Fast Electron Conversion Efficiency Scaling with Prepulse for Cone-Guided Fast Ignition

T. Ma[1, 2], P. K. Patel[1], A. G. MacPhee[1], C. D. Chen[1], L. Divol[1], D. Hey[1], A. J. Kemp[1], M. H. Key[1], D. J. Larson[1], S. Le Pape[1], H. S. McLean[1], Y. Ping[1], S. C. Wilks[1], D. Higginson[2], C. Murphy[2], H. Sawada[2], B. Westover[2], T. Yabuuchi[2], K. U. Akli[3], R. B. Stephens[3], R. R. Freeman[4], G. E. Kemp[4], A. G. Krygier[4], L. D. Van Woerkom[4], R. Fedosejevs[5], H. Friesen[5], Y. Y. Tsui[5], S. D. Baton[6], M. Koenig[6], F. Perez[6], D. Turnbull[7], and F. N. Beg[2]

[1]Lawrence Livermore National Laboratory, [2]University of California, San Diego, [3]General Atomics, [4]The Ohio State University, [5]University of Alberta, [6]Laboratoire pour l'Utilisation des Lasers Intenses, [7]Princeton University

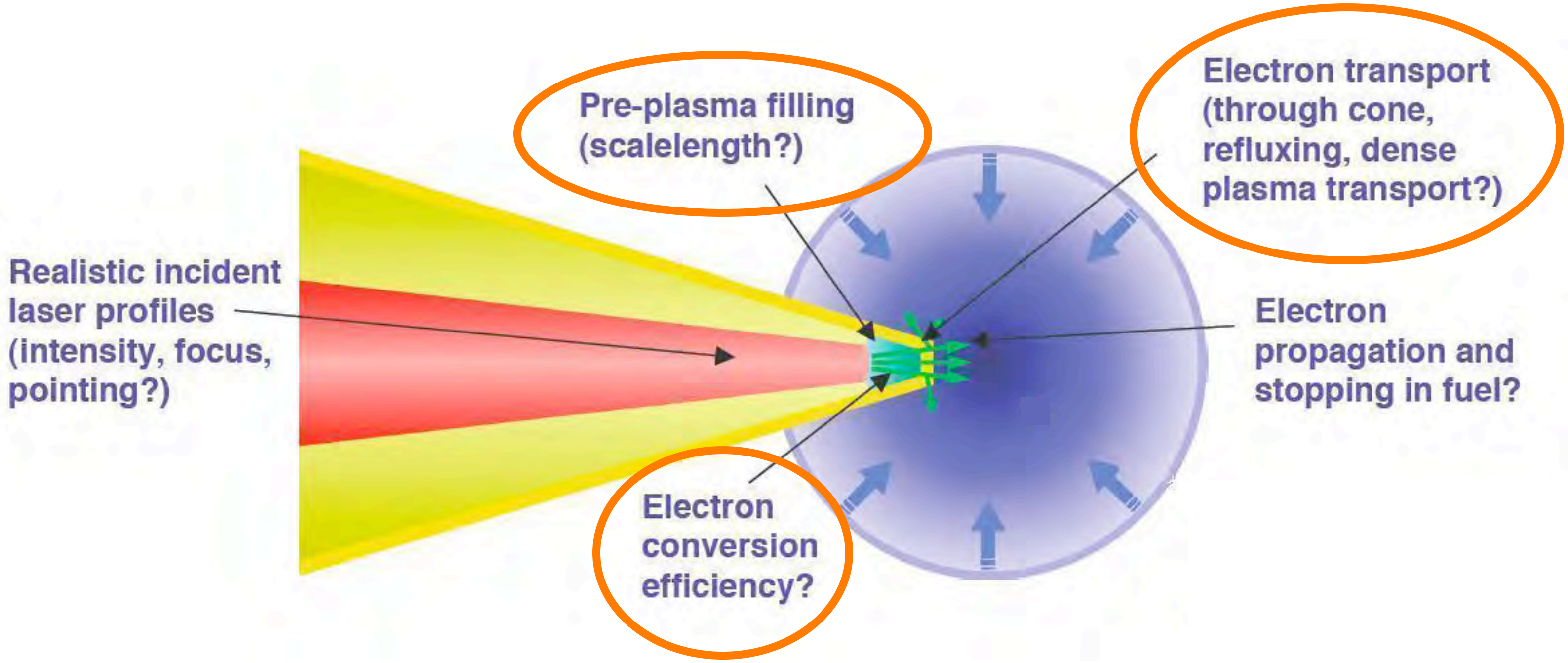
Omega Laser Facility Users Group Meeting

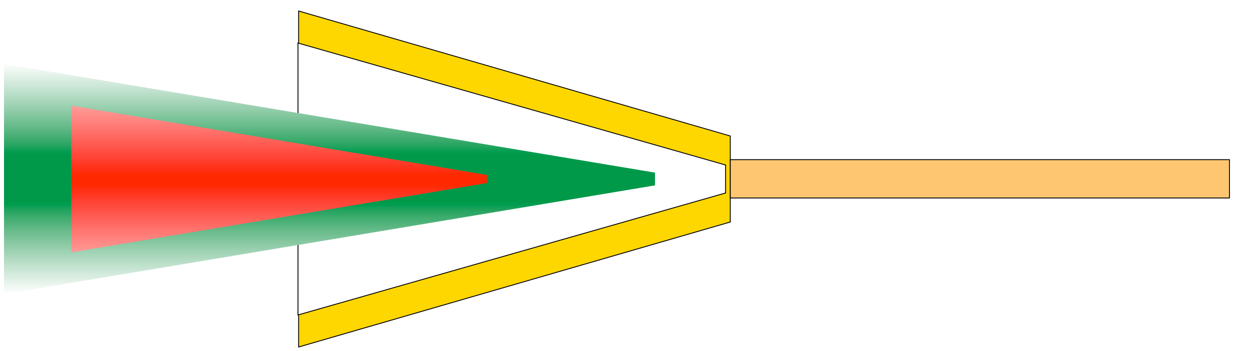
Rochester, New York

April 28-30, 2010

University of California, San Diego Department of Mechanical and Aerospace Engineering
9500 Gilman Ave., La Jolla, 92037
L-399, Lawrence Livermore National Laboratory, Livermore, CA 94551

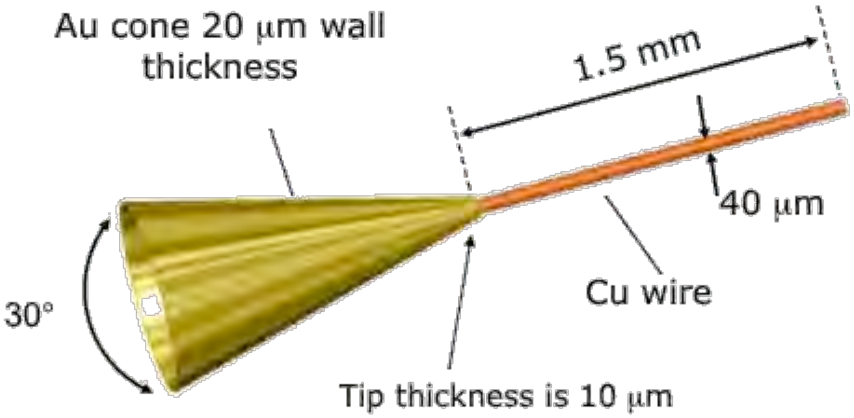
Two of the key issues for electron cone-guided fast ignition are conversion efficiency and e- transport





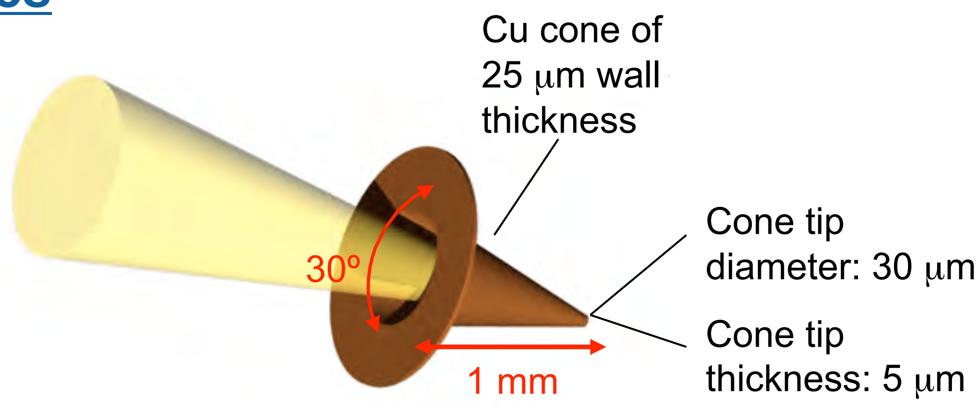
The effect of prepulse on coupling efficiency was studied with cone and cone-wire targets on Titan

Cone-Wires



Wire geometry allows e- propagation to be sudied w/o complexities of diverging beam

Cones

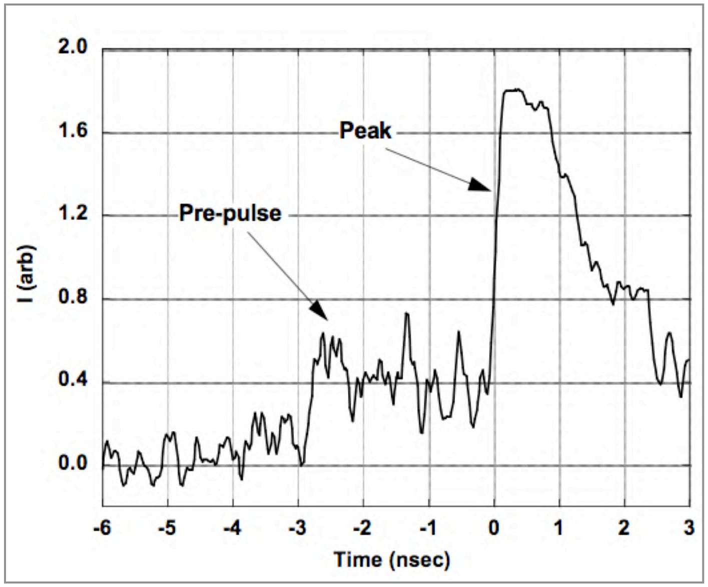


- Cones could provide direct access to dense core, but questions of preplasma confinement, electron origination, electron directionality
- Target materials carefully selected to allow preferential parts to fluoresce
- Cu cone allows imaging of interaction in cone, Cu wire allows imaging of coupling to tip and beyond

UCSD

Why is prepulse an issue?

- Even in a laser system with good intensity contrast (10^5-10^7), the pedestal can be sufficient to create a significant preplasma
- The preplasma can severely affect the absorption of the laser

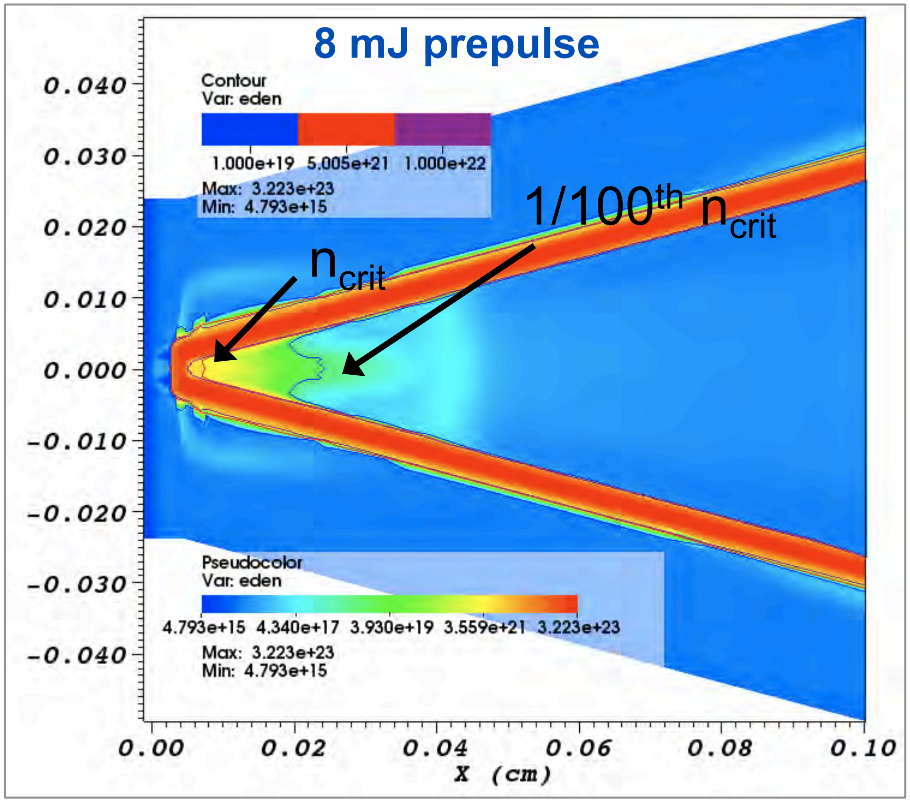


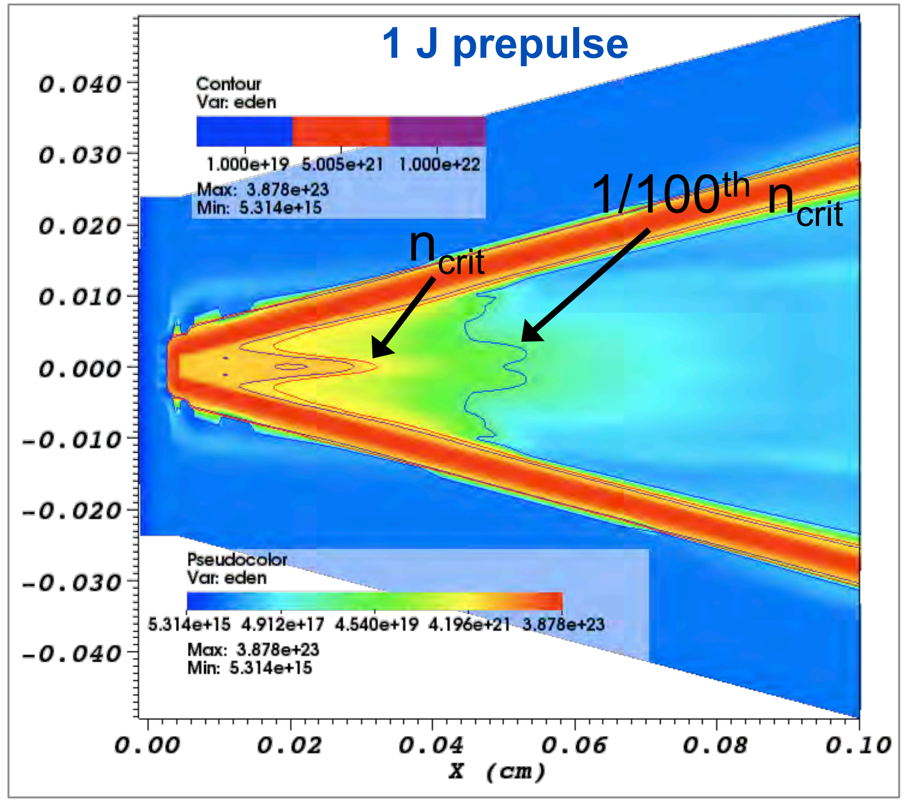
A prepulse measurement taken on the Titan laser

- Baton et al. (2009) showed that coupling beyond a cone target was decreased vs. no cone case -> hypothesized that preformed plasma in the cone was inhibiting transport beyond the cone
- Necessary to know the tolerable level of prepulse for fast ignition (full scale FI laser systems of 100 kJ are expected to have prepulses of 100 mJ – 1 J)

S. D. Baton et al., *Phys. Plasmas* **15,** 042706 (2008)

Hydra was used to model the plasma conditions inside the Au cone due to irradiation by the laser prepulse

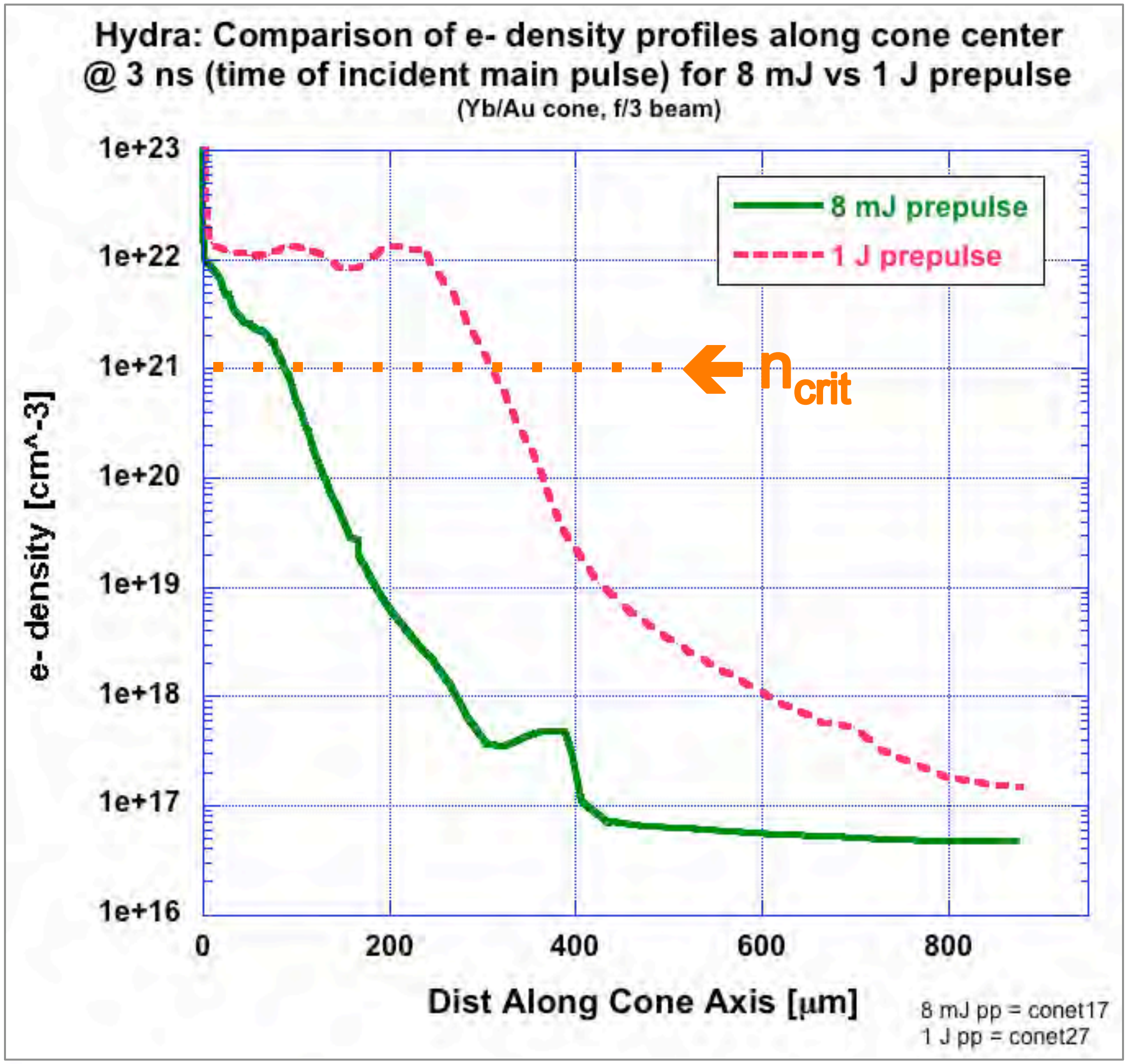




- Hydra is a 3-D rad-hydro code (simulations done in 2-D cylindrical geometry)
- From modeling, can predict the location of the critical surface relative to the cone tip and the extent of the underdense inside the cone

UCSD

Profiles taken along the cone axis show critical density occurs farther from cone tip with increasing pp



- profiles represent the density contour before the onset of the main pulse
- n_{crit} (location of hot e- creation) occurs ~200 μm farther from cone tip with 1 J prepulse compared to 8 mJ

The capability to inject artificial prepulses on the Titan laser allowed for a study of the effects of pp on coupling

Short-Pulse:

Wavelength: 1054 nm

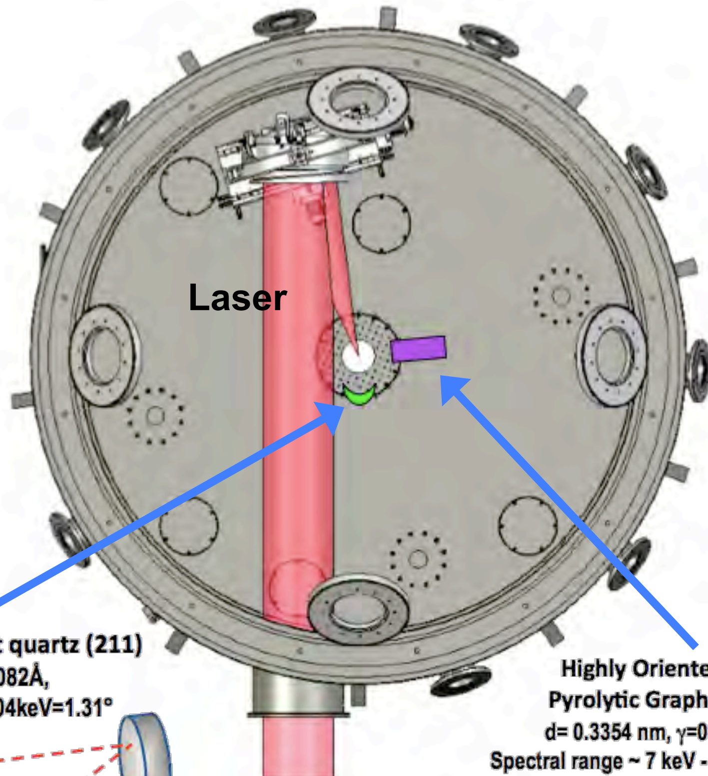
Energy: 150 J

Pulse Length: 0.7 ps

Spot Size: 7 μm FWHM

Intensity: 2×10^{20} W/cm^2

Intrinsic prepulse: 8 mJ

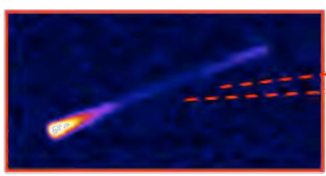


Artificial Prepulse Laser:

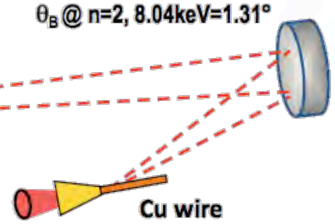
Location: coaxial to main beam

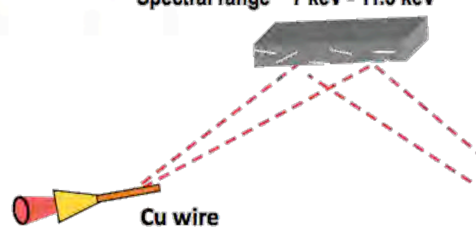
Timing: 3 ns duration,
-3 ns before main pulse (to overlap intrinsic)

Energy: 0 – 1 J

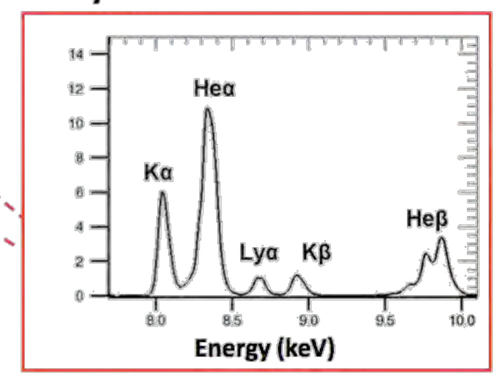


K-α crystal imager shows the hot e$^-$ spatial distribution

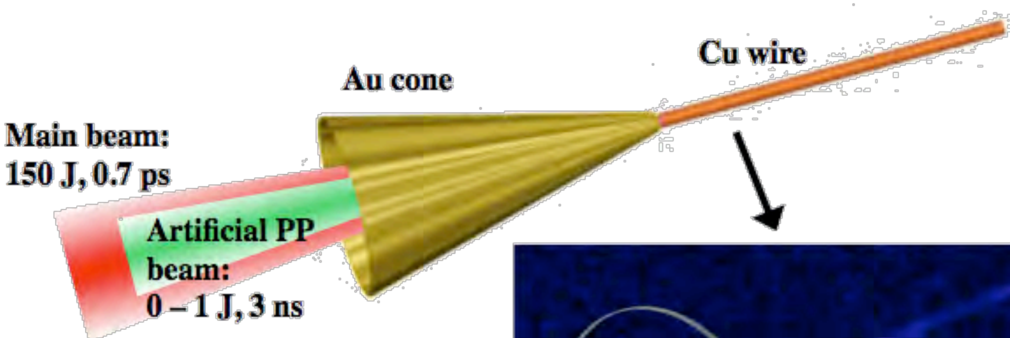


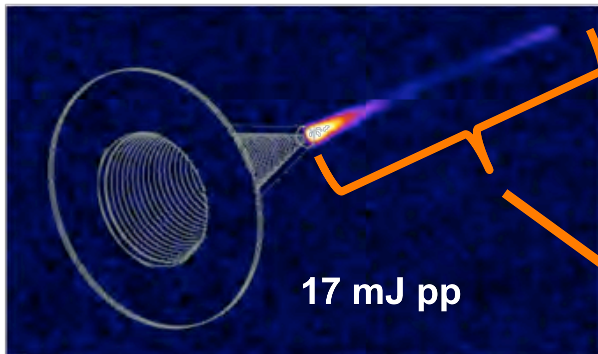


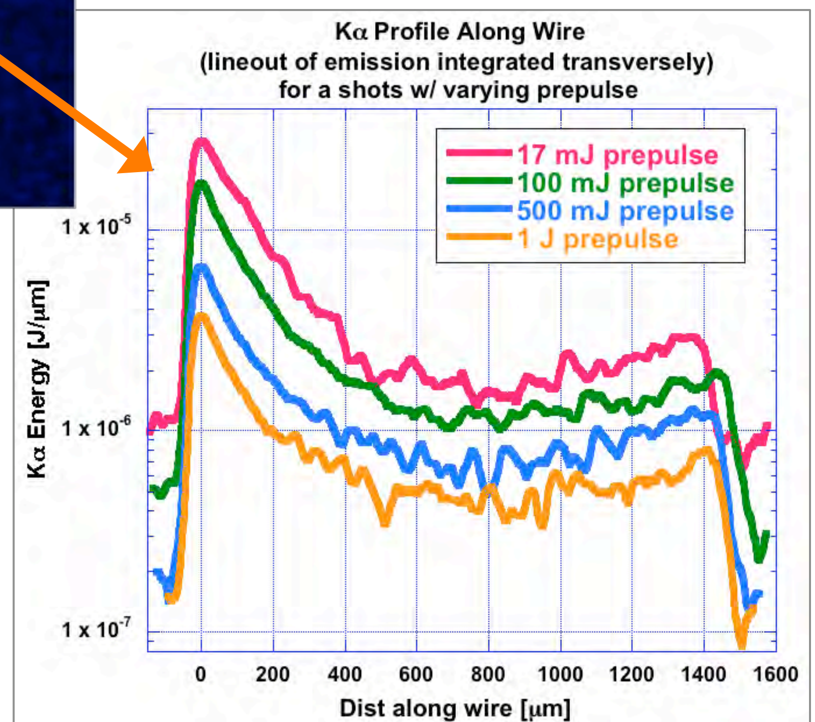
HOPG crystal spectrometer gives spectral information and absolute K-α yield



Cone-wire targets provided a quantitative scaling of coupling beyond the cone with varying levels of pp







- Kα originates from the electron source generated by the main short pulse, and which is injected via the tip of the cone into the wire

UCSD

Zuma is a 3D hybrid simulation code for relativistic electron transport in dense plasmas

- Based on Davies / Honrubia hybrid models (includes field generation) [1,2]:

$$\vec{E} = -\eta \vec{J}_{hot\ electron} + \frac{\eta}{\mu}\nabla \times \vec{B} \qquad \frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$

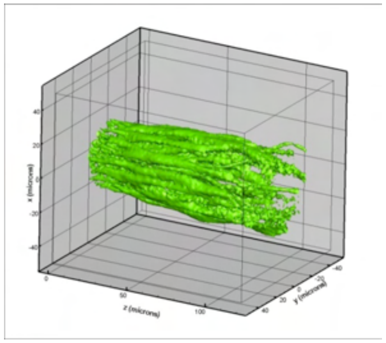
- Background high density plasma is a resistive fluid while the fast electrons are treated kinetically
- Assumptions are appropriate for high density, relatively cool (T< ~1 keV) quasi-neutral plasmas where kinetic effects are strongly damped by the plasma collisionality [1,3]
- Kinetic fast electrons are slowed by interaction w/ the background electrons and scatter off both the background ions and electrons.This process is modeled via the drag and scattering formulas reported by Atzeni, Schiavi and Davies [4]

[1] J.R. Davies, *Phys. Rev. E*, 65, 026407 (2002)

[2] Honrubia, et al., *Laser and Particle Beams*, 22, 129-135 (2004)

[3] L. Gremillet, et al., *Phys. Plasmas*, Vol. 9, No. 3 (2002)

[4] S. Atzeni, A. Schiavi, and J. R. Davies, *Plasma Phys. Control. Fusion*, 51, 015016 (2009)

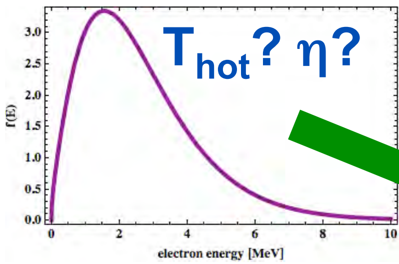


Electron density iso-surface

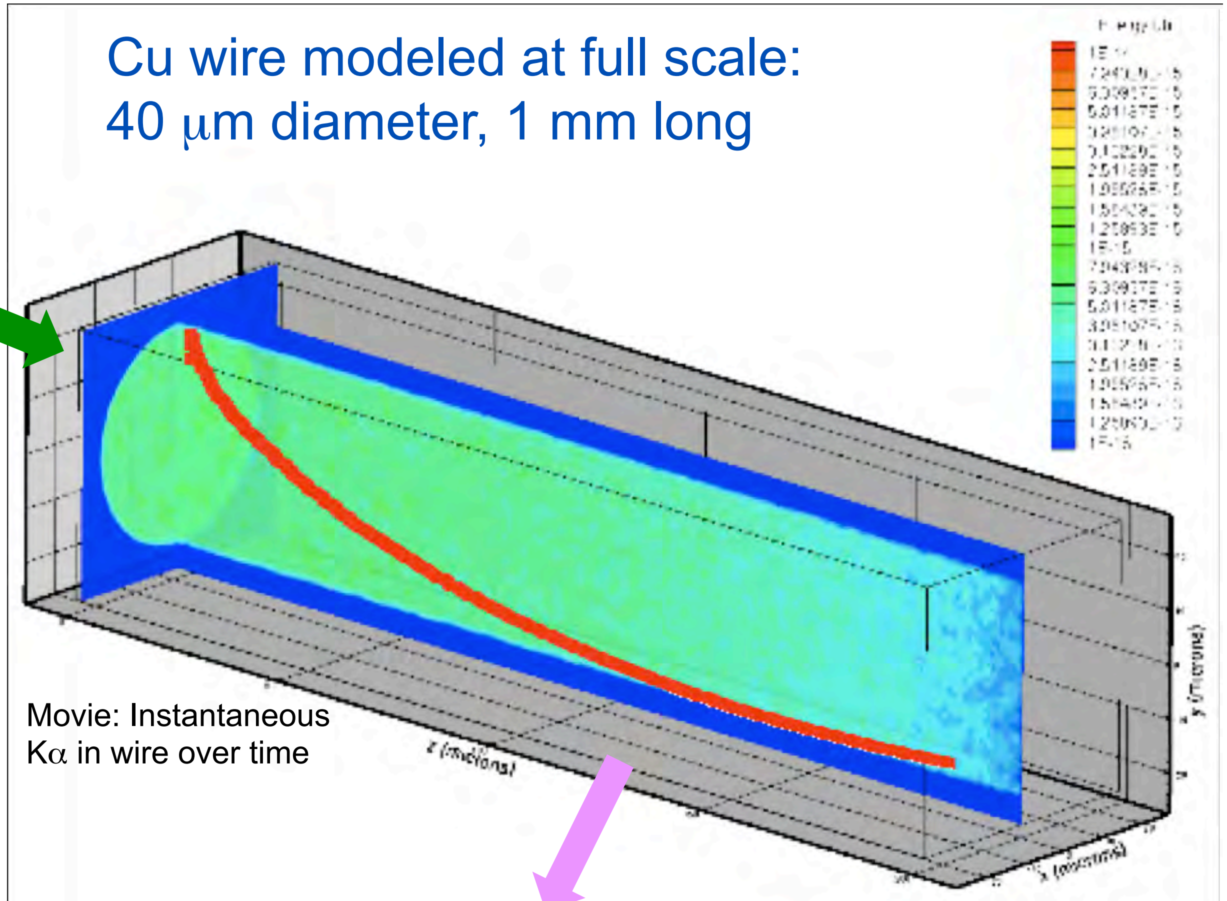
UCSD

Simulations in Zuma can help us infer the energy deposition by generating Kα profiles along the wire

Inject an e- spectrum:



Cu wire modeled at full scale:
40 μm diameter, 1 mm long



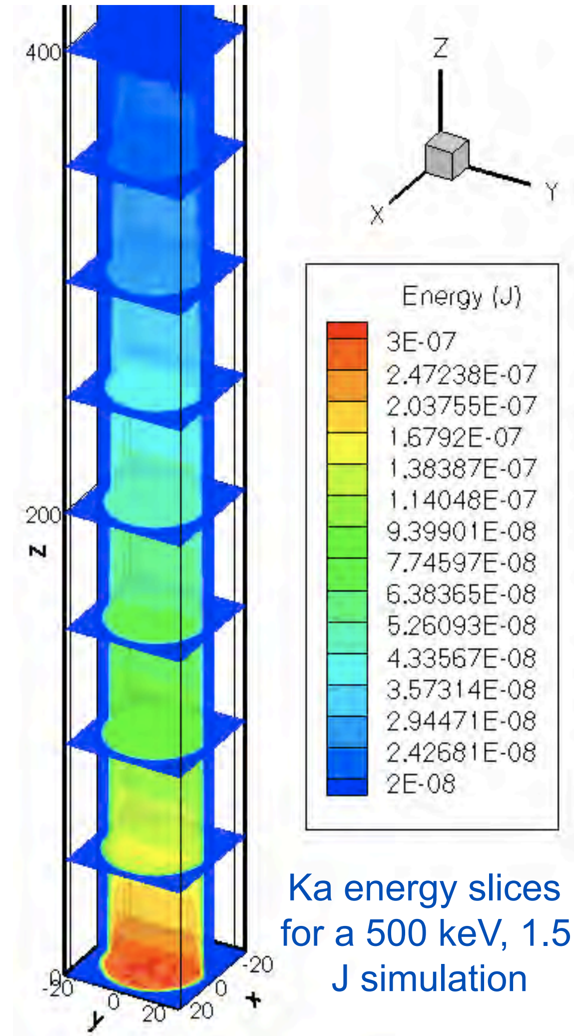
Movie: Instantaneous Kα in wire over time

At each axial point along the wire, transverse integration of Kα over all time gives profiles that can be matched to the experimental data

UCSD

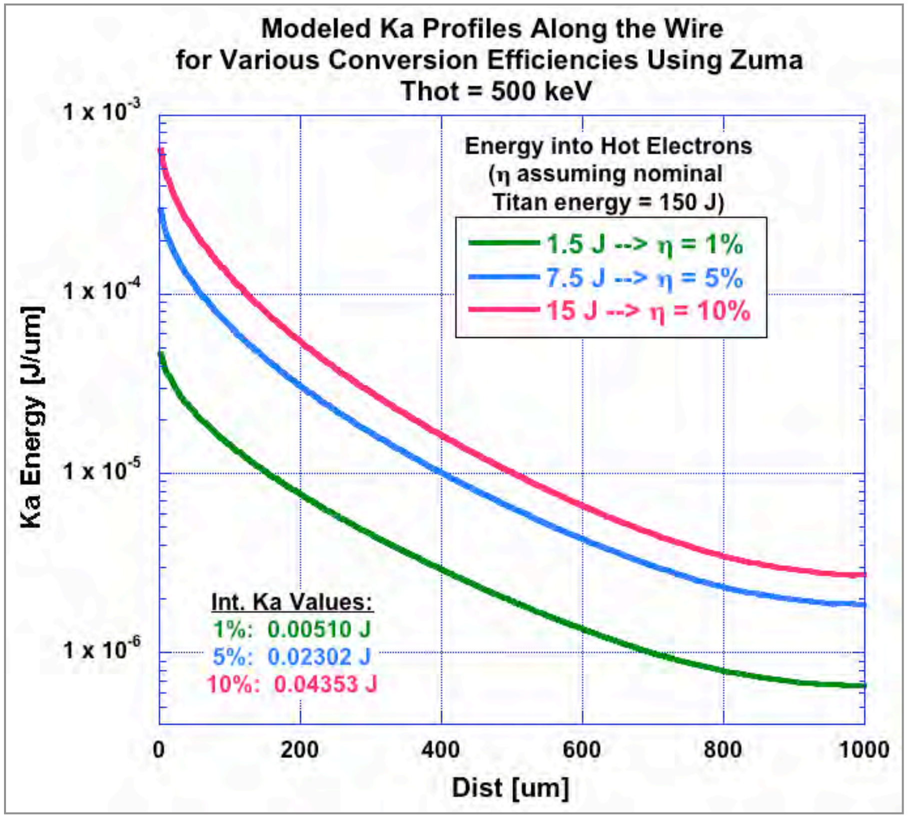
Initial assumptions used for Zuma modeling

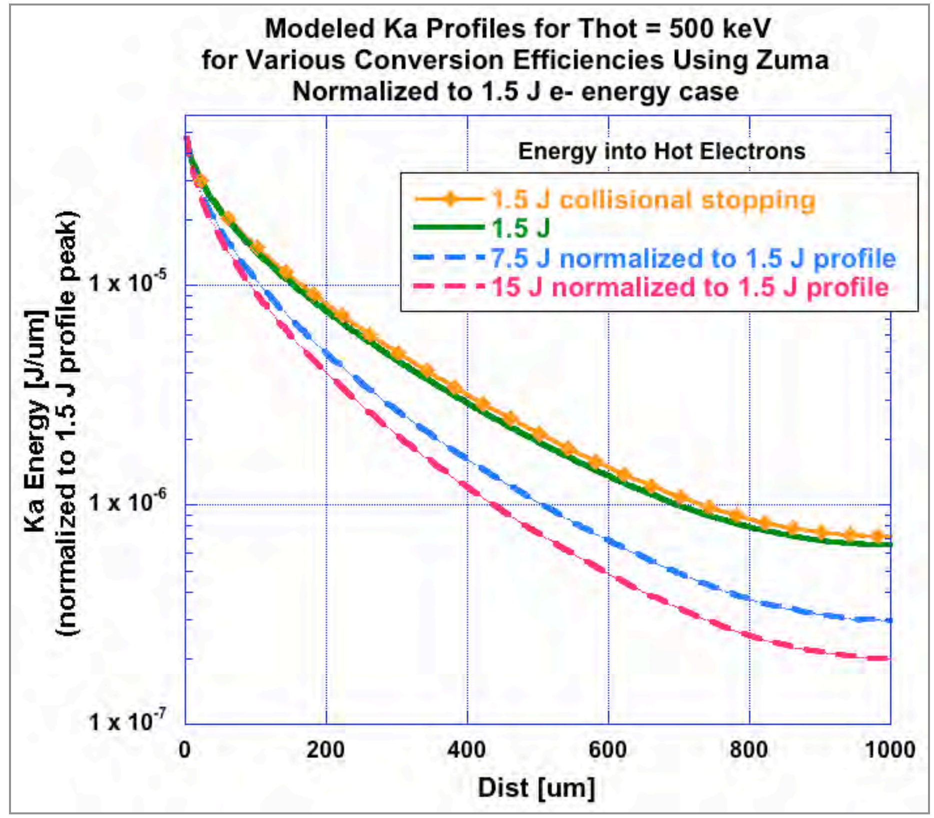
- Modeled as a 40 μm-diameter wire, 1 mm long
- Material = Copper
- Fully reflecting boundaries (wire edges, front, back)
- 2 μm resolution in each dimension
- Initial temperature = 0.1 eV
- Titan pulse (0.7 ps, gaussian in time, spatially uniform over area of wire)
- Electrons are injected at z = 0 (wire front face)
- 0° initial divergence angle
- 3D relativistic Maxwellian distribution w/ varying T_{hot}
- Injected electron energy varied from 0.15 J – 30 J
- Time to run: ~3 hours, 8 cpus



Ka energy slices for a 500 keV, 1.5 J simulation

A large parameter scan of varying T_{hot} and total injected electron energies was completed using Zuma

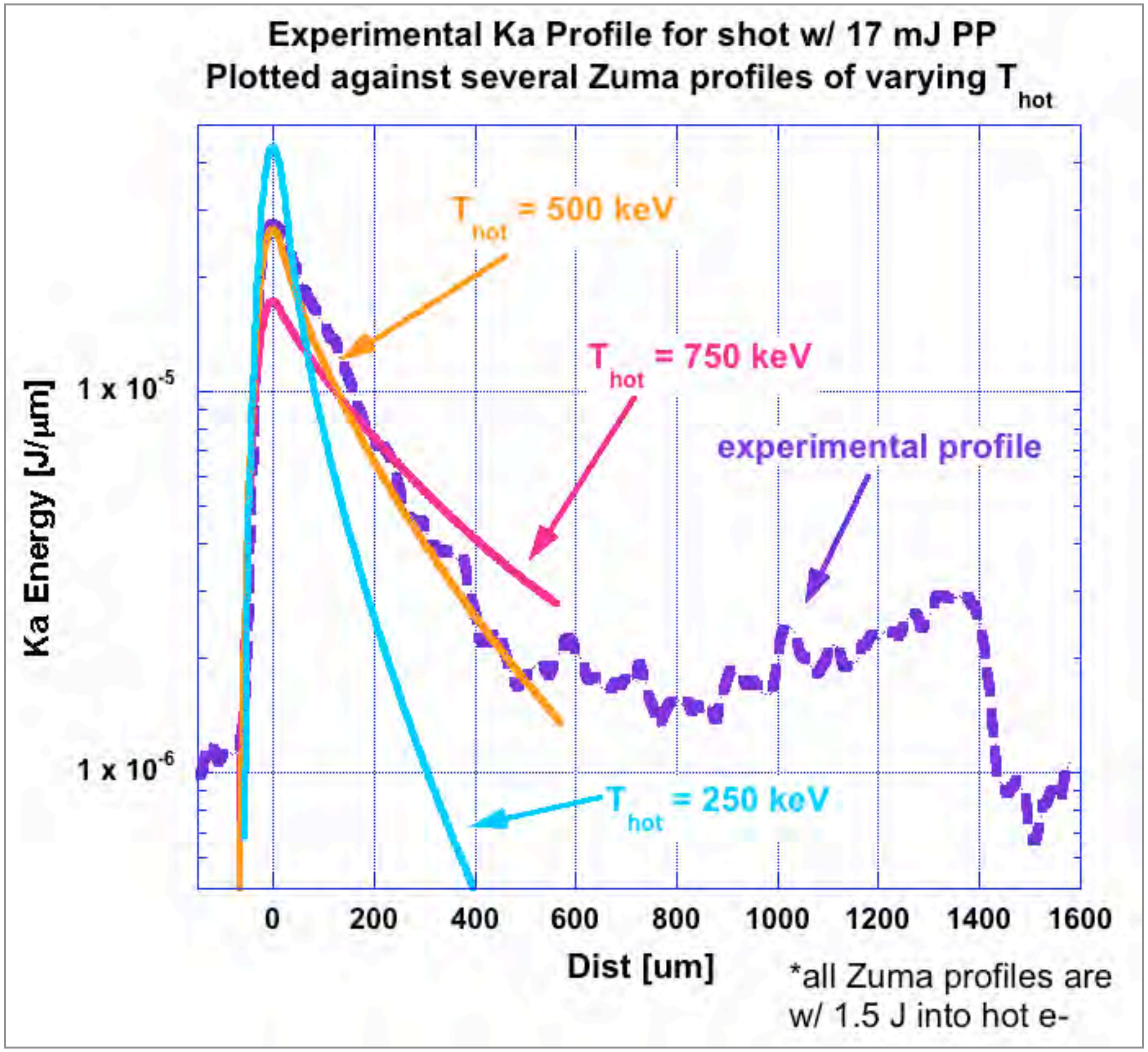




- Injecting a 500 keV T_{hot} e- beam at three different energies shows how the Kα profiles scale
- The same profiles, normalized, show regime where resistive effects become important

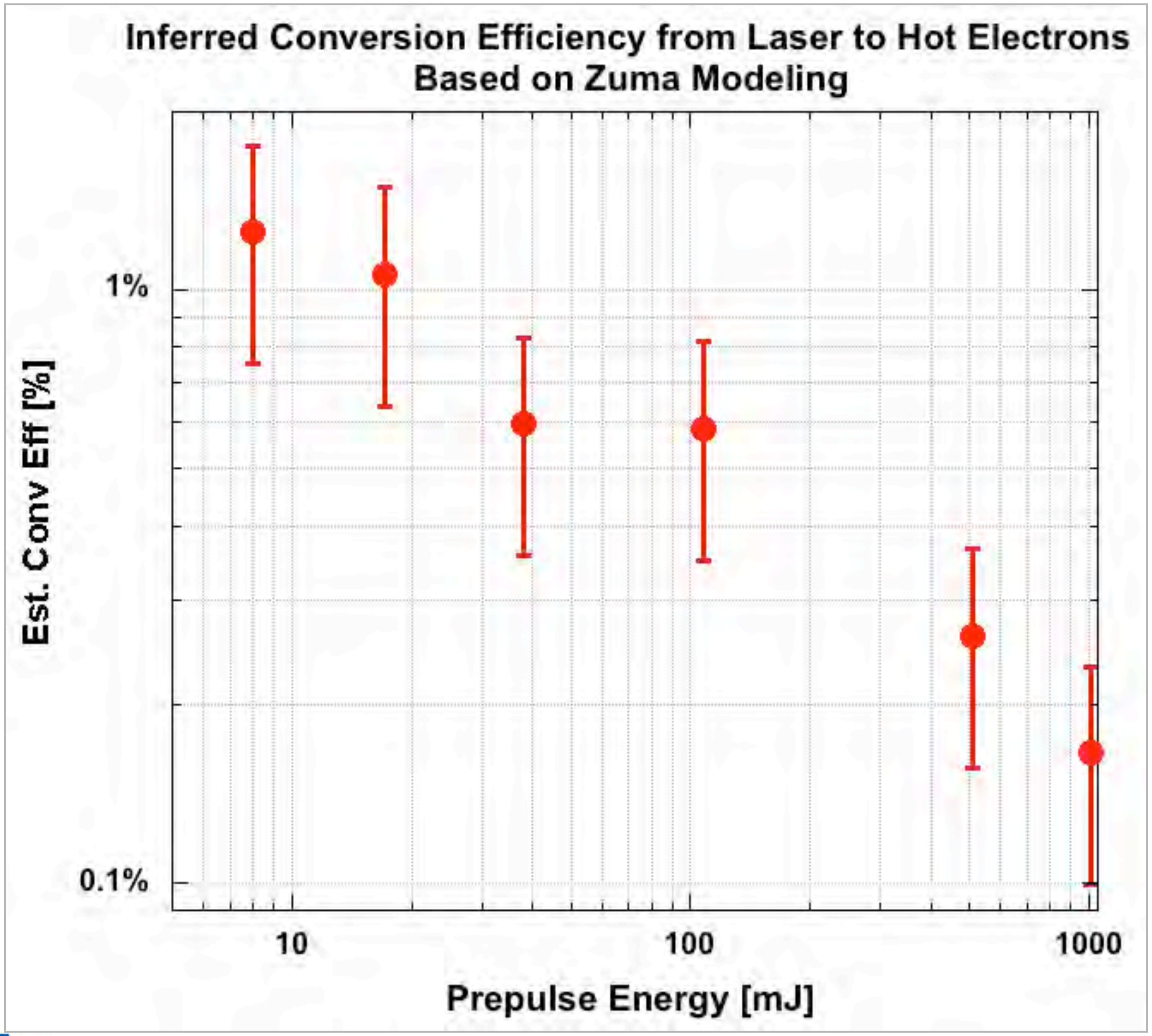
UCSD

For each experimental profile, the best fit predicted Kα profile from Zuma will be found



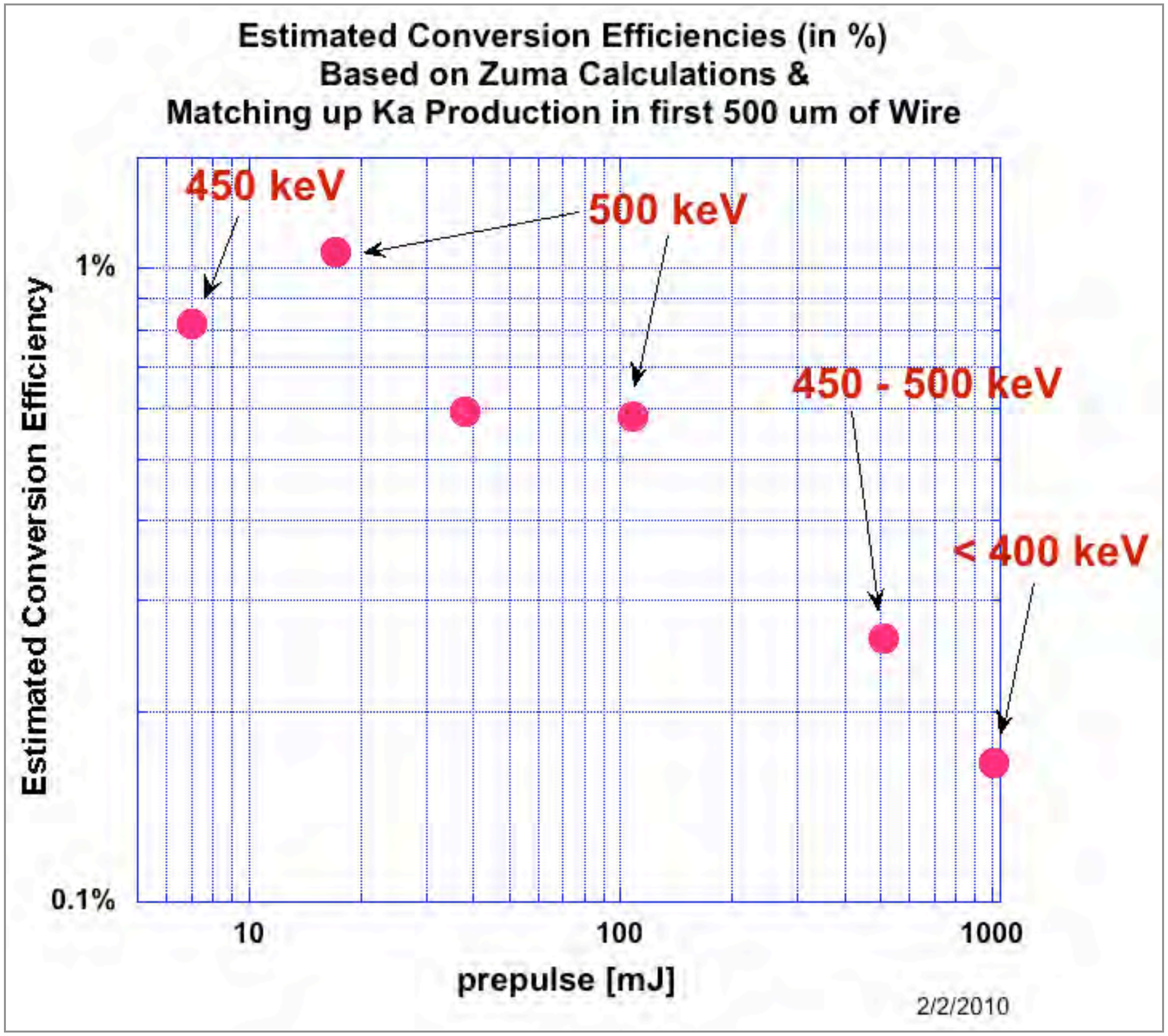
- Must match:
  - Peak Kα
  - Slope of fall-off
  - Total integrated Kα in first 500 μm
- Each experimental shot (Kα profile) will be fit with Zuma to infer T_{hot} and conv. efficiency

Coupling into forward-propagating electrons is clearly reduced with prepulse



- Coupling decreases by a factor of ~8 when prepulse increased from 8 mJ to 1 J
- Error bars represent shot-to shot variation and uncertainty in absolute calibration of Kα diagnostics

Hot electron temperatures vary little across large range of prepulse energies



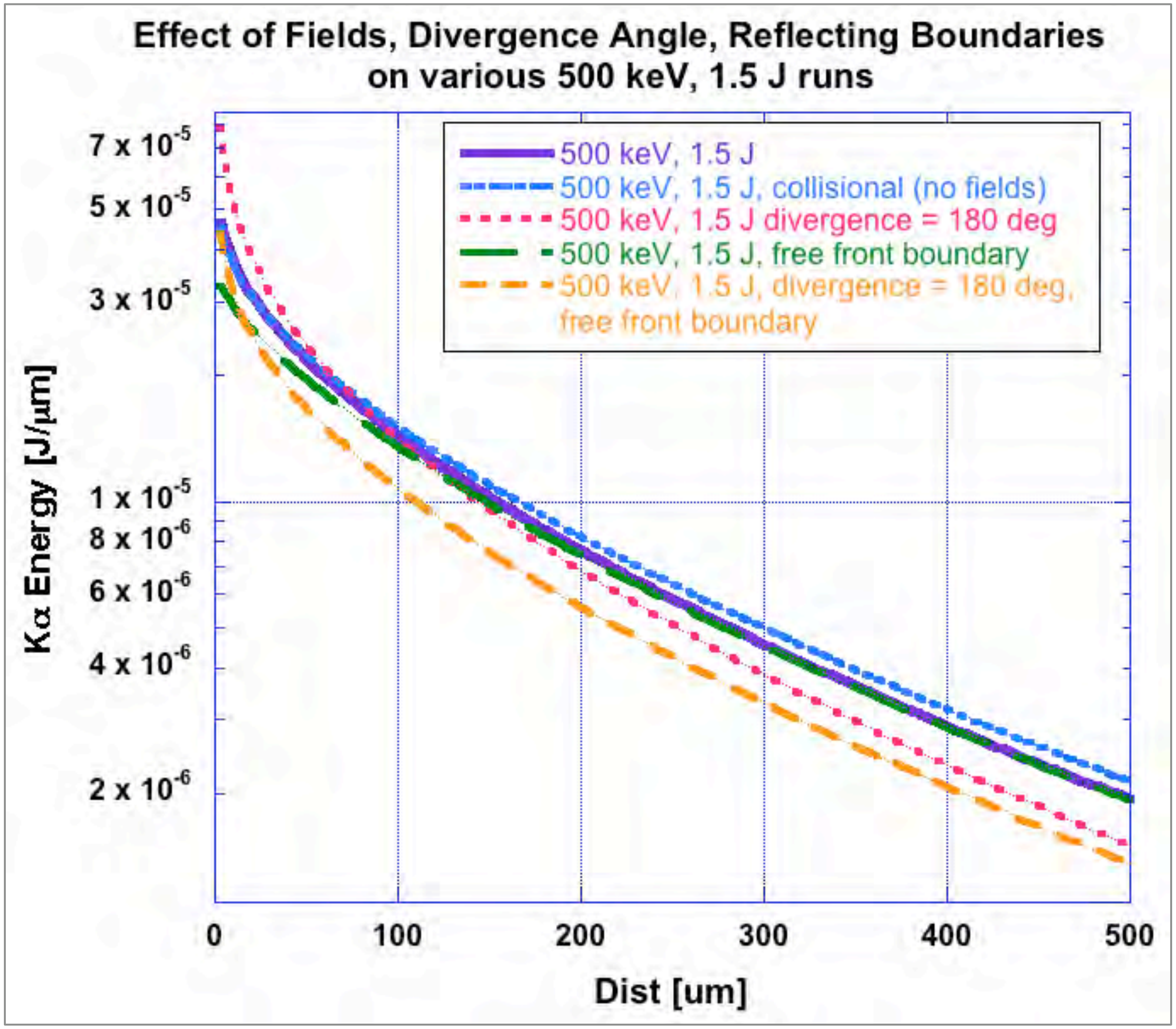
- Unvarying T_{hot} with prepulse

  ➔ no evidence of ponderomotive steepening at low prepulses

- 500 keV e- temperature (accelerated ponderomotively) would correspond to an $I\lambda^2$ of just 10^{18}

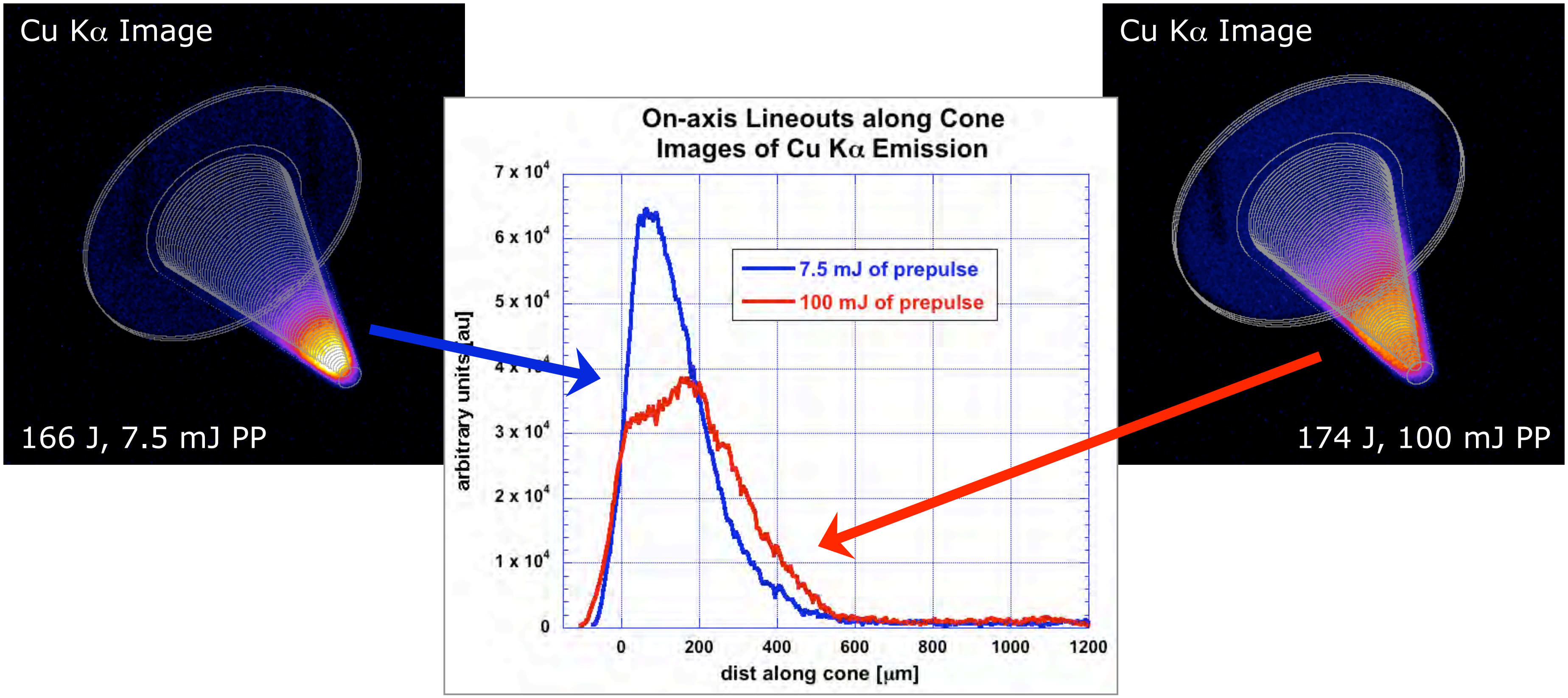
  ➔ representative of range of intensities in distribution?

We are also using Zuma to investigate the effect of reflecting boundaries, divergence angle, fields, etc.



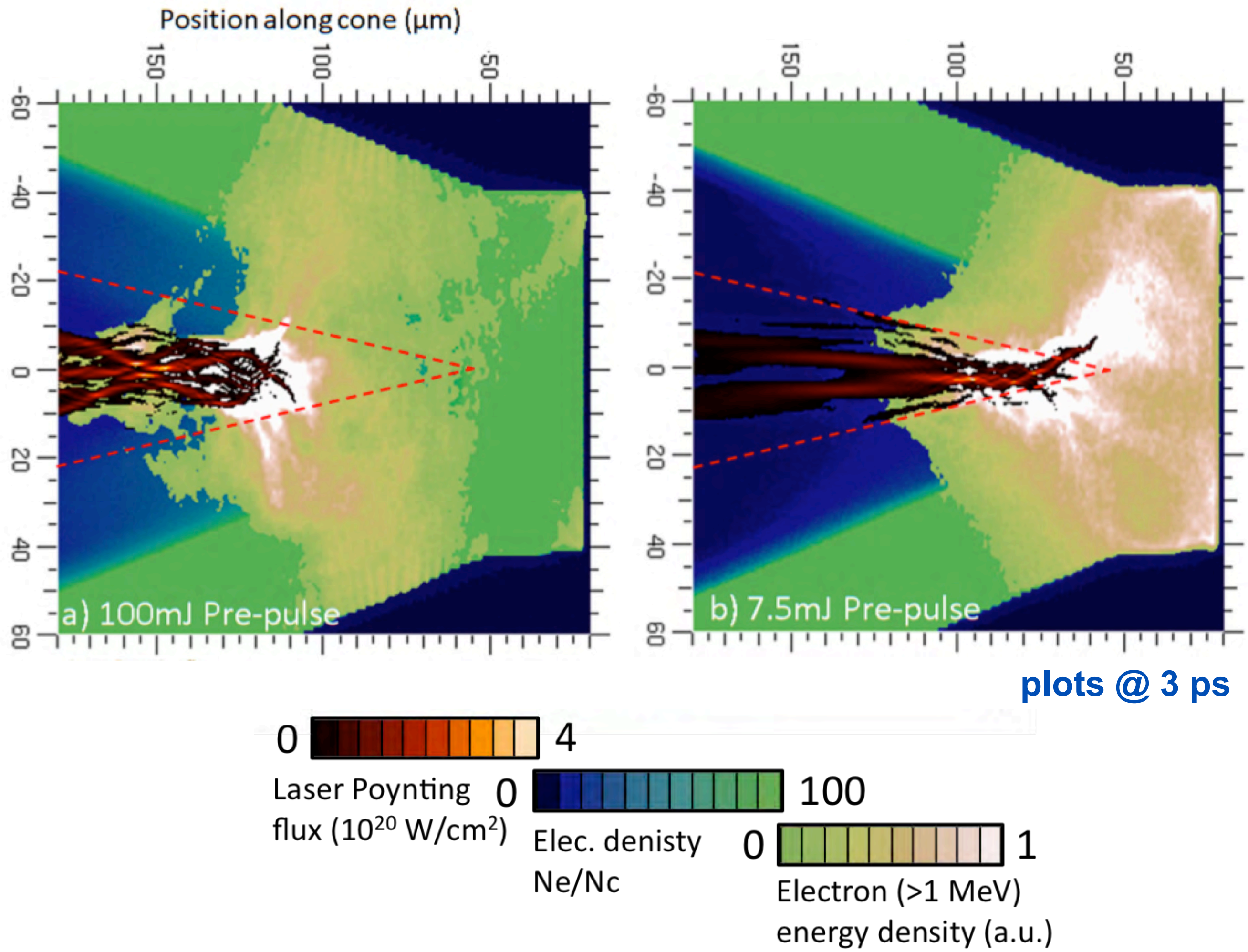
- Current conv. eff. estimates are a lower limit due to total refluxing assumption
- Extreme case of isotropic beam (180° divergence) would have little effect on absolute conv, up to 20% increase in T_{hot}
- Allowing electrons to escape out the front boundary, could boost conversion by ~10%
- In all cases, energy lost to E fields < 5%

Increasing the prepulse level into the cone gives larger region of electron heating



- Total integrated Kα yield is near-identical in both cases
- Low prepulse, higher Kα peak, 50 μm from tip.
- Larger prepulse gives larger, more diffuse heated region

PSC PIC modeling shows rapid filamentation of laser, transverse ejection of electrons w/ large pp

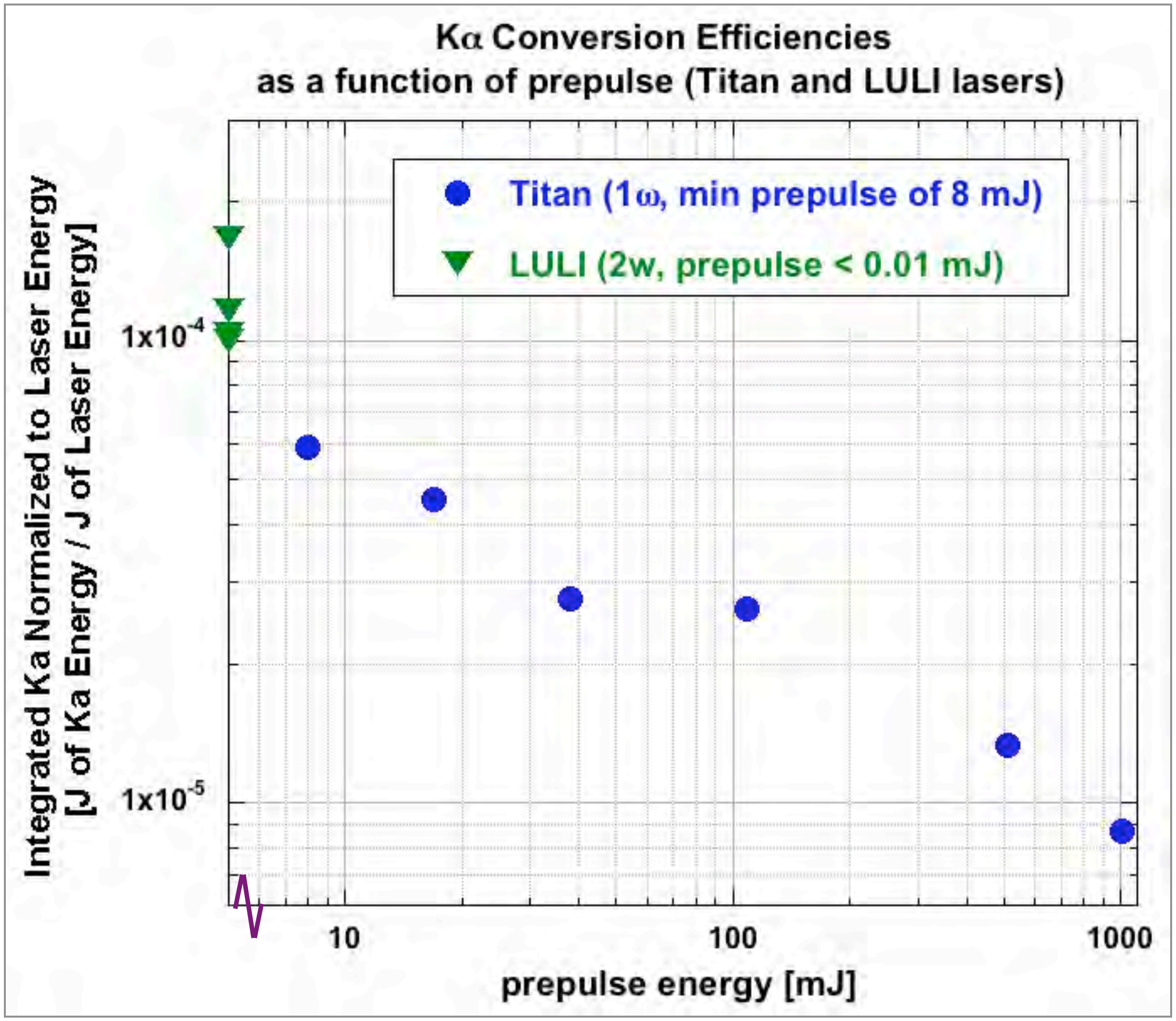


- Preplasma causes laser energy deposition earlier in cone and at wider angle
- At 7.5 mJ pp, one main filament bores a hole and reaches the tip
- At 100 mJ pp, multiple filaments are created and halt propagation of the beam, accelerating electrons transversely

MacPhee et al., *Physical Review Letters,* **104** 055002 (2010).

UCSD

How much could we improve coupling with no prepulse?



- Using LULI's 2ω, high-contrast (>10^{10} intensity) laser, identical cone-wire targets were irradiated
- Coupling is ~factor of 2 higher than highest coupling shot on Titan
- However, difficult to decouple low prepulse effects from 2ω physics

Summary & Future Work

<u>Laser-to-electron coupling in cone-wire targets:</u>

- **Strong reduction in coupling** into forward-going electrons as a function of prepulse
- Coupling efficiencies represent a **minimum estimate** b/c of total refluxing assumption
- With a 1-T fit, data is consistent with a **400-500 keV** temperature
- However, Kα profile shows **evidence of a higher temperature component**

  (bump at end of wire = confinement of very hot electrons by sheath?)

✓ Currently working on a comparison of **Zuma vs. LSP** to look at effects of vacuum boundaries, more complete physics model

✓ **PIC-Hybrid simulations** are in progress to model the full-scale laser interaction and transport in solid wire

Collaborators and Acknowledgements

F. N. Beg, T. Bartal, S. Chawla, D. P. Higginson, C. Murphy, H. Sawada, M. S. Wei, B. Westover, T. Yabuuchi
University of California, San Diego, La Jolla, CA

A. G. MacPhee, C. D. Chen, L. Divol, S. P. Hatchett, D. Hey, A. J. Kemp, D. J. Larson, M. H. Key, S. Le Pape, A. J. Mackinnon, H. McLean, P. K. Patel, Y. Ping, S. C. Wilks
Lawrence Livermore National Laboratory, CA

R. B. Stephens, K. U. Akli
General Atomics, San Diego, CA

L. D. Van Woerkom, R. R. Freeman, E. Kemp, A. G. Krygier
The Ohio State University, Columbus, OH

R. Fedosejevs, H. Friesen, Y. Y. Tsui
University of Edmonton, Alberta, Canada

S. D. Baton, M. Koenig, F. Perez
Laboratoire pour l'Utilisation des Lasers Intenses, Ecole Polytechnique, France

Funding

- Office of Fusion Energy Science (OFES)
  - Advanced Concept Exploration Program

ACFI

- Fusion Science Center (FSC)

FSC

- U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48

T. Ma is currently funded through the Lawrence Scholar Program Fellowship, and previously was funded under LLNL's Institute of Laser Science and Applications grant.