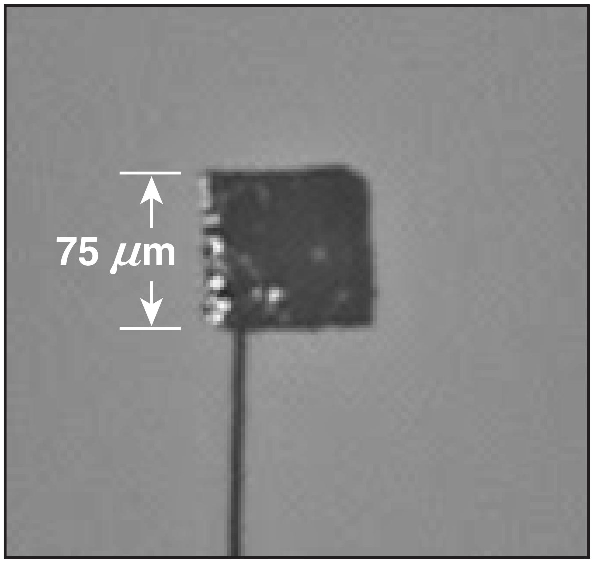
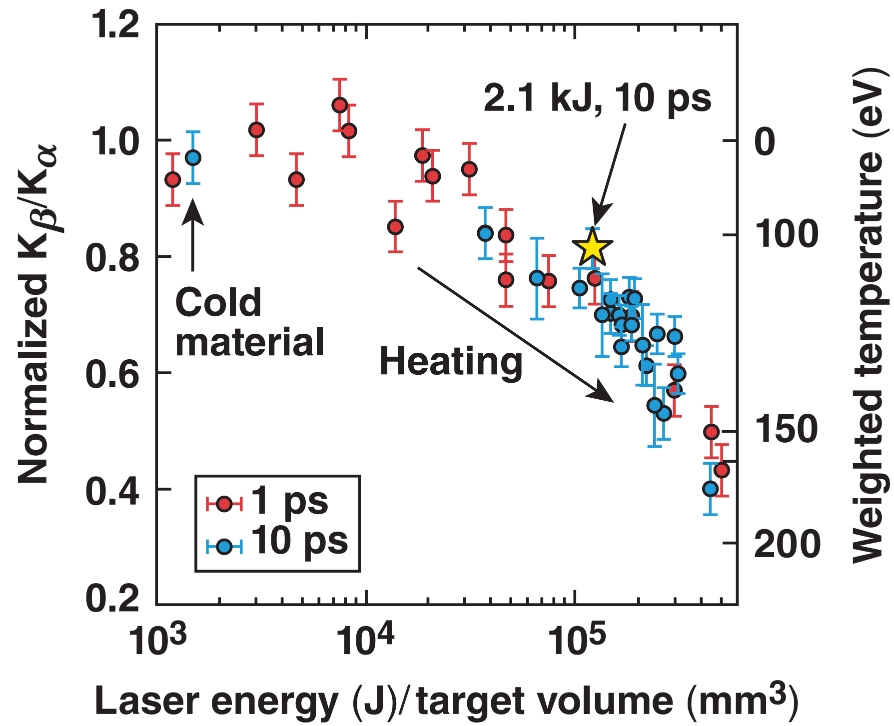
Scaling Hot-Electron Generation to High-Power, Kilojoule-Class Lasers



75 × 75 × 5 μm^3
copper target



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Summary

OMEGA EP experiments show constant energy—coupling efficiency to relativistic electrons from 1 J, 1 ps to 2.1 kJ, 10 ps

- The energy-conversion efficiency $\eta_{L\rightarrow e}$ into hot 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

- Target heating reduces the K_β to K_α ratio at high-energy densities and is used to diagnose $\eta_{L\rightarrow e}$

- An electron-refluxing model describes the dominant target physics

- Proton radiography verifies the formation of global target sheath fields

$$\eta_{L\rightarrow e} = 20\pm10\%$$

Collaborators

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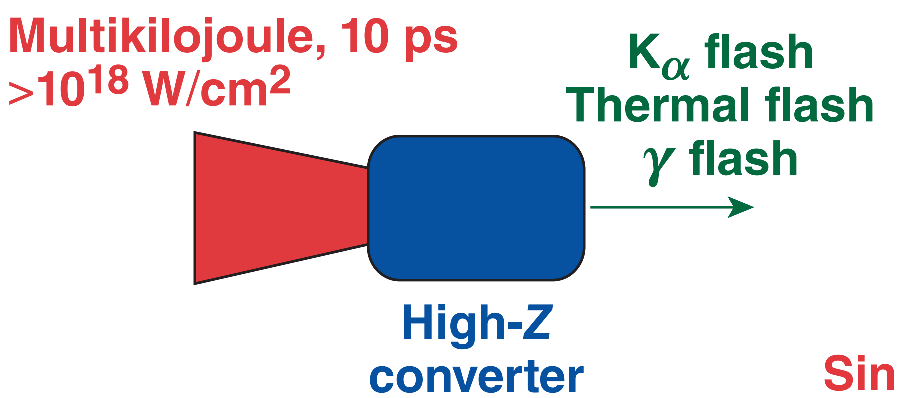
Outline

- Fast-electron sources
- Characterizing $\eta_{L \rightarrow e}$: the refluxing technique
- Target-heating experiments
- Target-charging experiments
- $\eta_{L \rightarrow e}$ scaling

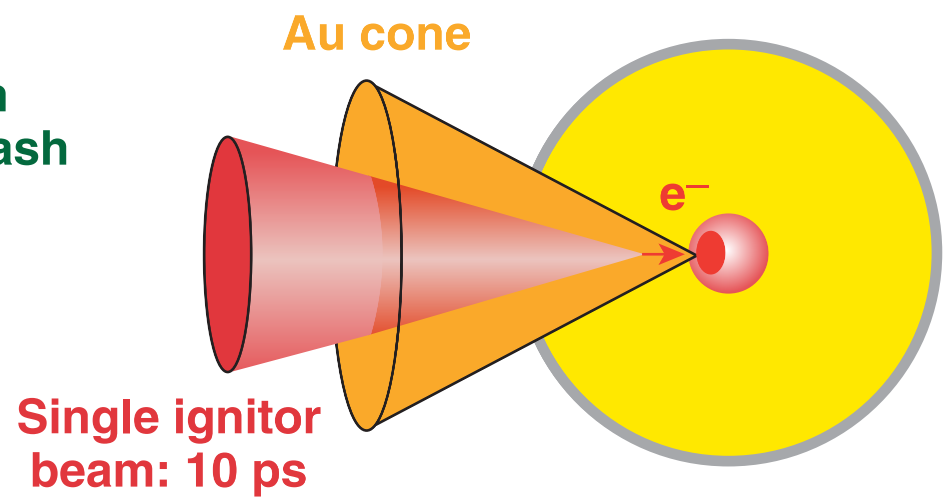
Motivation

High-energy petawatt laser–solid interactions generate powerful MeV electron sources

Laser-Driven Radiography[1,2]



Fast Ignition[3,4]



The energetic feasibility of these schemes relies on efficient energy coupling to hot electrons with 10-ps pulses.

[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).

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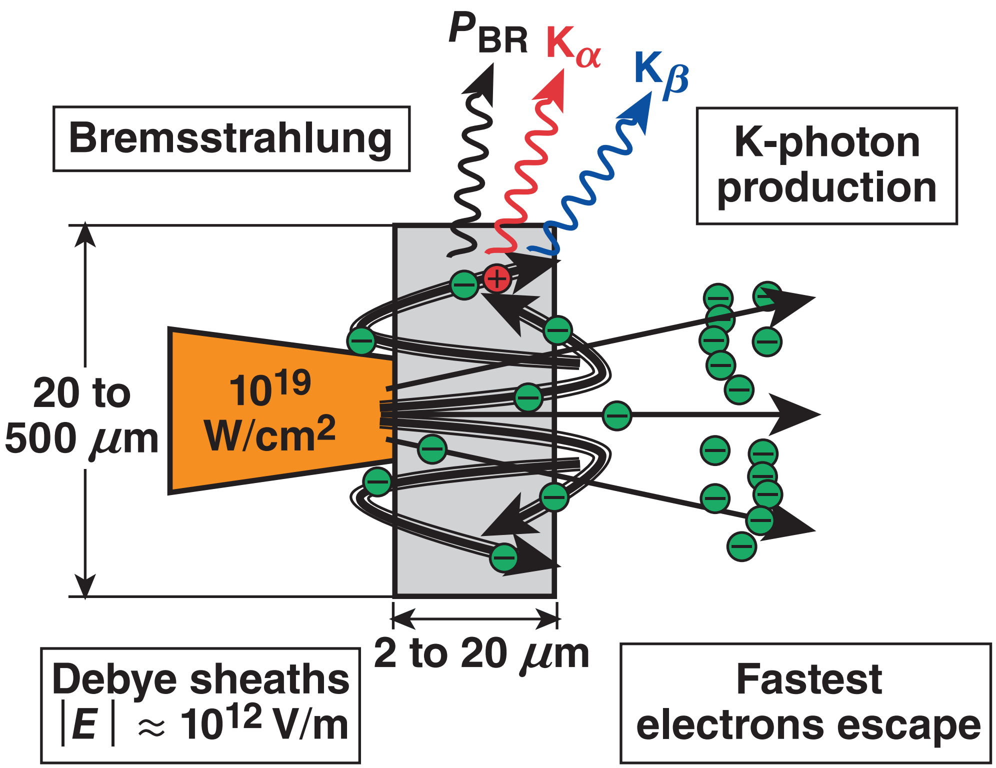
Fast-electron refluxing in mass-limited targets accesses high-temperature matter at solid density



Fast-electron "calorimeter"

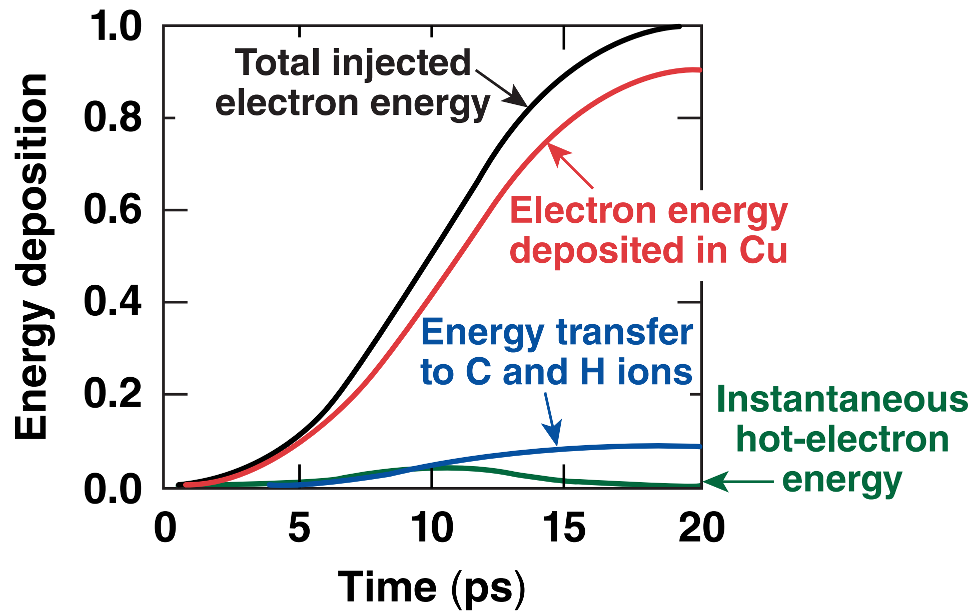
- Refluxing is caused by Debye-sheath field effects[1–5]
- Majority of fast electrons are stopped in the target
- Efficient radiators
  - K_α, K_β
  - thermal emission
- No fluor layers

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

Experimental Method

Most of the hot-electron energy goes to bulk target heating

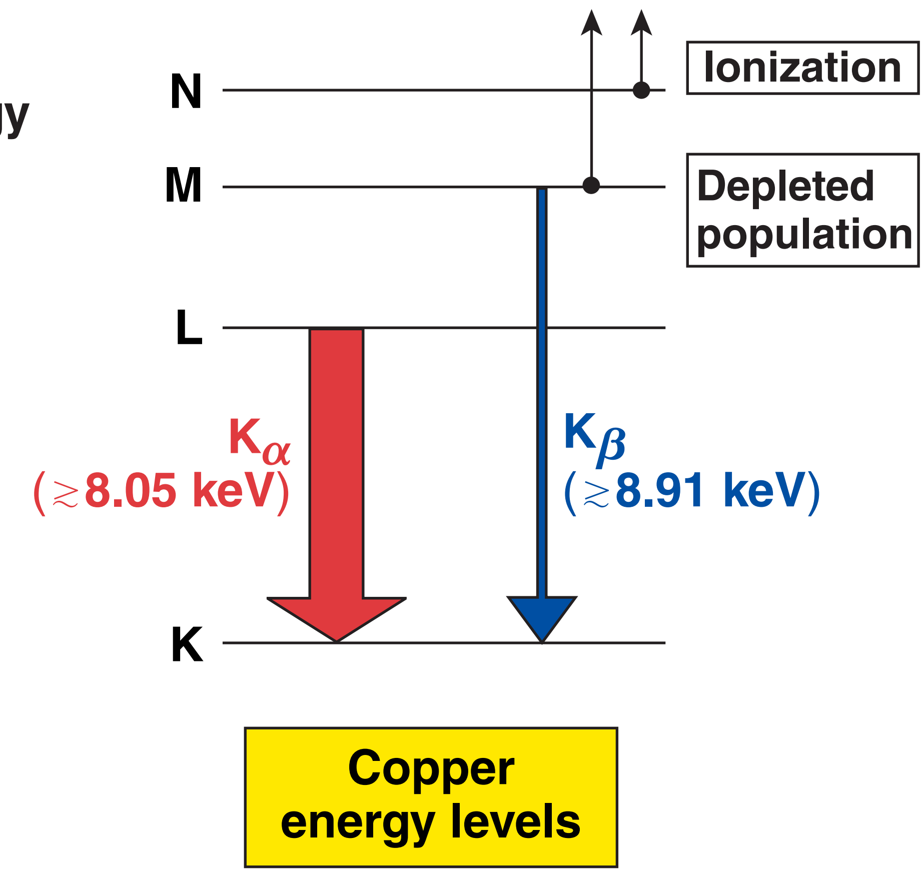
- Peak intensity $I = 7 \times 10^{18}$ W/cm^2
  10-ps (FWHM) Gaussian
- 20-μm-thick Cu target
  0.5-μm-thick, 1-g/cc CH (C^{4+} and H^+)
- CH layers are not depleted during the simulation



K-photon generation is modified by high thermal-electron temperatures.

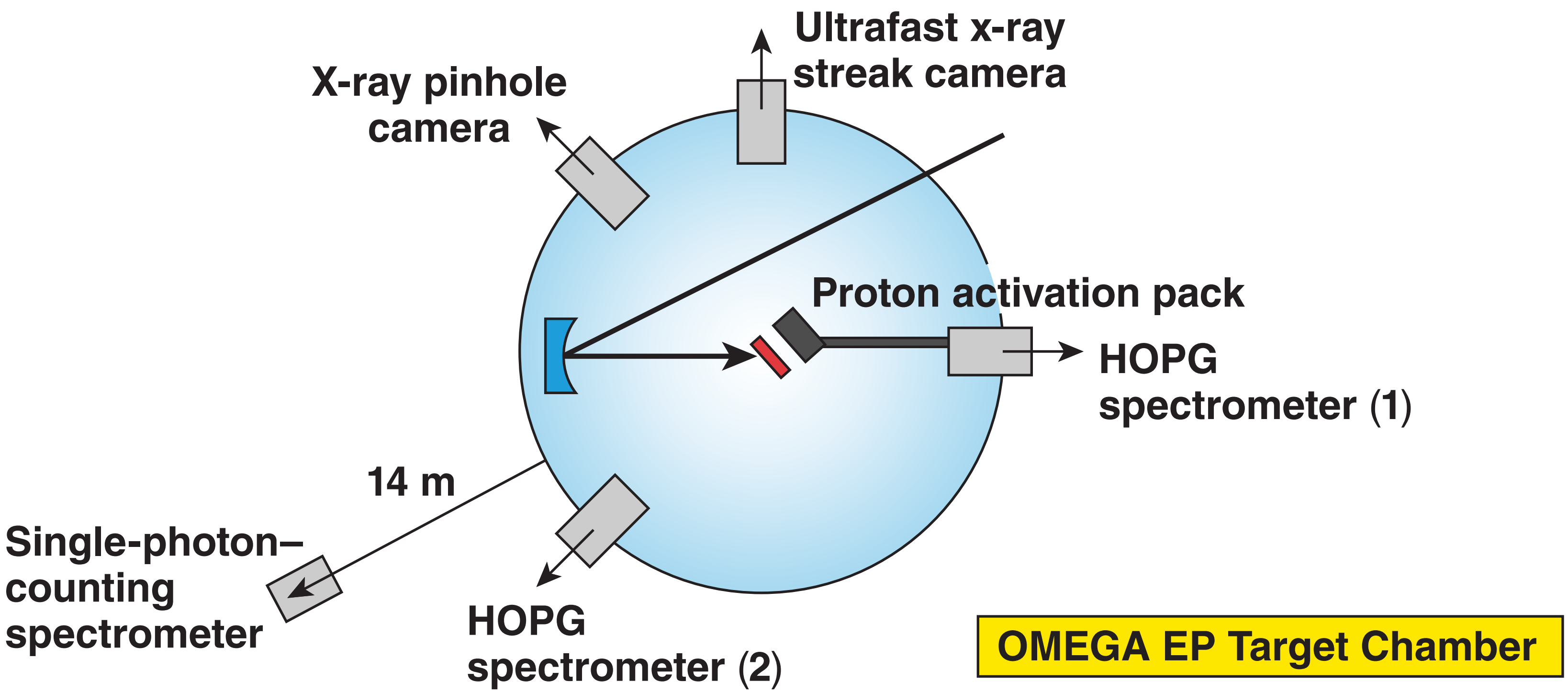
The bulk thermal-electron temperature is measured by the ratio of K_β to K_α

- K-fluorescence within solid targets diagnoses intense-energy coupling to hot electrons
- Inelastic electron–electron collisions heat the target
- $T_e > 100$ eV causes significant M-shell depletion
- Target heating is inferred from K_β/K_α
- $\eta_{L\rightarrow e}$ is found by comparison with simulations



P. M. Nilson *et al.*, Phys. Rev, E 79, 016406 (2009).
G. Gregori *et al.*, Contrib. Plasma Phys. 45, 284 (2005).
J. Myatt *et al.*, Phys. Plasmas 14, 056301 (2007).

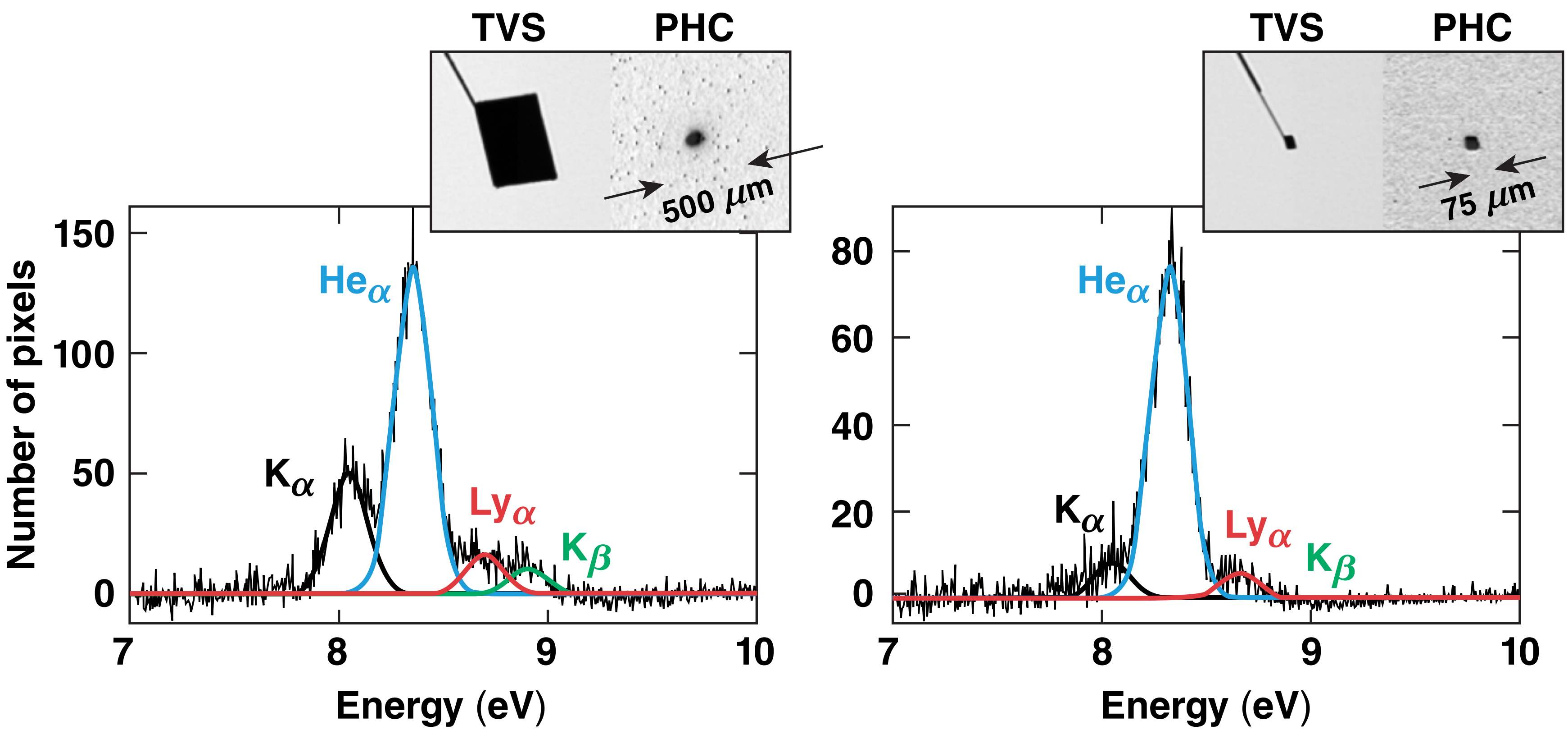
OMEGA EP experiments were performed with up to 2.1-kJ, 10-ps laser pulses



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

K-photon Spectroscopy

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



Target volume: 500 × 500 × 20 μm^3
Laser: 1049 J, 10 ps
Energy density: 2×10^5 J/mm^3

Target volume: 75 × 75 × 5 μm^3
Laser: 1042 J, 10 ps
Energy density: 4×10^7 J/mm^3

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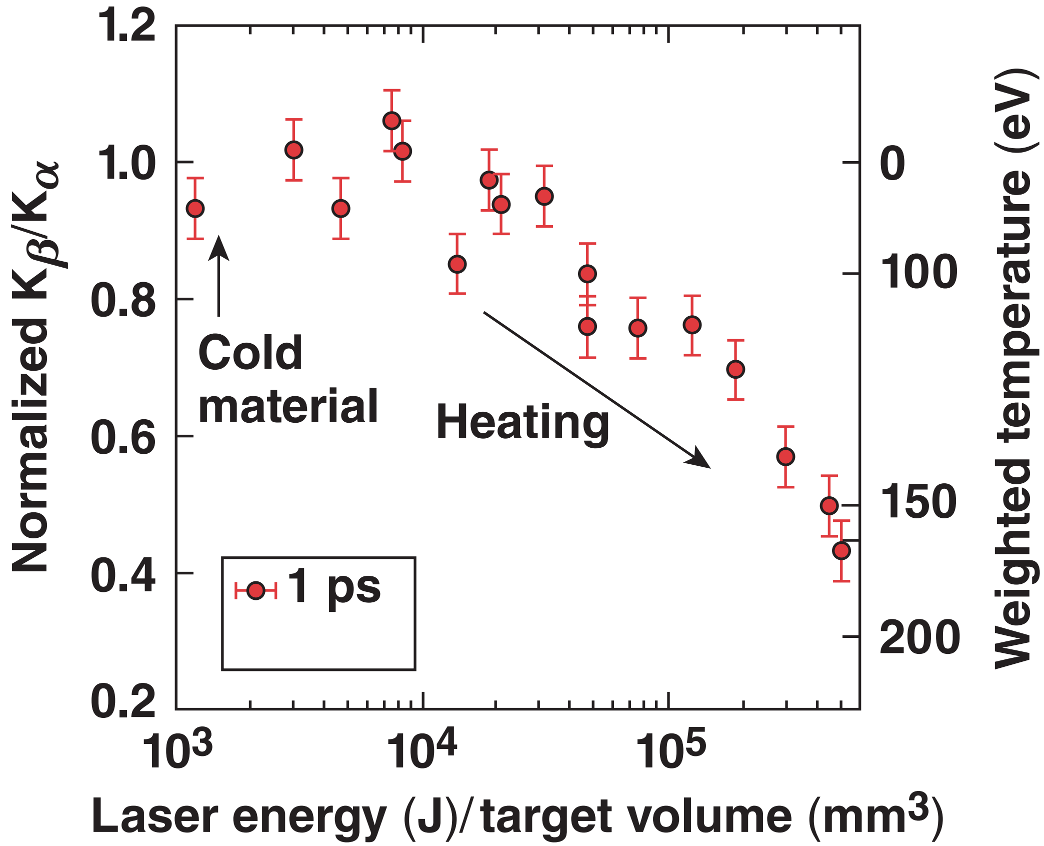
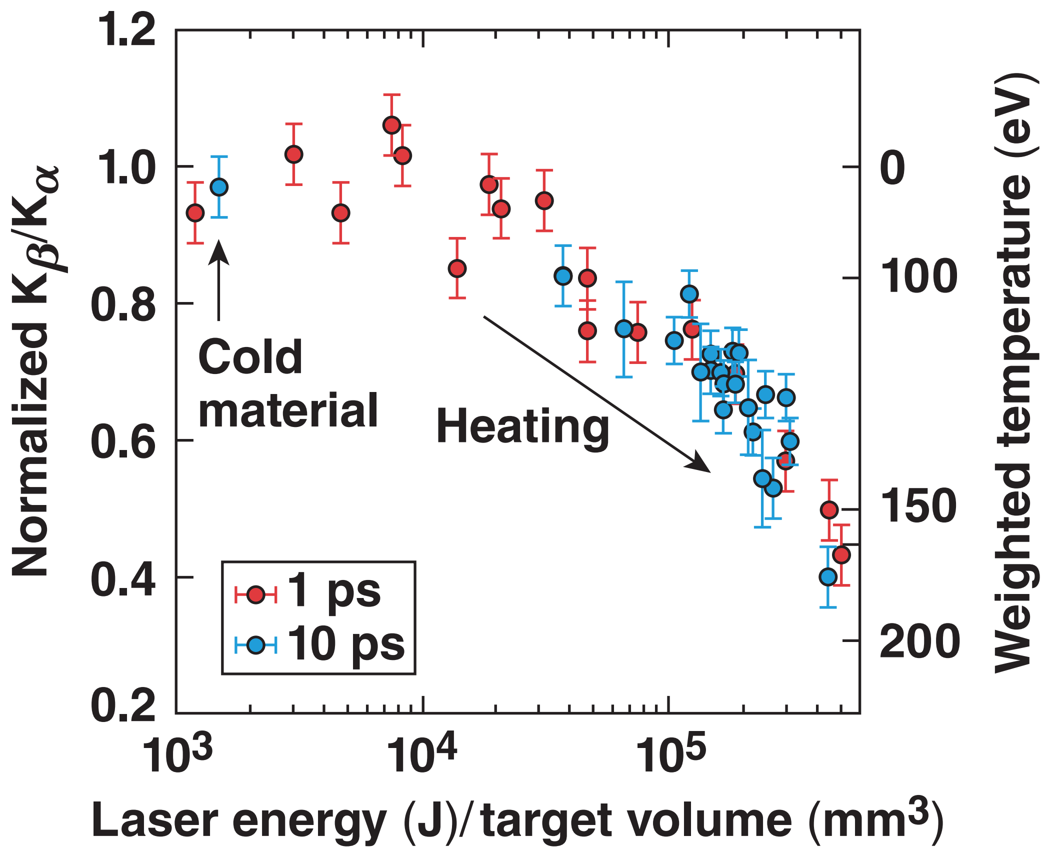
Intense-energy coupling to electrons is independent of laser energy and laser-pulse duration



Laser intensity: $>10^{18}$ W/cm^2
Laser energy: 1 to 5 J
Laser-pulse duration: 1 ps

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

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



Laser intensity: $>10^{18}$ W/cm^2
Laser energy: 1 J to 2.1 kJ
Laser-pulse duration: 1 to 10 ps

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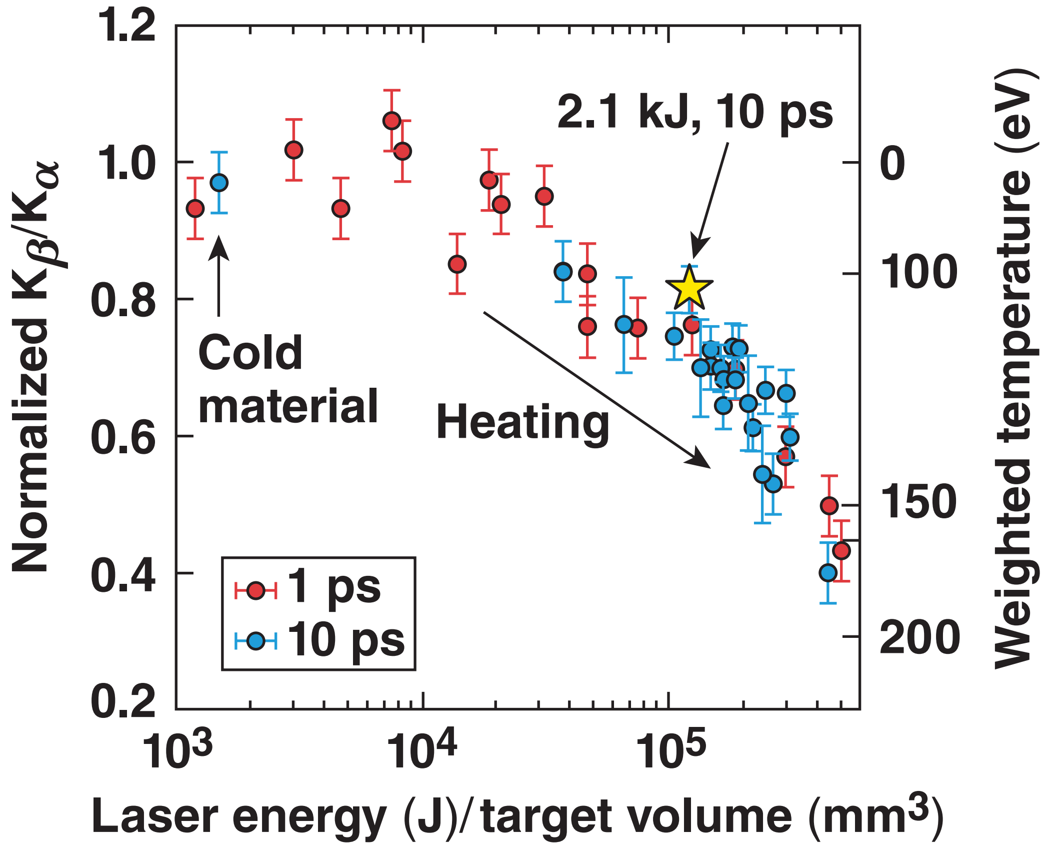
P. M. Nilson *et al.*, Phys. Rev. Lett. (to be published).
P. M. Nilson *et al.*, Phys. Rev. E 79, 016406 (2009).

$\eta_{L\rightarrow e}$ Scaling

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



Laser intensity:	>10^{18} W/cm^2
Laser energy:	1 J to 2.1 kJ
Laser-pulse duration:	1 to 10 ps

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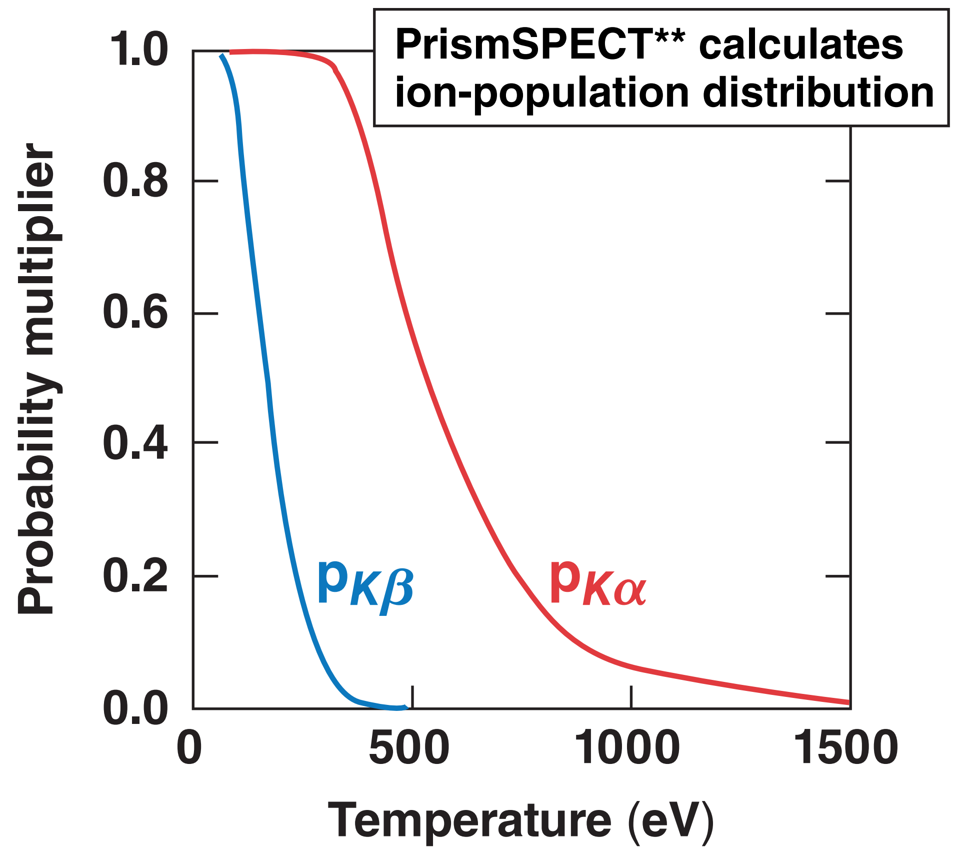
P. M. Nilson *et al*., Phys. Rev. Lett. (to be published).
P. M. Nilson *et al*., Phys. Rev. E 79, 016406 (2009).

Spatial and temporal variations in heating must be considered when calculating K_β/K_α

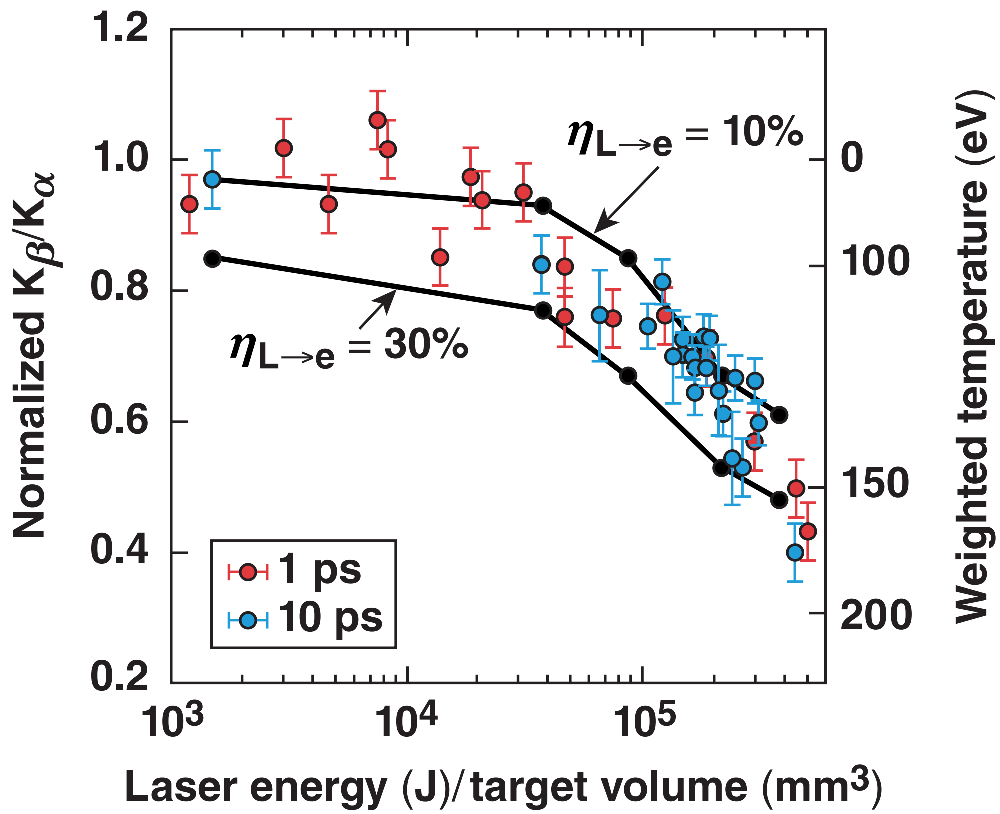
- *LSP** calculates target heating
- Fast-electron source is prescribed with varying energy
- Full target volume and interaction time scale are modeled
- Assumes a Thomas–Fermi EOS model
- Calculates EM fields self-consistently—accounts for refluxing
- Emission probability is calculated using the local temperature at the time of emission



* D. Welch *et al.*, Nucl. Inst. Methods Res. A 464, 134 (2001).
** Prism Computational Sciences, Inc., Madison, WI 53711

The laser-electron conversion efficiency $\eta_{L\rightarrow e}$ is independent of target energy density

- Target-heating calculations reproduce the experimental K_β/K_α trend
- Confirms the dominant target physics is being correctly accounted for
- Energy-conversion efficiency offset due to high-energy proton acceleration is assumed to be small



$(\eta_{L\rightarrow e})_{min} = 20\pm10\%$

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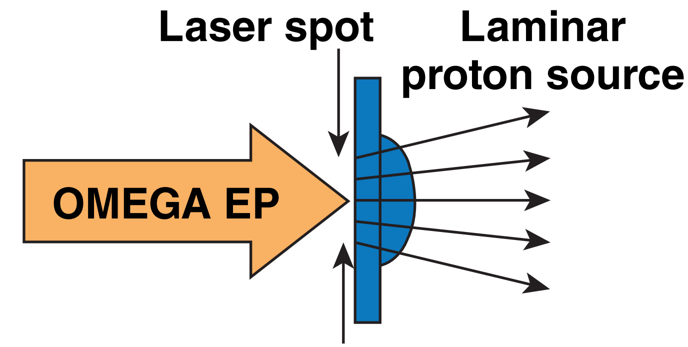
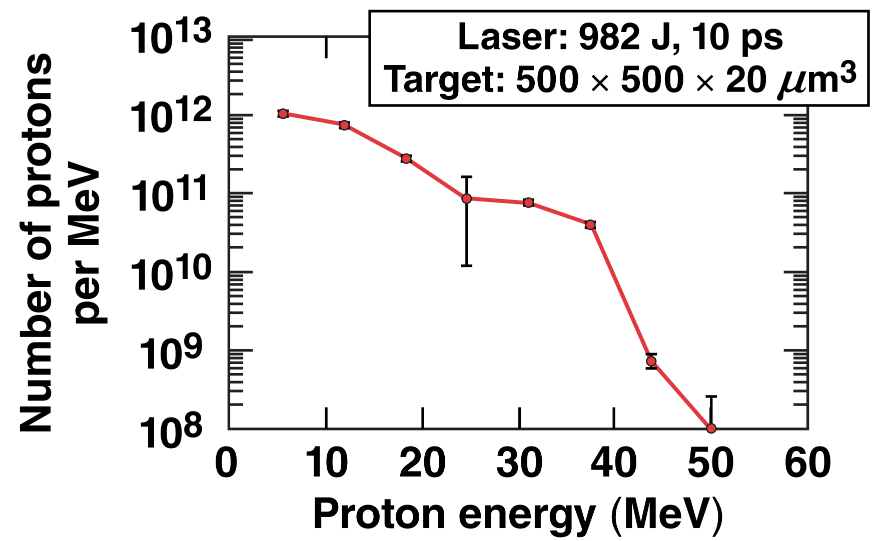
P. M. Nilson *et al.*, Phys. Rev. Lett. to be published.

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

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

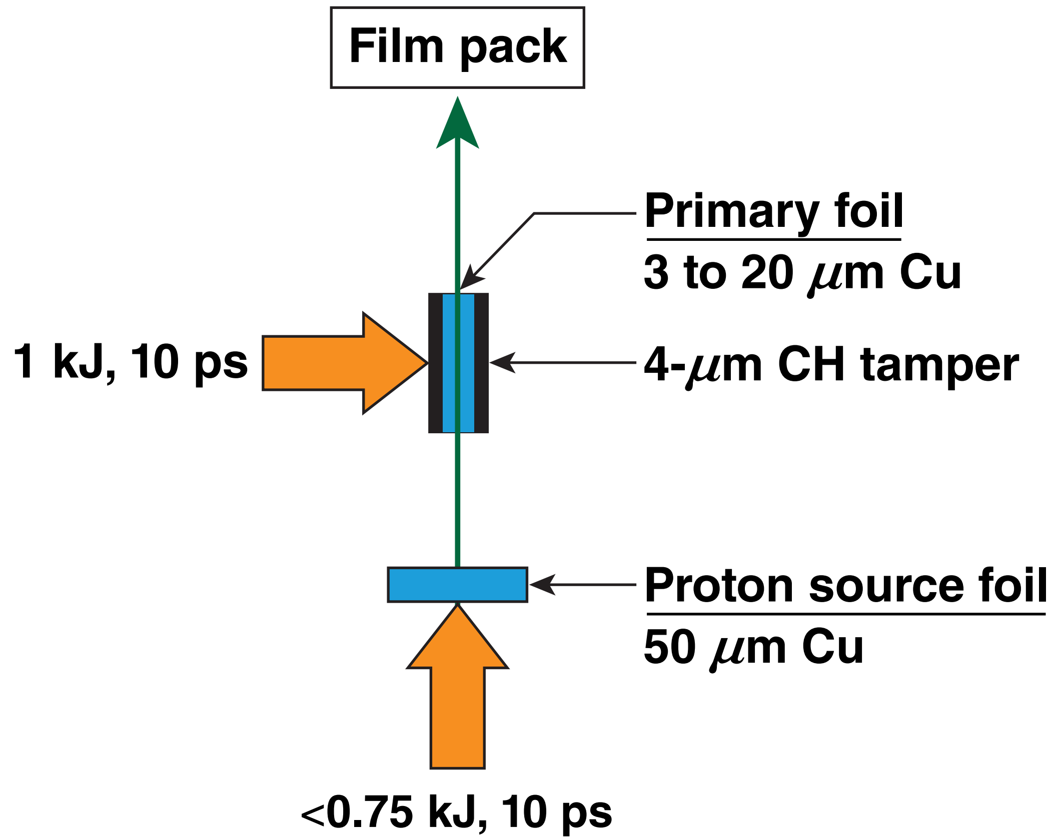




Typically 2% to 3% of the laser energy is converted into fast protons.

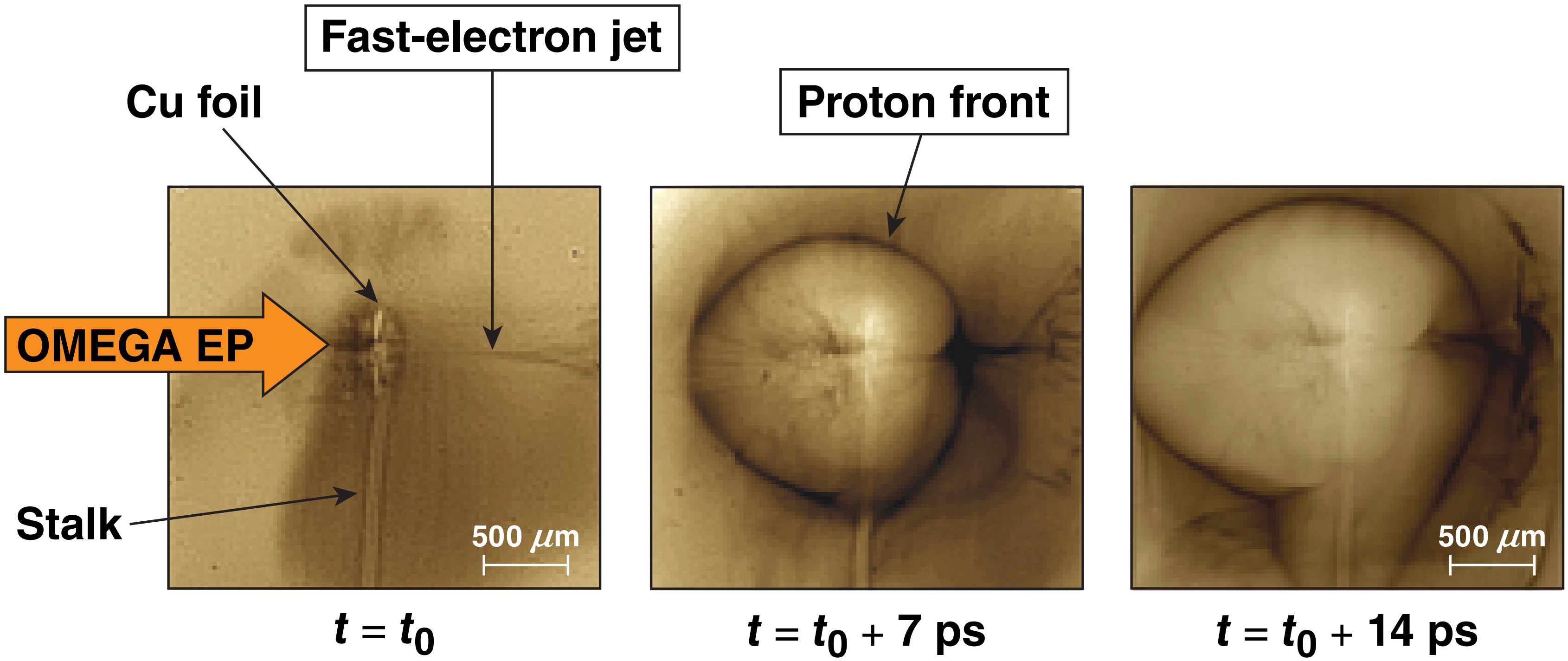
M. I. K. Santala *et al.*, Phys. Lett. 78, 19 (2001).
L. Gao (XO6.0001)

Proton radiography is used to verify the sheath model



Single-shot, multiframe imaging is achieved with μm-scale spatial resolution and ps-scale temporal resolution.

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



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

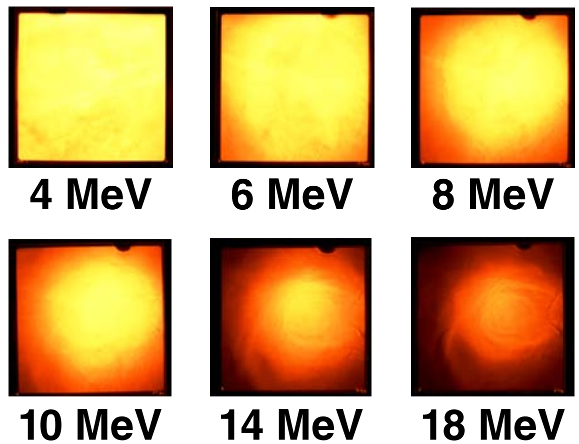
E18897c

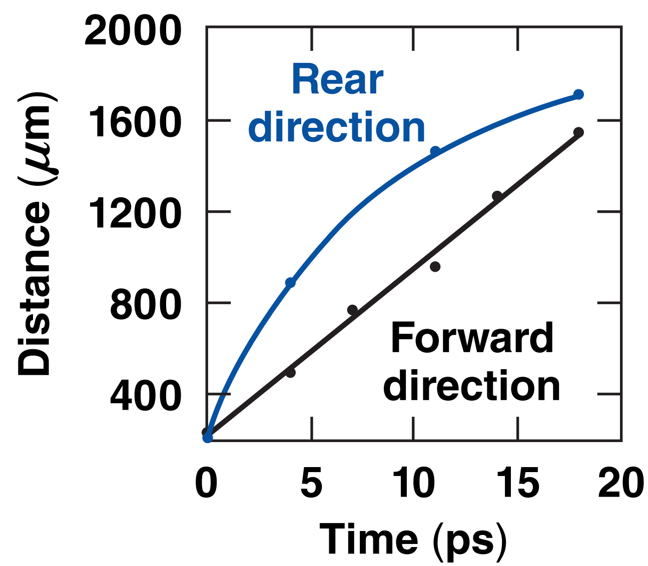
Sheath fields form at the surface of thin-foil targets in two distinct phases

FSC

UR LLE

- 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
  - proton energies ≥ 40 MeV
- Integrating both components gives 3% to 4% conversion efficiency to energetic protons





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E19383