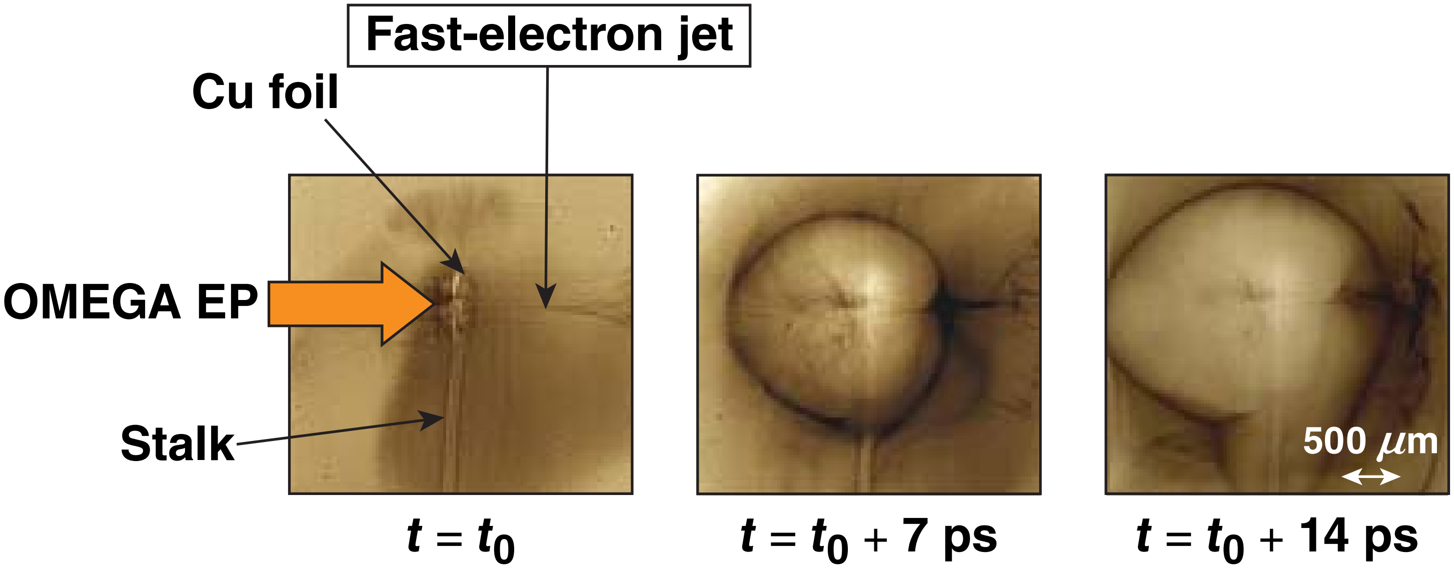
Intense-Energy Coupling with Multikilojoule, 10-ps Pulses on OMEGA EP



$t = t_0$ $t = t_0 + 7$ ps $t = t_0 + 14$ ps

Cu foil: 500 × 500 × 20 μm^3
1 kJ, 10 ps

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Omega Laser Facility
Users' Group Workshop
Rochester, NY
28–30 April 2010

Summary

OMEGA EP experiments show strong energy coupling to relativistic electrons with up to 2.1-kJ, 10-ps pulses

- The energy-conversion efficiency $\eta_{L \rightarrow e}$ into fast electrons is important for fast ignition and various HEDP applications
- Solid targets were irradiated over a wide range of laser parameters
  - laser intensity: $>10^{18}$ W/cm^2
  - laser energy: 1 J to 2.1 kJ
  - laser-pulse duration: 1 to 10 ps
- The intense-energy-coupling efficiency into fast electrons ($\eta_{L \rightarrow e}$) is ***independent*** of laser energy and laser-pulse duration

$$\boxed{(\eta_{L \rightarrow e})_{min} = 20\% \pm 10\%}$$

Collaborators

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Lawrence Livermore National Laboratory
Livermore, California

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General Atomics, San Diego

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CUOS, University of Michigan

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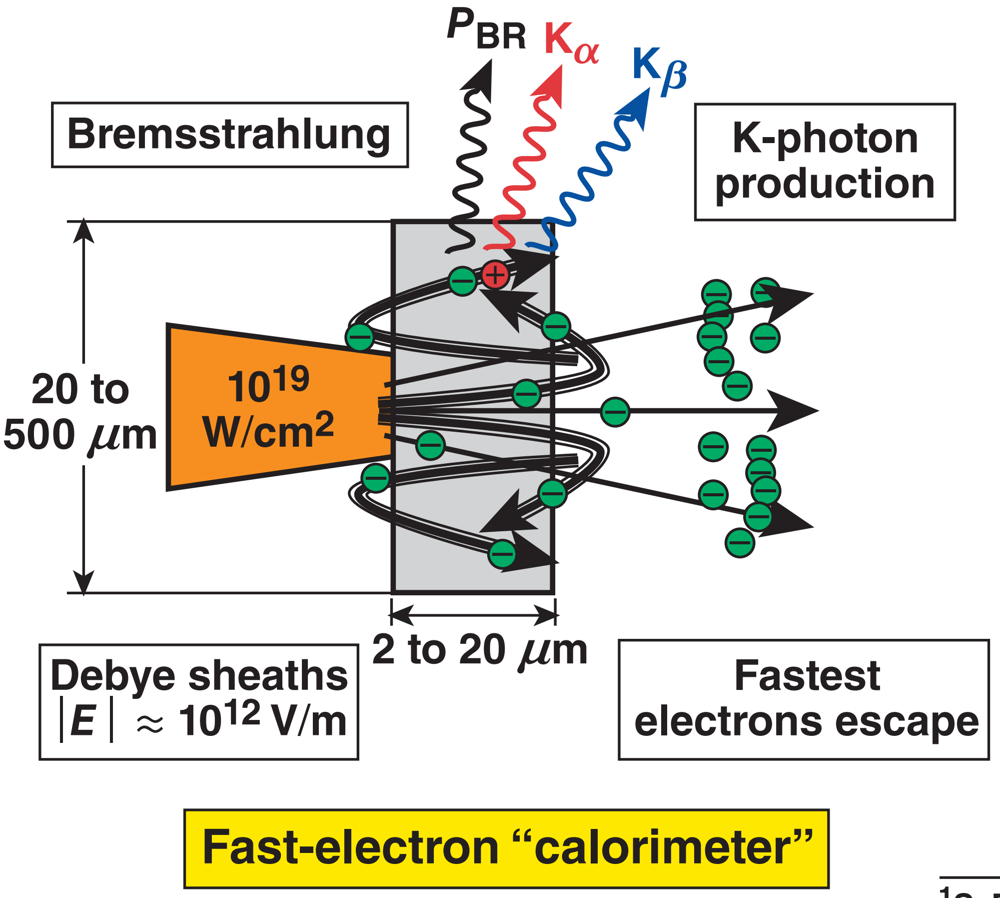
*Also Fusion Science Center for Extreme States of Matter and Fast-Ignition Physics, University of Rochester.

†Also Mechanical Engineering and Physics Department, University of Rochester.

Fast-electron refluxing in mass-limited targets accesses high-temperature matter at solid density



Fast-electron "calorimeter"

- Refluxing is caused by Debye-sheath field effects[1,2]
- Majority of fast electrons are stopped in the target
- Efficient radiators
  - K_α, K_β
  - thermal radiation
- No fluor layers

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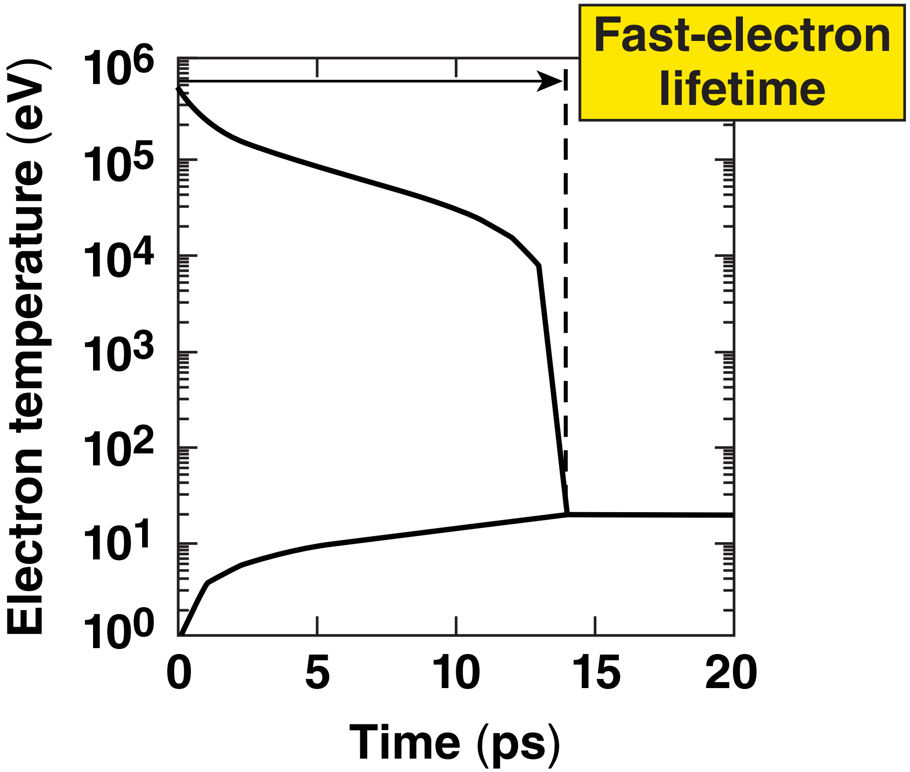
[1] S. P. Hatchett *et al.*, Phys. Plasmas 7, 2076 (2000).
[2] R. A. Snavely *et al.*, Phys. Rev. Lett. 85, 2945 (2000).
[3] W. Theobald *et al.*, Phys. Plasmas 13, 043102 (2006).
[4] J. Myatt *et al.*, Phys. Plasmas 14, 055301 (2007).

The fast-electron lifetime is governed by collisions with thermal electrons and adiabatic ion-front expansion

- 1-D energy relaxation model*
  - – electron–electron collisions
  - – adiabatic expansion cooling
- Initially cold, 20-μm-thick copper foil
- Fast-electron-energy loss causes heating to tens of electron volts



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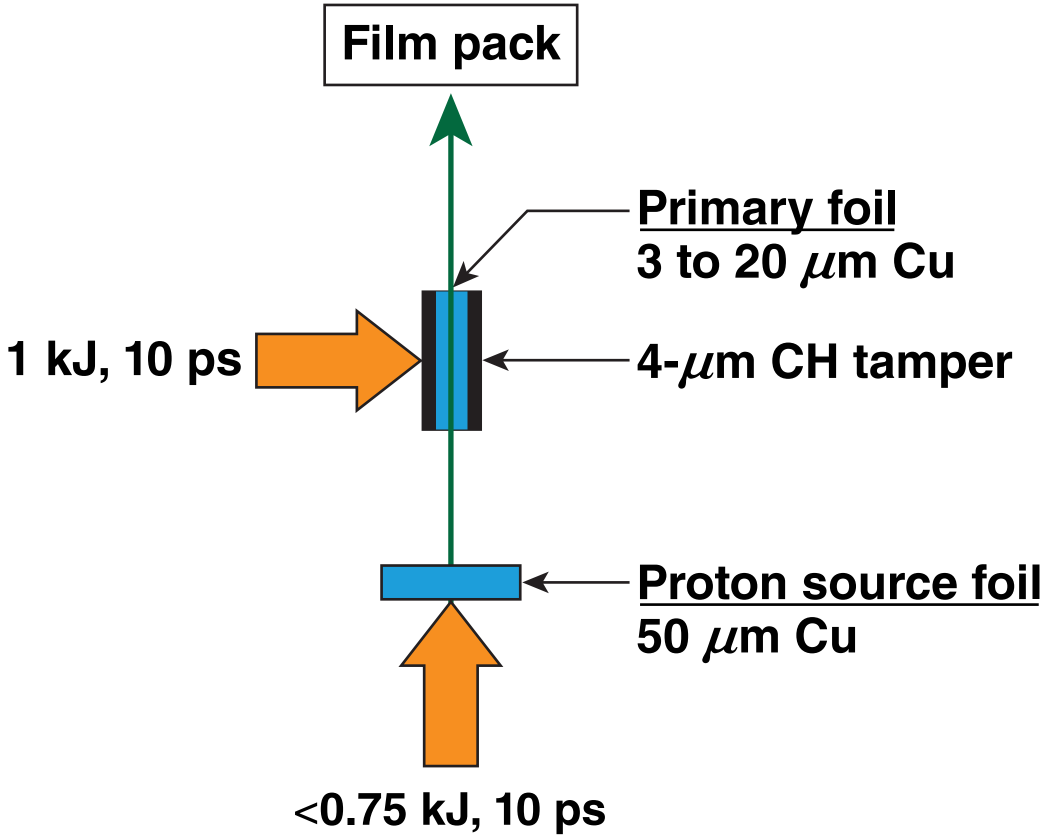
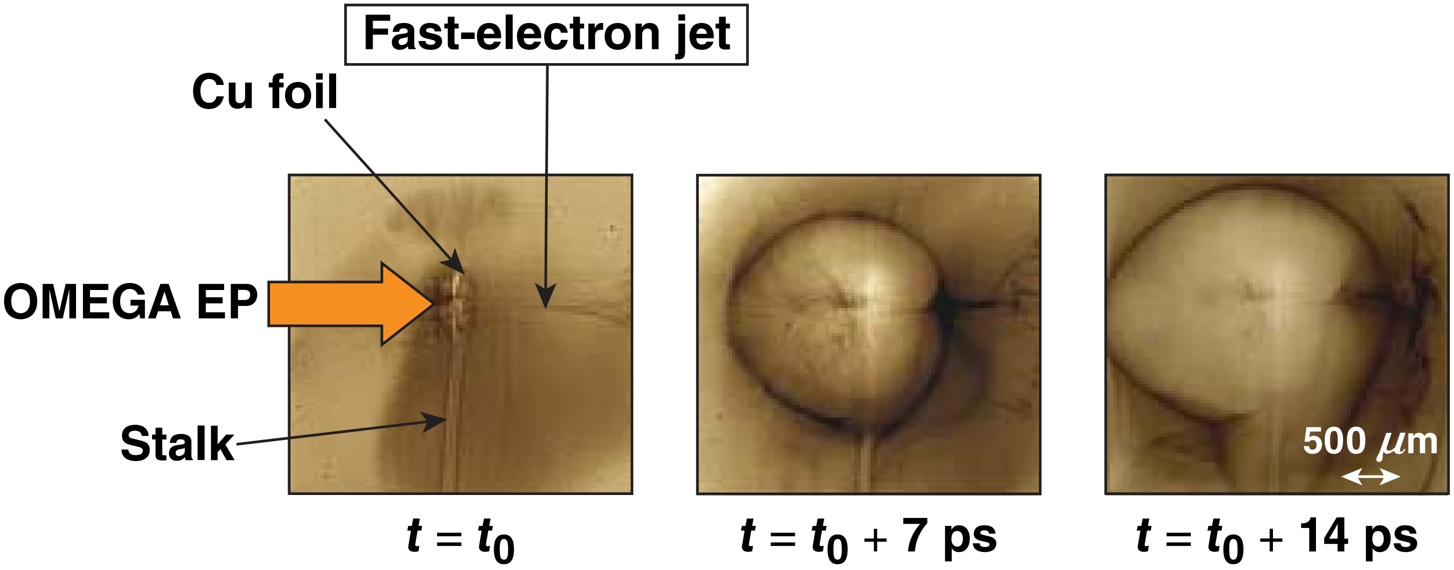
*H. Chen *et al*., Phys. Rev. E 76, 056402 (2007).

Target-charging experiments were performed using ultrafast proton radiography



Single-shot, multiframe imaging with few µm/ps resolution.

A fast-electron jet provides the primary target-charging mechanism



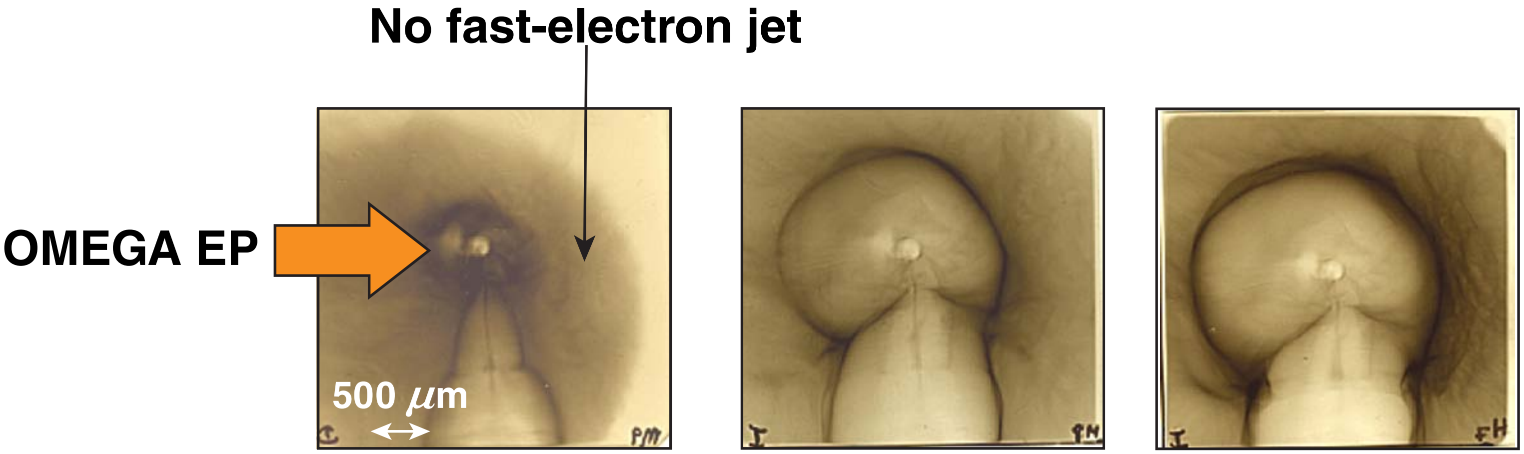
$t = t_0$ $t = t_0 + 7$ ps $t = t_0 + 14$ ps

Cu foil: 500 × 500 × 20 μm^3
1 kJ, 10 ps

Energy transfer to target is isochoric.

P. M. Nilson *et al.*, in preparation

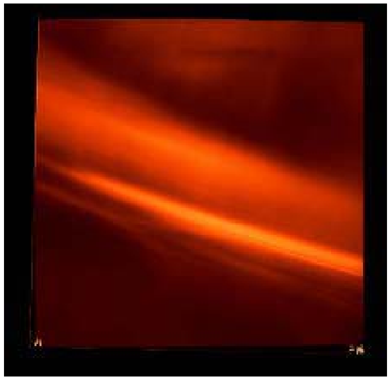
The refluxing efficiency in small-mass targets is nearly perfect



$t = t_0 + 4$ ps

$t = t_0 + 11$ ps

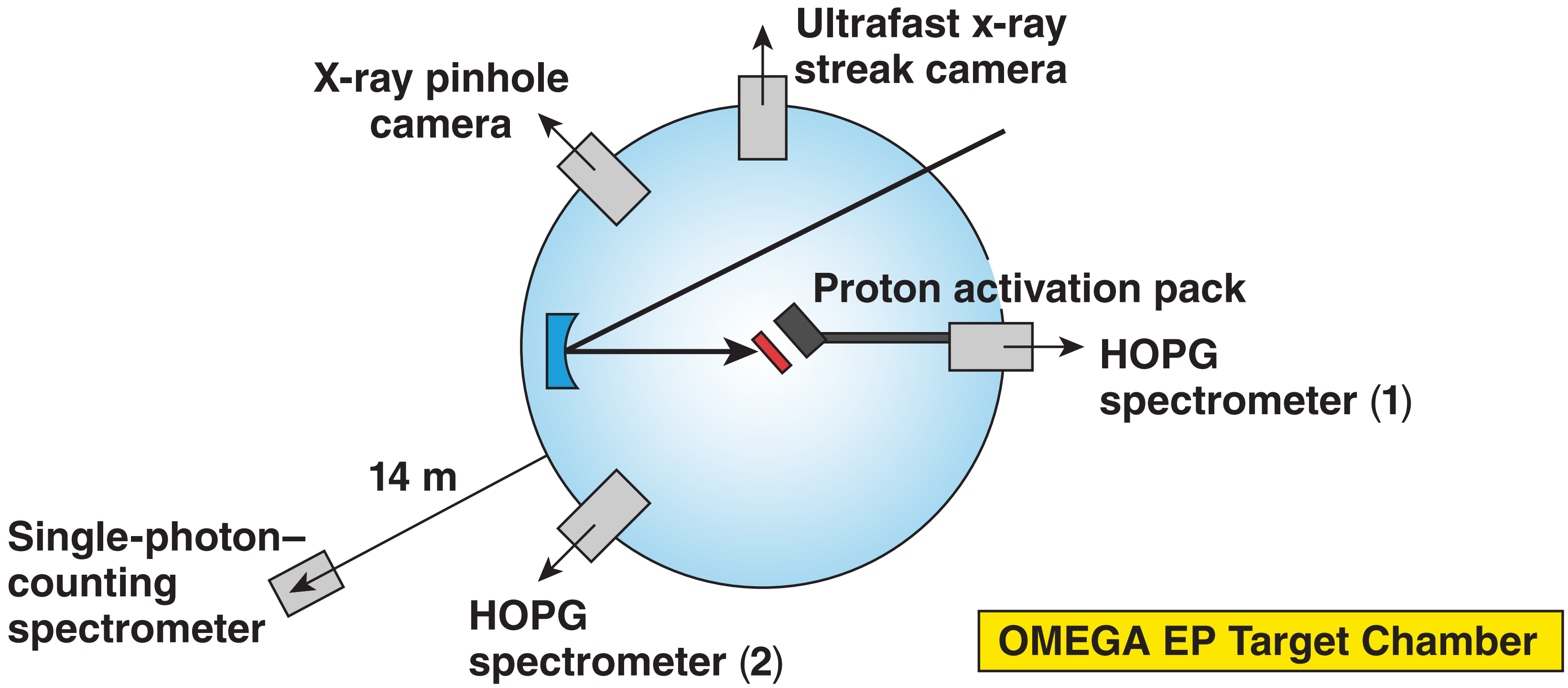
$t = t_0 + 18$ ps



Cu foil: $75 \times 75 \times 5\ \mu\text{m}^3$
1 kJ, 10 ps

The forward proton beam is destroyed because fast electrons travel around the target.

OMEGA EP experiments were performed with up to 2.1-kJ, 10-ps laser pulses

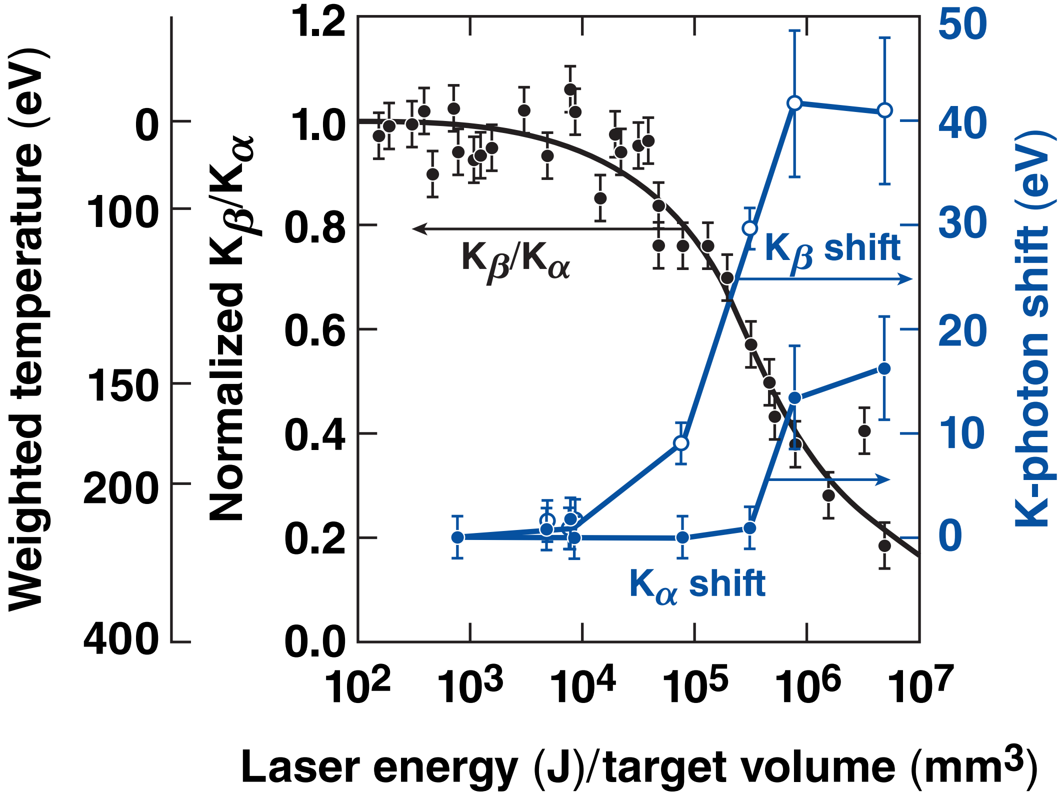


- Laser intensities $I \sim 5 \times 10^{18}$ W/cm^2
- Copper-foil targets
- Target volumes:
  500 × 500 × 50 μm^3 to 75 × 75 × 5 μm^3

Strong heating in small-mass targets is inferred by K-photon suppression and energy shifts

- **Inelastic electron–electron collisions heat the target**
- **Collisional ionization with the thermal background occurs**
- **L- and M-shell depletion at high bulk-electron temperatures causes spectral line shifts* and K_β/K_α suppression****

MTW laser: 1 J, 1 ps



Increasing energy density →

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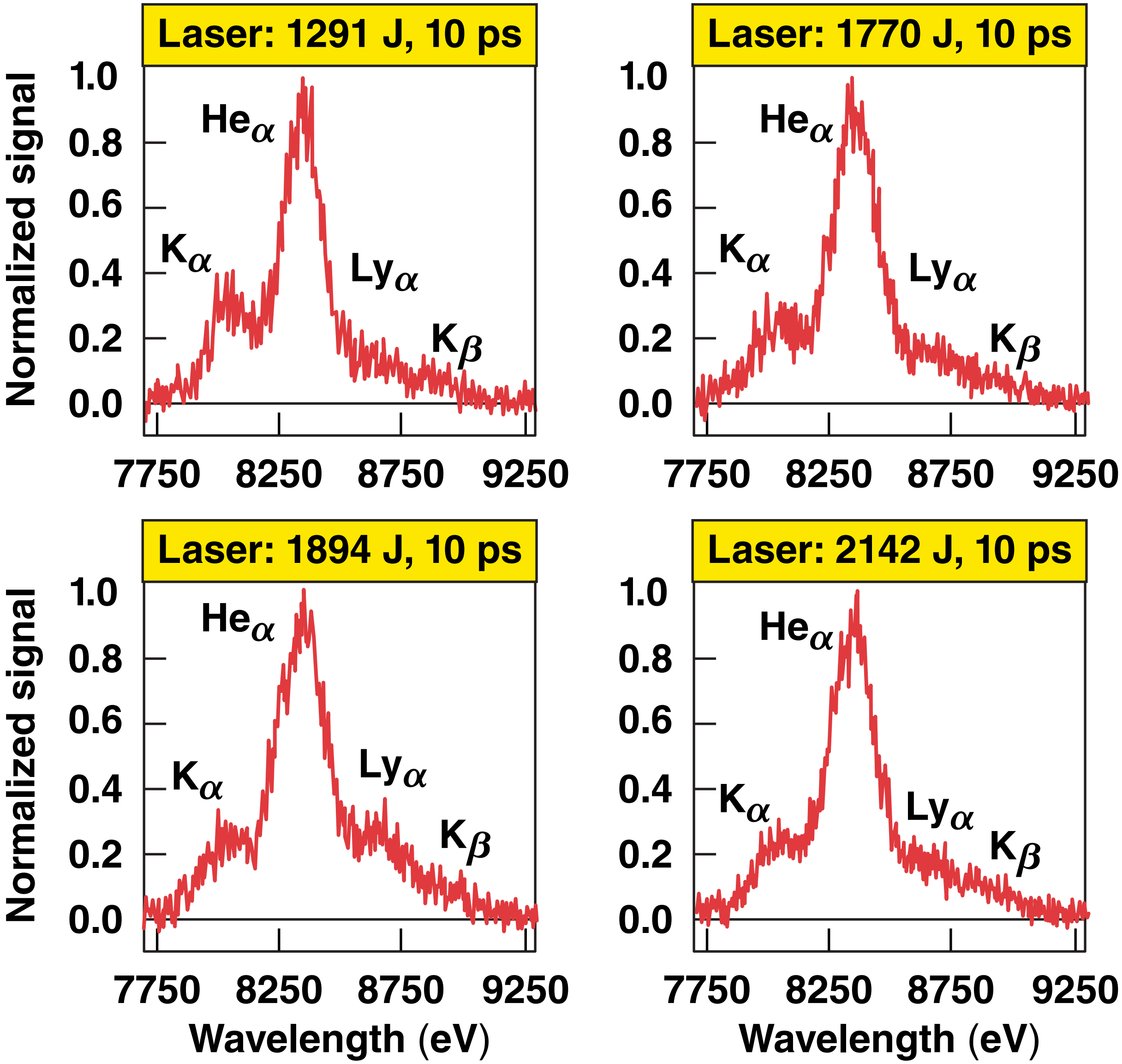
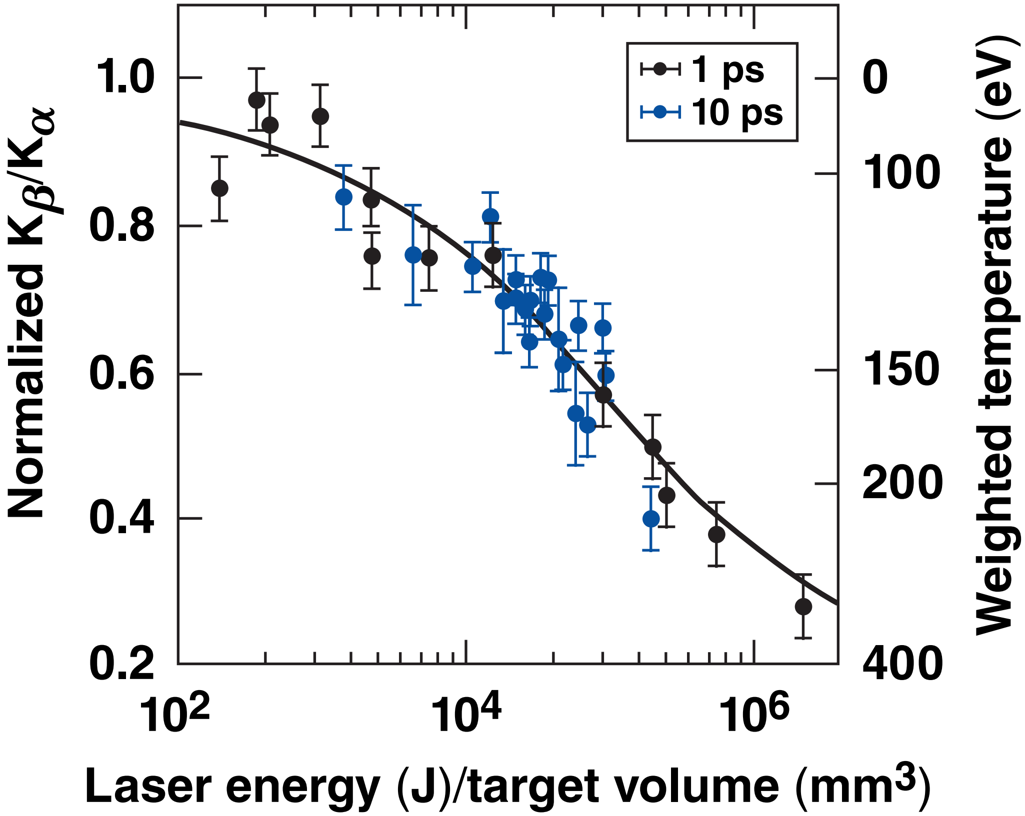
* G. Gregori *et al.*, Contrib. Plasma Phys. 45, 284 (2005).
** P. M. Nilson *et al.*, Phys. Plasmas 15, 056308 (2008).

X-ray-emission spectra were obtained with 10-ps pulses and greater than 2 kJ of laser energy



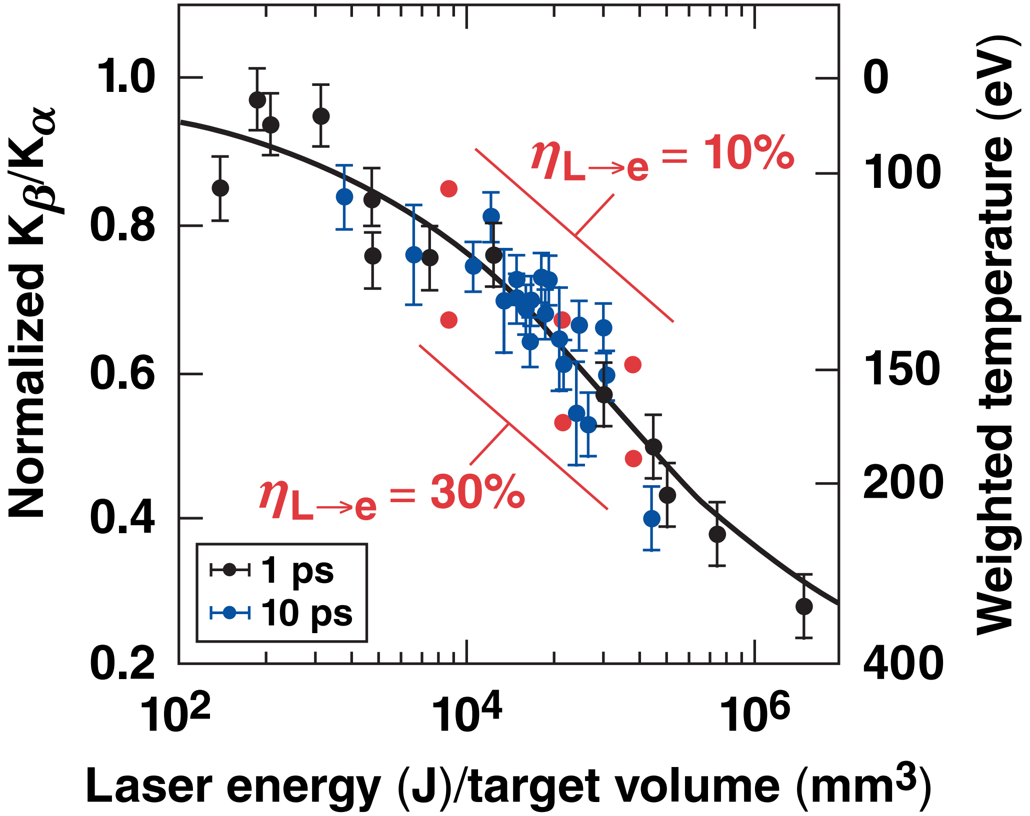
E18902

Intense energy coupling to electrons is independent of laser energy and laser-pulse duration



Laser intensity: $>10^{18}$ W/cm^2
Laser energy: 1 to 2100 J
Laser-pulse duration: 1 to 10 ps

Intense energy coupling to electrons is independent of laser energy and laser-pulse duration



Laser intensity: $>10^{18}$ W/cm^2
Laser energy: 1 to 2100 J
Laser-pulse duration: 1 to 10 ps

OMEGA EP experiments show strong energy coupling to relativistic electrons with up to 2.1-kJ, 10-ps pulses

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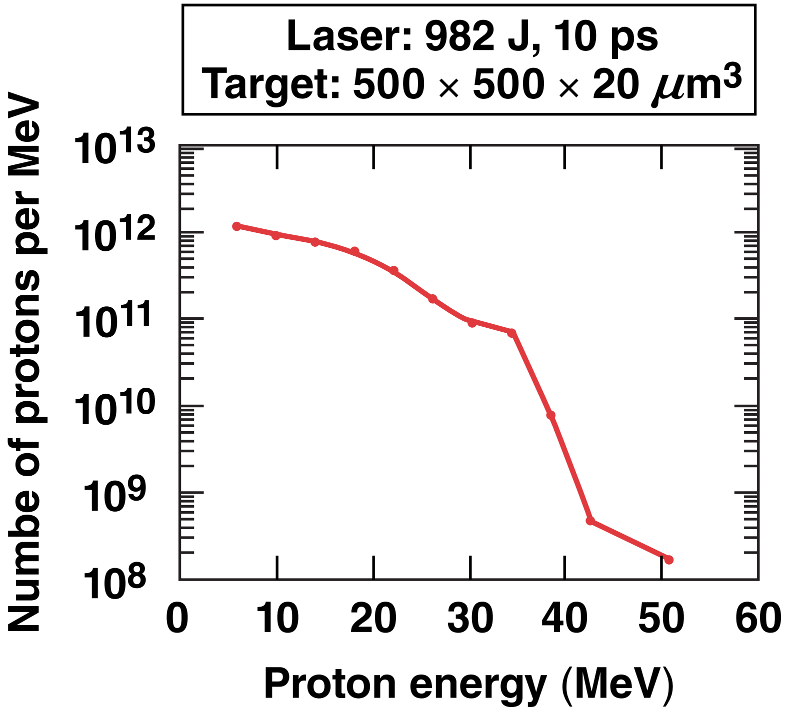
$$(\eta_{L\rightarrow e})_{min} = 20\% \pm 10\%$$

Nuclear activation of copper-film stacks determines the energy spectrum of the forward-accelerated protons

- Positron emitter
- ^{63}Cu (p,n) ^{63}Zn
- Reaction-energy threshold: 4 to 6 MeV
- Half-life: tens of minutes
- 511-keV annihilation gamma rays
- Response matrix method to recover the proton-energy spectrum

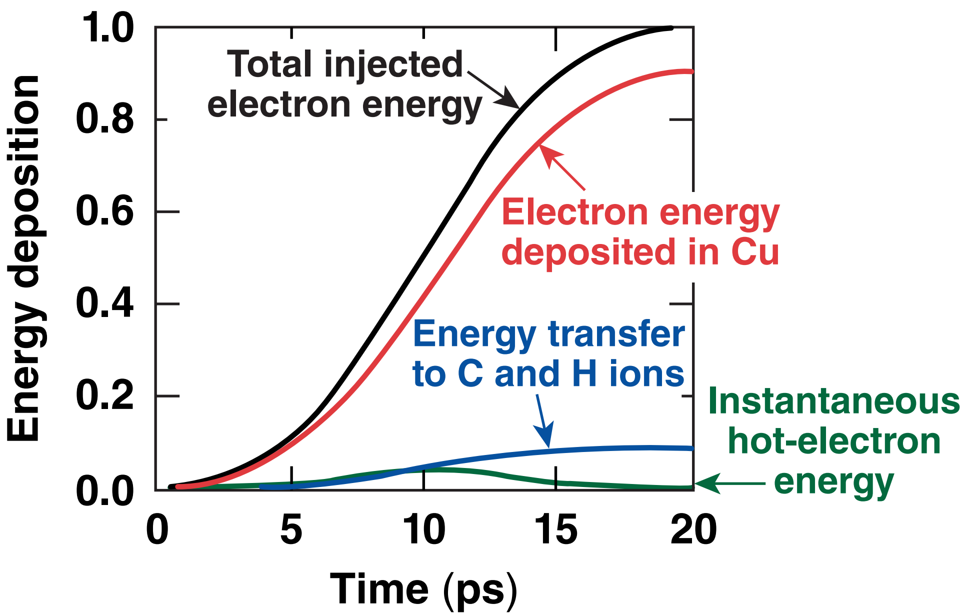


Typically <5% of the laser energy is converted into fast protons*

M. I. K. Santala *et al*., Phys. Lett. 78, 19 (2001).
*L. Gao *et al*., in preparation

1-D modeling suggests minimal electron-energy transfer to the expanding sheath field

- Peak intensity $I = 7 \times 10^{18}$ W/cm^2
  10-ps (FWHM) Gaussian
- 20-μm-thick Cu target
  0.5-μm-thick 1-g/cc CH (C^{4+} and H^{+})
- CH layers are not depleted during the simulation
- In reality, contaminant layers could be easily depleted



Intense-energy transfer efficiency to ions ~ 0.1 $\eta_{L \rightarrow e}$

Motivation

HEPW laser–solid interactions generate powerful MeV electron sources

Laser-Driven Radiography[1,2]

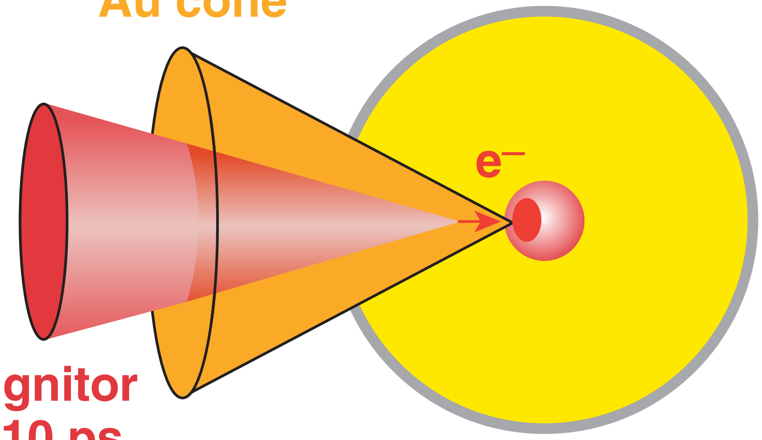
Multikilojoule, 10 ps
$>10^{18}$ W/cm^2

K_α flash
Thermal flash
γ flash

High-Z
converter

Fast Ignition[3,4]

Au cone



Single ignitor
beam: 10 ps

Efficient energy coupling to fast electrons with a 10-ps long pulse remains to be demonstrated.

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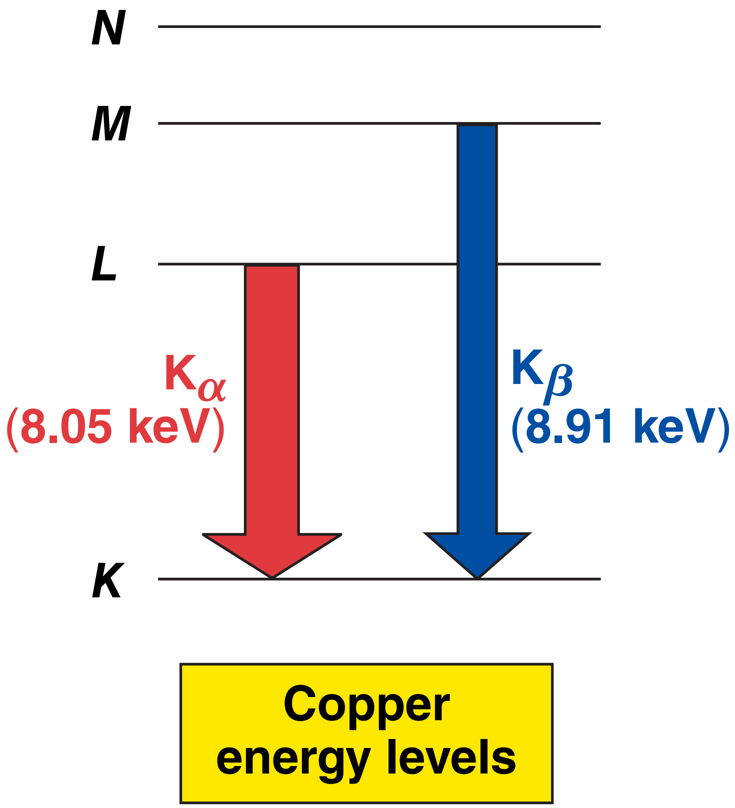
[1] M. D. Perry *et al.*, Rev. Sci. Instrum. 70, 265 (1999).
[2] R. D. Edwards *et al.*, Appl. Phys. Lett. 80, 2129 (2002).
[3] M. Tabak *et al.*, Phys. Plasmas 1, 1626 (1994).
[4] M. H. Key *et al.*, Phys. Plasmas 5, 1966 (1998).

K-fluorescence within solid targets diagnoses intense-energy coupling to fast electrons

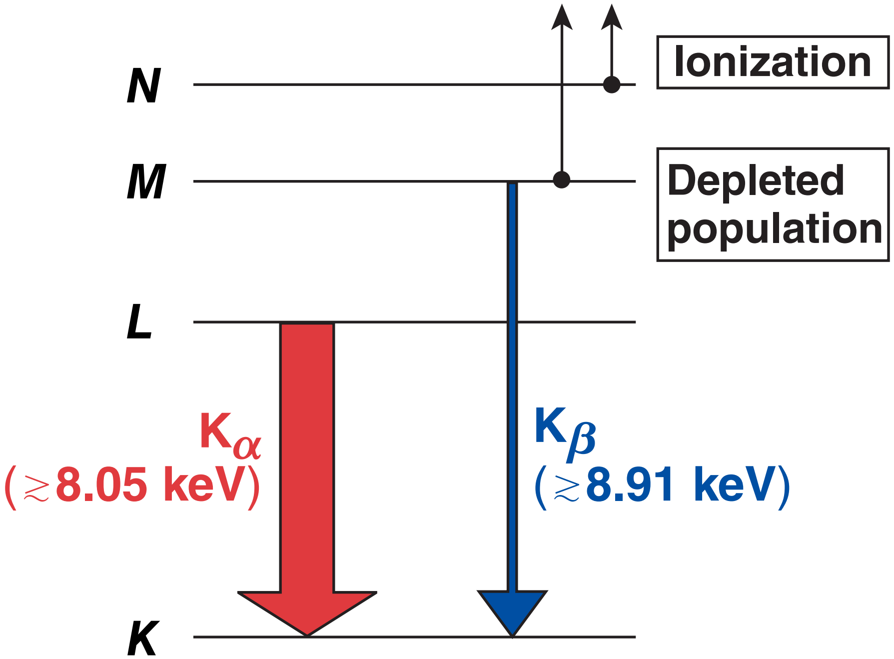
- Energetic electrons create K-shell vacancies ($E_k \approx 9$ keV)
- K-shell emission comes from the cold bulk material during the fast-electron lifetime



K. B. Wharton *et al.*, Phys. Rev. Lett. 81, 822 (1998).
R. B. Stephens *et al.*, Phys. Rev. E 69, 066414 (2004).
J. D. Hares *et al.*, Phys. Rev. Lett. 42, 1216 (1979).
W. Theobald *et al.*, Phys. Plasmas 13, 043102 (2006).

Target bulk heating affects $L \rightarrow K$ and $M \rightarrow K$ electron transitions*

- Inelastic electron–electron collisions heat the target
- Collisional ionization with thermal background plasma occurs
- $T_e > 100$ eV causes significant M-shell depletion
- Target heating is inferred from K_β/K_α



Copper energy levels

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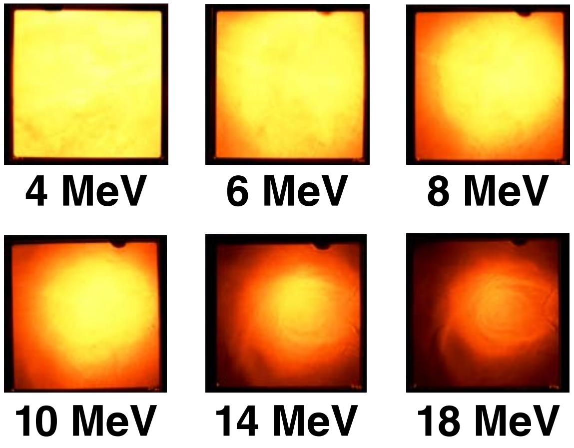
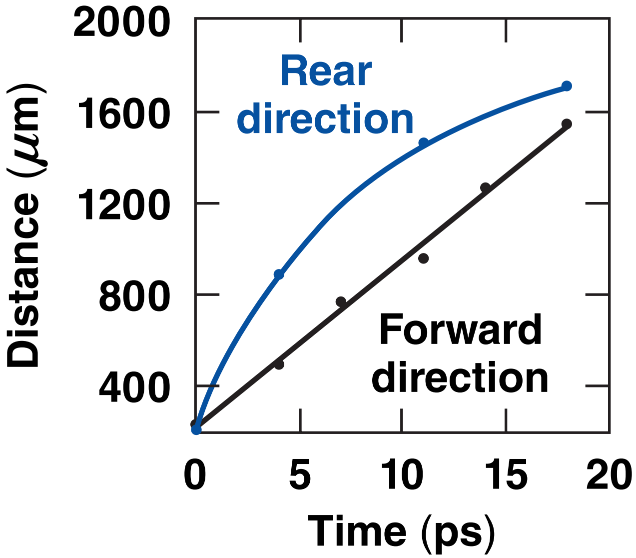
*J. Myatt *et al.*, Phys. Plasmas 14, 056301 (2007).
*G. Gregori *et al.*, Contrib. Plasma Phys. 45, 284 (2005).

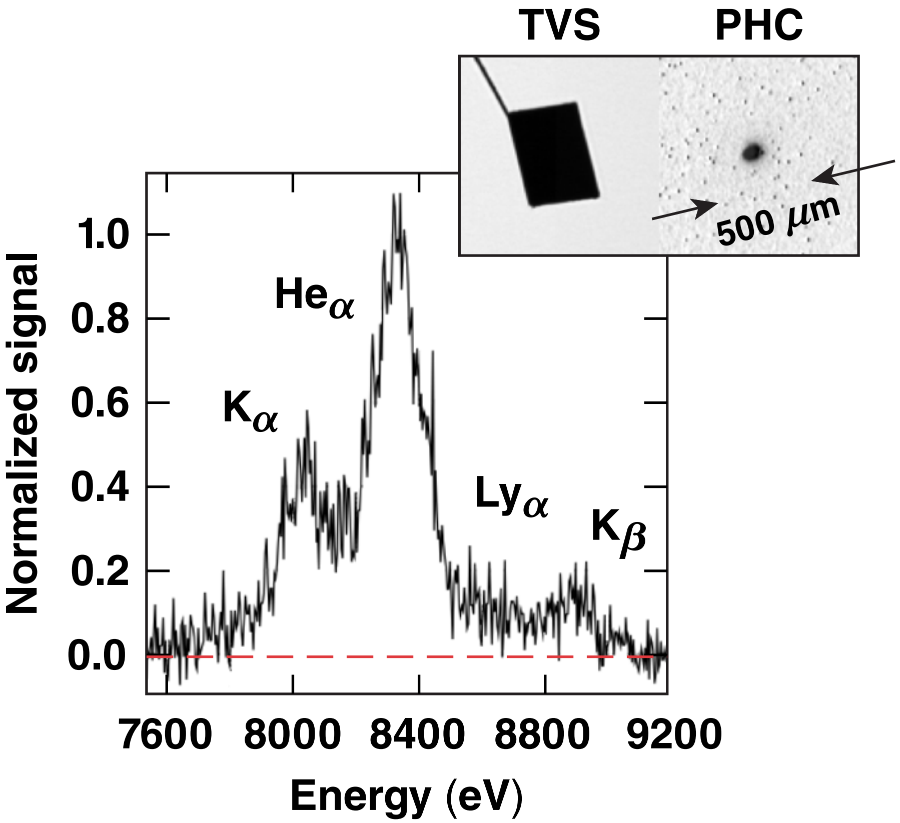
Sheath fields form at the surface of thin-foil targets in two distinct phases

- Escaping electrons
  - – rear-surface sheath field
  - – accelerates protons in forward direction
- Refluxing electrons
  - – global target-sheath field
  - – initial point-like energy deposition
  - – accelerates protons into 4π
- Asymmetric collisionless expansion
  - – forward direction: ~ 0.2 c
  - – rear direction: ~ 0.4 c

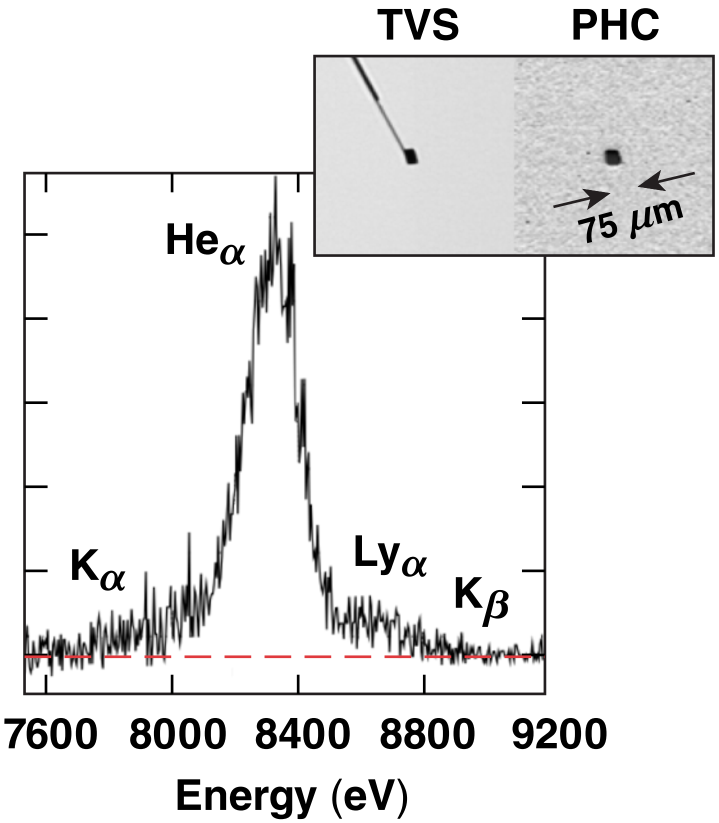




The effect of bulk-target heating on the K-shell-emission spectrum is observed with OMEGA EP

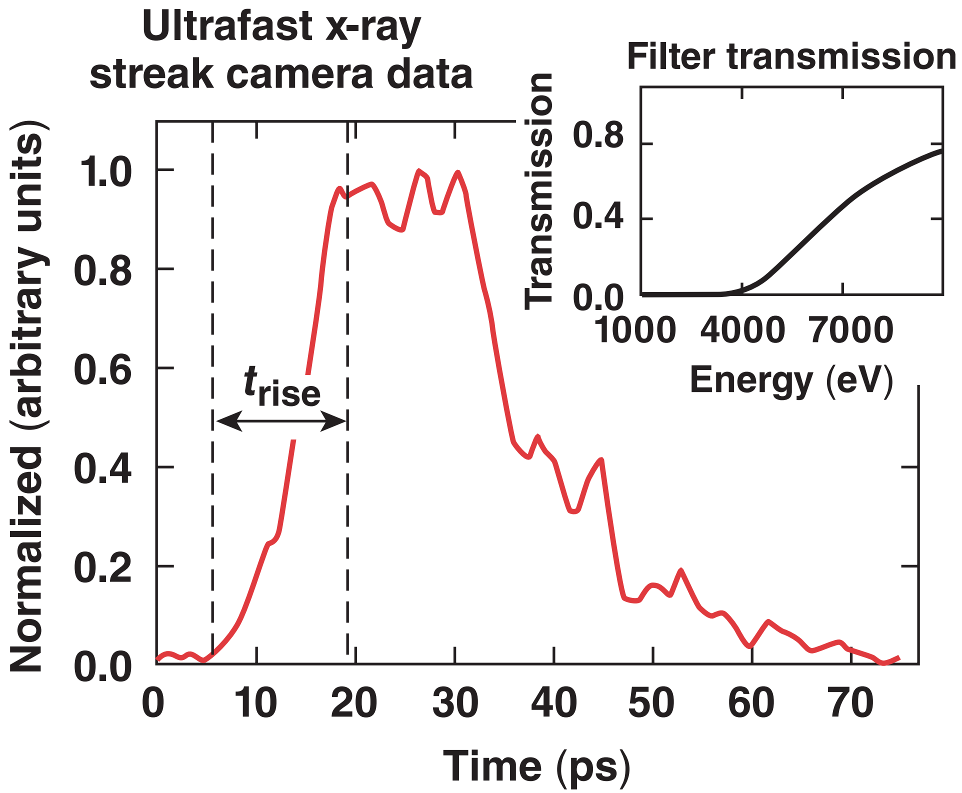


Cu target: 500 × 500 × 20 μm^3
Laser: 950 J, 10 ps



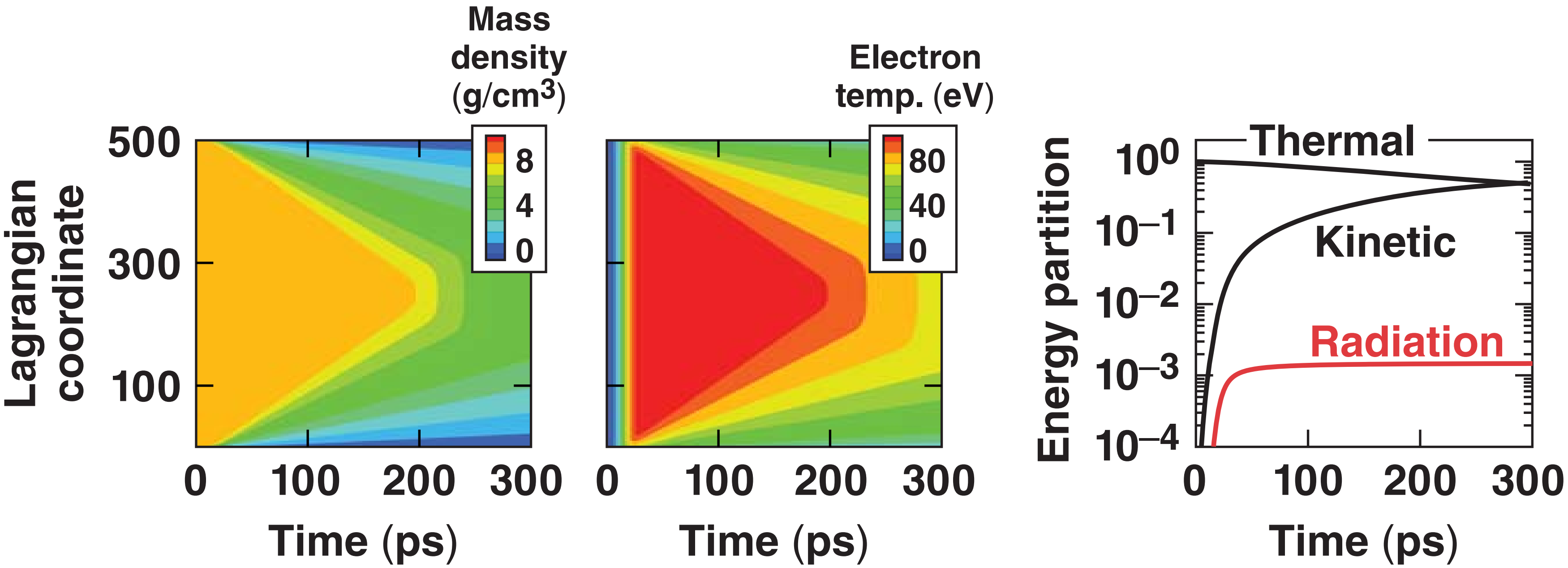
Cu target: 75 × 75 × 5 μm^3
Laser: 1042 J, 10 ps

Time-resolved x-ray-emission measurements suggest energy coupling occurs over the whole duration of the incident drive



X-ray-emission rise time correlates to the laser-pulse duration.

1-D *LILAC* calculations confirm target decompression is minimal over a 10-ps drive time

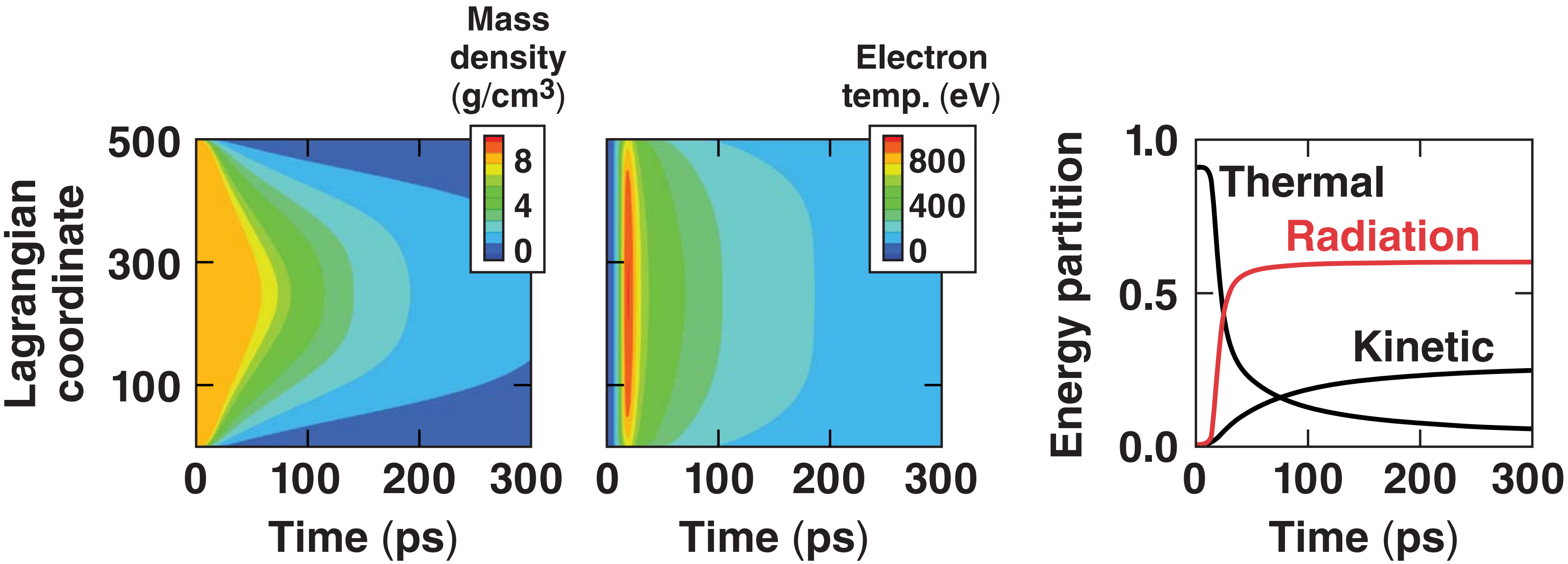


- 500 × 500 × 20-μm^3 Cu target
- 200 J of electron energy with $T_h = 1$ MeV
- 10-ps energy-deposition phase (FWHM)

Thermal decompression dominates.

E18095c

1-D *LILAC* calculations confirm target decompression is minimal over a 10-ps drive time



- $100 \times 100 \times 10$-μm^3 Cu target
- 200 J of electron energy with $T_h = 1$ MeV
- 10-ps energy-deposition phase (FWHM)

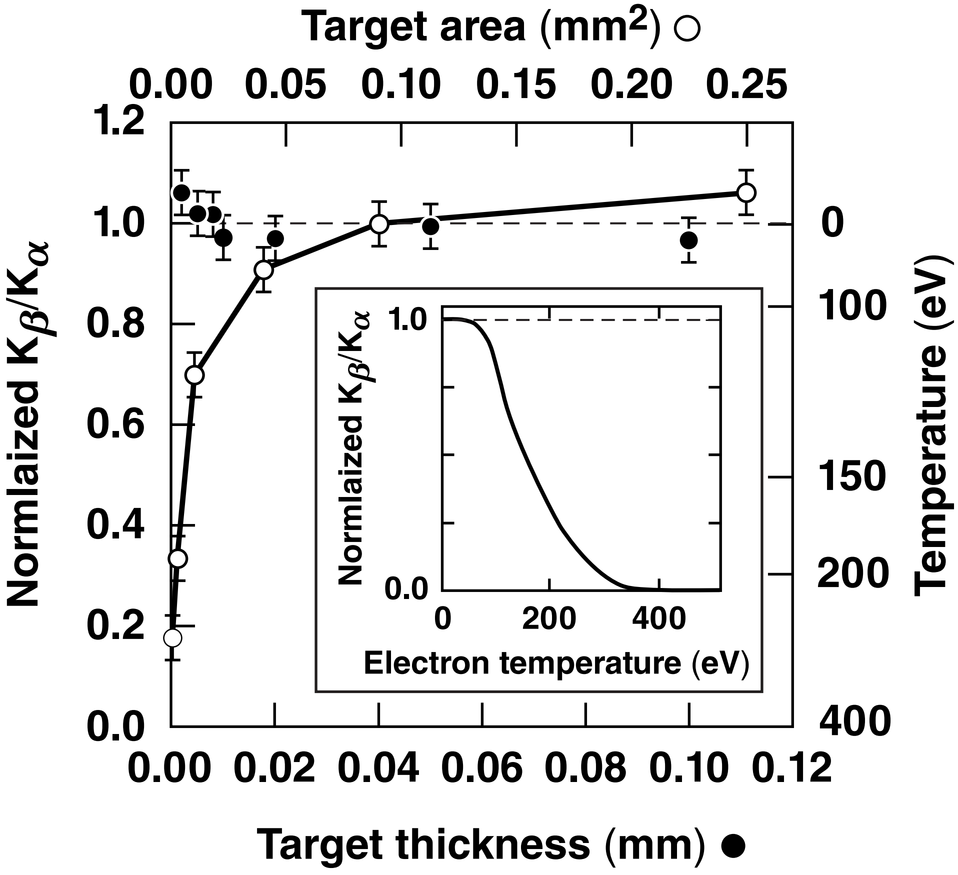
Radiation cooling quenches the HED state in mass-limited targets prior to decompression.

The highest temperature plasmas are generated by reducing target area and thickness

Target parameters study

- Vary thickness: 2 to 50 μm
- Fix area: 500 × 500 μm^2

- Vary area: 20 × 20 to 500 × 500 μm^2
- Fix thickness: 2 μm

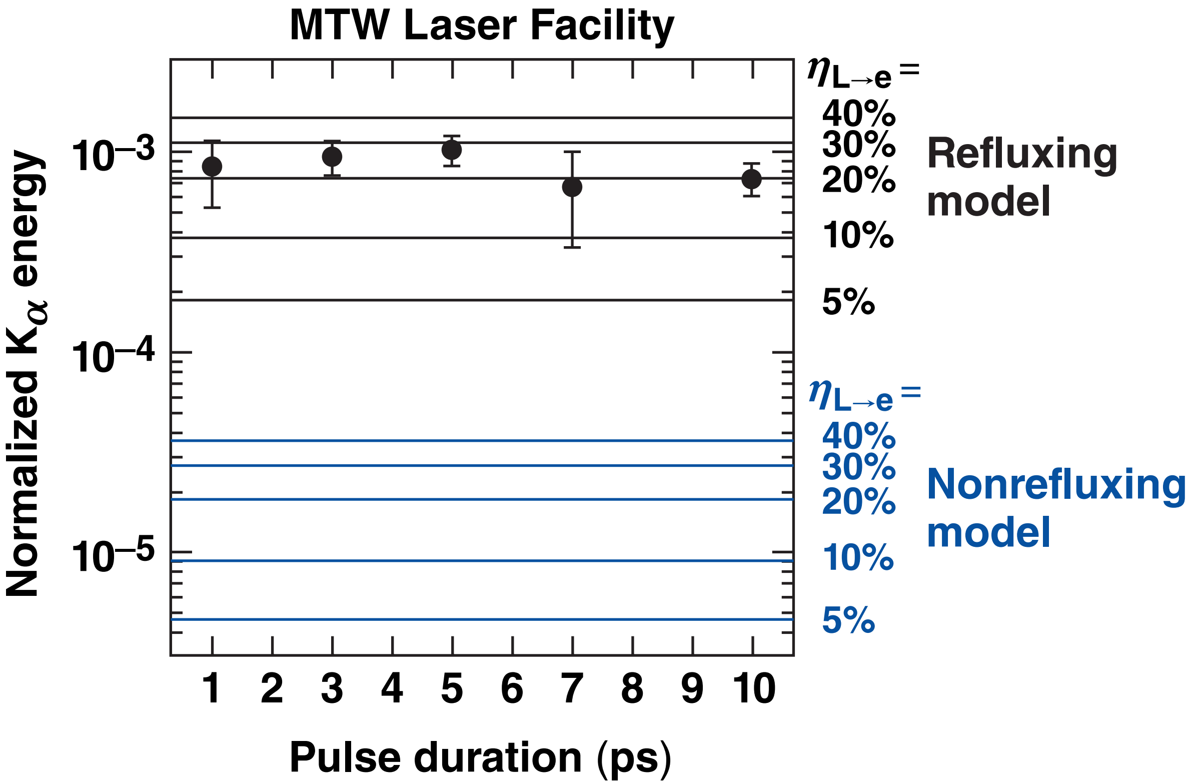


Refluxing and energy deposition in small-mass targets is a volumetric effect.

E18904

P. M. Nilson *et al.*, Phys. Rev. E 79, 016406 (2009).

For 1-ps pulses, K_α yields are consistent with an electron-refluxing model assuming $\eta_{L\rightarrow e}$ = 20%

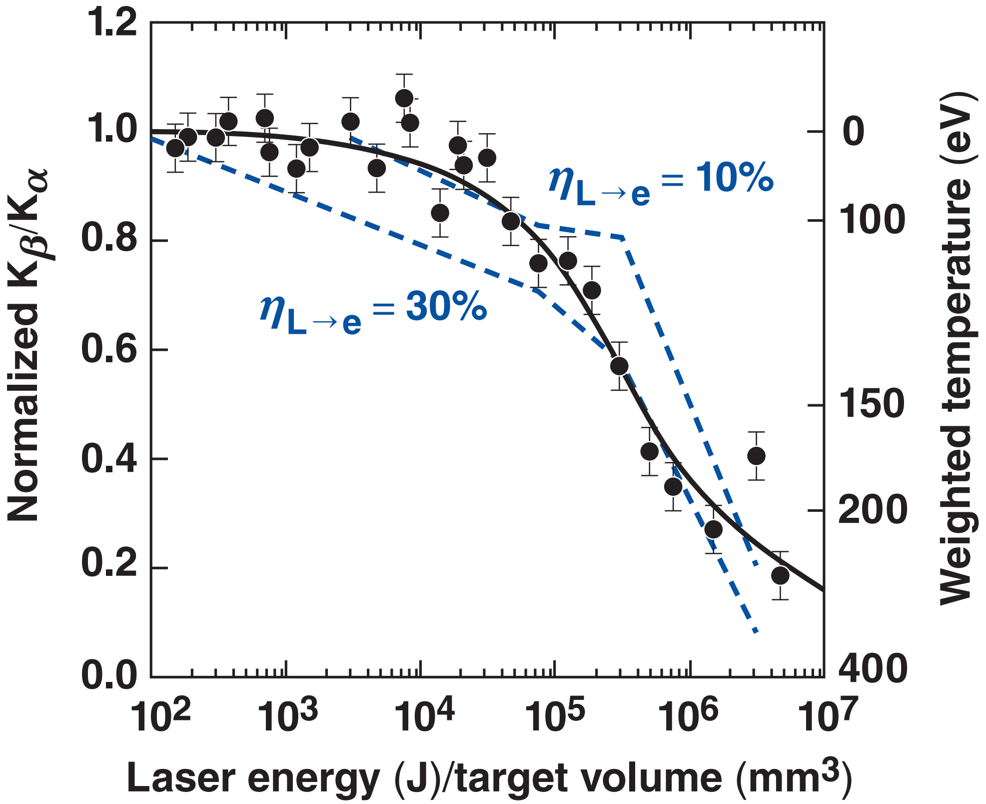


$\eta_{L\rightarrow e}$ is independent of the laser-pulse duration at fixed laser intensity.

P. M. Nilson *et al.*, in preparation

A comparison of K_β/K_α to *LSP* calculations gives $\eta_{L\rightarrow e} \approx$ 20% consistent with the K_α-yield measurements*

MTW laser: 1 J, 1 ps



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*P. M. Nilson *et al.*, Phys. Rev. E 79, 016406 (2009).

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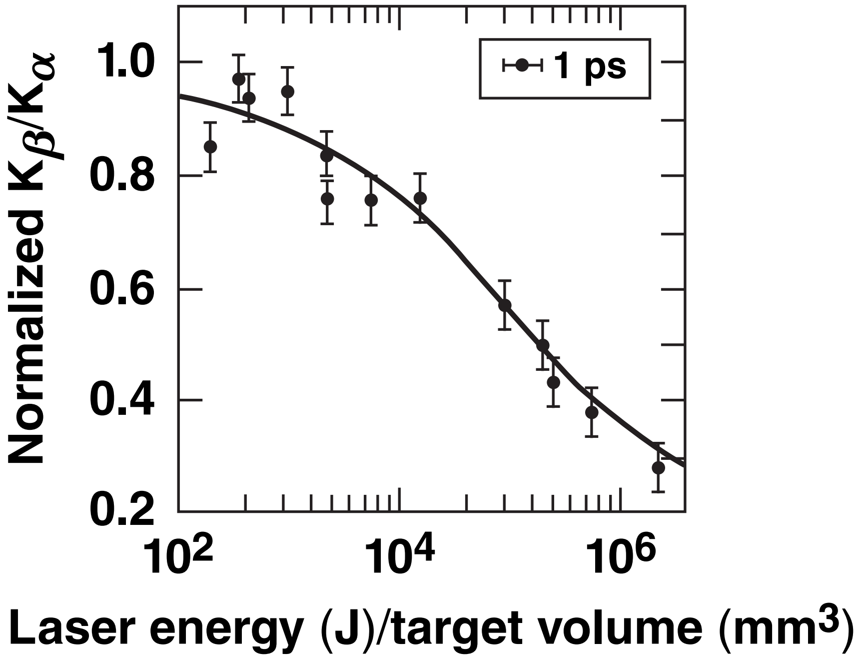

Laser energy: 1 to 2100 J
Laser pulse: 1 to 10 ps

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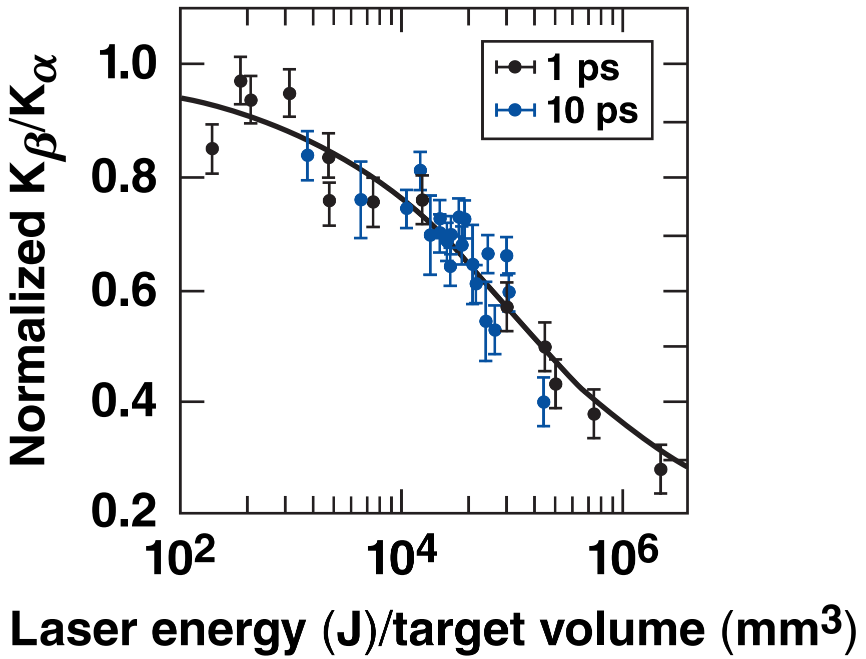

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Outline

- Fast-electron sources
- Characterizing $\eta_{L \rightarrow e}$: the refluxing technique
- OMEGA EP target-charging experiments
  - ultrafast proton radiography
- Intense energy-coupling to electrons
  - MTW experiments: 1- to 10- J, 1- to 10-ps pulses
  - OMEGA EP experiments: 40- J to 2100- J, 10-ps pulse
- $\eta_{L \rightarrow e}$ scaling

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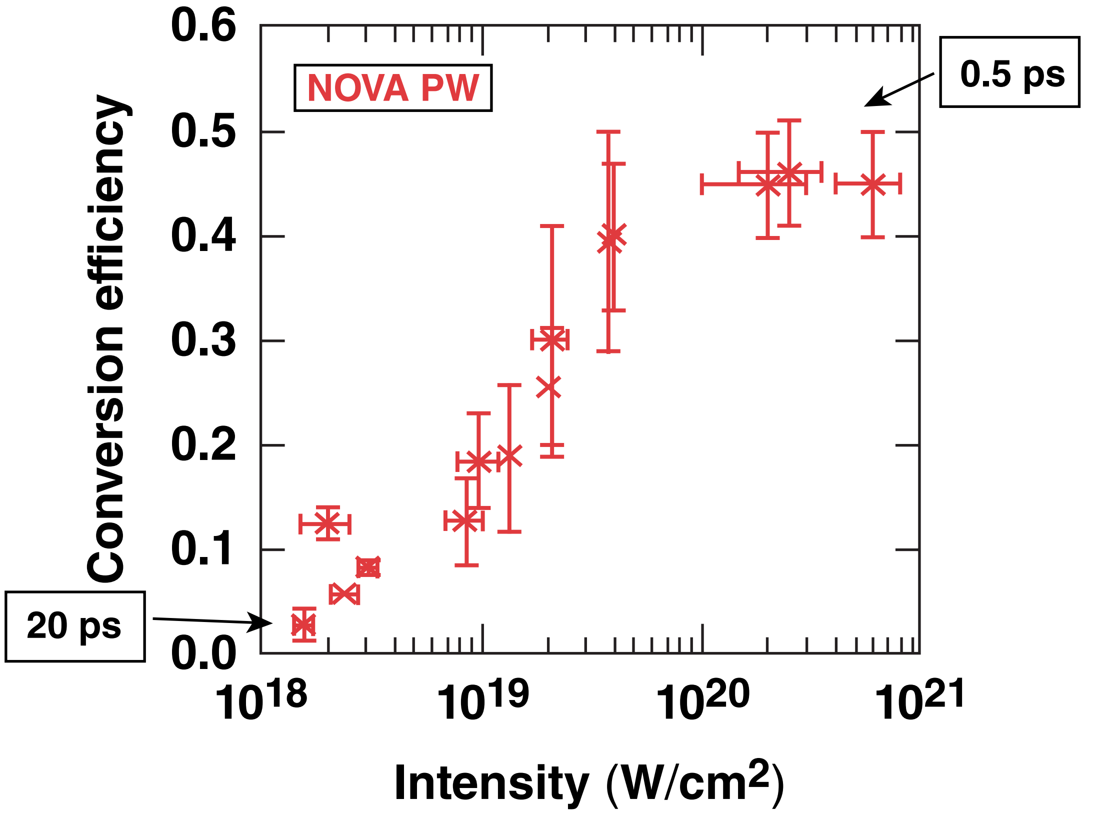
Motivation

The scaling of $\eta_{L\rightarrow e}$ with laser energy and laser-pulse duration is unclear



Solid–target interactions

M. H. Key *et al*., Phys. Plasmas 5, 1966 (1998).

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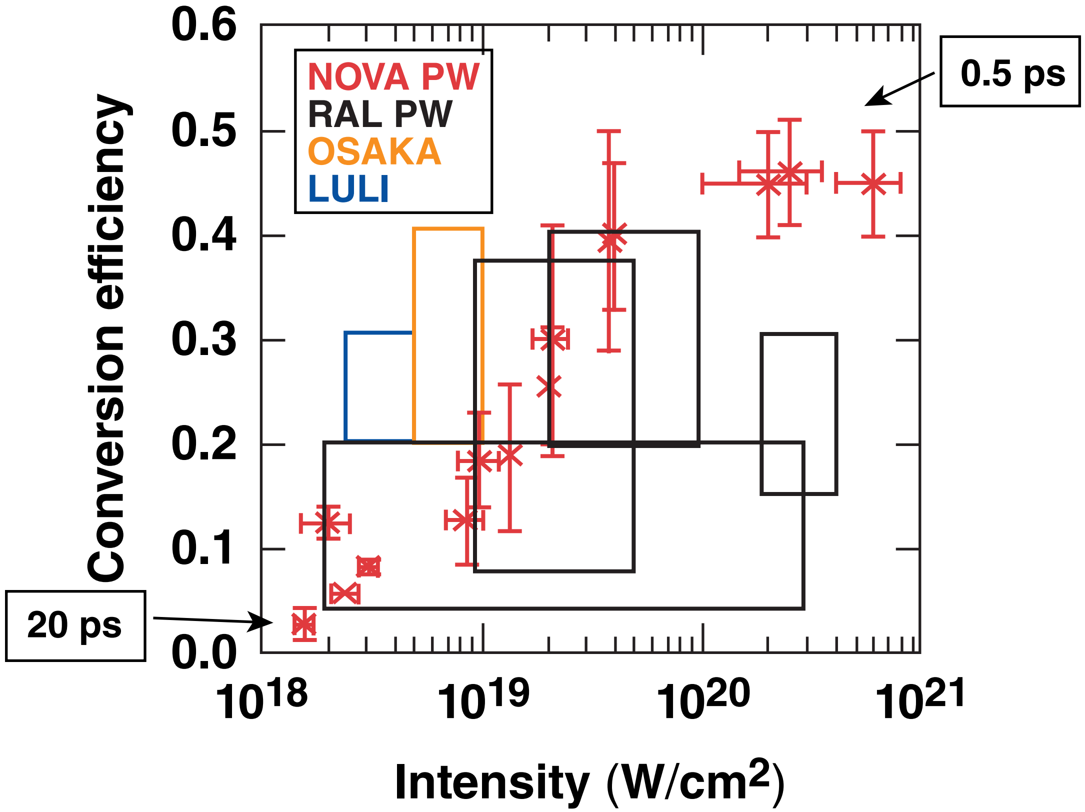

Solid–target interactions

M. H. Key *et al*., Phys. Plasmas 5, 1966 (1998).
W. Theobald *et al*., Phys. Plasmas 13, 043102 (2006).
J. Davies *et al*., PPCF 51, 014006 (2009).

E18830a

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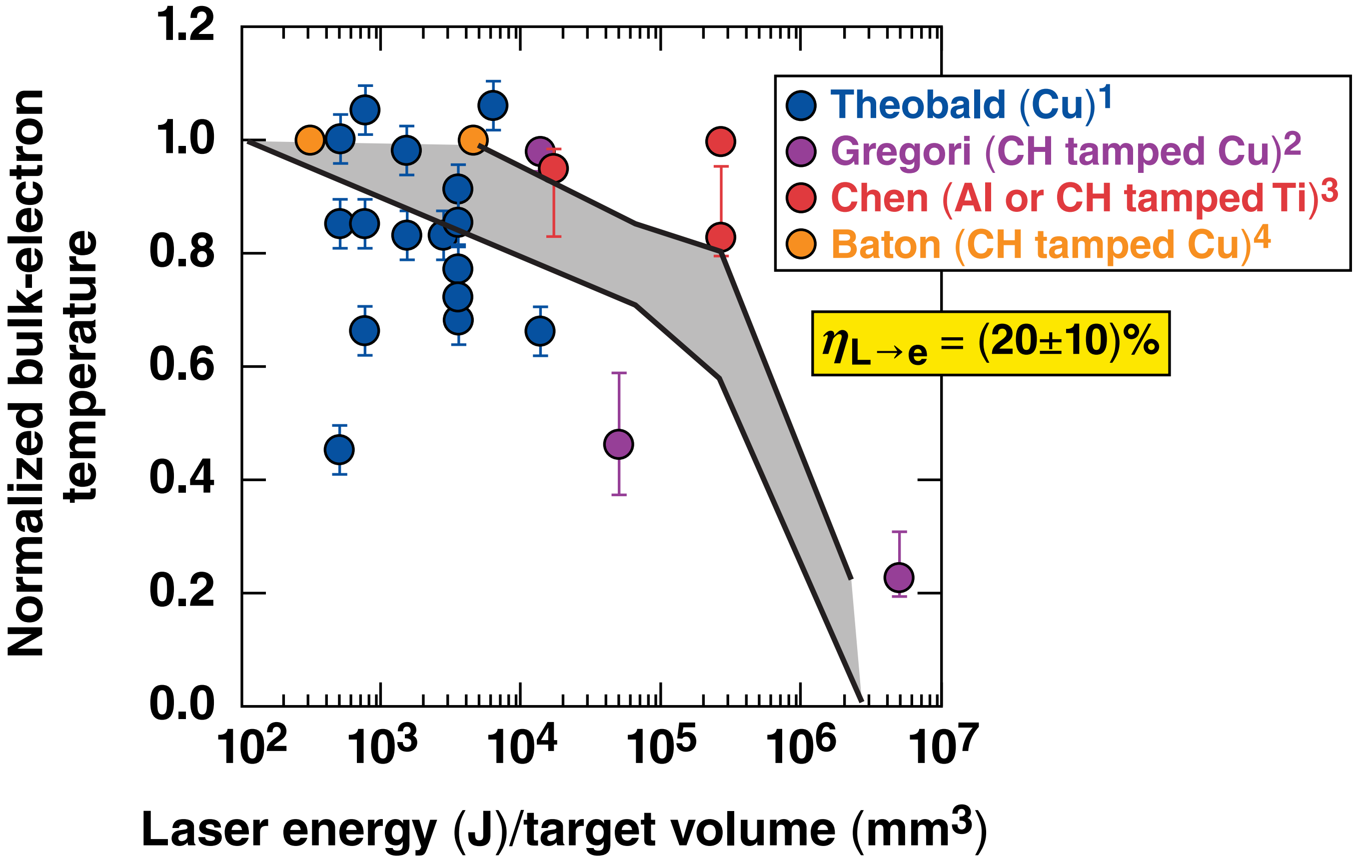
Previous heating experiments show significant scatter making theoretical comparisons challenging



$\eta_{L \rightarrow e}$ = (20±10)%

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[1] W. Theobald *et al.*, Phys. Plasmas 13, 043102 (2006).
[2] G. Gregori *et al.*, Contrib. Plasma Phys. 45, 284 (2005).
[3] S. N. Chen *et al.*, Phys. Plasmas 14, 102701 (2001).
[4] D. Baton *et al.*, High Energy Density Phys. 3, 358 (2007).

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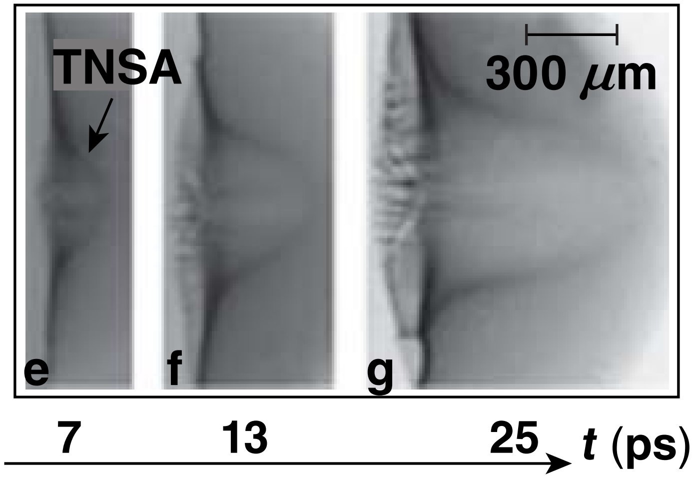
A high-quality proton source is generated by target normal sheath acceleration (TNSA)

<u>Source properties</u>

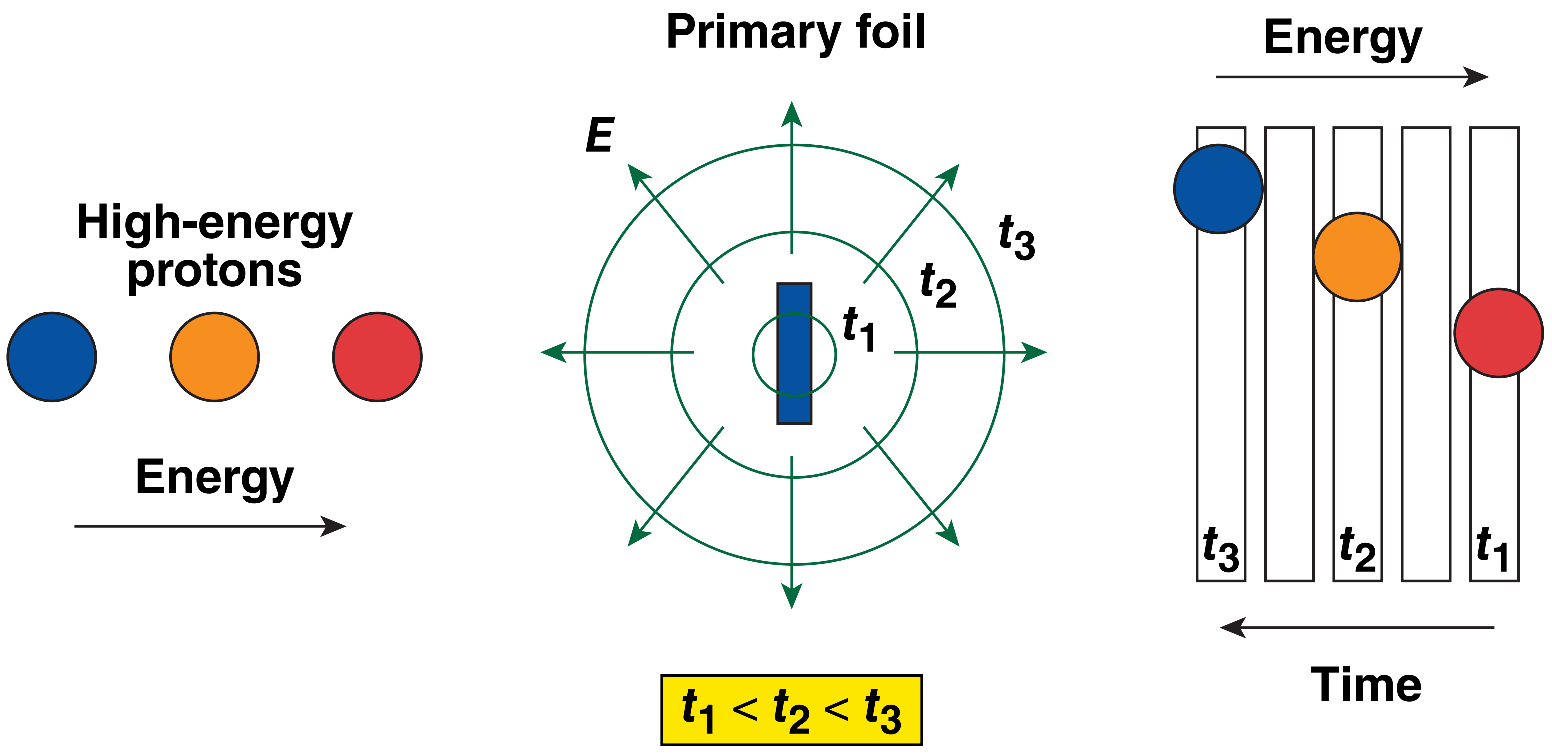
- Ultralow emittance
- Short temporal burst: few ps
- High-energy: up to 60 MeV
- Low divergence: 20°
- High brightness
  - – 10^{11} to 10^{13} protons > 3 MeV per shot



Thin-foil sheath expansion

S. C. Wilks *et al.*, Phys. Plasmas 8, 542 (2001).
M. Borghesi *et al.*, Phys. Rev. Lett. 92, 055003 (2004).
T. E. Cowan *et al.*, Phys. Rev. Lett. 92, 204801 (2004).
L. Romagnani *et al.*, Phys. Rev. Lett. 95, 195001 (2005).

Time-of-flight dispersion and a filtered stack detector produces a multiframe imaging capability



High-energy protons

Energy

Primary foil

E

t_1

t_2

t_3

$t_1 < t_2 < t_3$

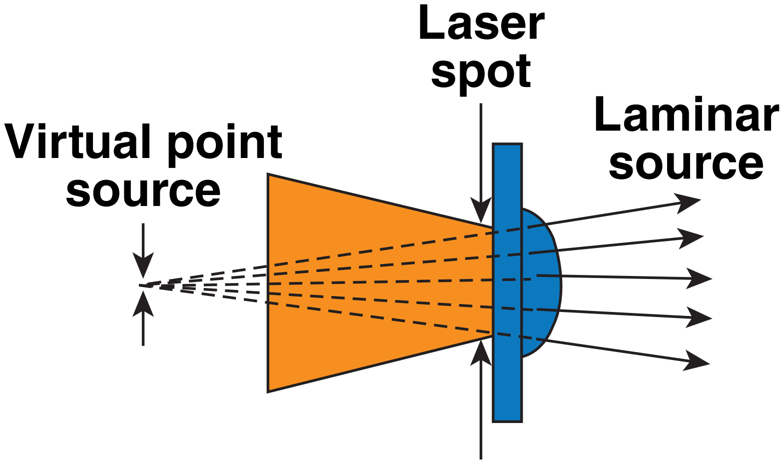
Energy

t_3 t_2 t_1

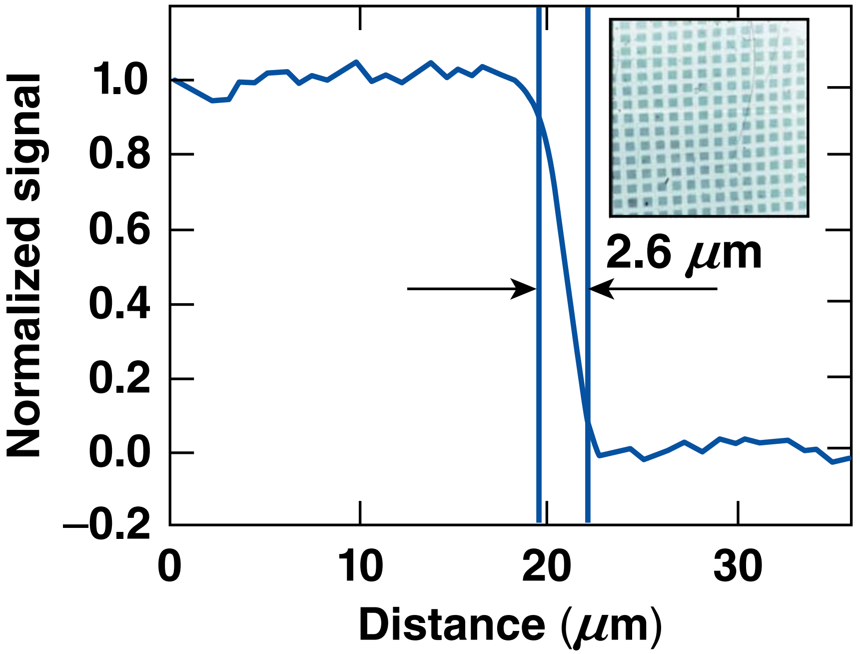
Time

M. Borghesi *et al*., Phys. Plasmas 9, 2214 (2002).

The virtual proton source is much smaller than the laser spot



Virtual source size: 4±2 μm



5-MeV protons
26-μm wire, 35-μm hole

M. Borghesi *et al*., Phys. Rev. Lett. 92, 055003 (2004).
T. E. Cowan *et al*., Phys. Rev. Lett. 92, 204801 (2004).

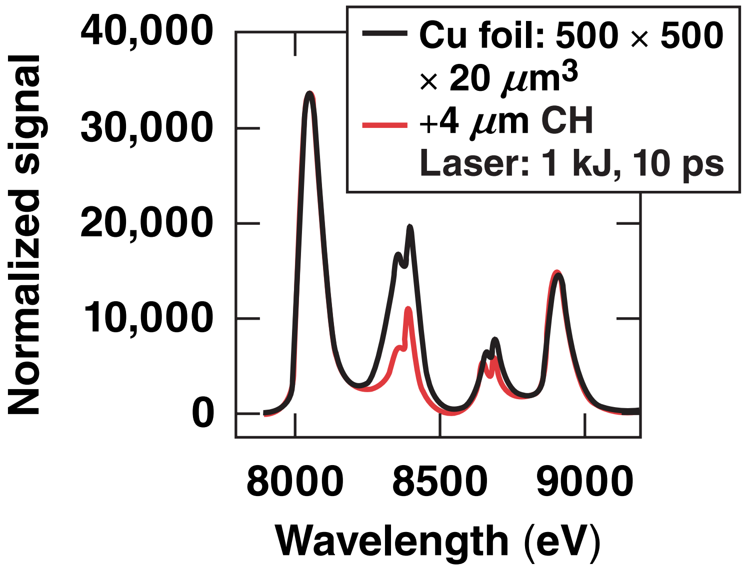
Outline

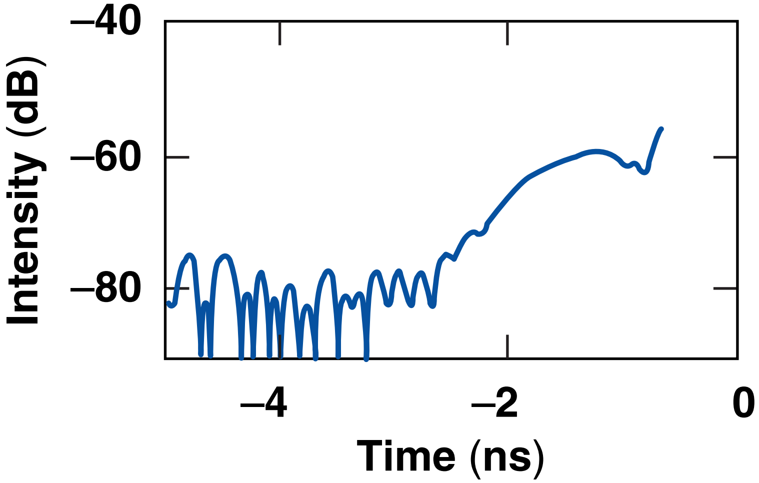
- Fast-electron sources
- Characterizing $\eta_{L \rightarrow e}$: the refluxing technique
- OMEGA EP target-charging experiments
  - ultrafast proton radiography
- Intense energy-coupling to electrons
  - MTW experiments: 1- to 10- J, 1- to 10-ps pulses
  - OMEGA EP experiments: 40- J to 2100- J, 10-ps pulse
- $\eta_{L \rightarrow e}$ scaling

Prepulse-driven plasma expansion preconditions a solid target prior to intense laser irradiation

- Foil targets without CH tampers show the same energy coupling to electrons
- On-shot fast-diode and scope measurement*
- Up to ≈ 0.5 ns before the pulse
- 80-dB range

The pedestal contains around 10^{-4} of the main pulse energy (50 to 150 mJ).





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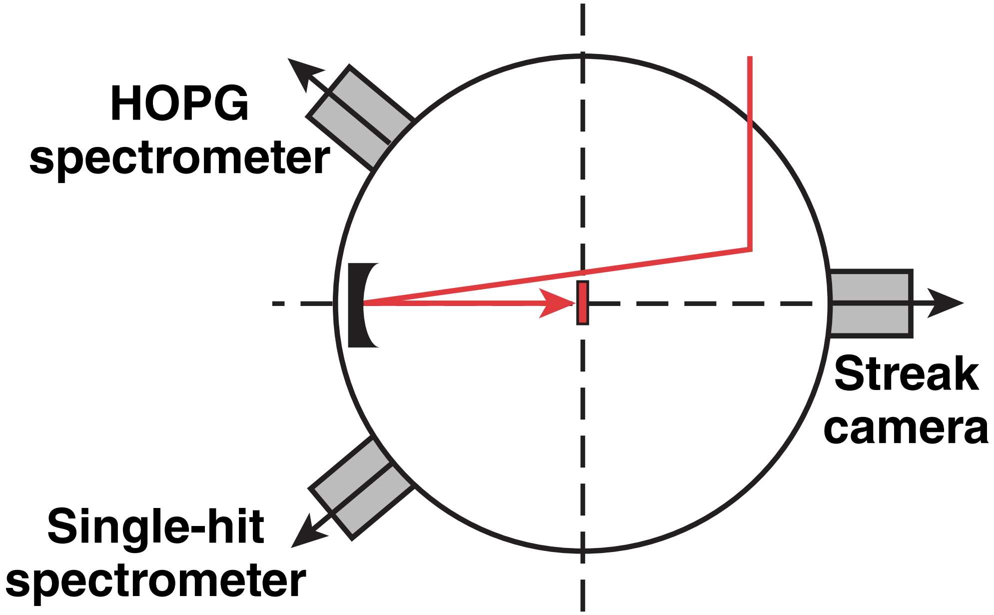
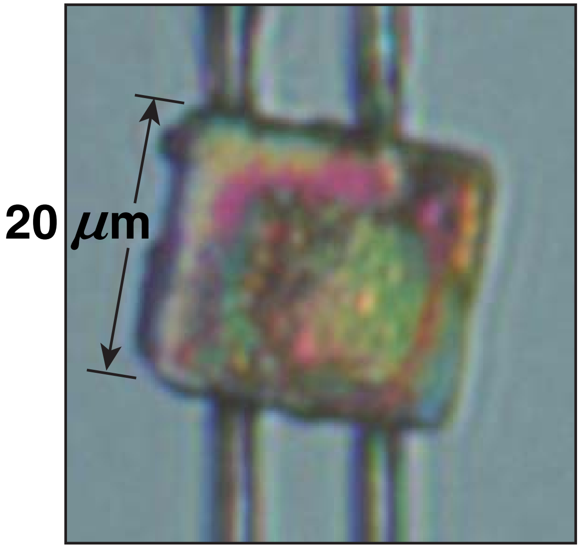
*C. Dorrer *et al.*, OMEGA Lasers Users Group Workshop, Rochester, NY (28–30 April 2010).

Multiterawatt (MTW) experiments were performed with up to 10-J, 10-ps laser pulses

MTW Laser Facility: ≤10 J, ≤10 ps

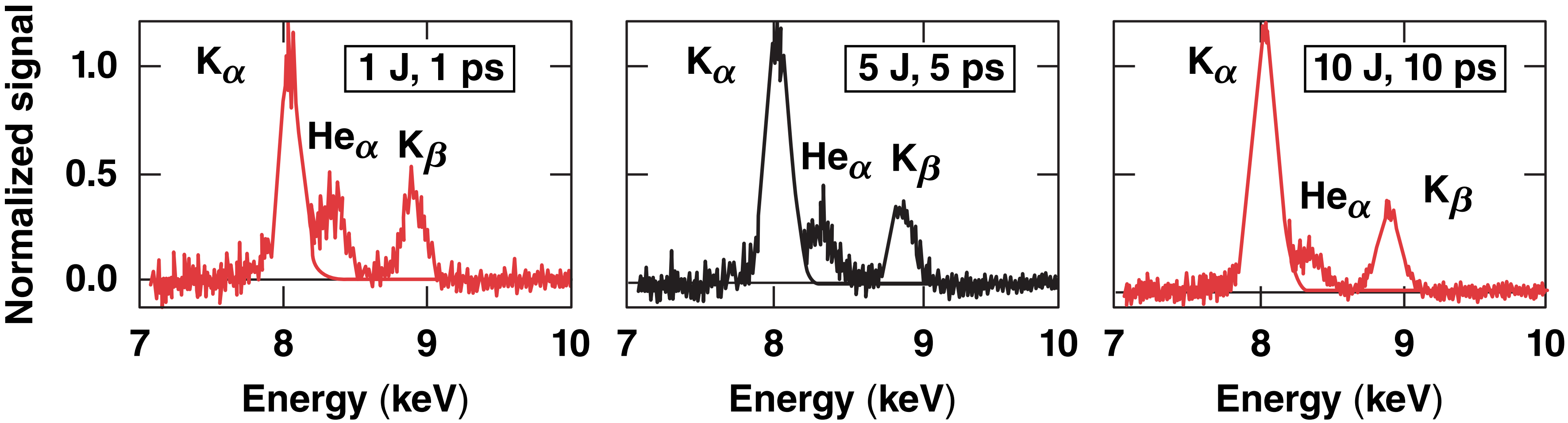




Spider-silk mounted $20 \times 20 \times 2\ \mu m^3$ copper target

- Laser intensities $I < 2 \times 10^{19}$ W/cm^2
- Copper targets
- Target volumes $V > 20 \times 20 \times 2\ \mu m^3$

The normalized K_α yield (Y_{K_α}/E_L) is independent of laser-pulse duration at constant intensity

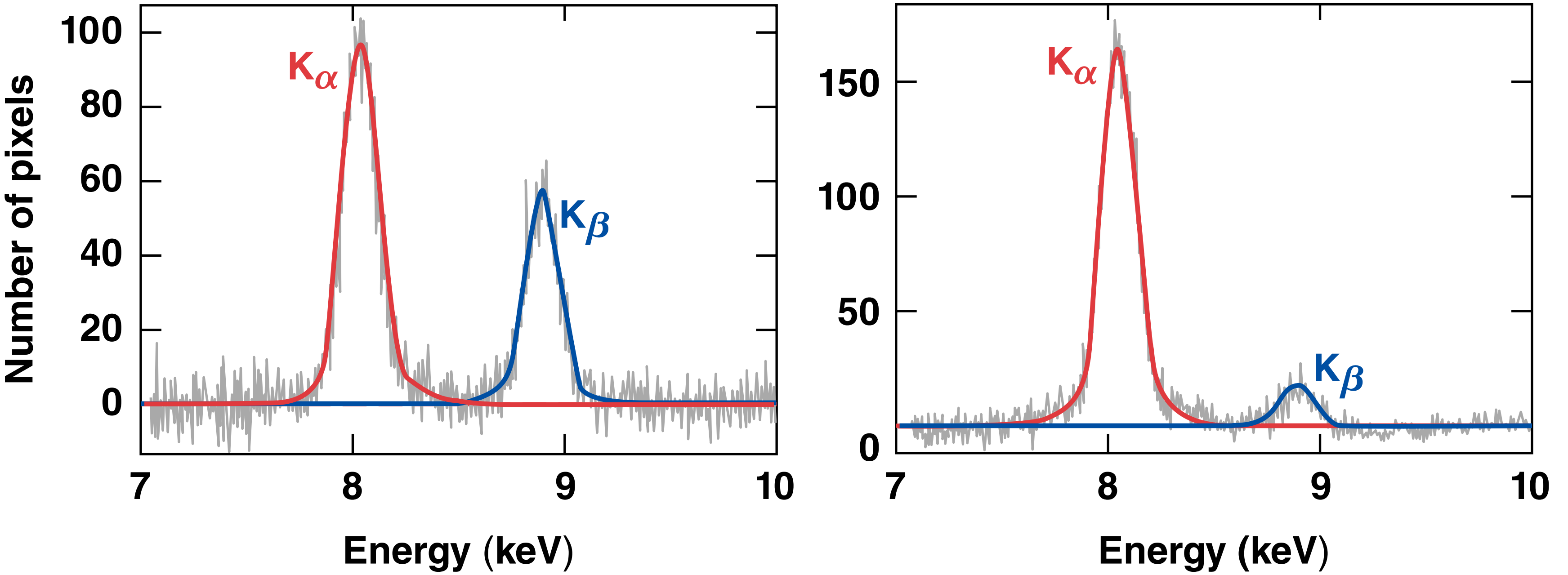


Target volume: 500 × 500 × 20-μm^3 Cu
Intensity: ~5×10^{18} W/cm^2

P. M. Nilson *et al.*, in preparation

The effect of bulk target heating on the K-shell-emission spectrum is observed on the MTW

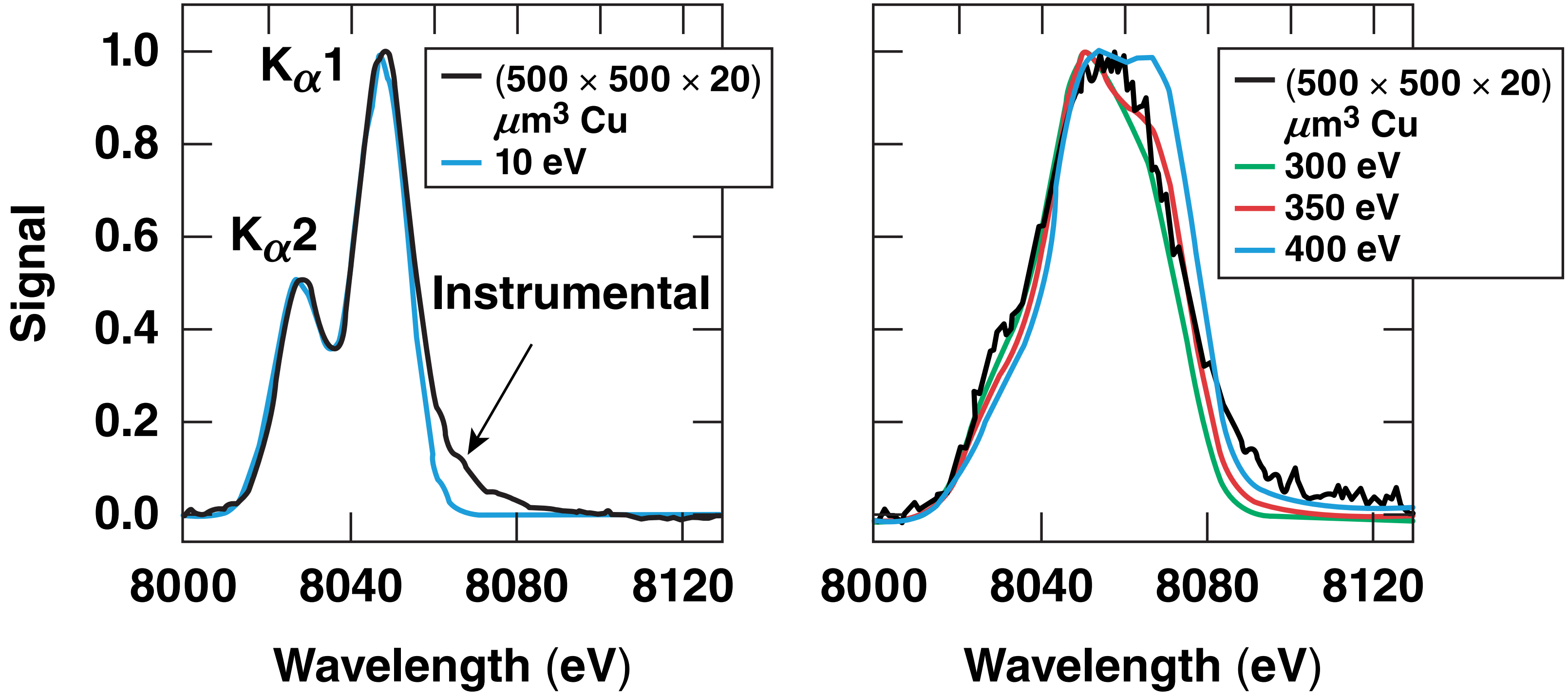
Laser: 5 J, 1 ps
Intensity: 2 × 10^{19} W/cm^2



Cu target: (500 × 500 × 50) μm^3

Cu target: (20 × 20 × 3) μm^3

Measured K_α spectra are fit with PrismSPECT* assuming a linear heating gradient



A single, time-independent thermal-electron temperature is unable to reproduce the high T_e data.

E18832

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*Prism Computational Sciences, Inc., Madison, WI 53711.

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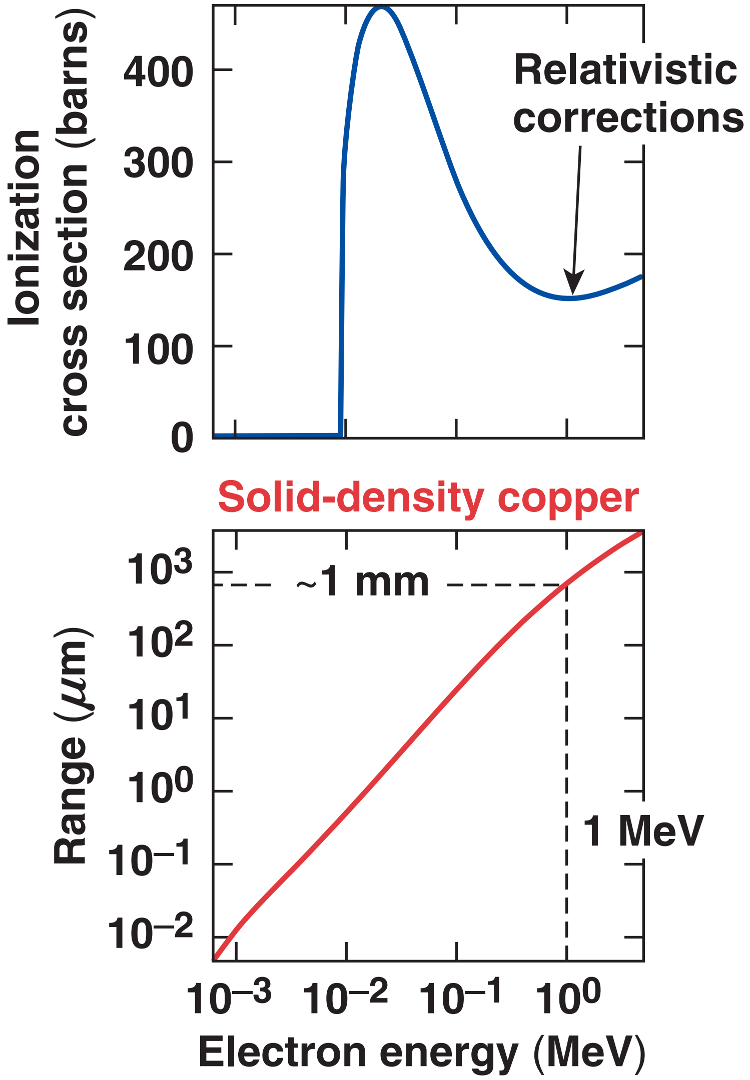
Intense-energy coupling to electrons is inferred using a K_α production model

- K-photon generation calculated as in an infinite medium
- Relativistic K-shell ionization cross sections[2] included
- Classical slowing down approximation (CSDA)[1]
- Negligible target heating

The calculated $\eta_{L \to e}$ parameter represents a minimum value.



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[1] H. O. Wyckoff, *ICRU Report* 37, Intern. Comm. on Radiation Units and Measurements, Inc., Bethesda, MD (1984).

[2] H. Kolbenstvedt, J. Appl. Phys. 38, 4785 (1967).

3-D *LSP* simulations include spatial and temporal variations in heating when calculating K_β/K_α

- Fast-electron source is prescribed
- The same target volumes and interaction time scales are modeled
- Assumes a Thomas–Fermi model
- Calculates EM fields self-consistently
- Emission probability calculated using the local temperature at the time of emission

Target interactions with 1-ps and 10-ps pulses are successfully modeled.

J. Myatt *et al.*, Plasmas 14, 056301 (2007).