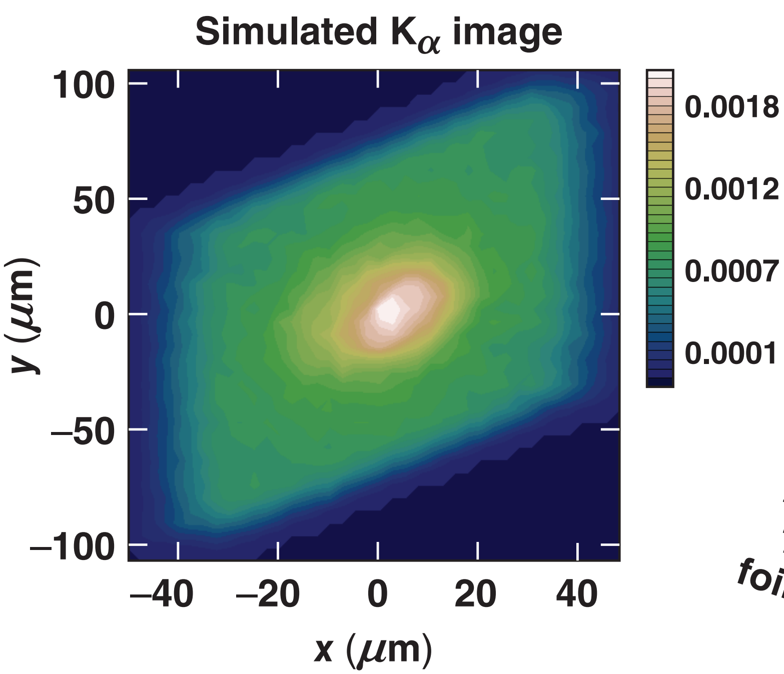
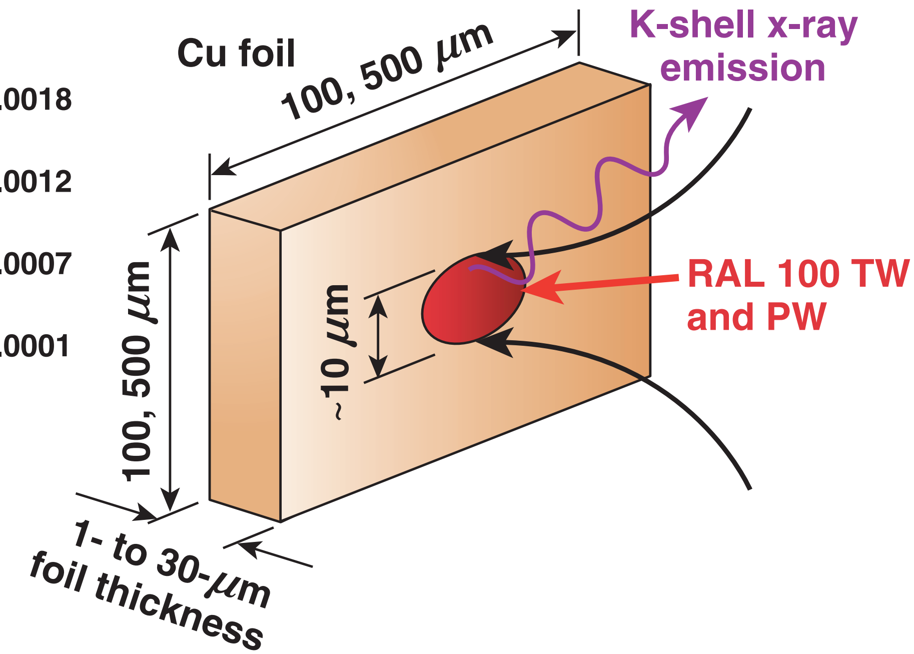
High-Intensity Laser Interactions with Solid Targets and Implications for Fast-Ignition Experiments on OMEGA EP





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

Summary

K_α and K_β emission from PW laser interaction with mass-limited foils at RAL is well predicted

UR LLE

- A semi-analytic model describes the K_α data well and is supported by implicit-hybrid PIC calculations (*LSP**).
- Mass-limited targets simplify the modeling (good "test bed" for FI).
- The experimental K_α yields are consistent with classical stopping and a constant hot-electron conversion efficiency of ~10%.
- The ratio of K_β to K_α signal is sensitive to target heating and provides a consistency check on conversion efficiency.

*D. Welch *et al*., Nucl. Instrum. Methods Phys. Res. A 464, 134 (2001).

TC7467

Collaborators

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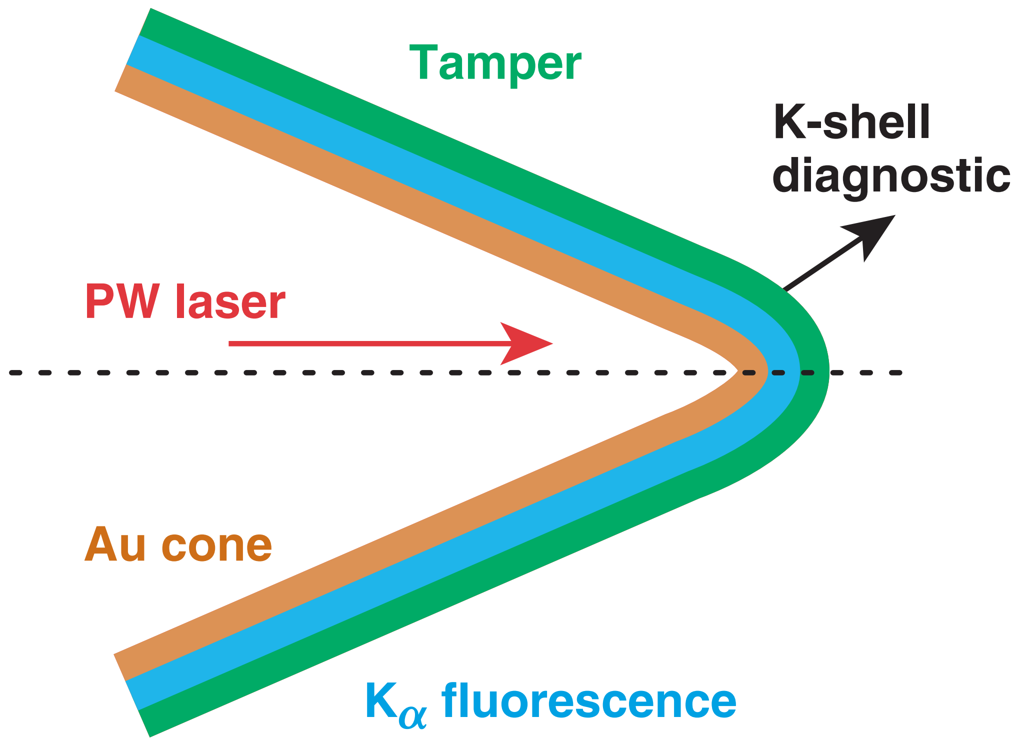
Outline

- Petawatt-foil experiments are relevant to FI scheme, particularly cone-in-shell
- Experiments
- Mass-limited targets
- Conversion efficiency
- Target heating
- Future experiments

PW-foil experiments are relevant to cone-in-shell fast ignition and high-brightness backlighting

- In the cone-in-shell scheme, the PW laser interacts with a solid–density interface
- Foils are a simple test bed for:
  - hot-electron spectrum
  - conversion efficiency
  - transport
- Interaction conditions are similar



K-fluorescence from high-intensity laser-irradiated mid-Z foils provides an important diagnostic of hot electrons*

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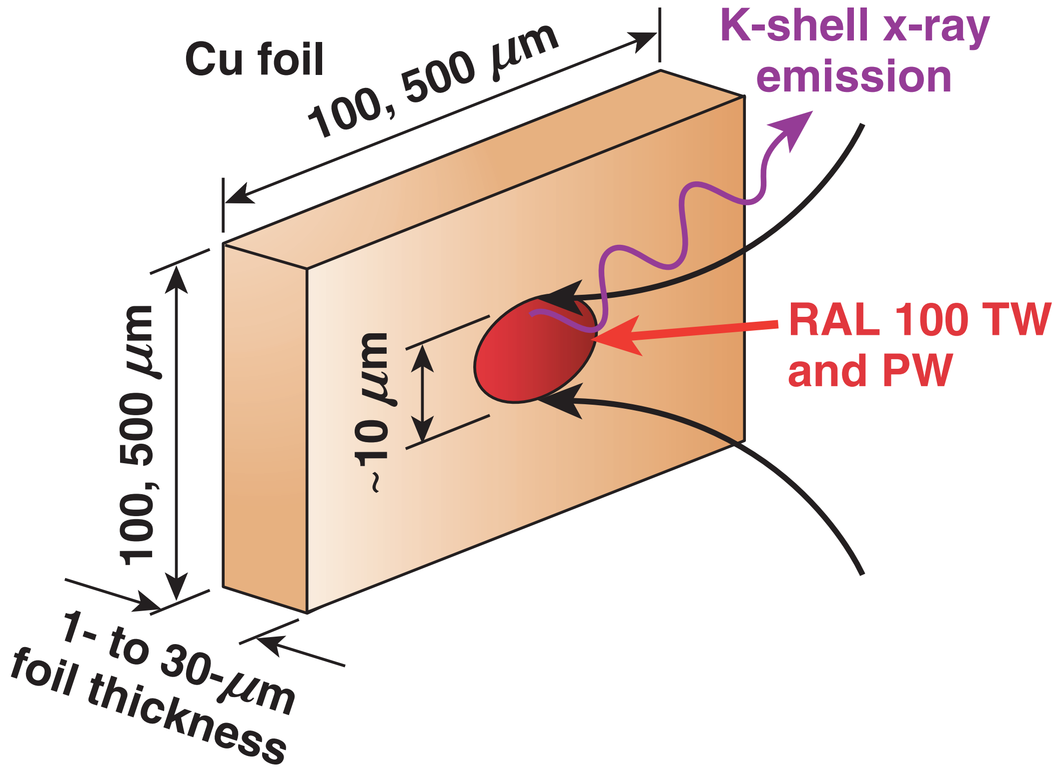
- Hot electrons create K-shell vacancies
- L→K (M→K) transition gives K_α (K_β) emission
- Emission occurs during hot-electron lifetime (few ps)



* R. B. Stephens *et al*., Phys. Rev. E 69, 066414 (2004).
J. D. Hares *et al*., Phys. Rev. Lett. 42, 1216 (1979).

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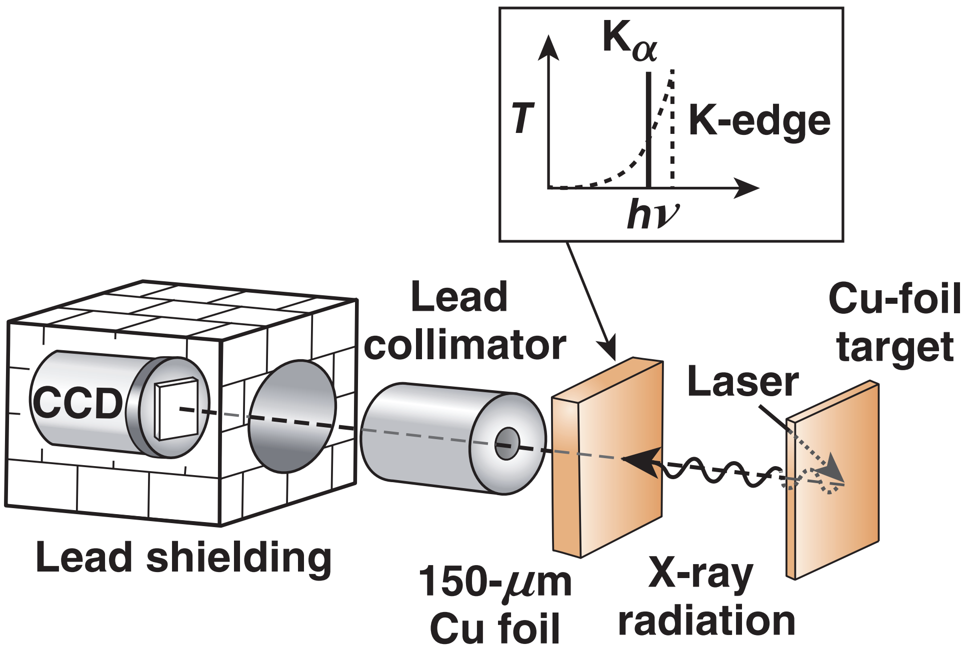
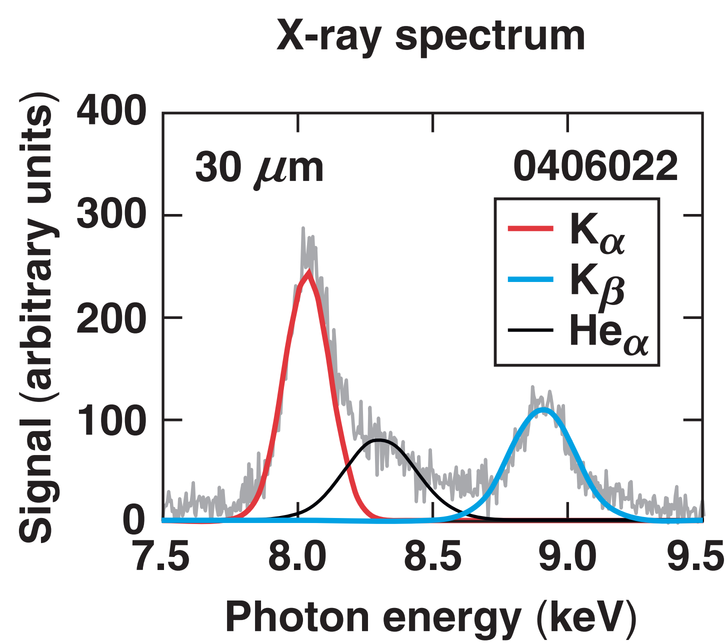
Measurements of K-shell emission from mass-limited targets have been performed at the RAL 100 TW and PW facilities*

- Laser intensities of $10^{18} < I < 10^{20}$ W/cm^2
- A range of target volumes: $10^{-5} < V < 10^{-1}$ mm^3
- Solid copper targets





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*W. Theobald *et al.*, Phys. Plasmas 13, 043103 (2006).

Mass-limited targets have some remarkable properties that simplify the modeling

- The majority of hot electrons stop in the target due to space-charge (refluxing)
- Secondary radiation production is simple to compute (as in infinite medium)
- Efficient K_α, K_β radiators
- Transparent to K-shell x rays
- Access high temperatures at solid density
- Can be used to benchmark codes—*LSP* can model the whole target in 3-D (implicit-hybrid mode)
- Good test bed for hot-electron conversion and volumetric heating

A combination of semi-analytic modeling and implicit-hybrid PIC calculations have been used to investigate RAL 100 TW and PW experiments

- The semi-analytic model is a modification of calculation in Green and Cosslett*
  - classical CSDA stopping, relativistic K-ionization cross sections
  - refluxing effect is included
  - re-absorption included
- *LSP* contains additional physics
  - collision model requires tuning
  - self-generated fields
  - resistive inhibition and instability of hot current
  - target heating

*M. Green and V. E. Cosslett, J. Phys. D 1, 425 (1968).

TC7472

The refluxing efficiency is a parameter in the model, but in *LSP* the trajectories are computed self-consistently

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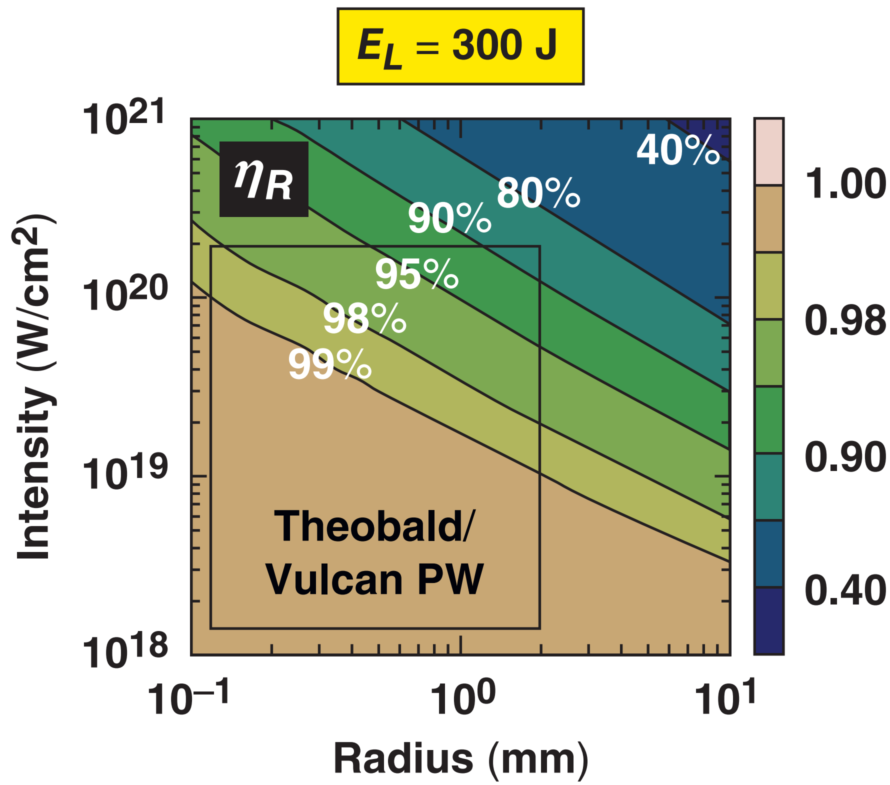
- For the parameters of the RAL experiments, the hot electron refluxing is nearly perfect.
- A capacitor/Boltzmann electron model is used to estimate the importance of refluxing.



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Both the semi-analytic model and *LSP* require the hot-electron spectrum and its dependence on laser intensity to be specified

- We chose an exponential distribution for hot-electron energy characterized by a temperature T_{hot}.
- We assume that for different laser intensities the distribution is changed through only the temperature moment.
- Intensity is allowed to be a function of space.
- The temperature is given by the "ponderomotive scaling" (Wilks*).

$$T_{hot}\,(\text{MeV}) = 0.511\left[\left(1 + I_{18}\lambda^2_{\mu m}/1.37\right)^{1/2} - 1\right]$$

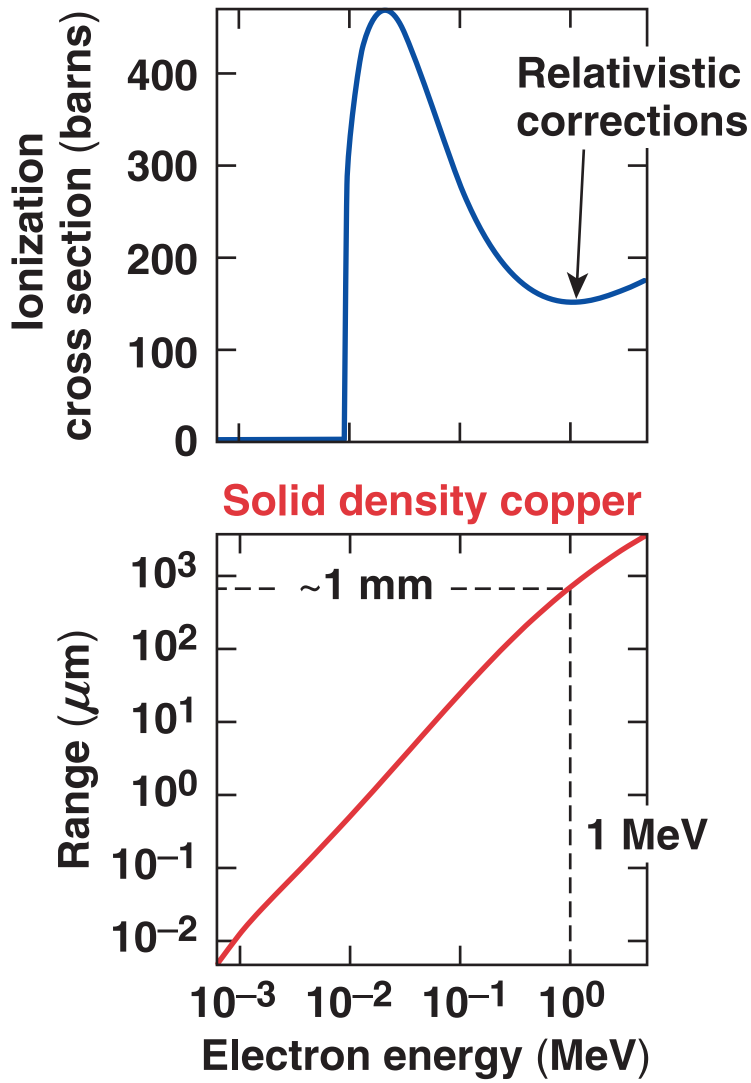
TC7475

*S. C. Wilks *et al*., Phys. Rev. Lett. 69, 1383 (1992).

To complete the model K-shell ionization cross section and hot-electron stopping power are required

- $\sigma_K(E)$ [taken from Kolbenstvedt[1]], relativistic corrections are essential
- The fluorescence probability ω_K is taken for cold matter at solid density
- CDSA range[2]

Need to specify: $E_e (= \eta_{L \rightarrow e} E_L)$



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

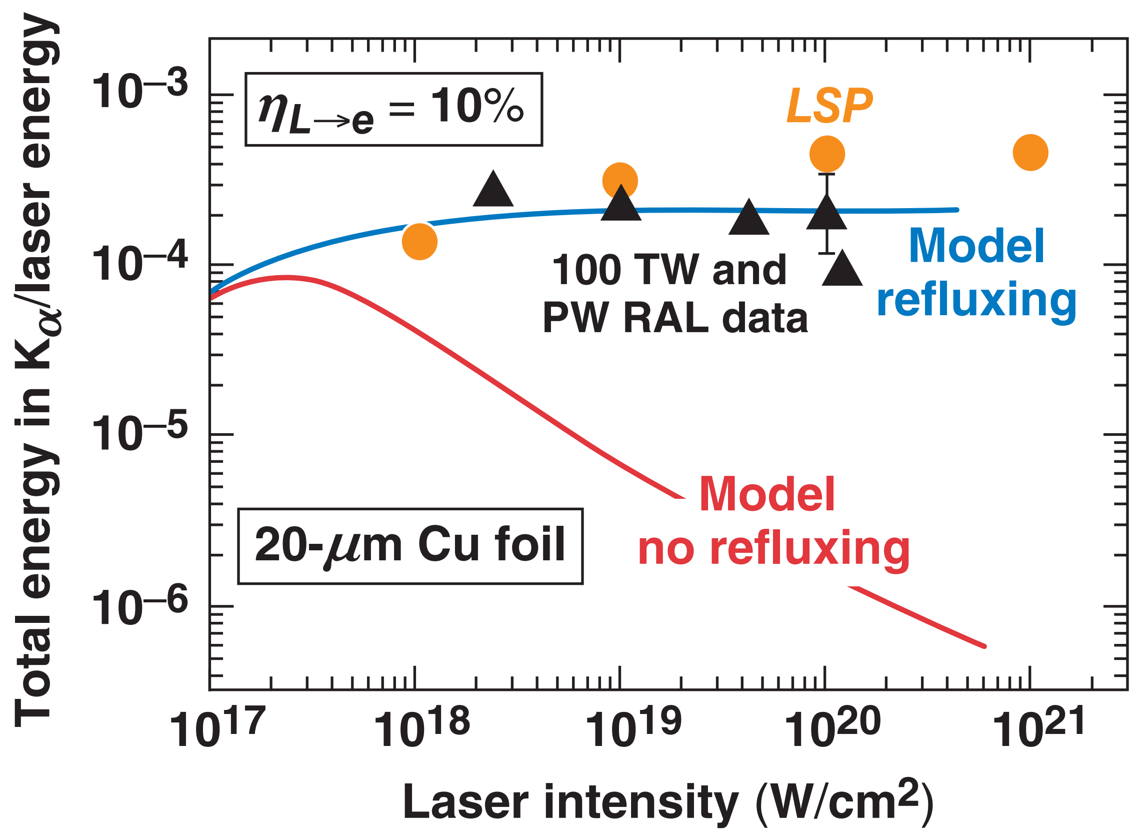
[2] H. O. Wyckoff, *ICRU Report* 37, Intern. Comm. on Radiation Units and Measurements, Inc., Bethesda, MD (1984).

TC7474

The semi-analytical model and the *LSP* calculations agree on the K_α yield

UR LLE

- Hot electron range in *LSP* is the same as CSDA range
- Insensitivity to the laser energy is a direct result of refluxing



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Resistive inhibition would reduce the hot-electron range and lead to a lower K-fluorescence production efficiency

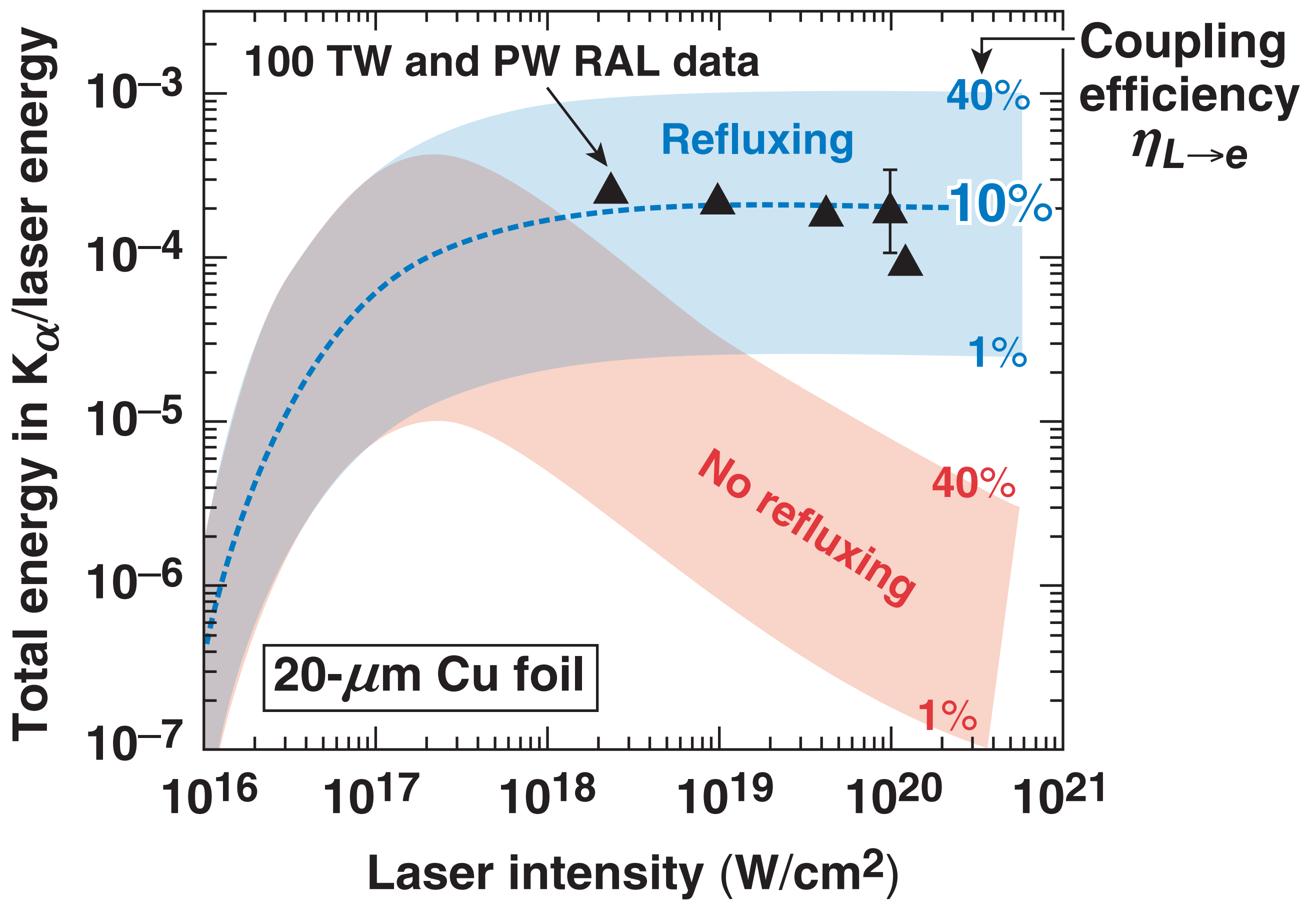
UR LLE

- *LSP* calculations, using Lee and Moore electrical conductivity, show that resistive inhibition is unimportant for the parameters of the RAL experiments
- Compare classical range with "resistive range"
- The electric field E (= j/σ_{Cu}) ~2 × 10^5 kV/cm and would stop a 1-MeV electron in 50 μm.
- This is much less than the collisional range ~700 μm at 1 MeV
- Greater than target thickness
  - refluxing hot electrons provide the return current (much less collisional)
- Transit time is only 0.1 ps

The hot-electron conversion efficiency can be determined by a fit to the RAL data

UR LLE

- The experimental data (here for a particular geometry) is consistent with a constant conversion efficiency of ~10%.

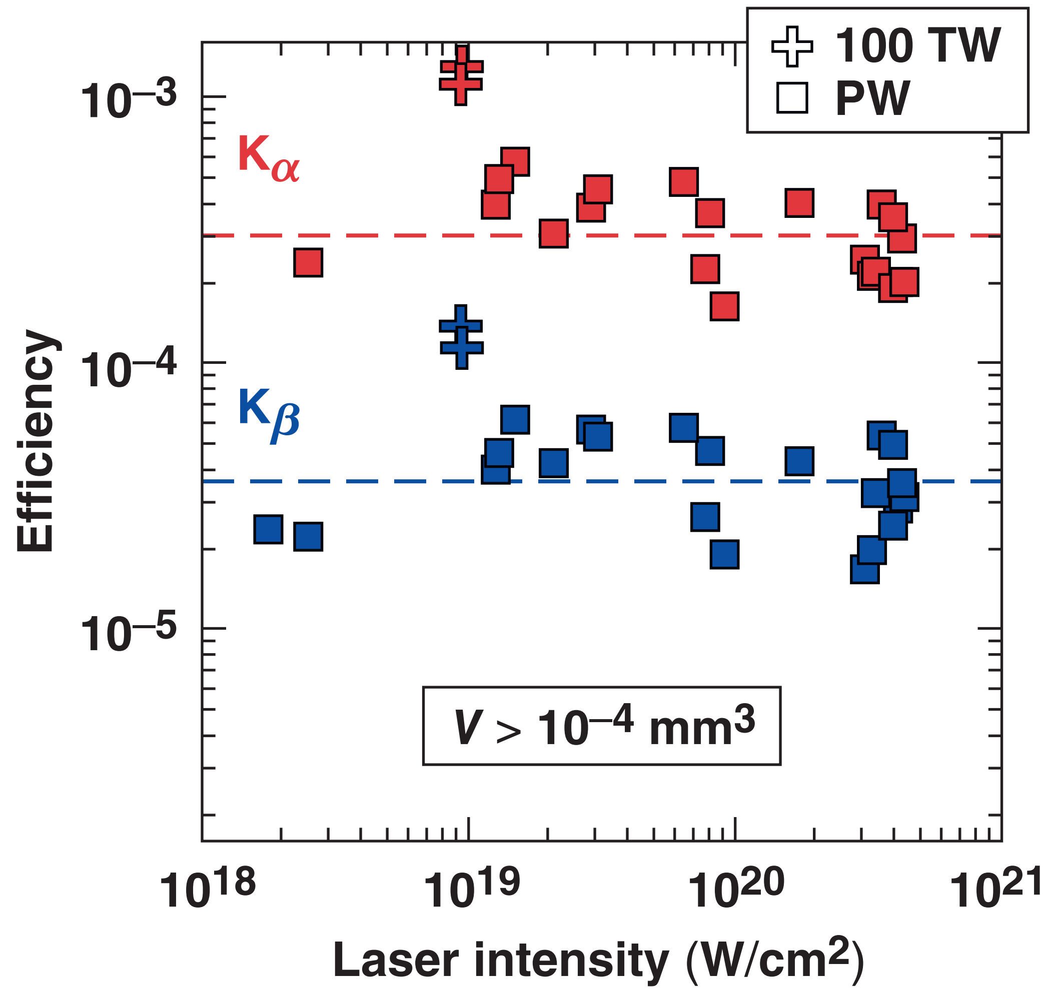


TC7243a

The experimental K_α and K_β yields are essentially independent of the target geometry and laser intensity

UR LLE

- This is a direct prediction of refluxing plus cross-section and stopping power
- E_L varies by a factor of 5
- Foil geometry varies widely $10^{-4} < V < 10^{-1}$ mm^3
- Very small mass targets ($V < 10^{-4}$ mm^3) are excluded



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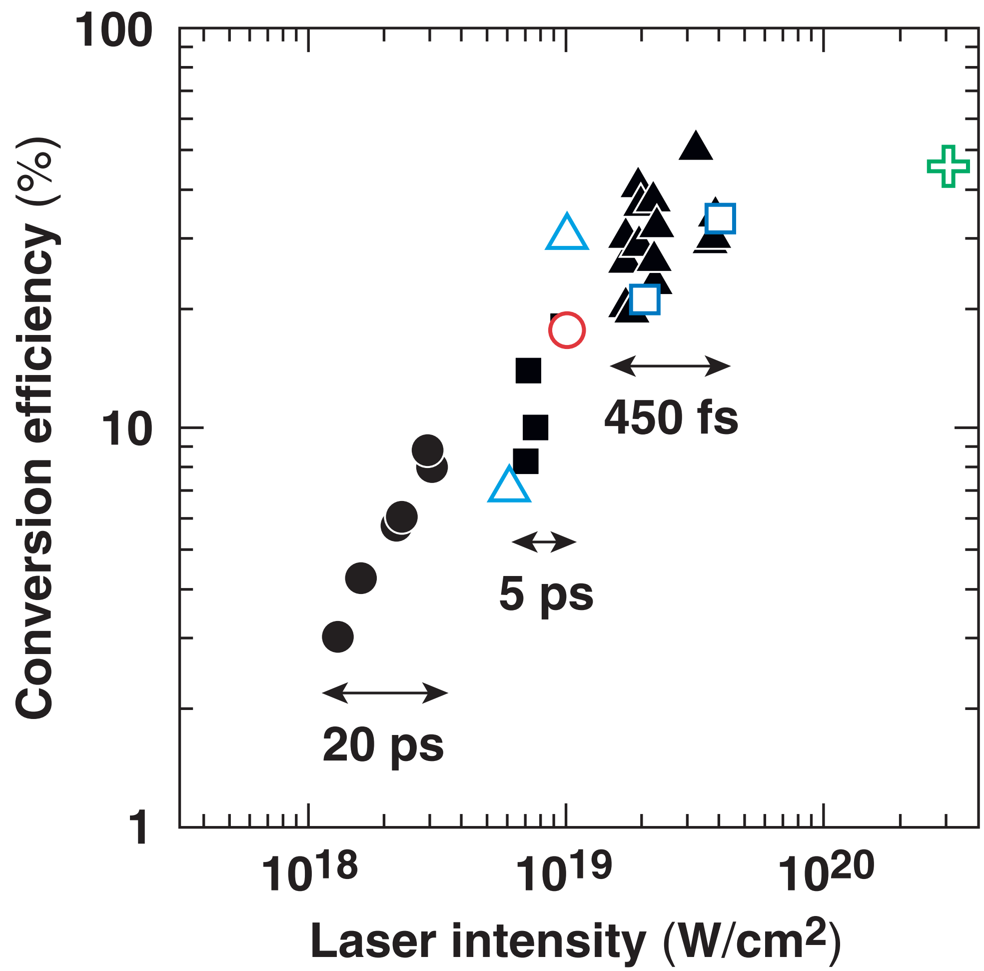
Previous experiments* indicated that the hot-electron conversion efficiency increases dramatically with laser intensity

- These experiments are compromised by poorly characterized interaction conditions.
- These are indirect measurements and rely on model calculations.



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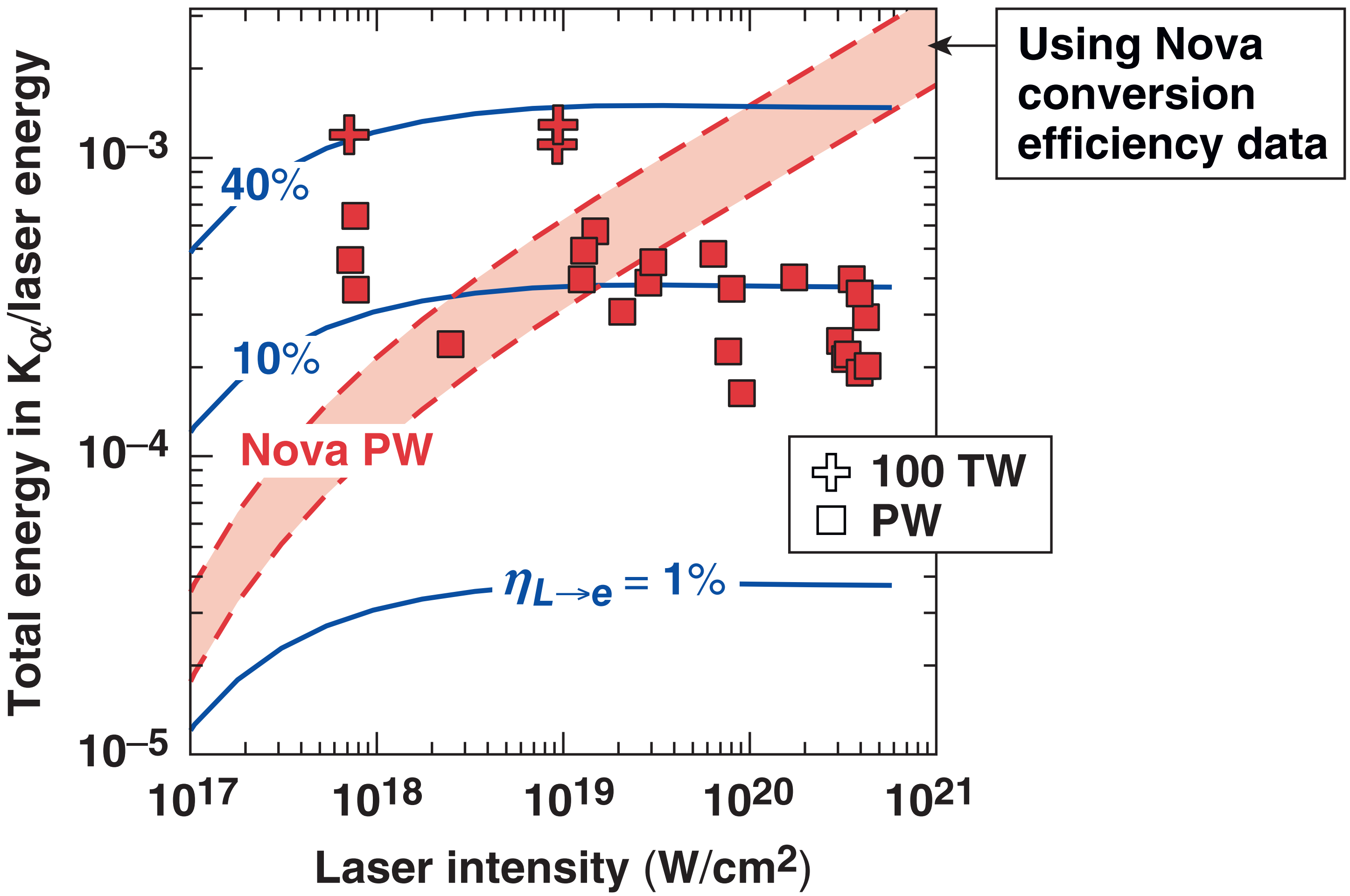
*M. Key *et al.*, Phys. Plasmas 5, 1966 (1998).

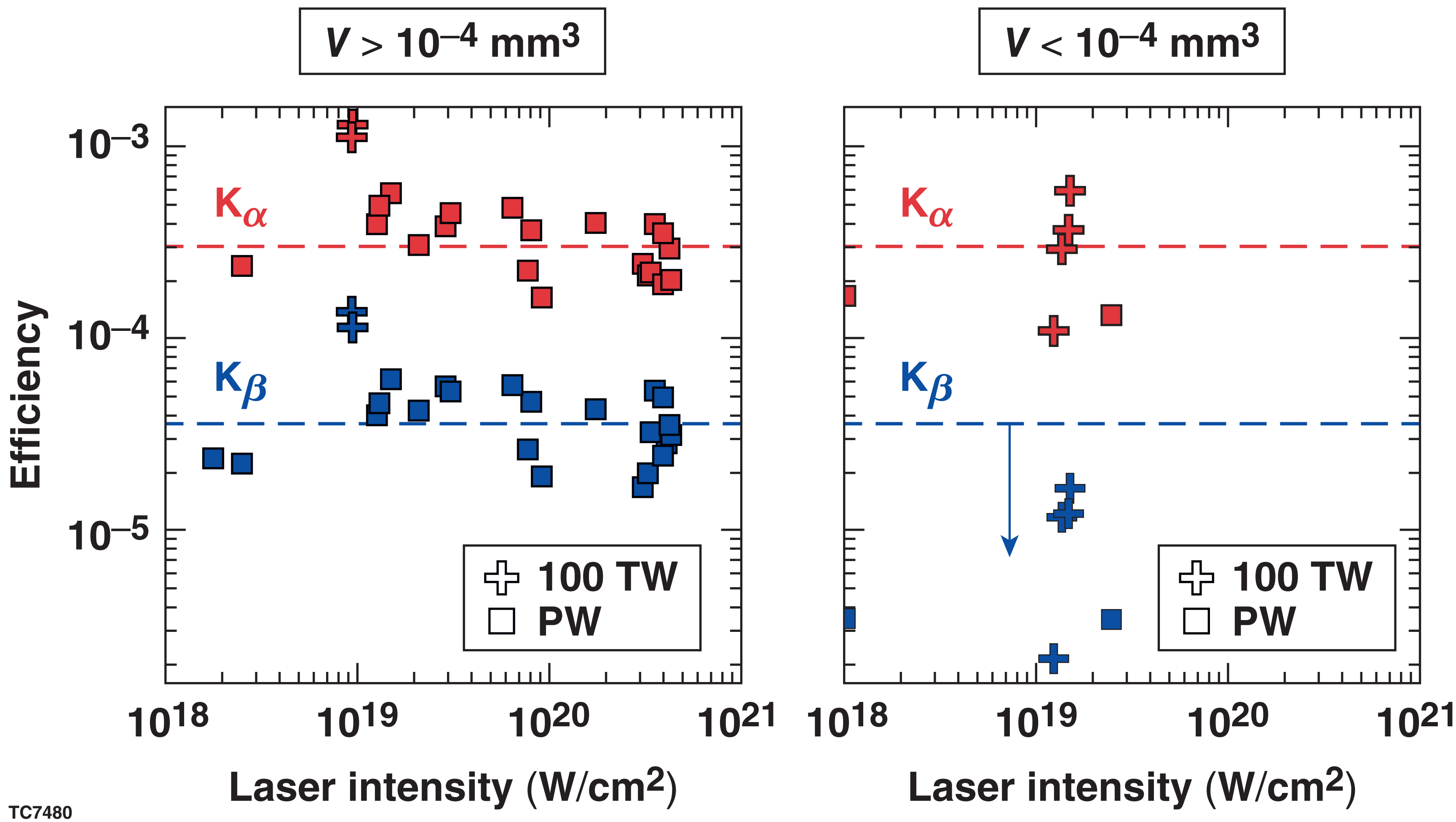
The model is completely specified if the hot-electron conversion efficiency is known



The K_β/K_α ratio can be used as a consistency check on the hot-electron conversion efficiency

UR LLE

- For small volume targets, $V < 10^{-4}$ mm^3, the K_β efficiency is dramatically reduced



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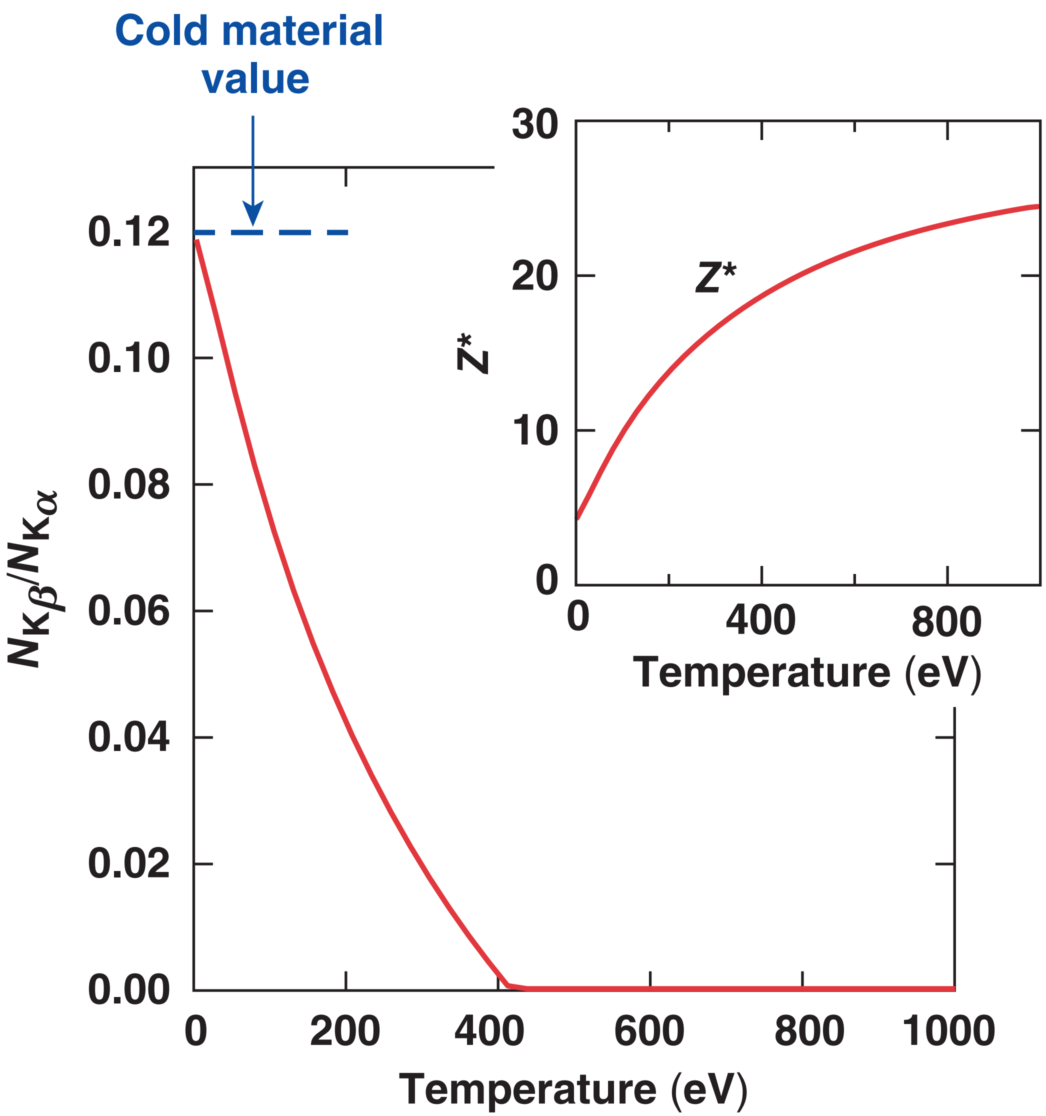
The reduction in K_β/K_α ratio for small target volumes is expected due to target heating

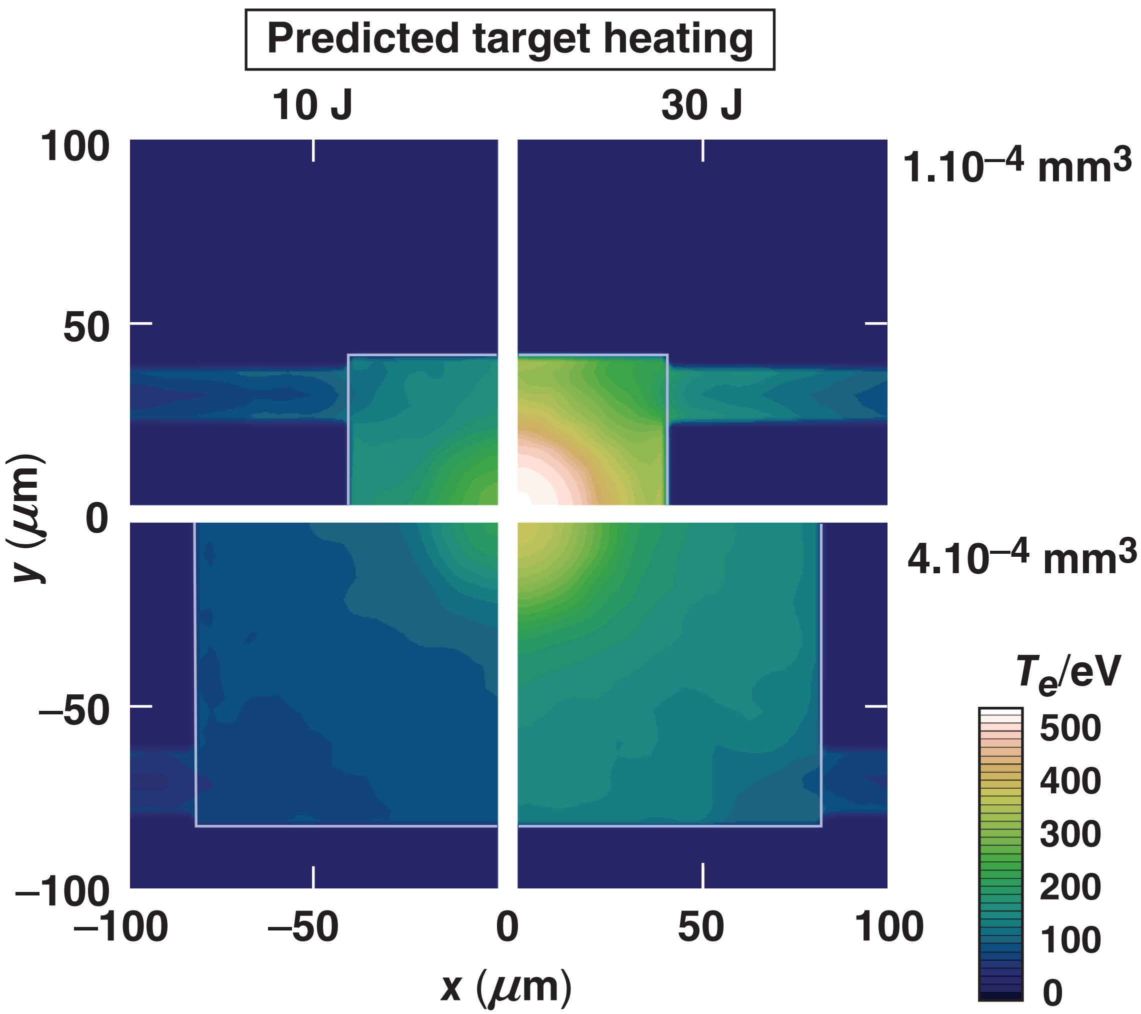
- Small volume targets can reach temperatures of several hundred eV
- Depletion of the copper M-shell reduces the K_β emission relative to K_α
- We use T-F to get Z^* from local $[n(x,t), T(x,t)]$
- Modify $(p_{K\alpha}, p_{K\beta})$ appropriately



TC7481

3-D *LSP* calculations predict target heating for a given conversion efficiency

- Essentially all of the hot-electron energy is deposited in the target
- Temperature rise depends upon the energy deposited
- Assuming Thomas–Fermi EOS model
- Smallest volume $V \sim 10^{-4}$ mm^3 targets are predicted to reach several hundred eV



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The K_β/K_α ratio is computed in *LSP* by modifying the K-photon emission probabilities using the local temperature

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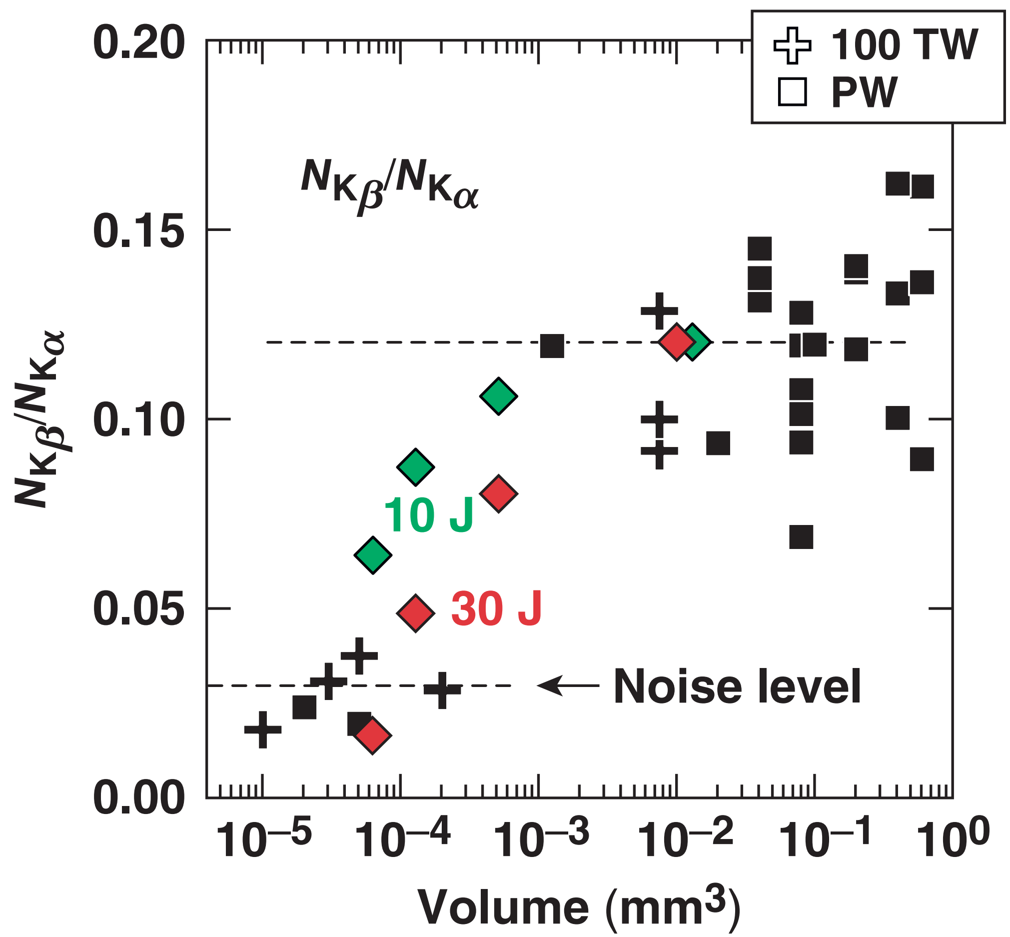
- The data is not sufficiently precise to either confirm or reject the conversion efficiency obtained by fitting the absolute K_α yield
- Spatial/temporal profile has to be taken into account (*LSP*)



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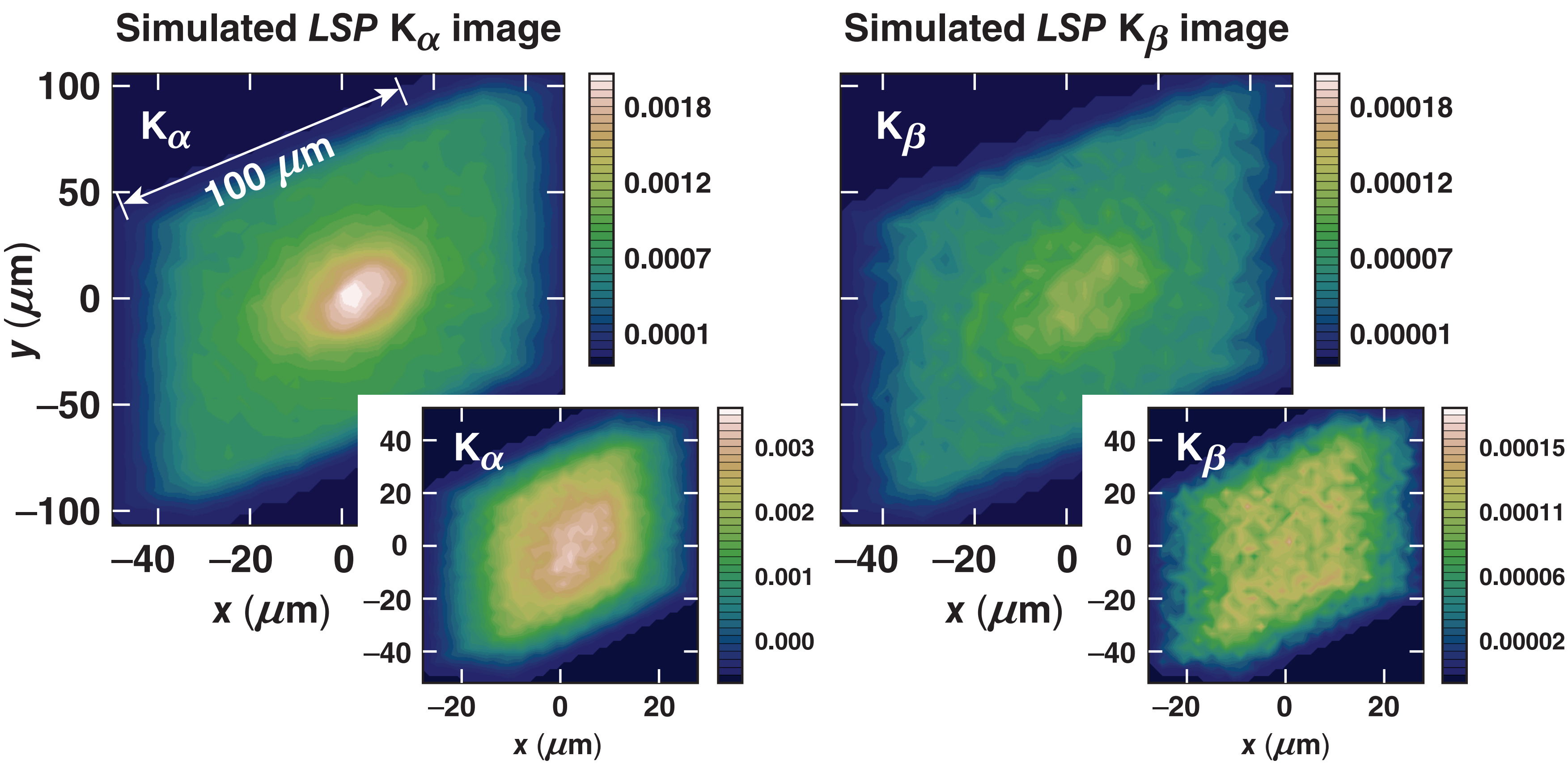
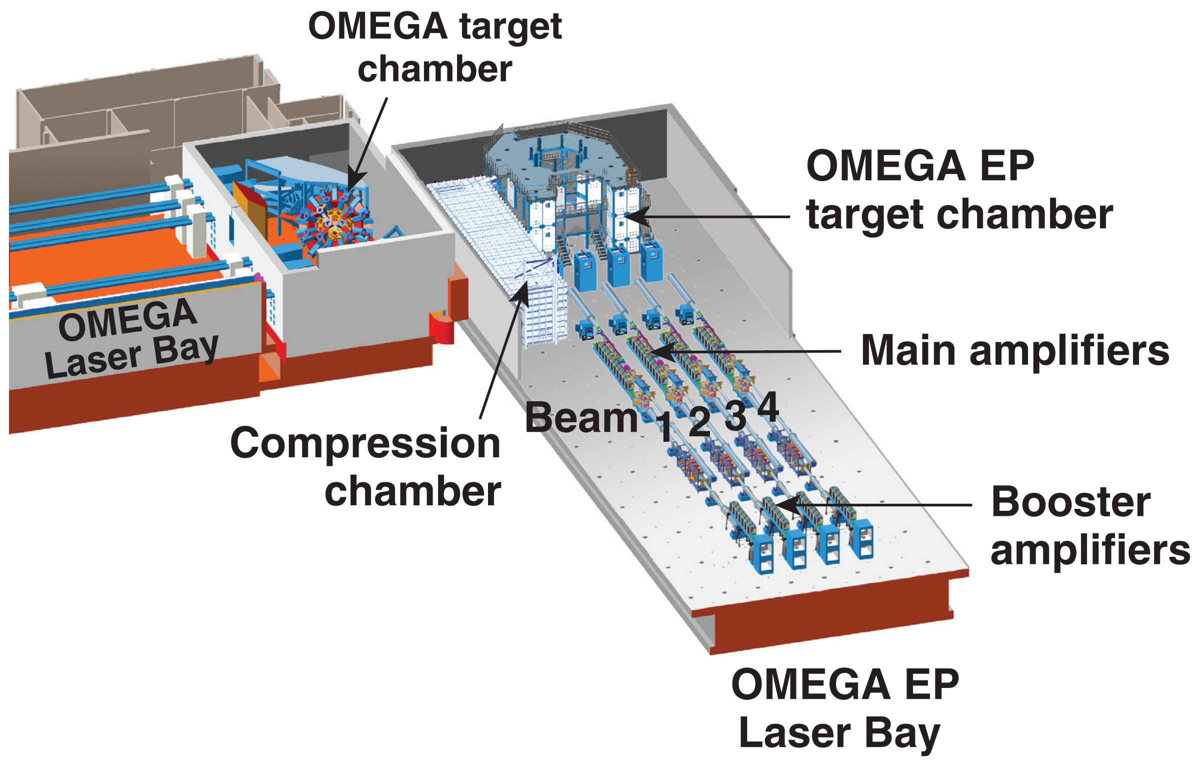
LSP calculations predict the spatial distribution of K-emission which will be compared with experiment

Three-dimensional *LSP* calculations



The results suggest future mass-limited foil experiments on OMEGA EP

- Dedicated experiments with well-characterized interaction conditions
- K_{β}/K_{α} ratio probes bulk temperature
  - relevant for FI
  - imaging
- Consistency between absolute yield and line ratio
- XUV probes surface temperature
- Benchmark codes



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