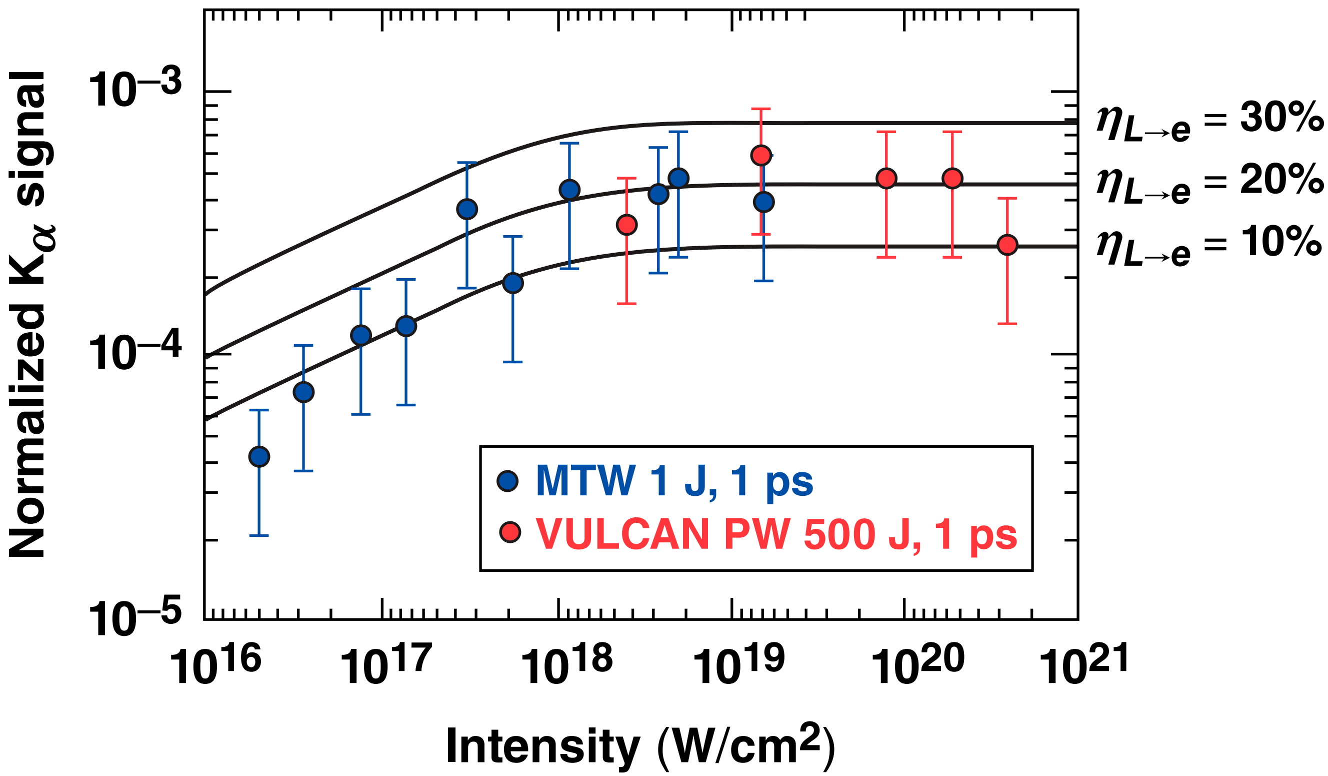
High-Intensity Laser–Plasma Interactions in the Refluxing Limit



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Summary

The laser-to-electron energy-conversion efficiency is $\eta_{L\rightarrow e}$ = 20% for laser intensities $I > 10^{18}$ W/cm^2

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- Comparison of K_α yields from small-mass targets with a K_α production model infers $\eta_{L\rightarrow e}$ = 20%±10% for 1-ps pulses at $I > 10^{18}$ W/cm^2
- Target heating affects $L\rightarrow K$ and $M\rightarrow K$ electron transitions
- K_β/K_α signals are consistent with numerical target-heating calculations for $\eta_{L\rightarrow e}$ = 20%±10% over a wide range of target volumes

Solid-density material heated to >200 eV using a 5 J, 1-ps laser pulse

E16140

Collaborators

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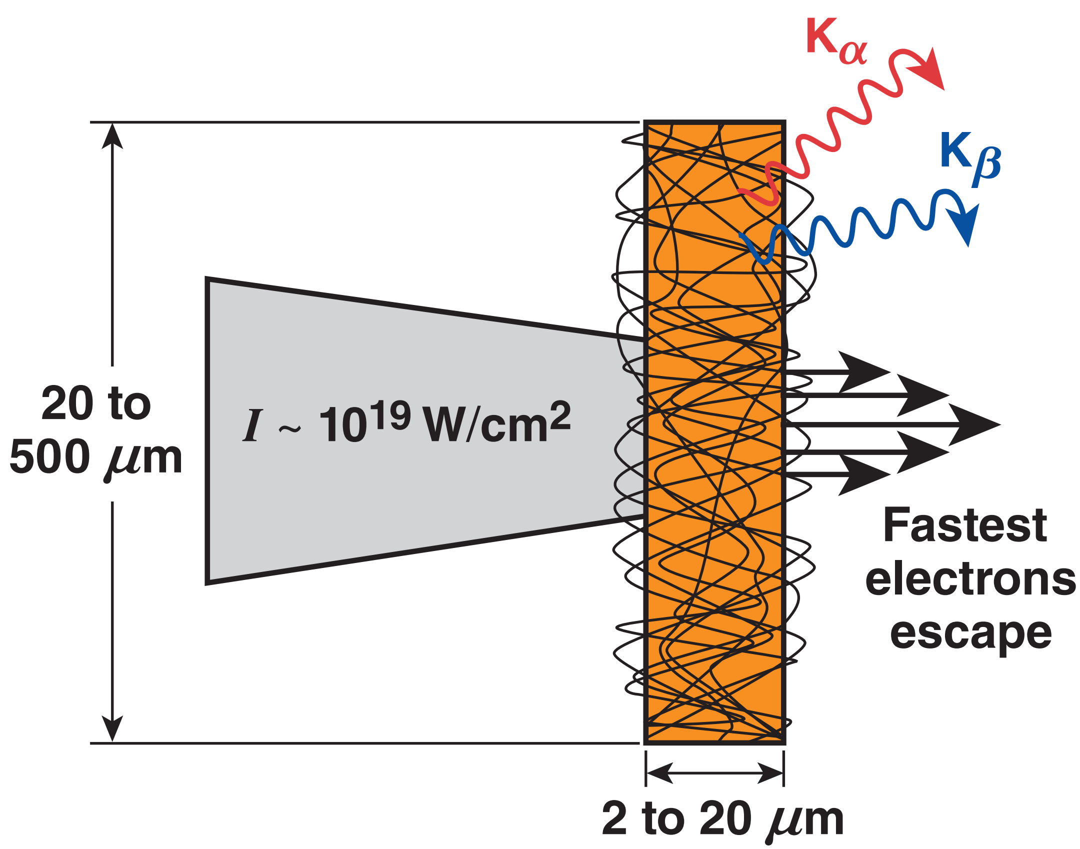
Outline

- High-temperature matter at solid density
- Small-mass foil targets
- Electron refluxing
- K_α-yield experiments
- Bulk target-heating experiments
- Future experiments

Fast-electron refluxing in small-mass targets allows access to high-energy-density phenomena



- Refluxing is caused by Debye sheath field effects[1,2]
- Majority of fast electrons are stopped in the target
- Provides a simple geometry for testing laser-coupling, electron-generation, and target-heating models[3,4]

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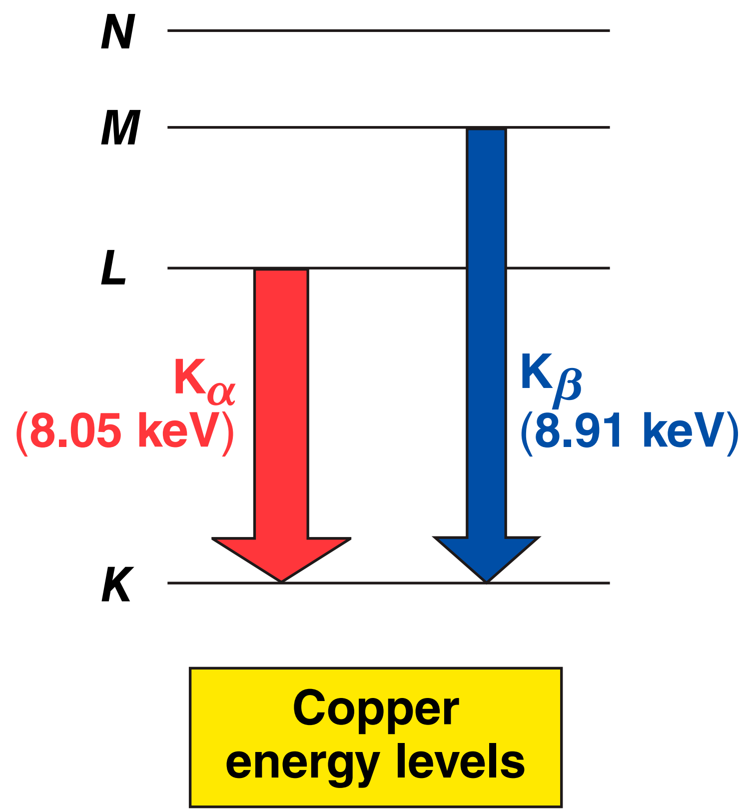
[1]S. P. Hatchett *et al.*, Phys. Plasmas 7, 2076 (2000).
[2]R. A. Snavely *et al.*, Phys. Rev. Lett. 85, 2945 (2000).
[3]W. Theobald *et al.*, Phys. Plasmas 13, 043102 (2006).
[4]J. Myatt *et al.*, Phys. Plasmas 14, 056301 (2007).

E16142

The laser-to-electron energy-conversion efficiency $\eta_{L \rightarrow e}$ is inferred from the absolute K_α yield

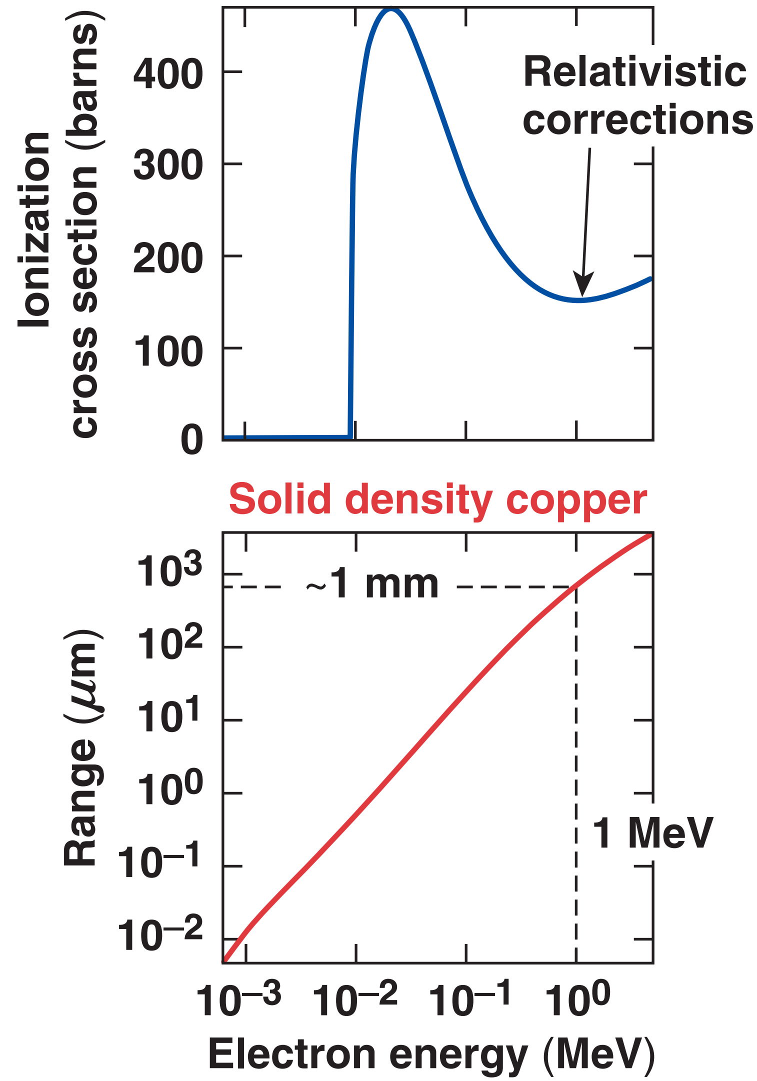
- Energetic electrons create K-shell vacancies ($E_k \gtrsim 9$ keV)
- K-shell emission comes from the cold bulk material during the fast- electron lifetime



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).

Refluxing in small-mass targets allows a number of simplifications in calculating K-photon production

- K-photon generation calculated as in an infinite medium
- Relativistic K-shell ionization cross sections[2] included
- Classical slowing down approximation (CSDA)[1]
- Fluorescence probability for cold matter is corrected for finite temperature



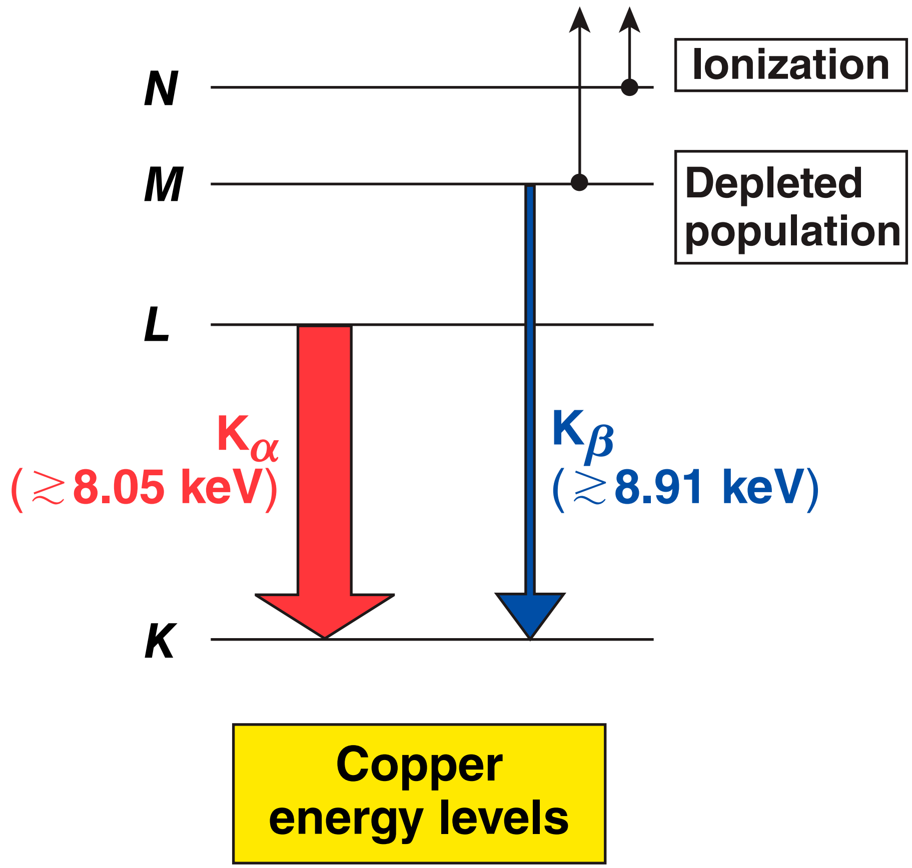
[1] H. O. Wyckoff, *ICRU Report* 37, Intern. Comm. on Radiation Units and Measurements, Inc., Bethesda, MD (1984).

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

TC7474b

Target bulk-heating affects *L*→*K* and *M*→*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

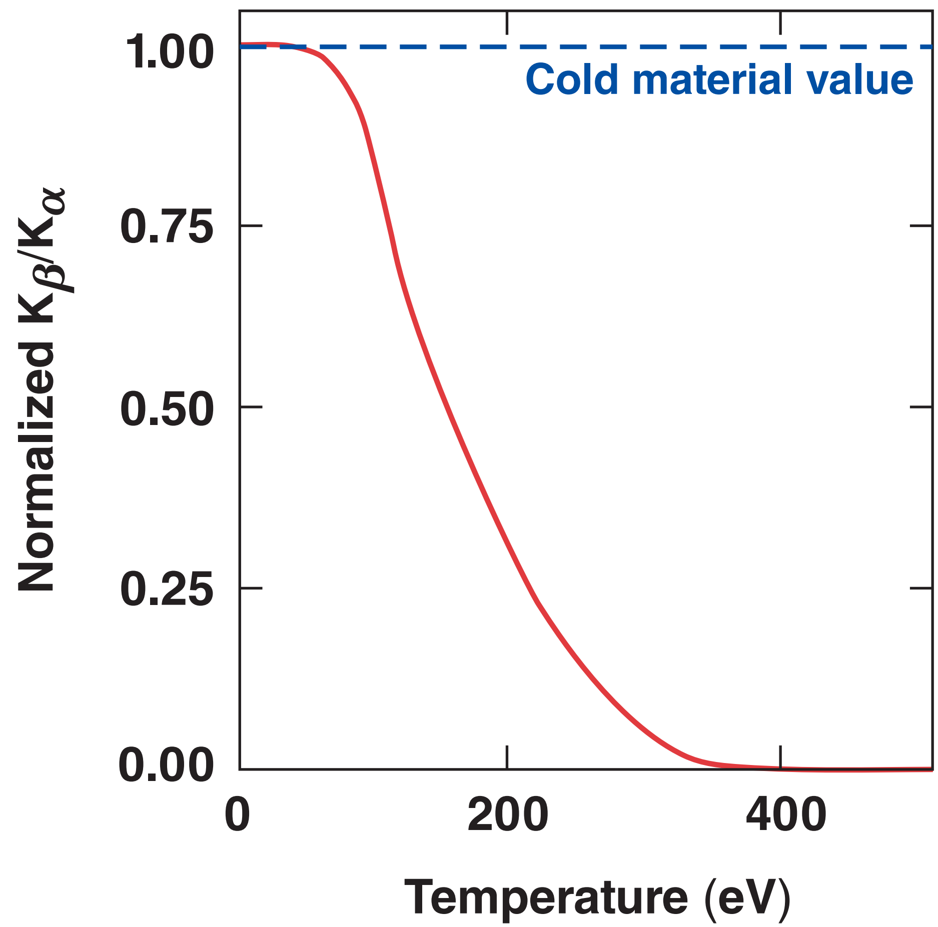


*J. Myatt *et al*., Phys. Plasmas 14, 056301 (2007).
*G. Gregori *et al*., Contrib. Plasma Phys. 45, 284 (2005).

E16143a

The K_β/K_α ratio is sensitive to the bulk-electron temperature

- In the cold limit $K_\beta/K_\alpha \approx 0.14$
- For T_e = 400 eV, the copper M-shell is completely depleted
- K_β/K_α variation with temperature can be studied experimentally using various mass targets (for fixed laser conditions)



Decreasing target volume →

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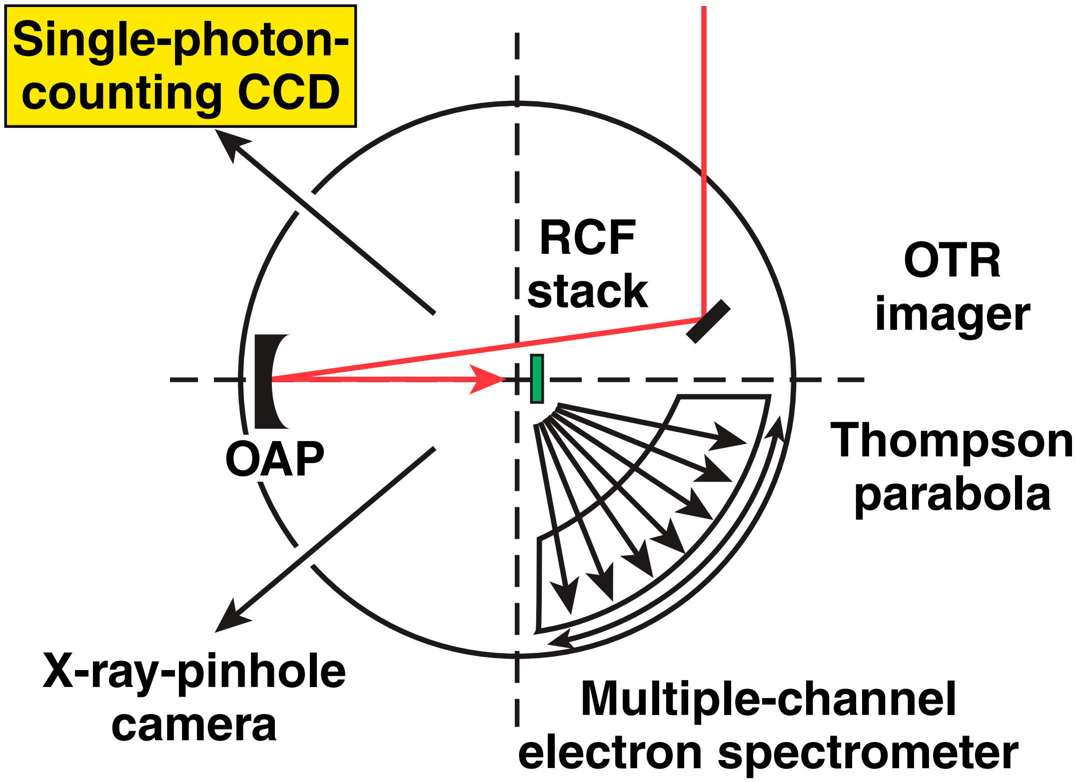
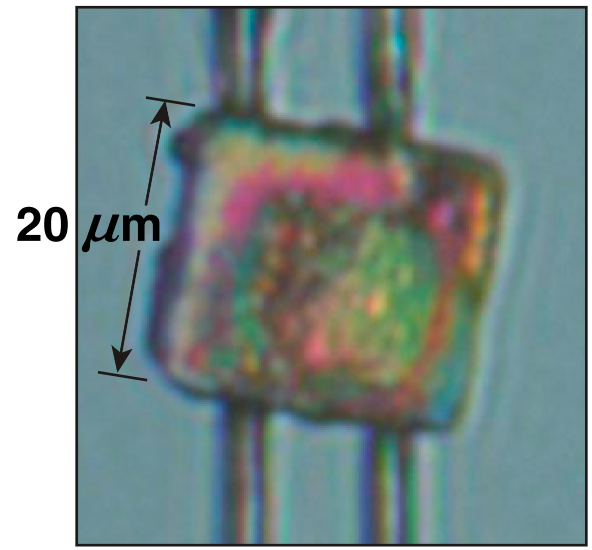
The experiments were performed on the Multi-Terawatt (MTW) Laser Facility at LLE

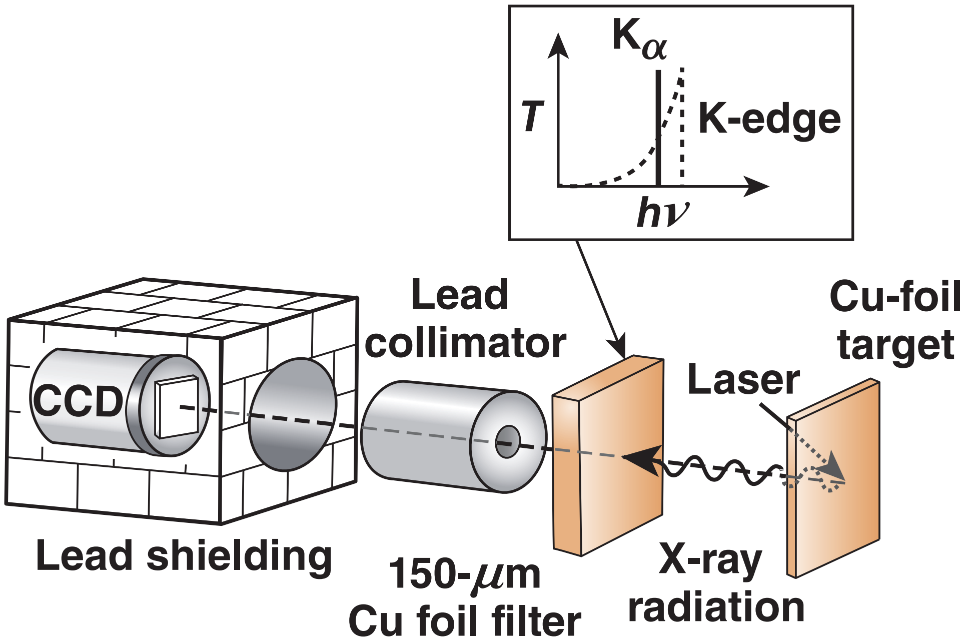


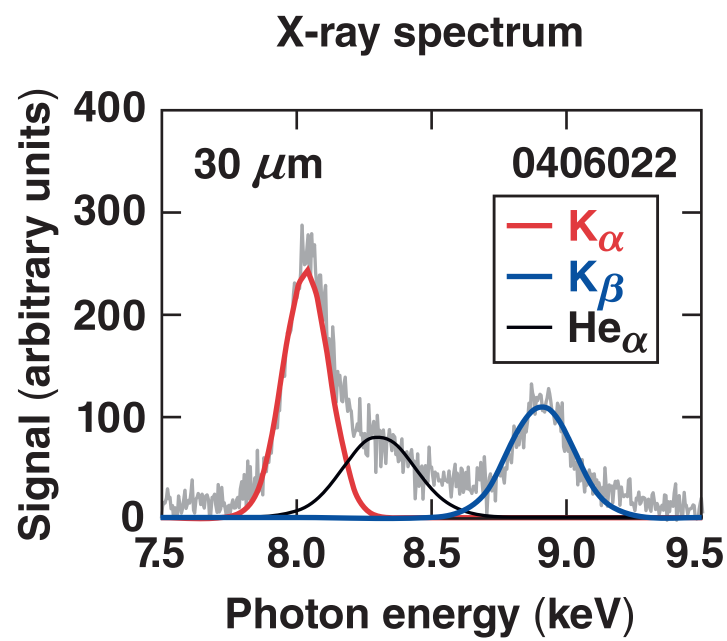


Spider-silk mounted $20 \times 20 \times 2\ \mu m^3$ copper target

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

A single-photon-counting x-ray CCD* measures the absolute K_α and K_β yields





*Stoeckl *et al.*, Rev. Sci. Instrum. 75, 3702 (2004).

The K_α production model requires the fast-electron spectrum and its intensity dependence to be specified

- An exponential fast-electron spectrum is assumed
- The fast-electron-temperature scaling with laser intensity is given by either a phenomenological scaling* or the ponderomotive scaling**

$$T_e\ (\text{MeV}) = 0.05\, I_{18}^{1/3}$$ ...for $I < 10^{18}$ W/cm^2

$$T_e\ (\text{MeV}) = 0.511\, [(1 + I_{18}\, \lambda_{\mu m}^2/1.37)^{1/2} - 1]$$ ...for $I > 10^{18}$ W/cm^2

* P. Gibbon and E. Förster, Plasma Phys. Control. Fusion 38, 769 (1996).
**S. C. Wilks *et al.*, Phys. Rev. Lett. 69, 1383 (1982).

E16316

The laser-to-electron energy-conversion efficiency $\eta_{L\rightarrow e}$ is inferred using a K_α production model

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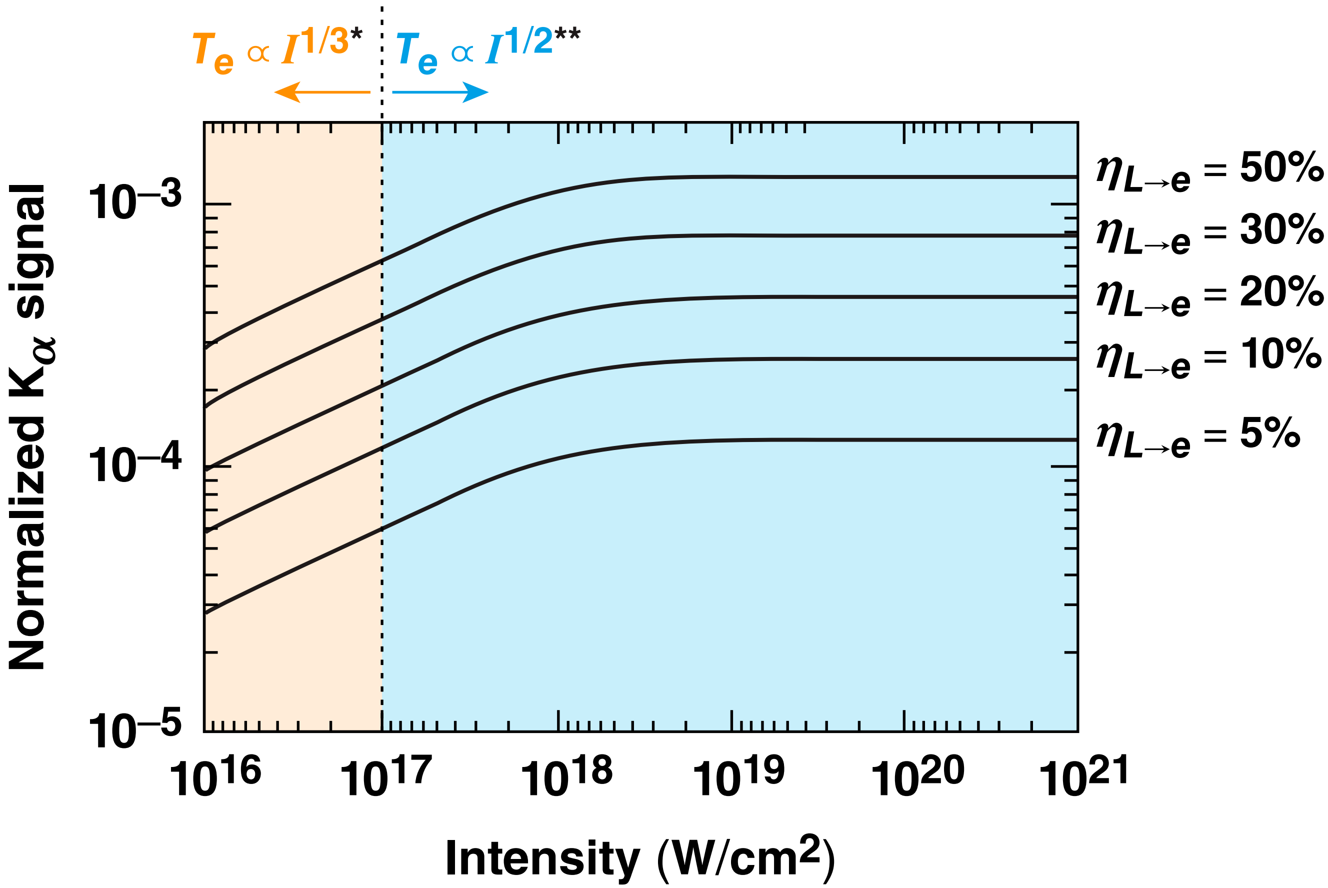
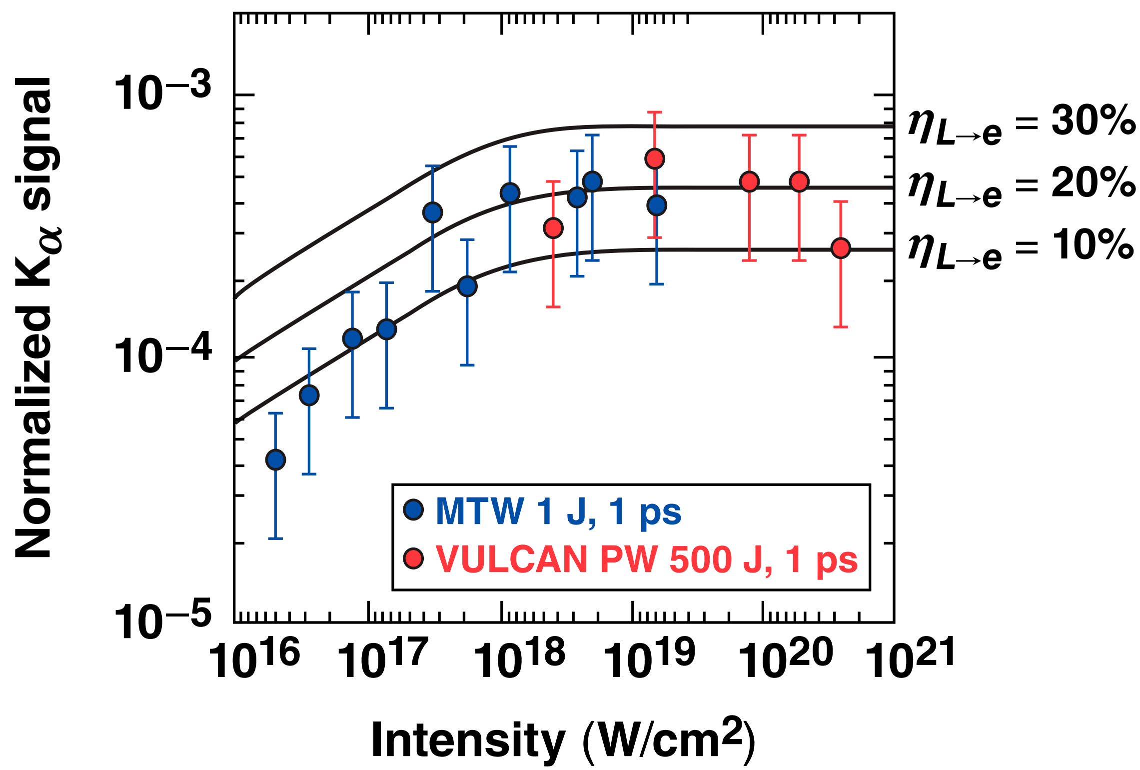


* P. Gibbon and E. Förster, Plasma Phys. Control. Fusion 38, 769 (1996).
**S. C. Wilks *et al*., Phys. Rev. Lett. 69, 1383 (1982).

E16145

K_α yields are consistent with the refluxing electron model assuming $\eta_{L\rightarrow e}$ = 20% and $I > 10^{18}$ W/cm^2

- K_α production is insensitive to fast-electron energy spectrum and range for $I > 10^{18}$ W/cm^2
- Confirms previous observations from Vulcan PW*



Cu targets: 500 × 500 × 20 μm^3

E16150

*W. Theobald *et al.*, Phys. Plasmas 13, 043102 (2006).

K_β/K_α variations with target heating were observed in experiments on the Vulcan Laser Facility*

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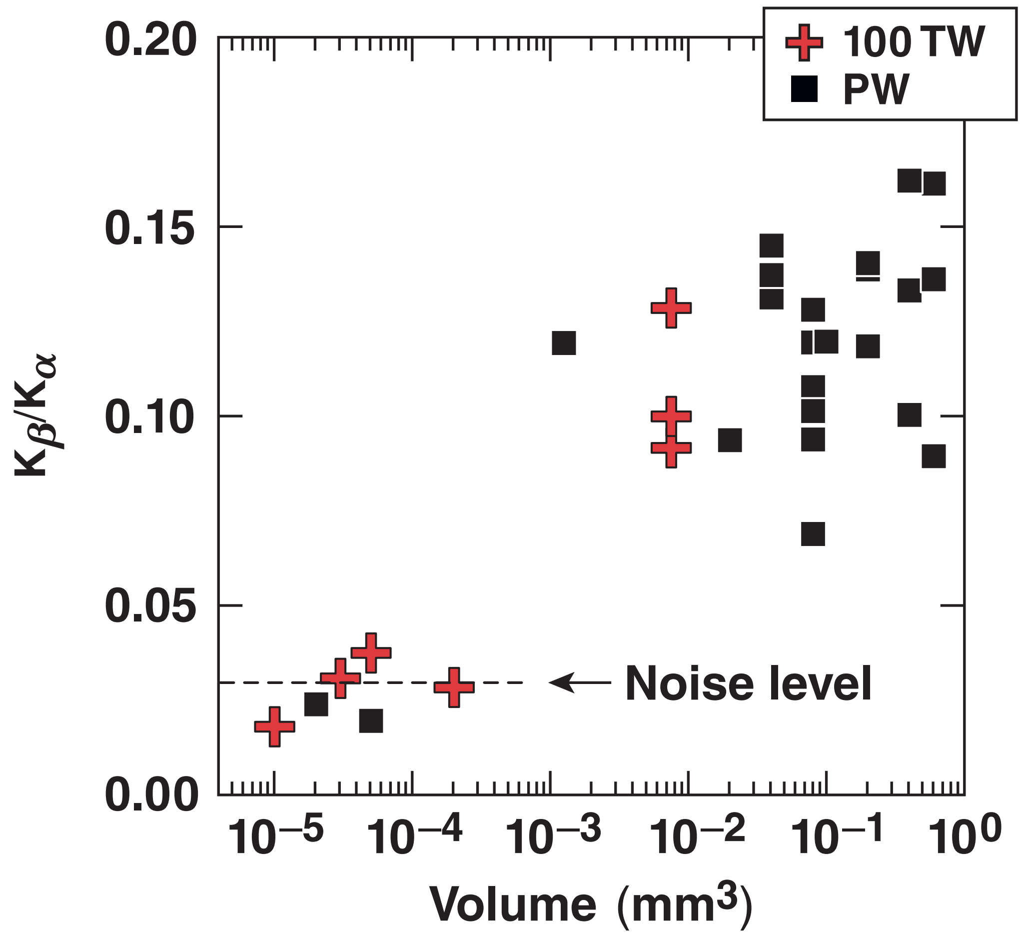
- Large scatter in datasets
- Scale targets to MTW (5 J, 1 ps) accordingly

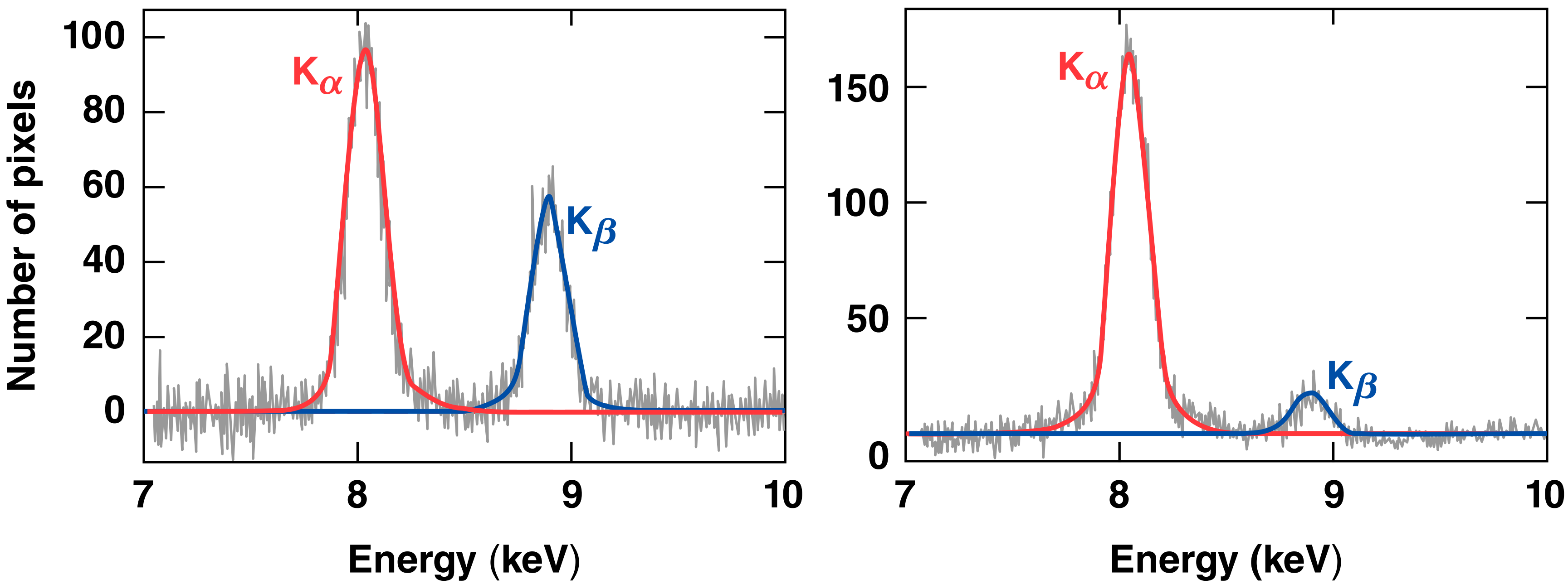


E16317

*W. Theobald *et al*., Phys. Plasmas 13, 043102 (2006).

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

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

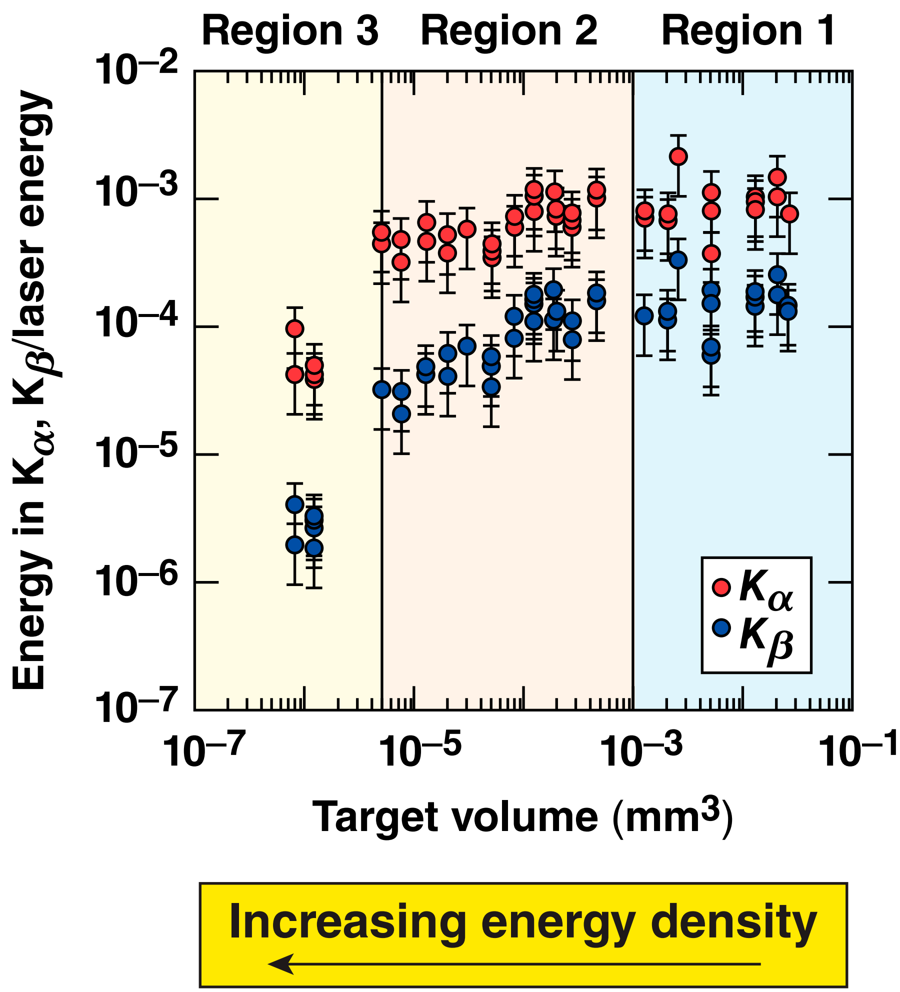


Cu target: $(500 \times 500 \times 50)\ \mu m^3$

Cu target:$(20 \times 20 \times 3)\ \mu m^3$

E16040

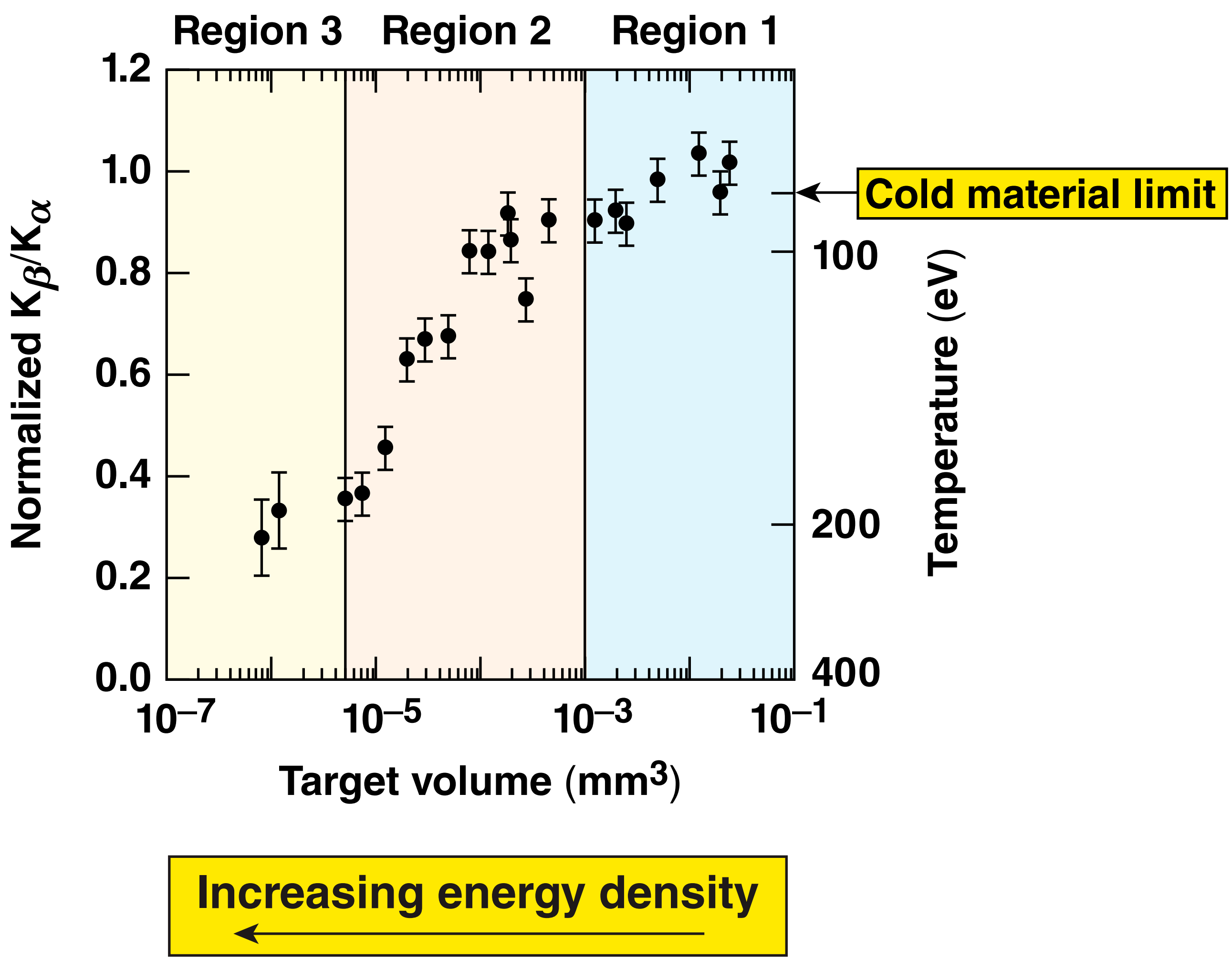
Three regimes are observed in the K-shell emission spectra due to an increase in energy density



- Copper target: 5 J, 1 ps
- Intensity: 2×10^{19} W/cm^2
- Region 1:
  cold material limit
- Region 2:
  K_α yield constant,
  K_β yield falls
- Region 3:
  both K_α and K_β
  yields decrease

E16041

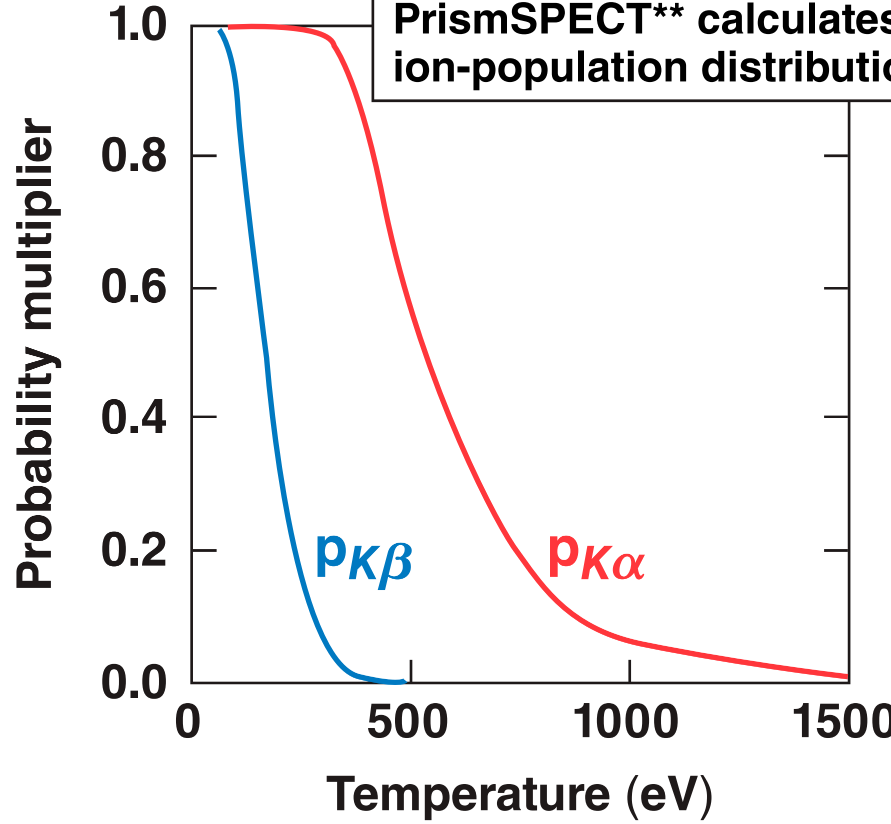
A 3.5× reduction of K_β/K_α for target volumes $V = 10^{-6}$ mm^3 is consistent with bulk-electron temperatures $T_e \approx 200$ eV



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

- 3-D *LSP** calculates target heating
- Fast-electron source is prescribed with varying energy
- Same target volumes and interaction timescales are modelled (no scaling)
- Assumes a Thomas–Fermi model
- Calculates EM fields self-consistently
- Emission probability calculated using the local temperature at the time of emission

PrismSPECT** calculates ion-population distribution

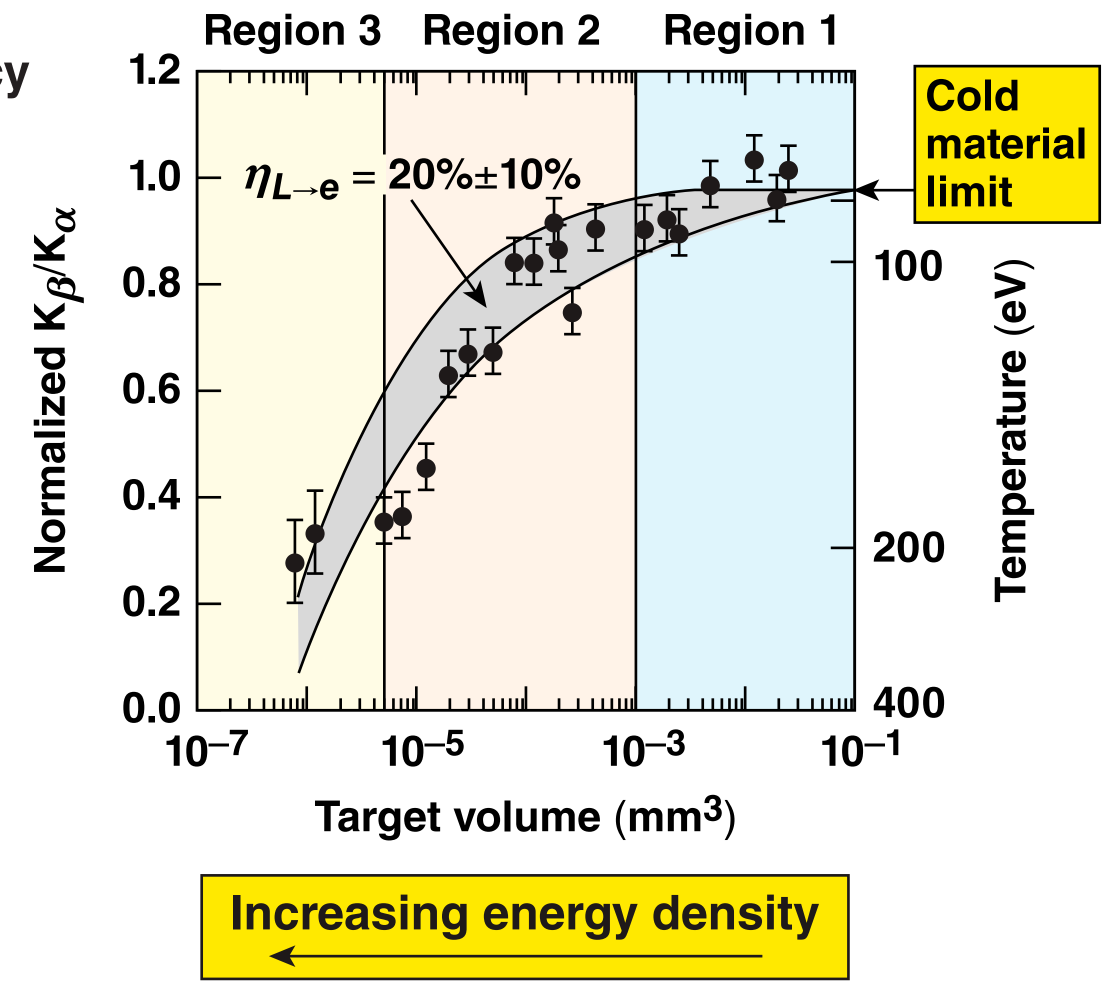


* D. Welch *et al.*, Nucl. Inst. Methods Res. A 464, 134 (2001).
** Prism Computational Sciences, Inc., Madison, WI 53711

E16038

A comparison of K_β/K_α to *LSP* calculations give $\eta_{L\rightarrow e} \approx$ 20% consistent with those from fitting the absolute K_α yield

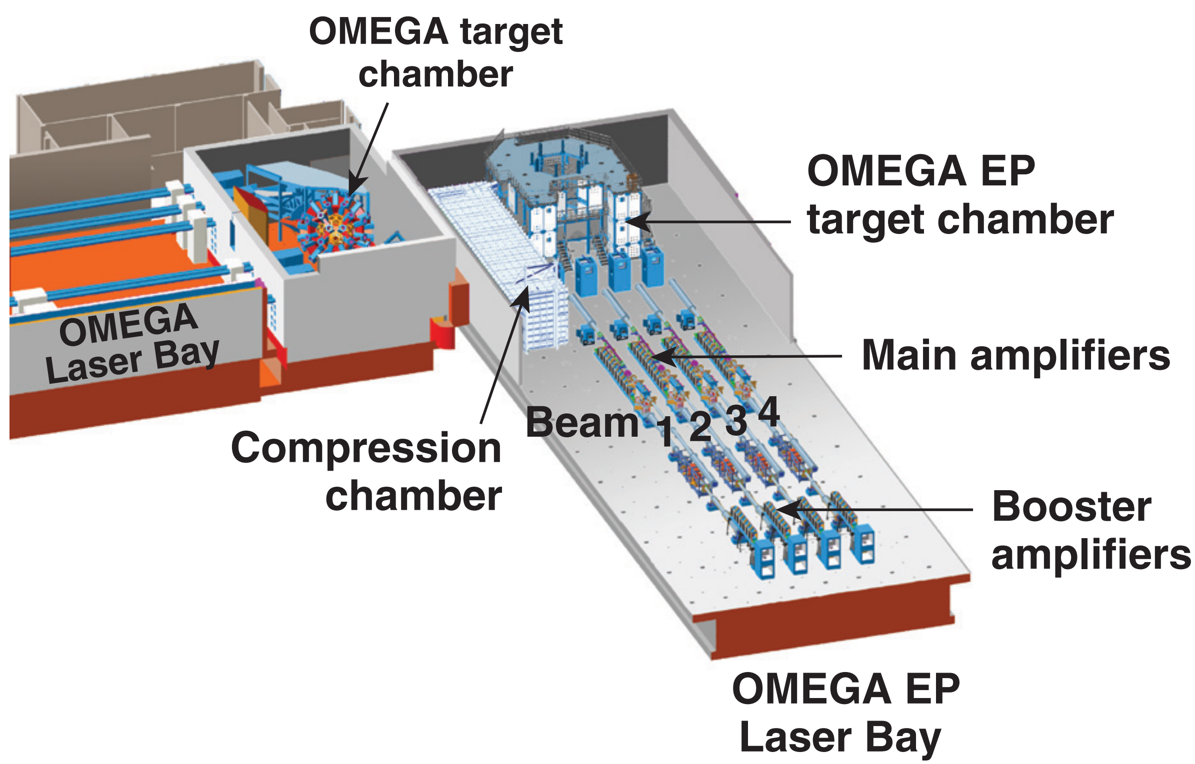
- Provides a self-consistency check on $\eta_{L\rightarrow e}$
- Confirms that the dominant physics in the simple refluxing K_α production model are correctly accounted for
- Provides a detailed data set for comparison to future experiments at higher energy densities



E16314

OMEGA EP will allow access to temperatures $T_e > 1$ keV using refluxing in small-mass solid targets

- OMEGA EP: 2.6 kJ, 10 ps
- Relevant to backlighter applications
- Relevant to fast ignition
- Study $\eta_{L\rightarrow e}$ up to the 10-ps regime
- Benchmark codes



D. D. Meyerhofer (TO6.00001)

Summary/Conclusions

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- K_β/K_α signals are consistent with numerical target-heating calculations for $\eta_{L \to e}$ = 20%±10% over a wide range of target volumes

Solid-density material heated to >200 eV using a 5 J, 1-ps laser pulse

E16140