the ablation surface.

TC10350a

A laser–plasma interaction experiment was performed in planar geometry with overlapping beams to infer ablation pressure and to study hot-electron generation



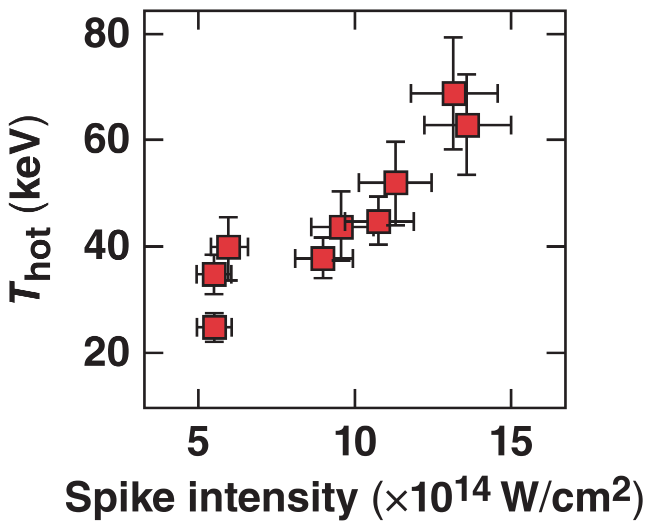


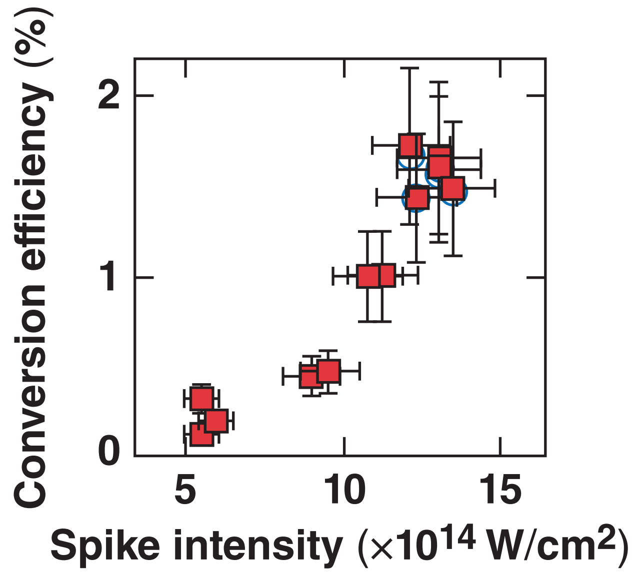
- Phase plates and DPR's with ~900-μm focal spots were used in plasma-generating beams (cone 2 and cone 3)
- Phase plates with an ~600-μm focal spot were used in six high-intensity beams (cone 1)
- L_n ~ 350 μm

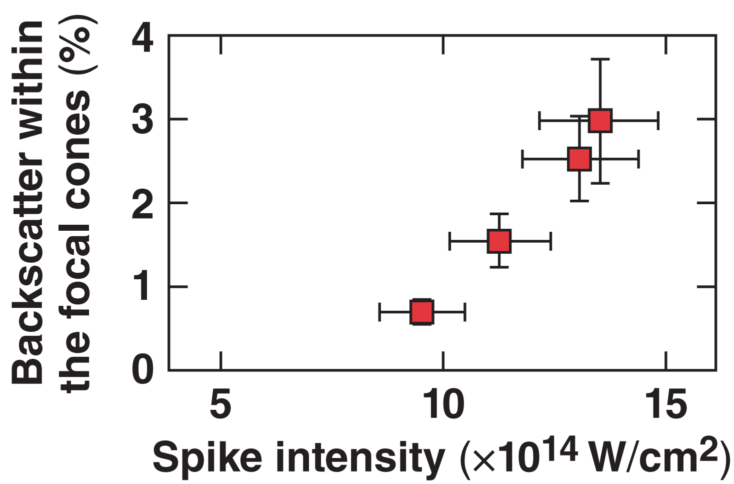
M. Hohenberger *et al.*, Phys. Plasmas 21, 022702 (2014).
* Velocity interferometer system for any reflector
** Streaked optical pyrometer

E20455e

The hot-electron temperature and hot-electron fraction increase with spike laser intensity

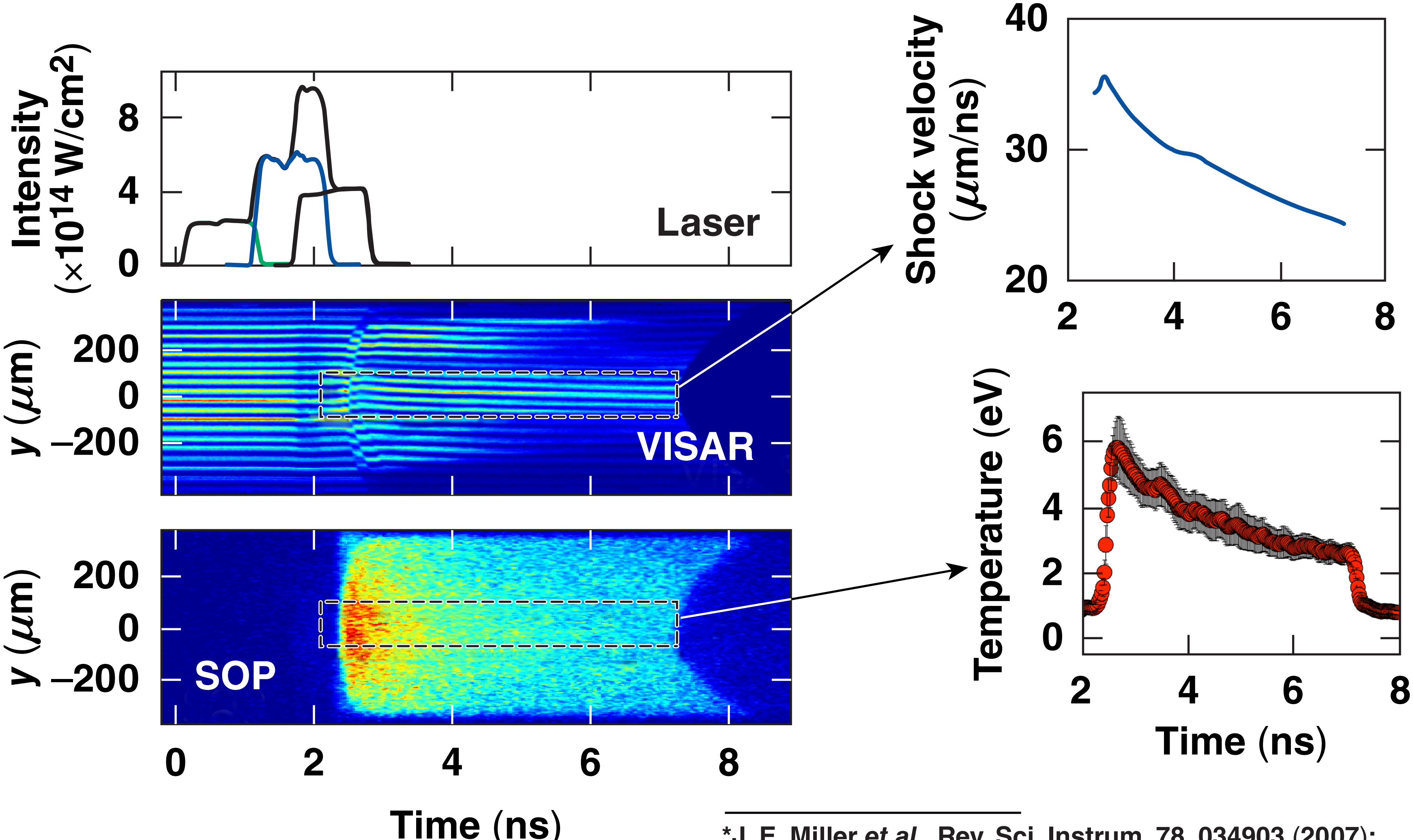






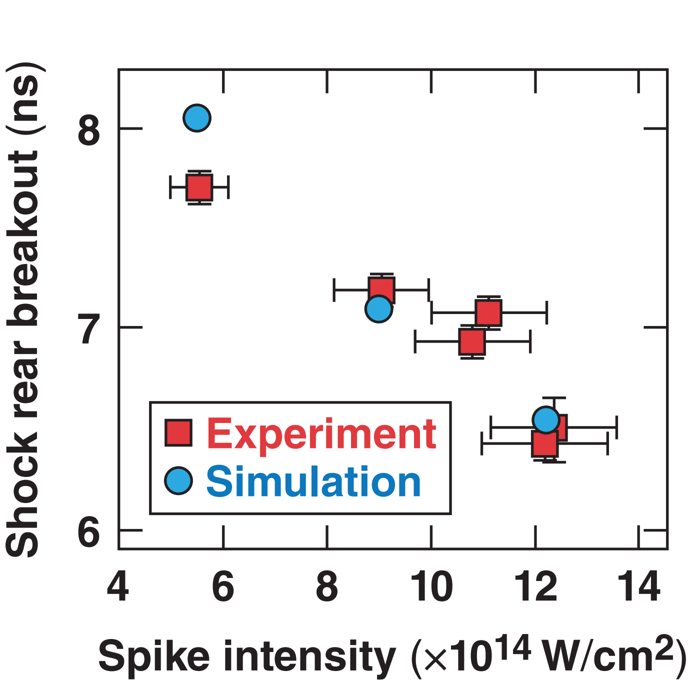
E20783

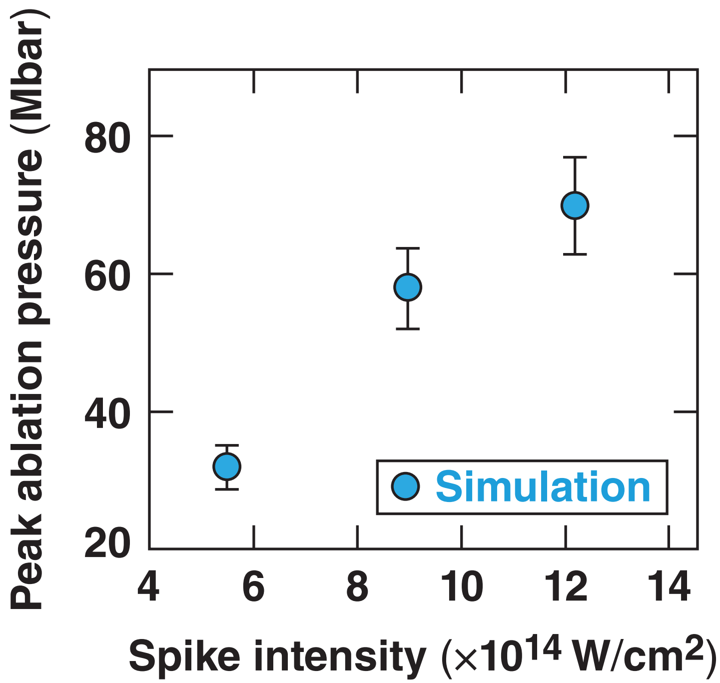
The shock propagation in quartz was observed with SOP and VISAR*



*J. E. Miller *et al.*, Rev. Sci. Instrum. 78, 034903 (2007); P. M. Celliers *et al.*, Rev. Sci. Instrum. 75, 4916 (2004); M. Hohenberger *et al.*, Phys. Plasmas 21, 022702 (2014).

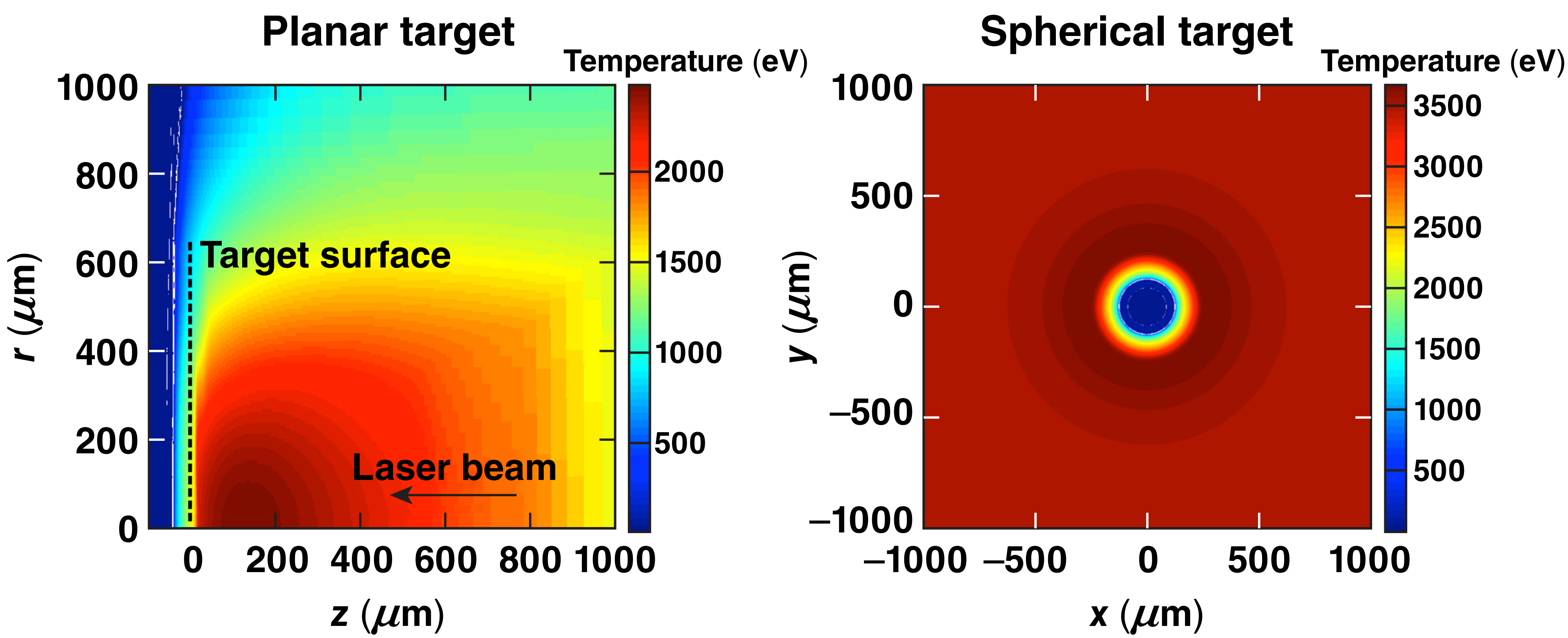
Two-dimensional *DRACO* simulations reproduce well the shock dynamics over a range of spike intensities





- The ablation pressure reaches ~75 Mbar at 1.2×10^{15} W/cm^2

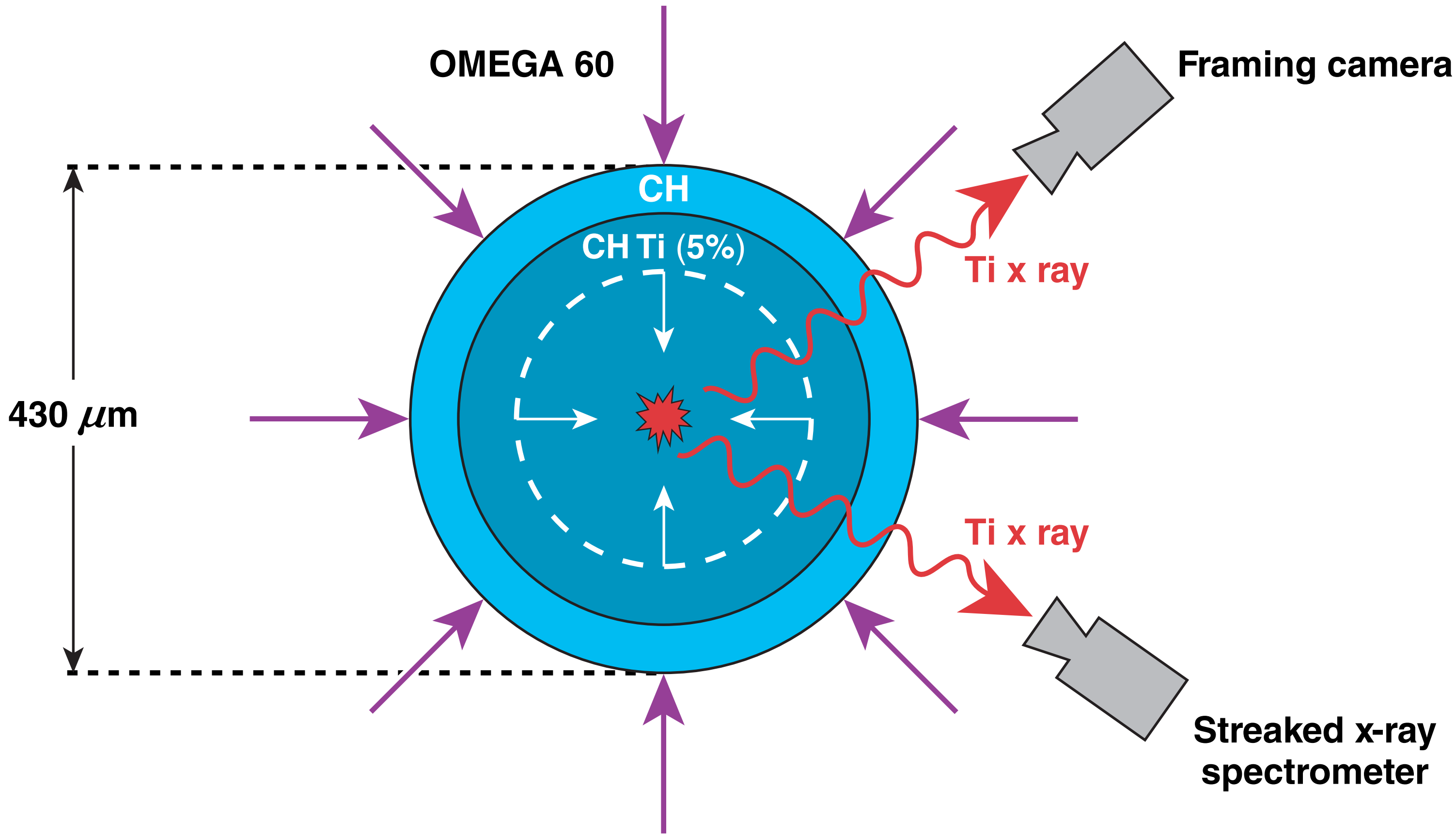
Ablation pressures in planar target experiments are limited by lateral heat losses



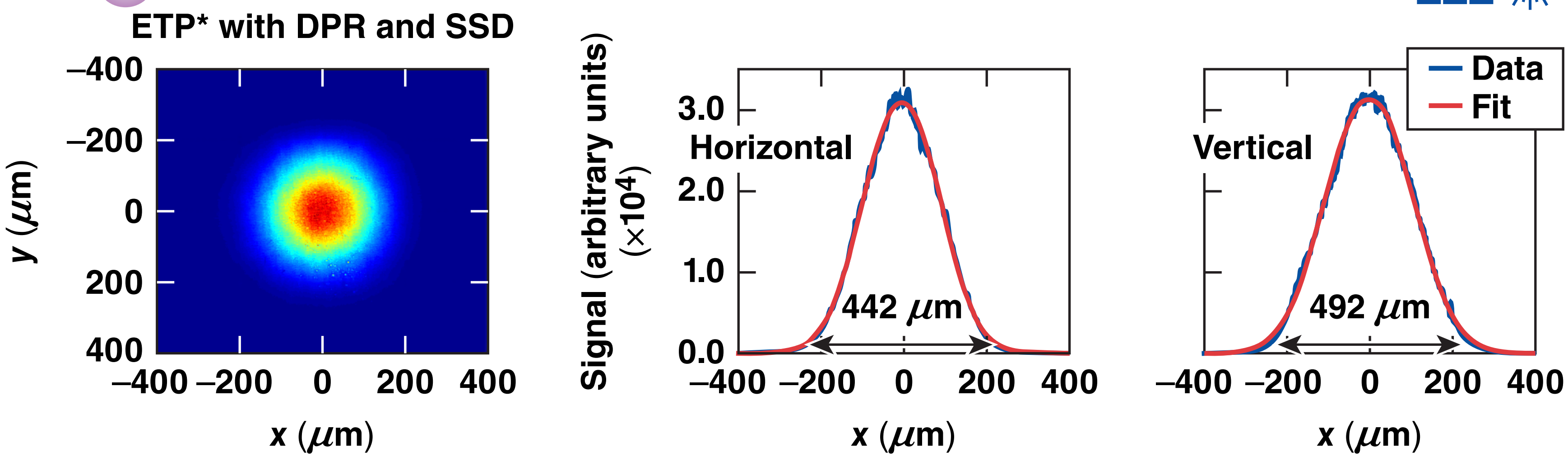
Heat flux: $Q = -\kappa_{th} \nabla T$

Higher ablation pressures can be achieved in spherical geometry.

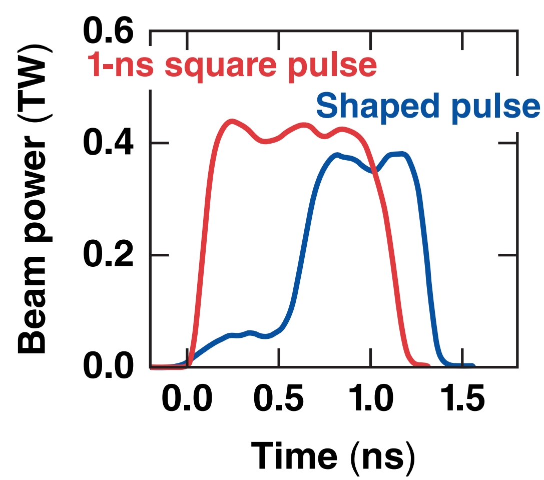
A new OMEGA platform has been developed to study the generation of strong shocks in spherical targets



The small solid target was irradiated by 60 high-intensity beams equipped with small-spot phase plates

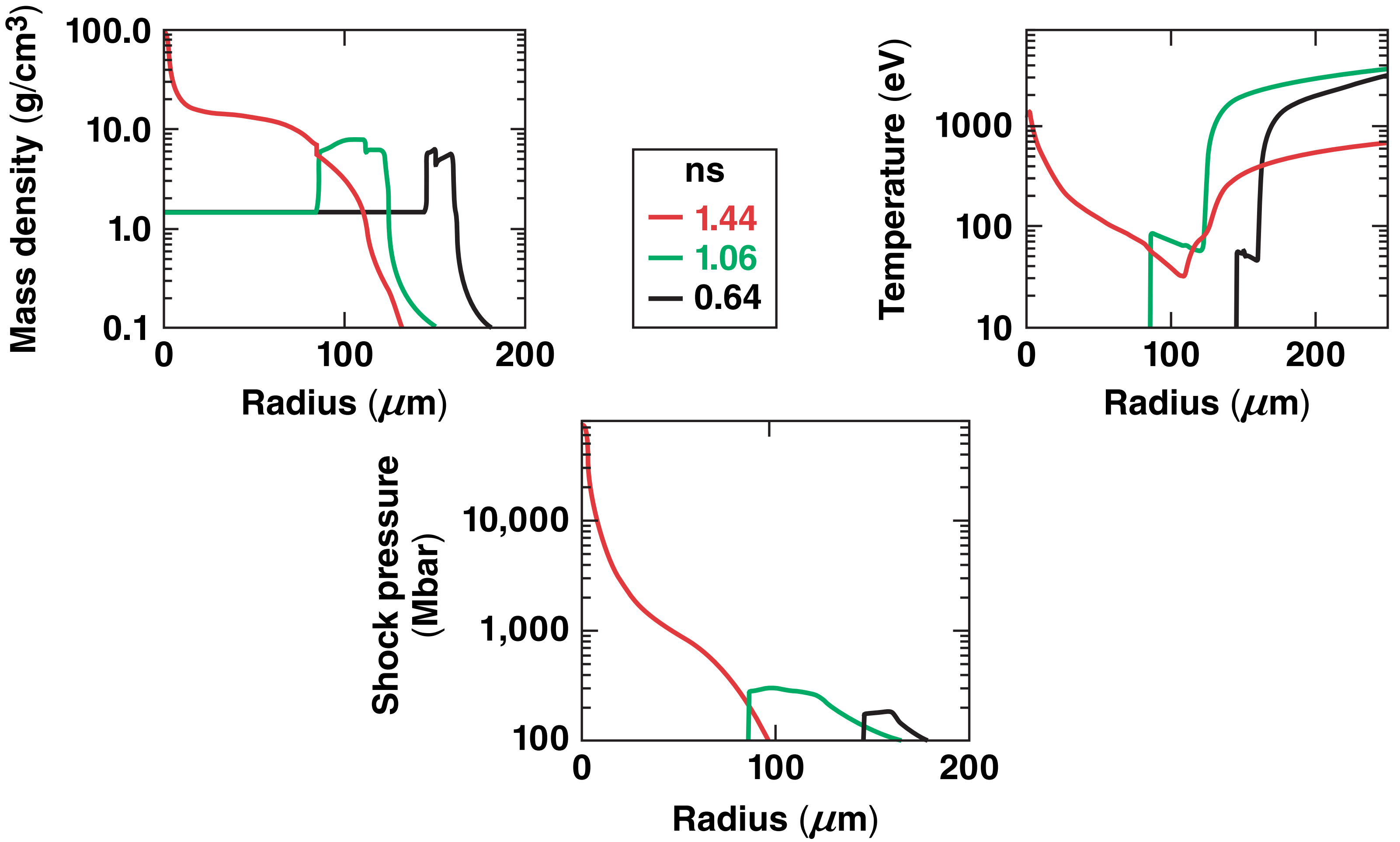


- Small-spot phase plates
- DPR's
- SSD
- $\langle I \rangle \sim 3 \times 10^{15}$ W/cm^2
- Density scale length $L_{n_c/4}$ ~120 μm



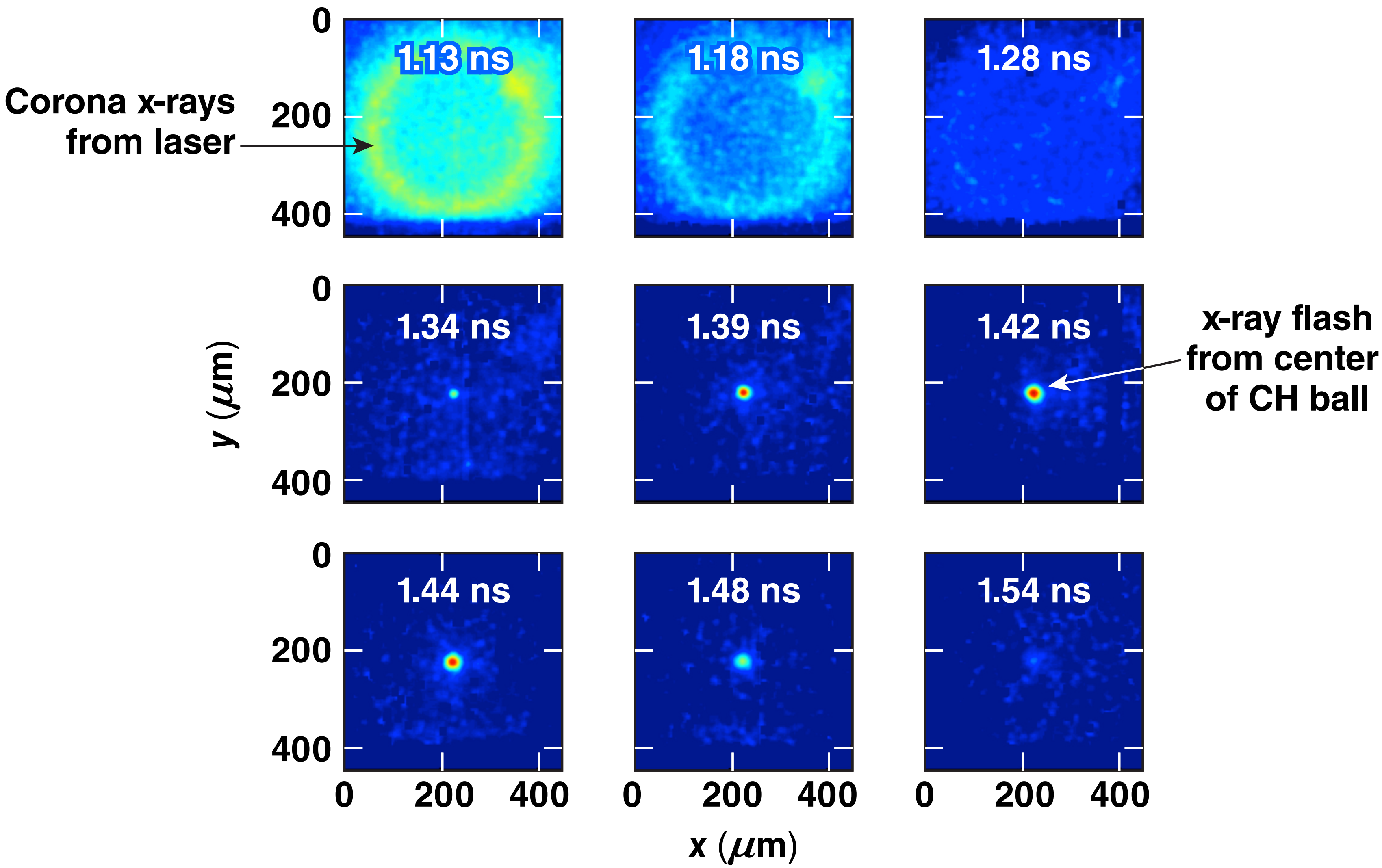
*Equivalent target plane

One-dimensional *LILAC* simulations predict a strong spherical shock wave that converges in the center of the solid target



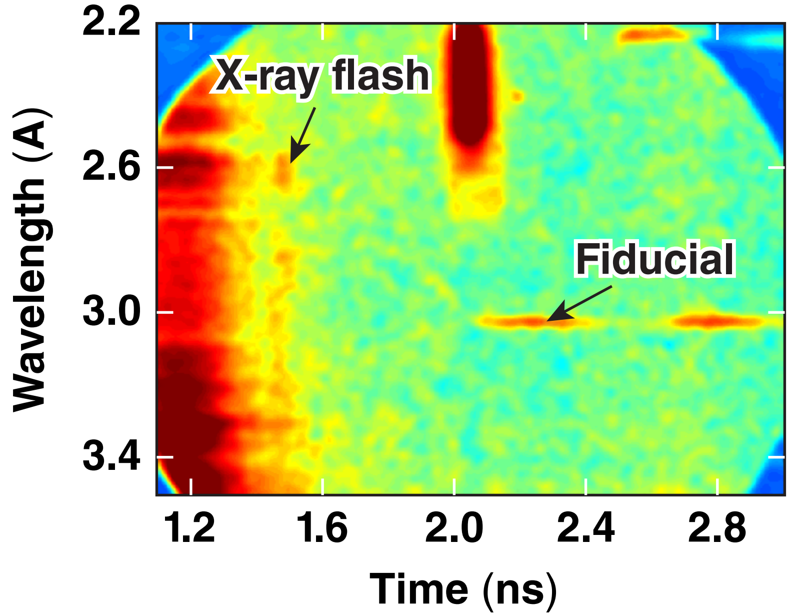
E22459a

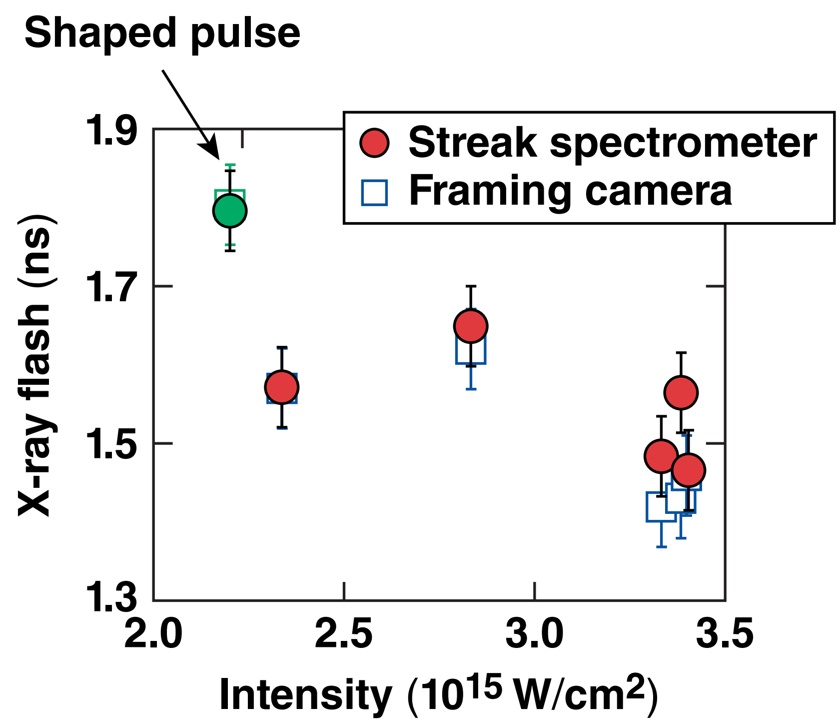
An x-ray framing camera captured a short x-ray flash at the time when the shock converged in the center



E23233

The x-ray flash was measured with a streaked x-ray spectrometer





E22461a

The x-ray flash was emitted from a small volume of ~10^3 μm^3 in less than 50 ps

FSC

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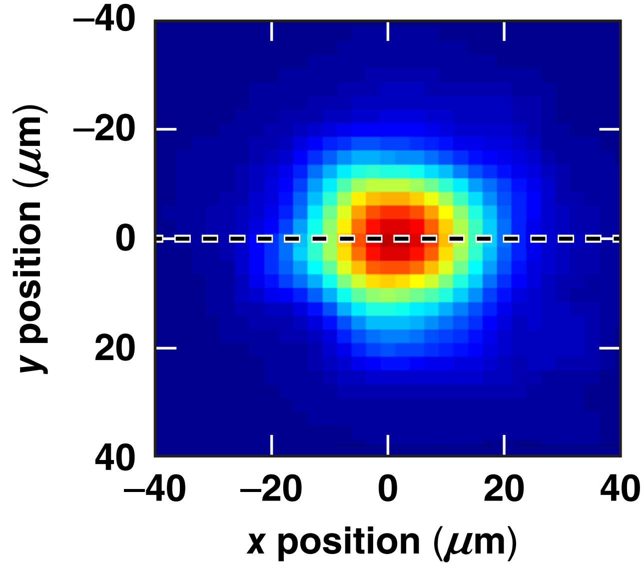
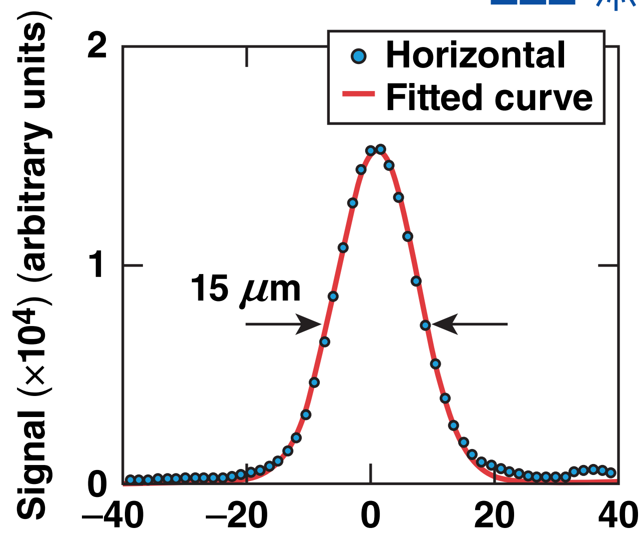
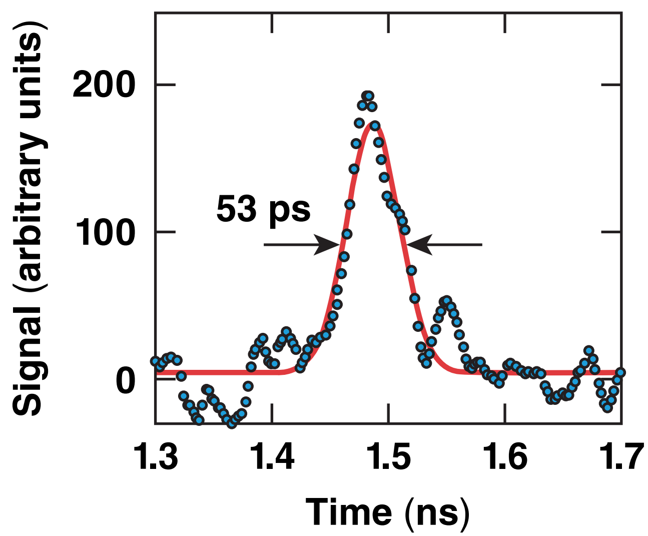
Framing-camera images from target center





Ti He$_\alpha$ flash from streak camera

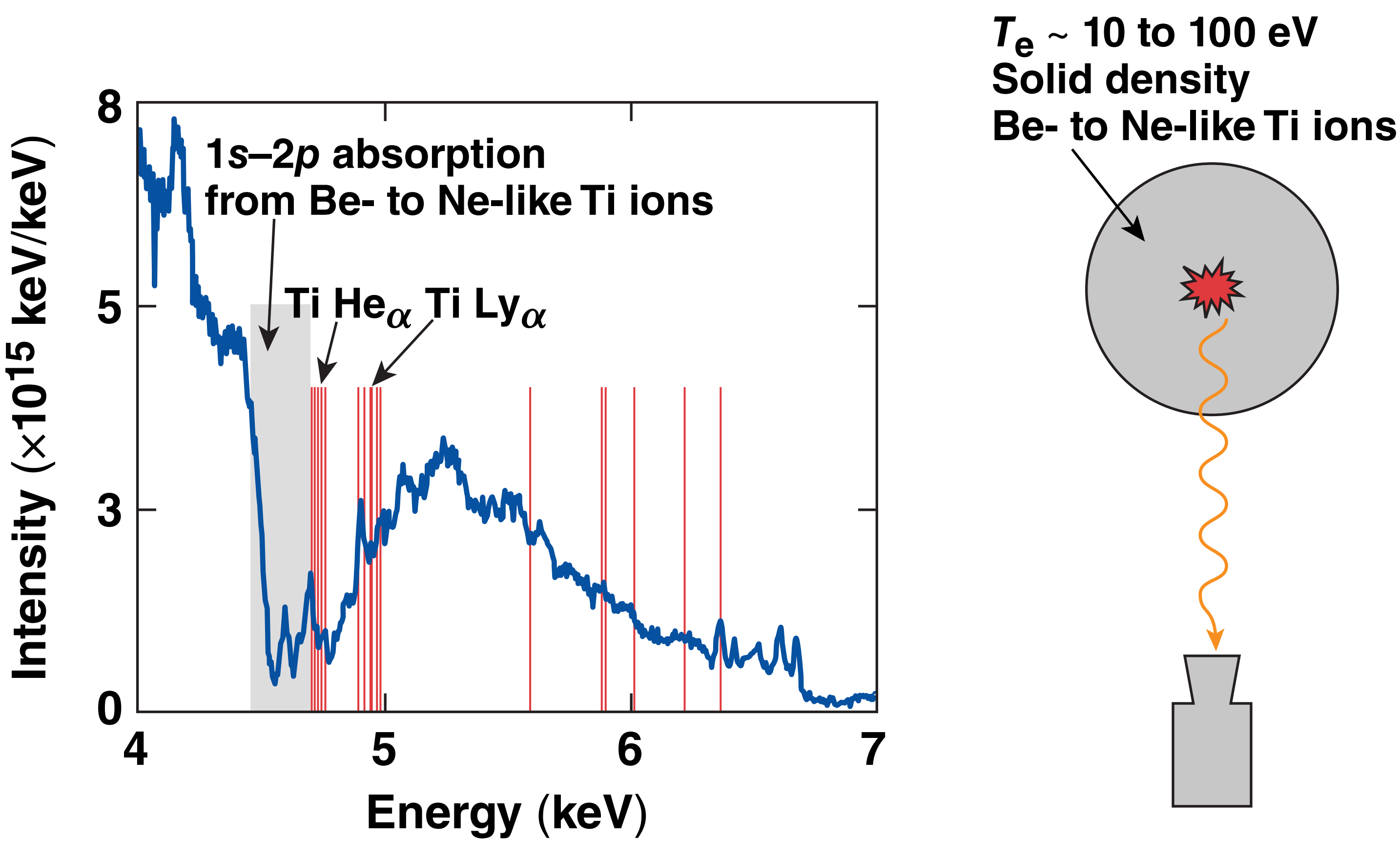


$$\Delta x \approx \sqrt{(15\ \mu m)^2 - (12\ \mu m)^2} \approx 9\ \mu m$$

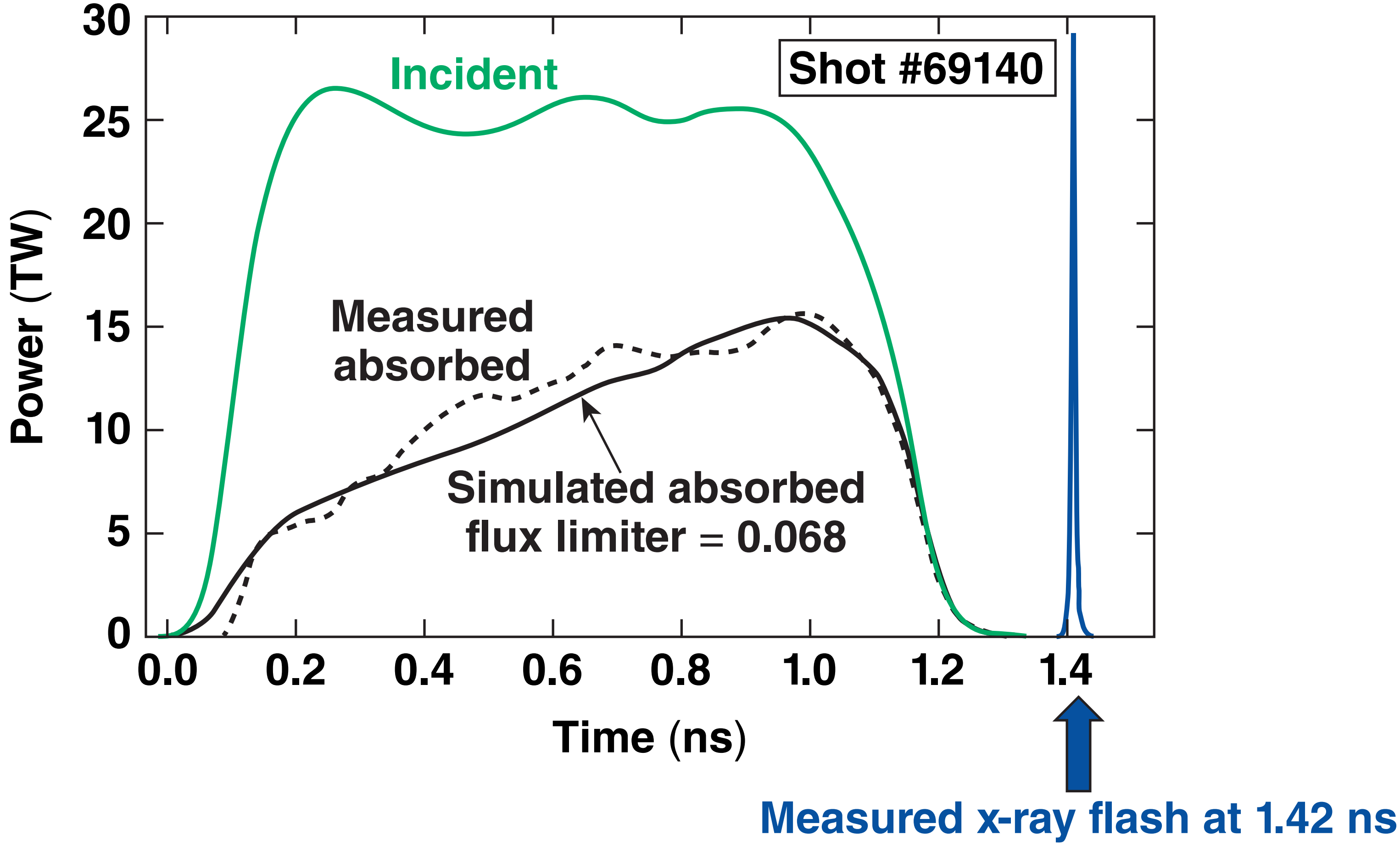
$$\Delta t \approx \sqrt{(53\ ps)^2 - (40\ ps)^2} \approx 35\ ps$$

E22462a

Time integrated x-ray spectra reveal strong 1*s*–2*p* absorption features from Ti ions of various charge states

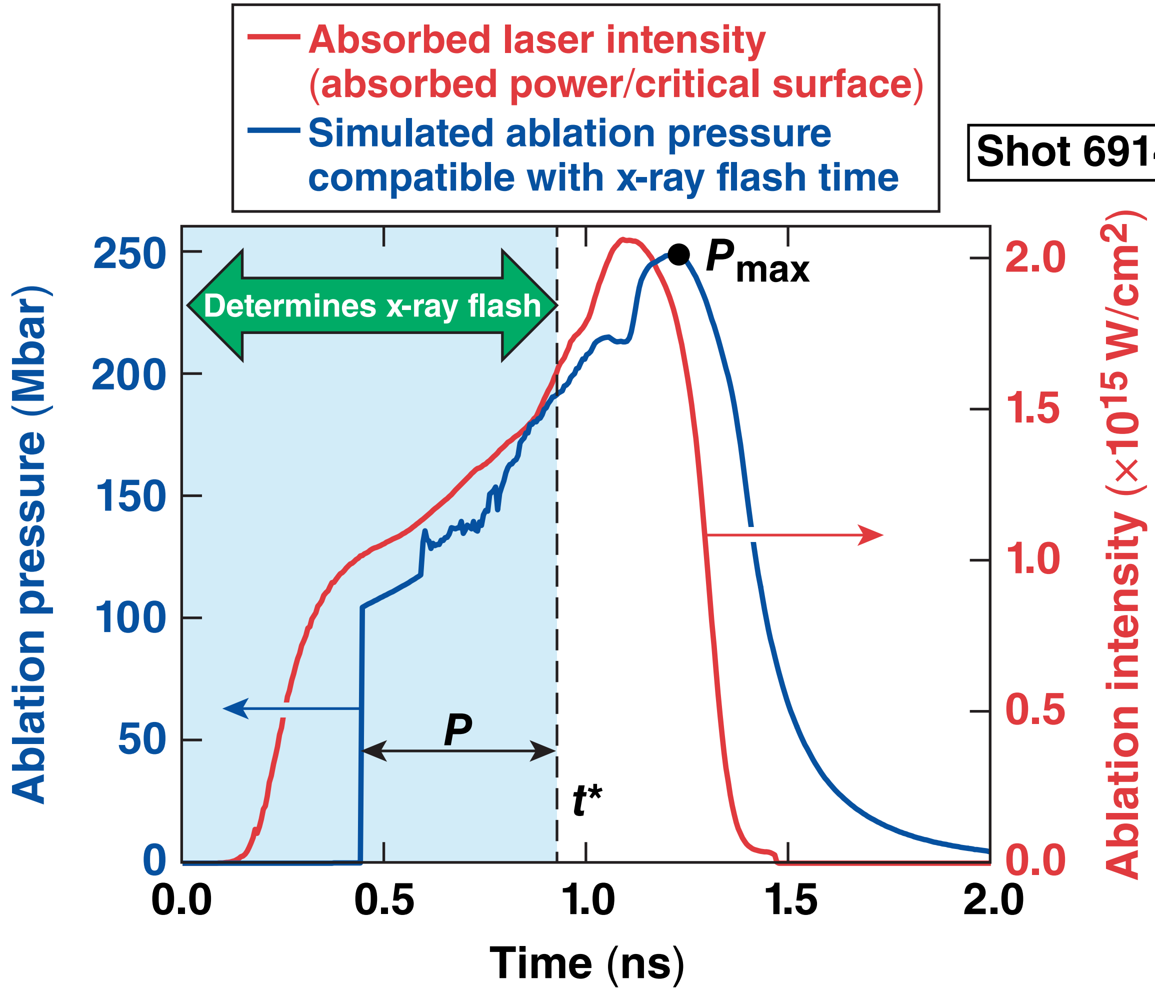


One-dimensional simulations reproduce the measured x-ray flash time when the flux limiter is adjusted to match the absorbed laser-power time history



E23184

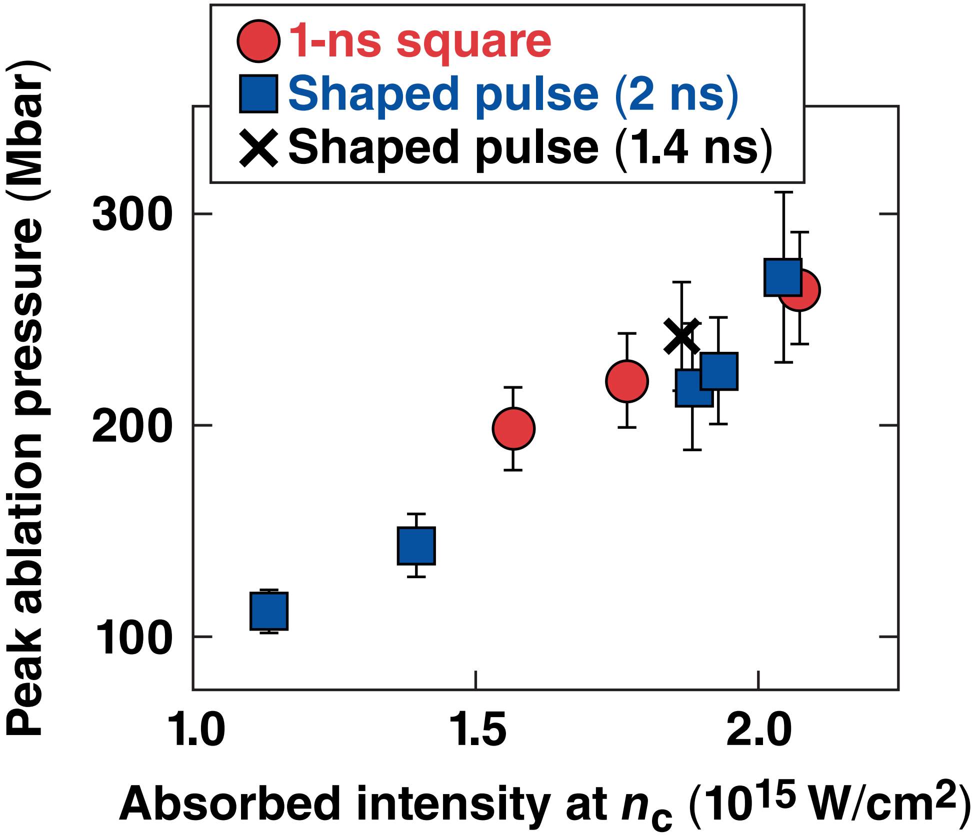
The last 400 ps of the laser pulse does not affect the x-ray flash time



Simulated $P(t < t^*)$ constrained by the measured laser absorption and x-ray flash.
Simulated P_{max} is constrained only by measured absorption.

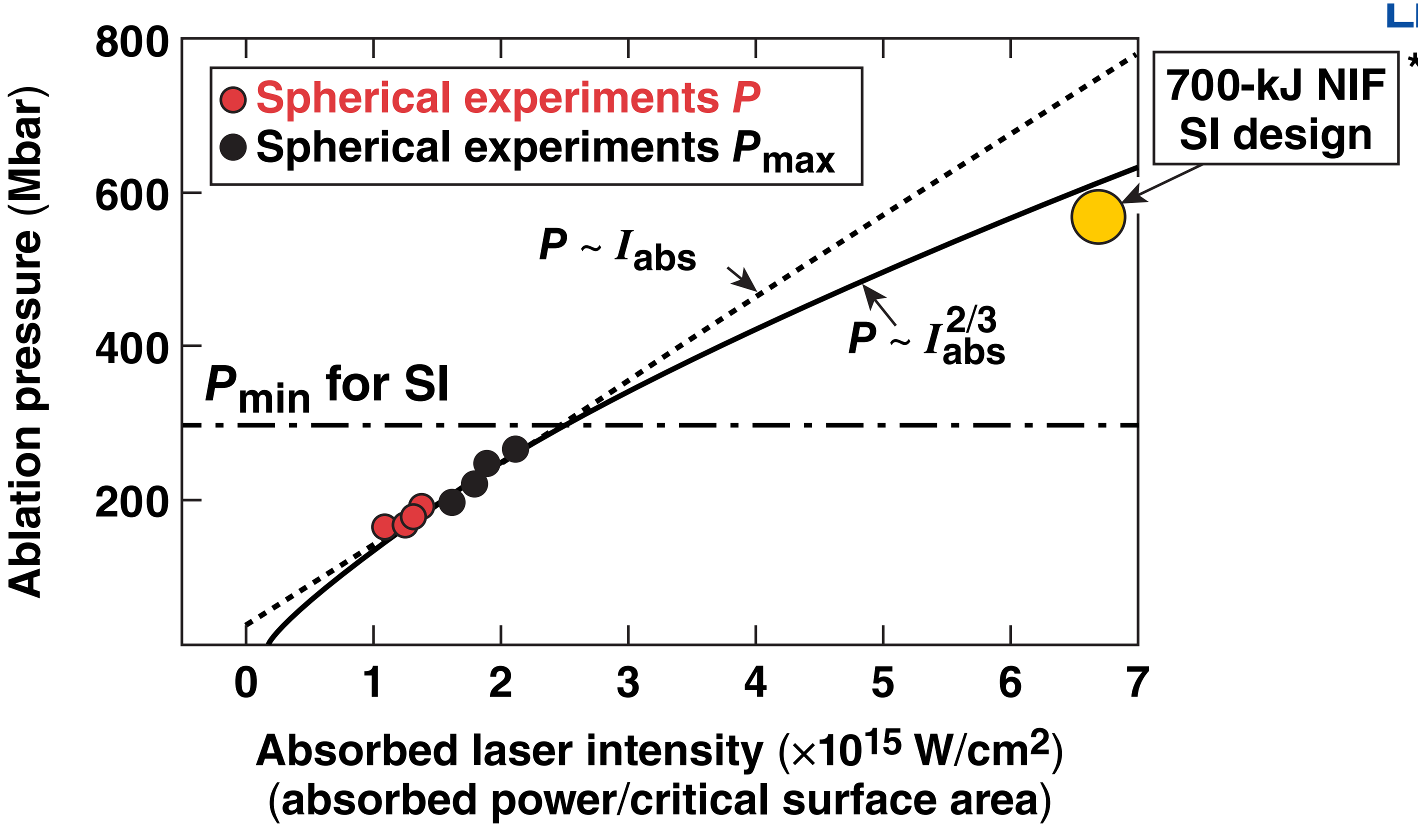
E23187

Peak ablation pressures of up to 270 Mbar were inferred from simulations constrained by the observables



E23188

A plot of the ablation pressure versus the absorbed intensity shows the extrapolation required for the SI 700-kJ NIF point design



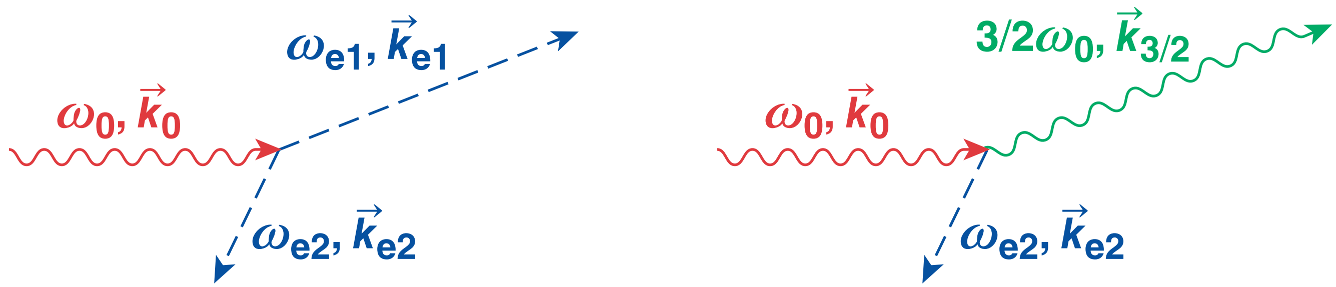
The ablation pressure in the OMEGA experiments approaches the minimum requirements for SI of 300 Mbar. Demonstration of ~600 Mbar for the SI NIF design may require experiments on the NIF.

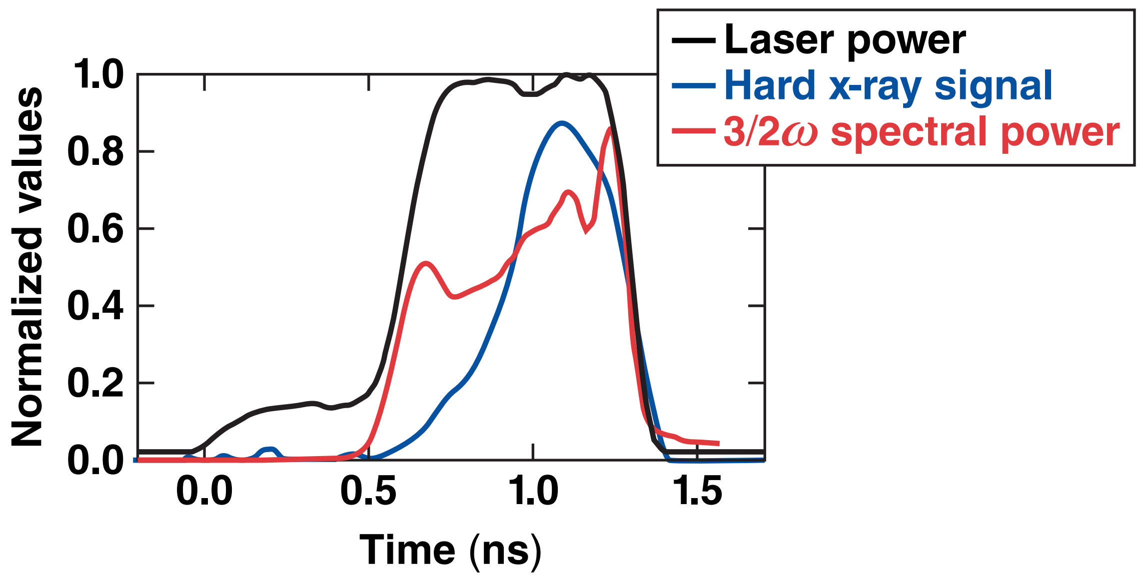
*K. S. Anderson *et al.*, Phys. Plasmas 20, 056312 (2013).

The two-plasmon–decay (TPD) instability is important for the hot electron generation in the spherical strong-shock experiments

$n_e \sim n_c/4$

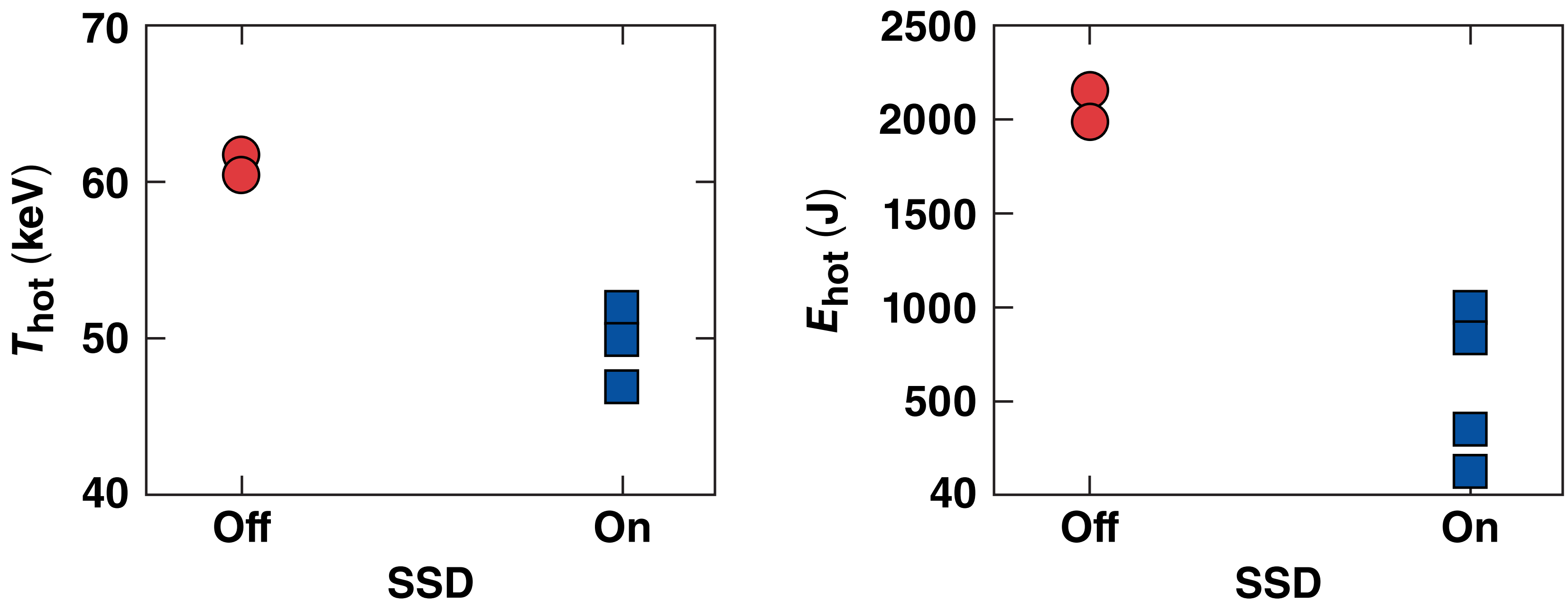
$\omega_{e1} \sim \omega_{e2} \sim \omega_0/2$





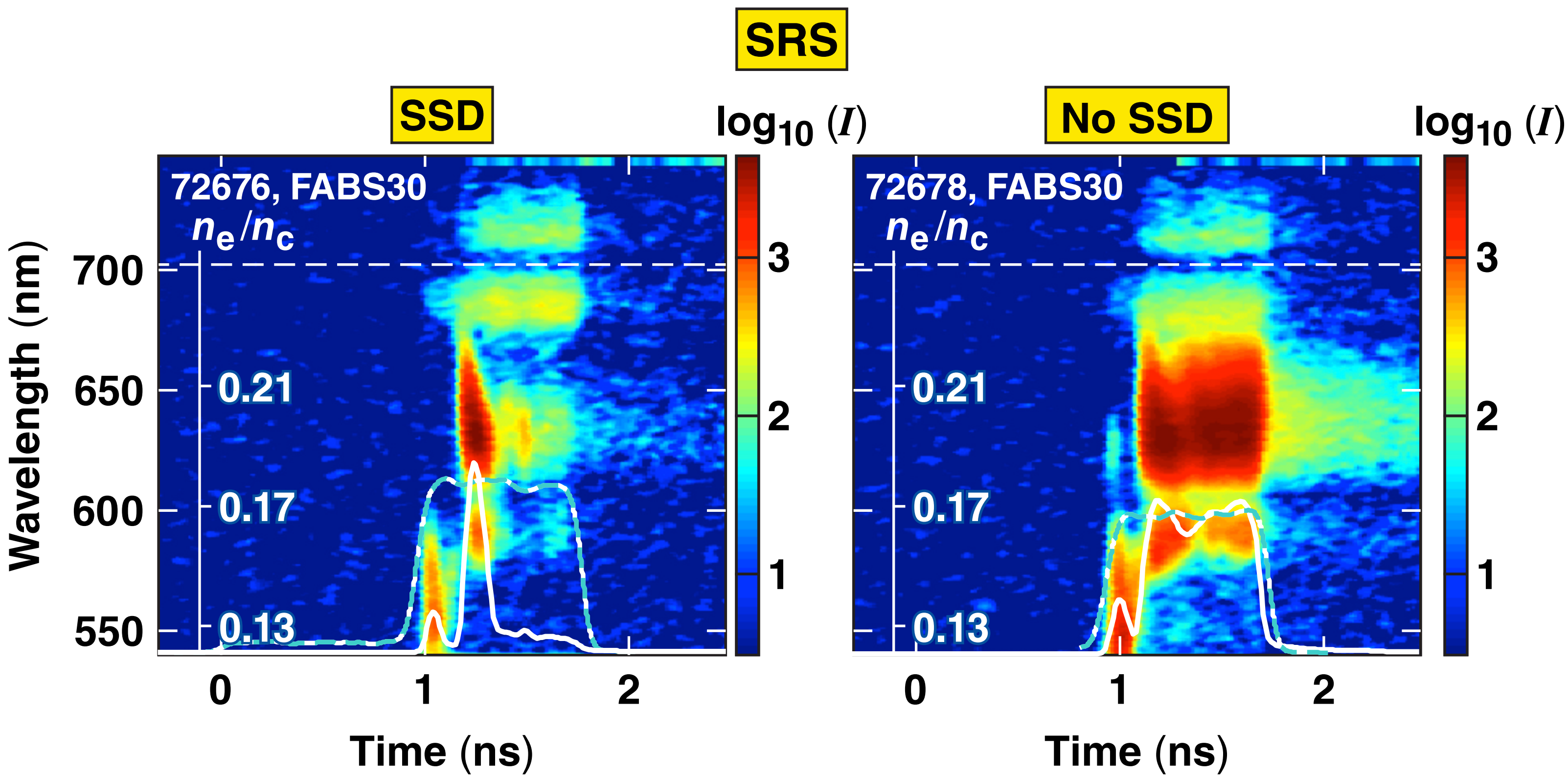
Switching the SSD bandwidth off has a significant impact on the laser–plasma interaction

~3×10^{15} W/cm^2



- Measured with nine channel imaging-plate diagnostic
- A hotter electron distribution and more hot electrons were produced when SSD was turned off
- Up to ~10% of the laser energy was converted into hot electrons

SRS increases significantly (~5× in FABS) when SSD is turned off*



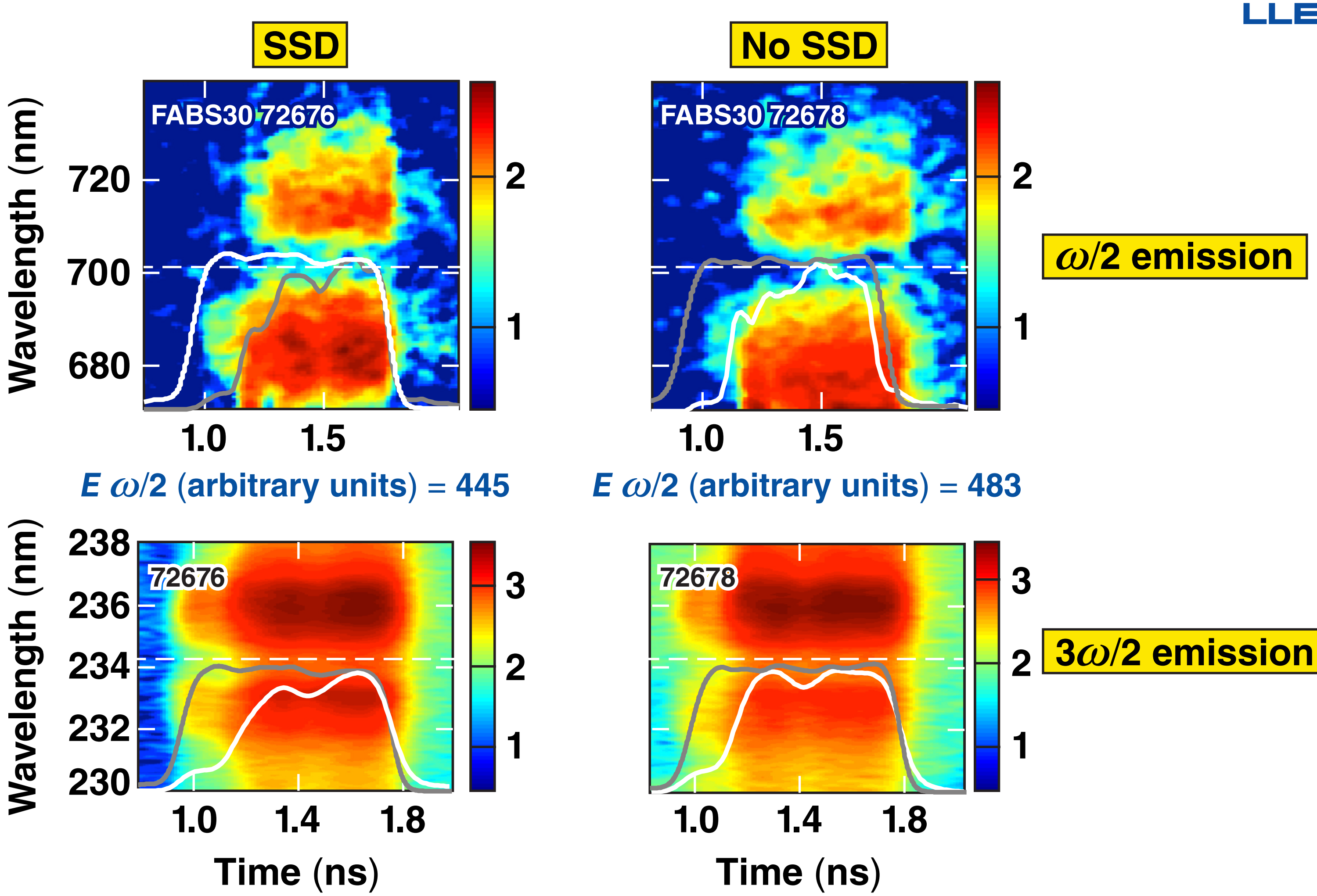
E (arbitrary units) = 291

E (arbitrary units) = 1563

*W. Seka *et al.*, this conference

E23226

TPD is largely unaffected by SSD in contrast to backscattered SRS



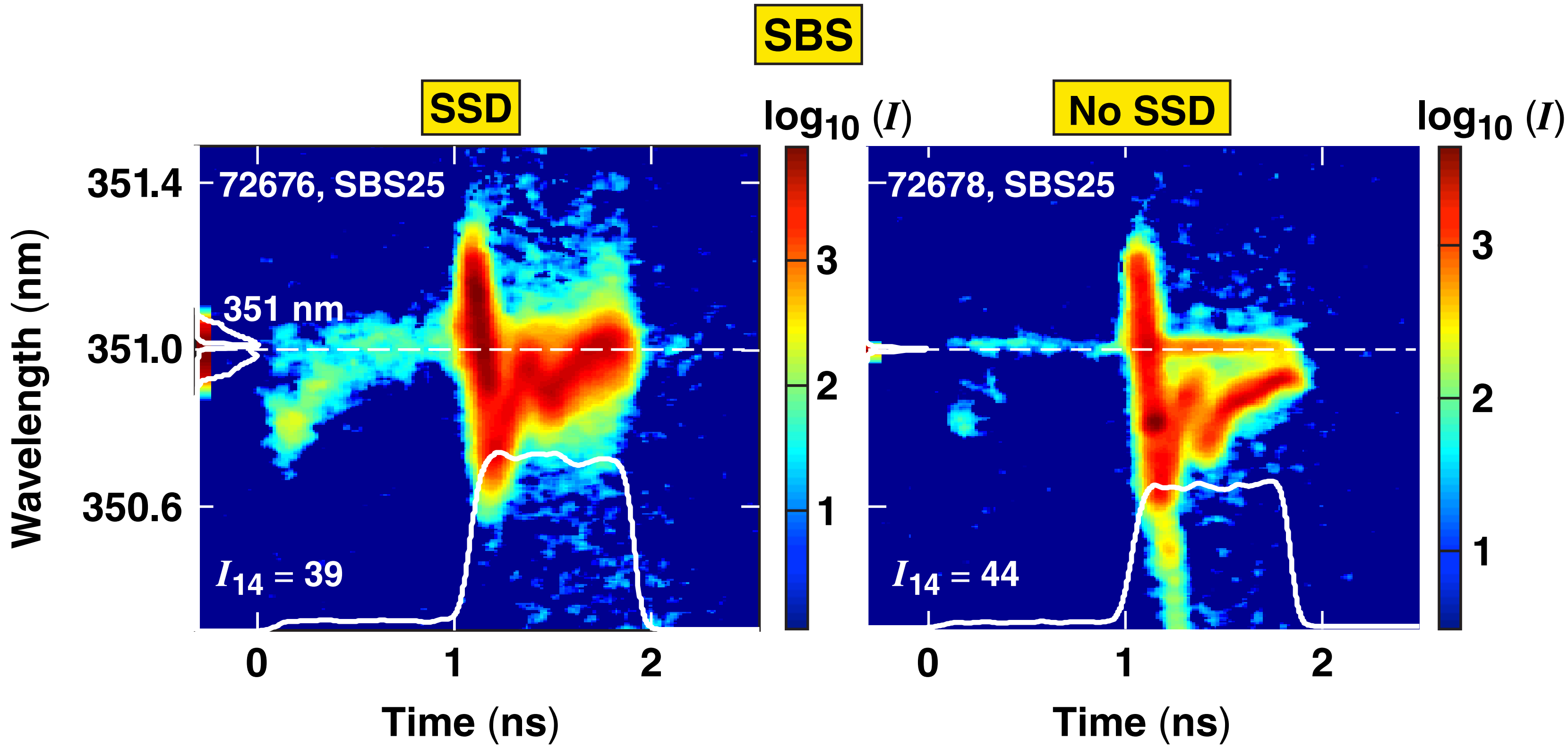
E $\omega/2$ (arbitrary units) = 445

E $\omega/2$ (arbitrary units) = 483

E_{TPD} (arbitrary units) = 420

E_{TPD} (arbitrary units) = 328

The SBS backscatter signal is insensitive to SSD

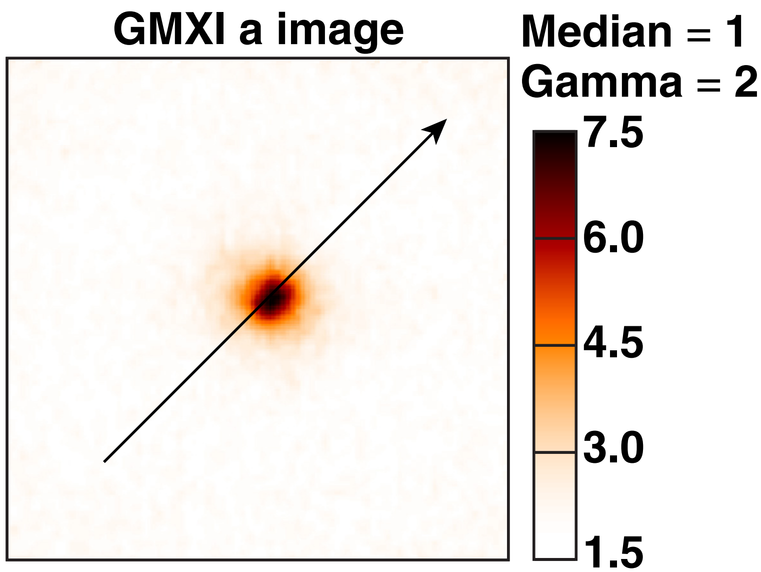


SBBS = 10% (instant)

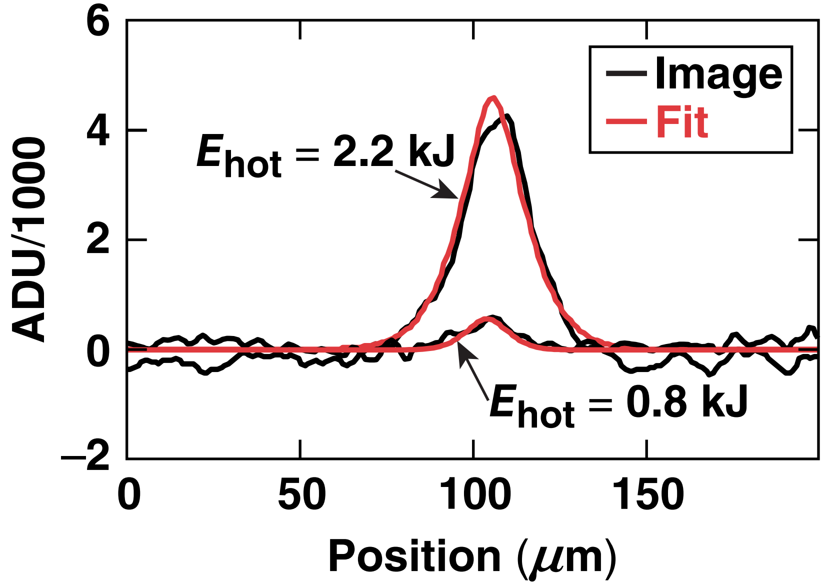
SBBS = 12% (instant)

E23228

The increase in electron production correlates with an increase in the x-ray emission from the target center



Filter: 6.5 mils Be
200 × 200-μm region



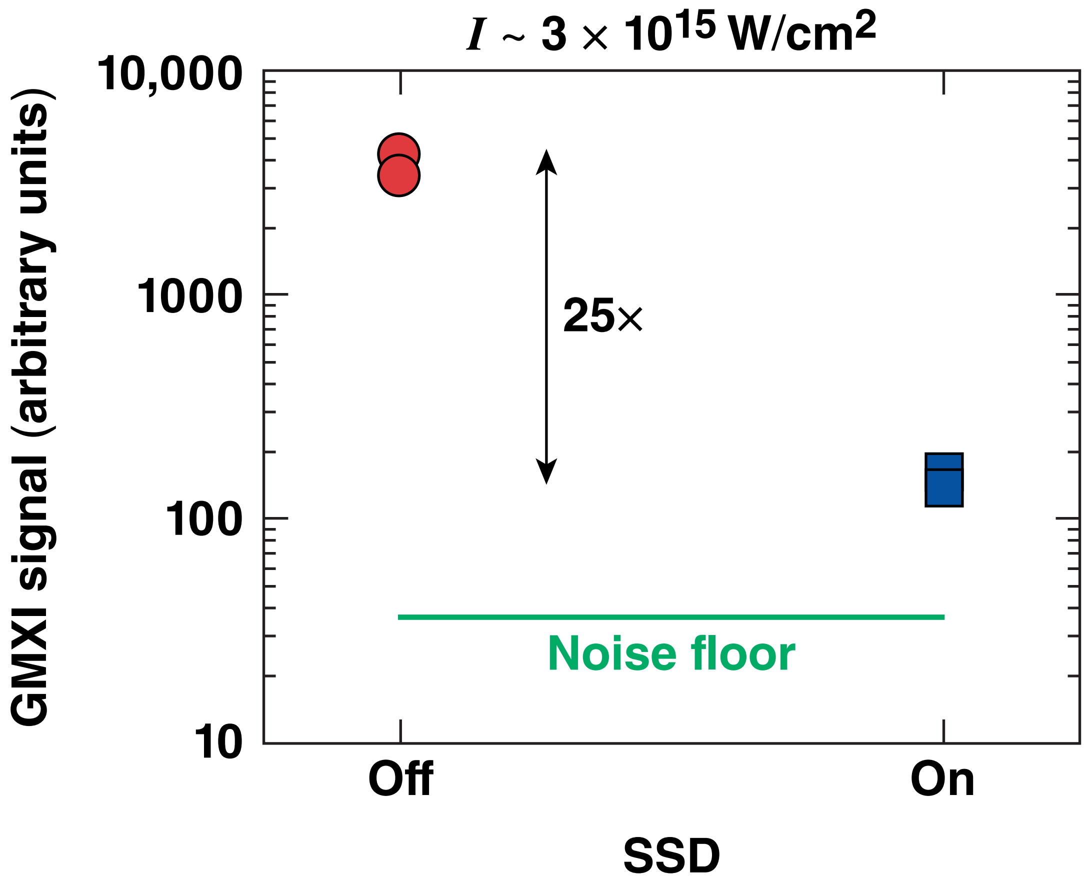
Instrument spatial resolution ~7 μm

Time integrated x-ray microscope* data from the core center

E23191

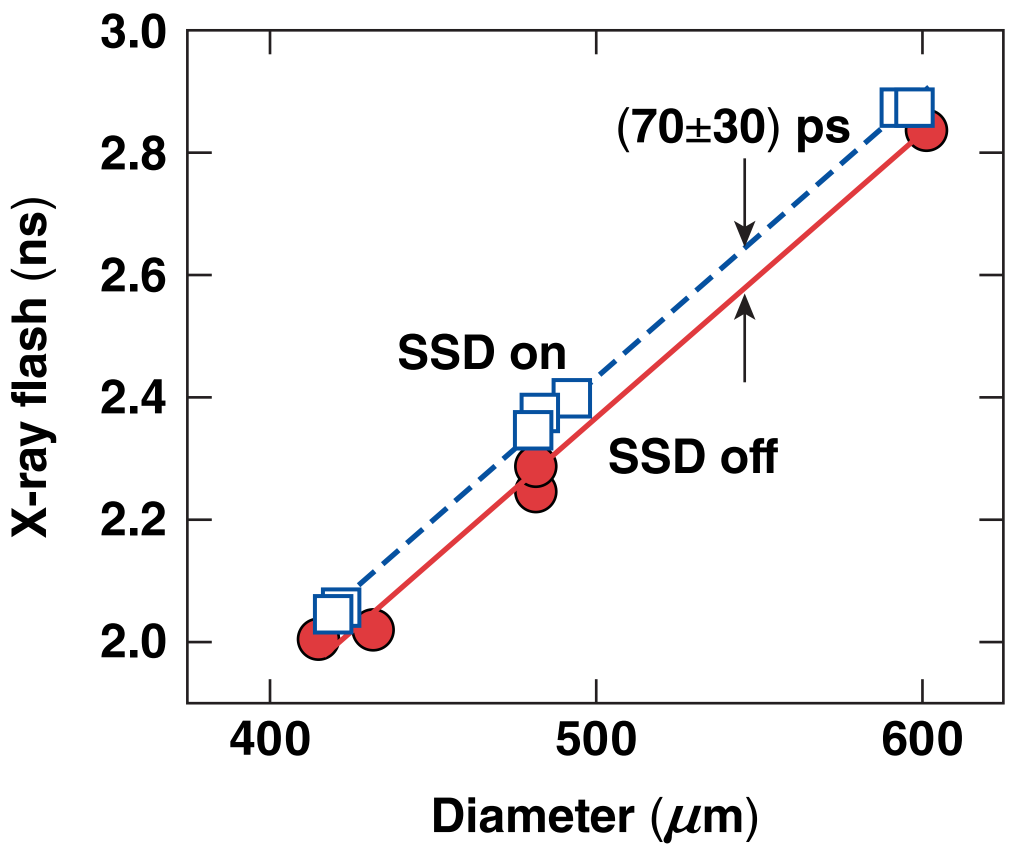
*F. J. Marshall *et al*., Phys. Plasmas 5, 1118 (1998).

The x-ray emission strongly increased when SSD was turned off



E23192

An earlier flash time was measured when SSD was turned off



Summary/Conclusions

High-intensity shock-ignition (SI) experiments on OMEGA provide valuable data on hot-electron production and shock ablation pressure

FSC

UR LLE

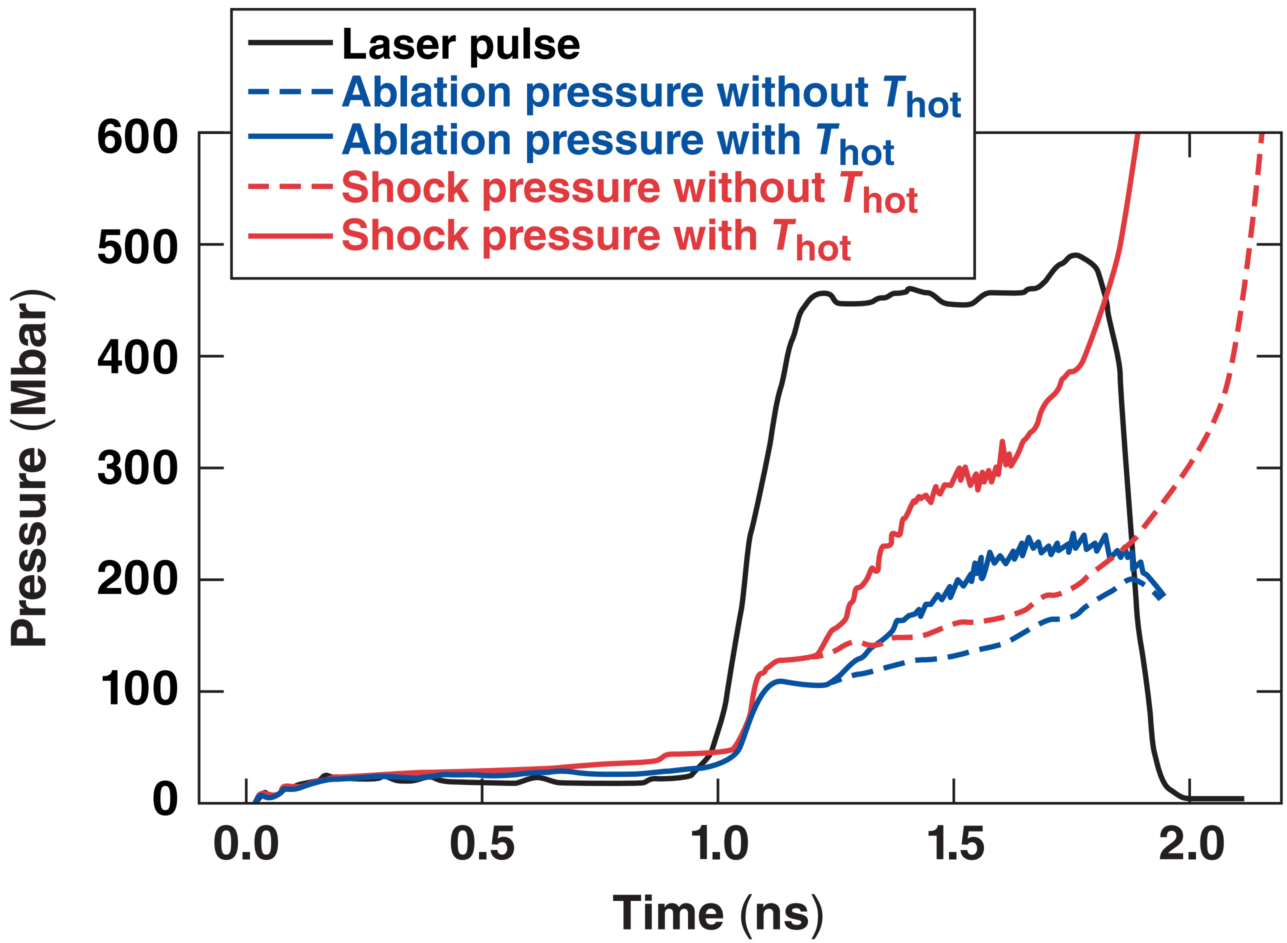
- Multiple overlapping high-intensity beams generate an energetic hot-electron distribution (<100 keV) with a conversion efficiency of up to ~10%
- Turning off smoothing by spectral dispersion (SSD) in overlapping high-intensity beam experiments increased the hot-electron fraction and shock strength
- Stimulated Raman scattering (SRS) increases significantly (~5×) when SSD is turned off, while two-plasmon–decay (TPD) is unaffected
- Moderate hot electrons may be beneficial to shock ignition by coupling energy to the outer layer of the imploding capsule

The inferred ablation pressures of 270 Mbar at ~3×10^{15} W/cm^2 approaches the minimum SI requirement of 300 Mbar.

E23174

LILAC simulations indicate that hot electrons greatly enhance the shock pressure

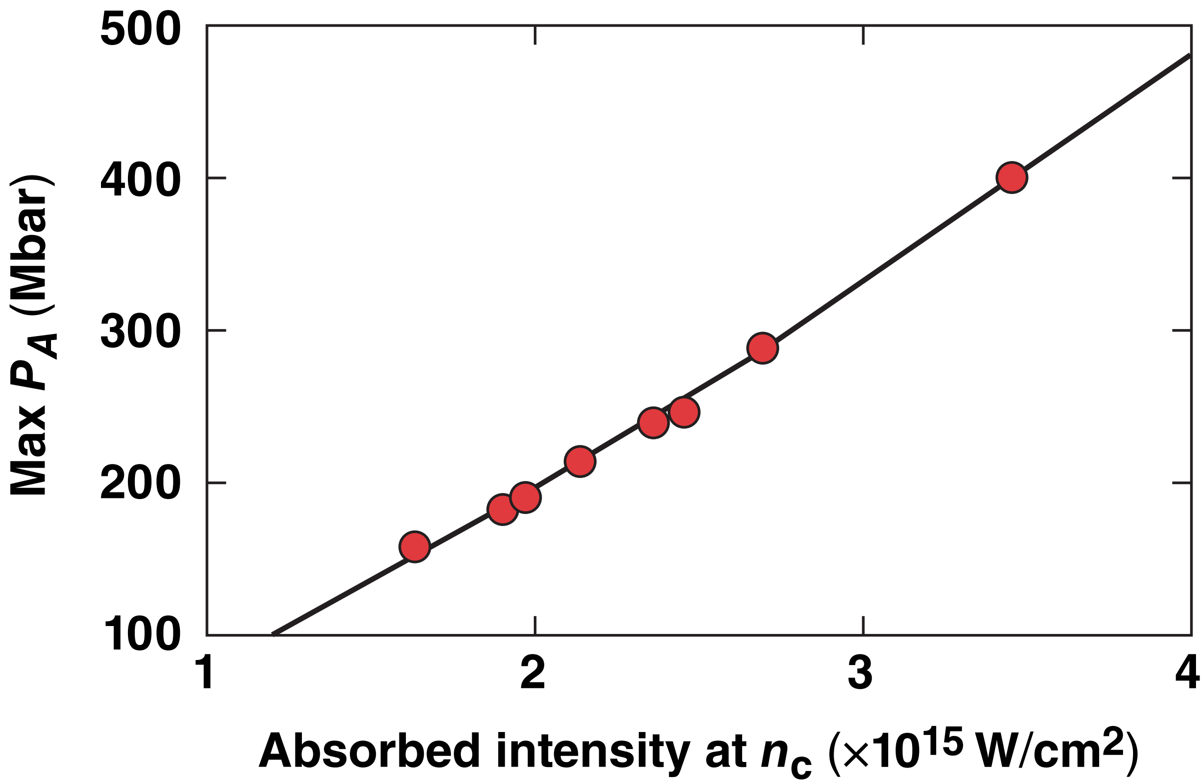
UR LLE



E23271

UNIVERSITY of ROCHESTER

The simulated maximum ablation pressure with hot-electron deposition increases more than linear with the laser intensity



$$P_A^{max} \sim (80\ \text{Mbar}) \cdot I_{abs}^{1.3}$$

E23272