TRANSPORT OF INTENSE LASER-PRODUCED ELECTRON BEAMS IN MATTER

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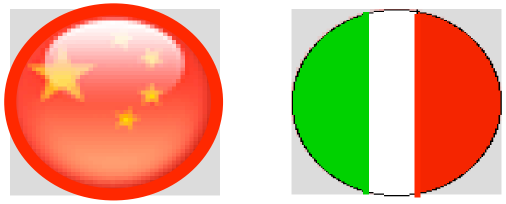

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Development, Science and Emerging Applications

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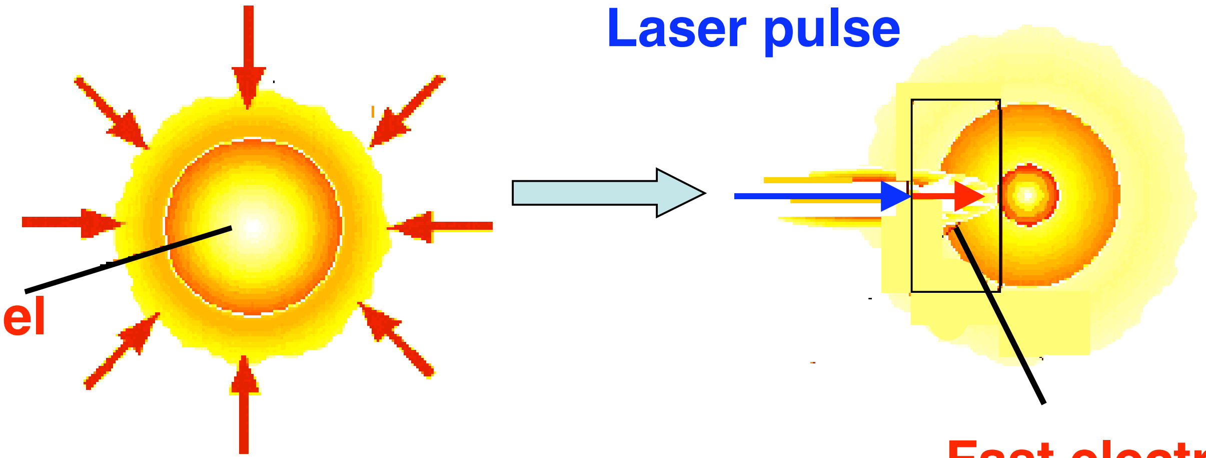
The concept of fast ignition

- 1: “normal” compression with ns laser beams
- 2: a CPA laser creates a beam of relativistic electrons (lateral hot spot)



Laser pulse

DT fuel

Fast electrons

- Study of fast electron propagation is essential and it turns out that it could be inhibited by self generated electric fields. Bell's model

$$z_o\ (\mu\ \mathrm{m}) = 3\ 10^{-3}\ \sigma\, (10^{6}\ (\Omega\ \mathrm{m})^{-1})\ T^{2}_{fast}\, (\mathrm{keV}) \,/\, \eta\ I_L\ (10^{17}\ \mathrm{W/cm^{2}})$$

σ ELECTRICAL CONDUCTIVITY OF BACKGROUND MATERIAL

Goals of the experiment

- Study of the transport in matter of intense electron beams produced by high intensity laser pulses

- Kα images on x-ray CCD studied as a function of target material (*insulators vs. conductors*) and target thickness

- Set of “updated” diagnostics:
    - Kα x-ray CCD
    - Shadography (2ω)
    - RCF film stack for proton emission
    - Pin Hole Camera (PHC) for X-ray emission

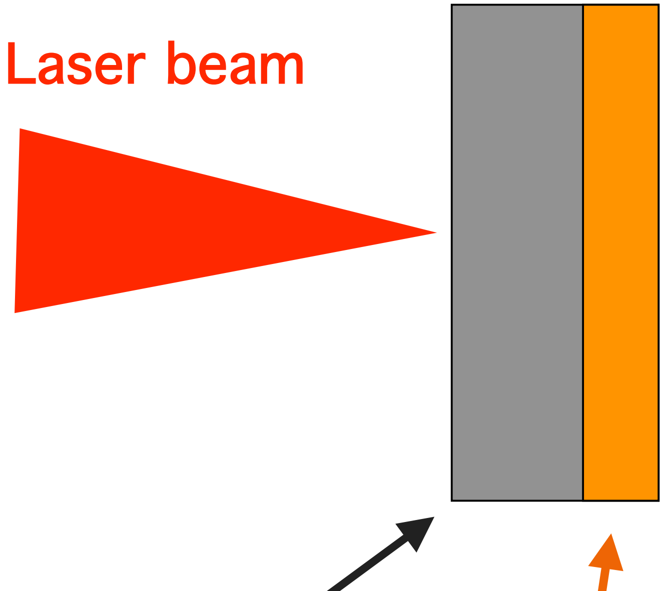
Xtream Light-III

Chinese Academy of Sciences, Beijing

15 J / 50 fs / 20 min, 350TW

Ti: sapphire λ=800 nm

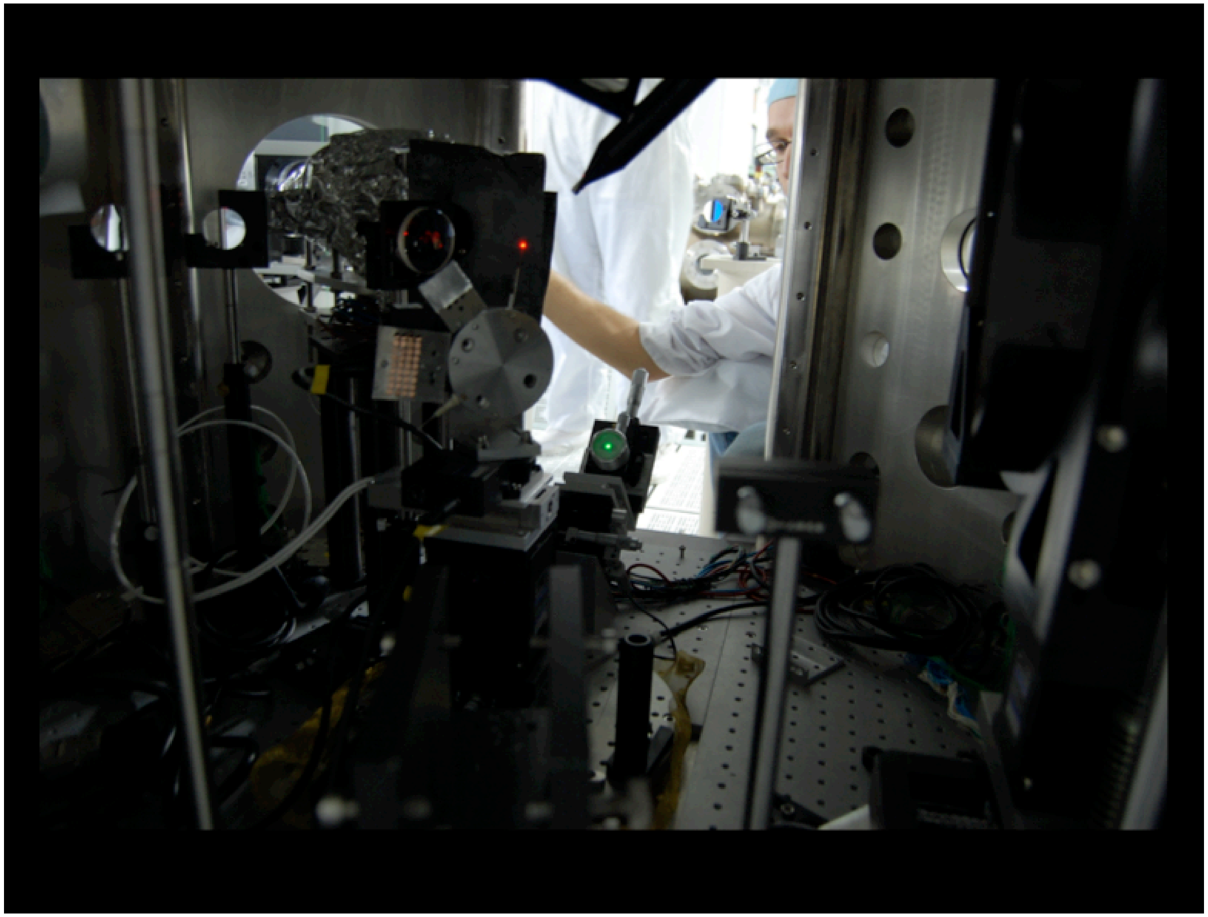
Targets

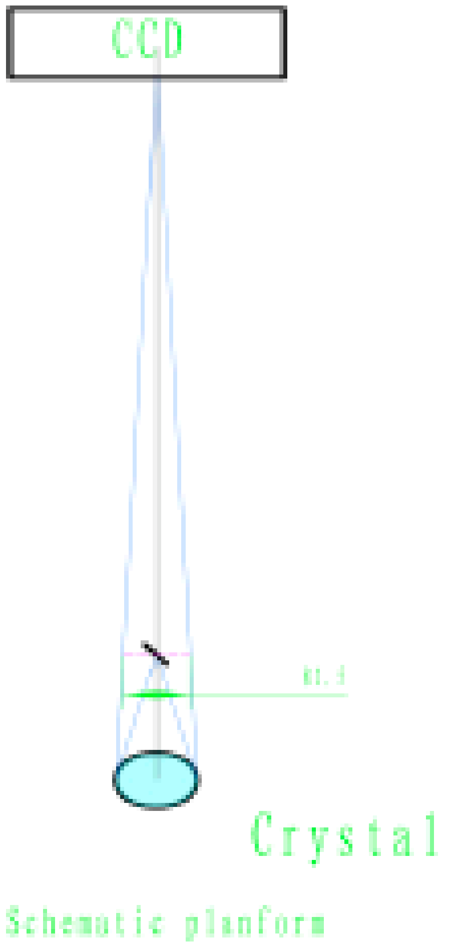


DOUBLE LAYER TARGETS:

- Propagation layer:
  - Al, CH (15 - 40 - 75 *μ*m)
  - Copper 0 - 40 *μ*m (i.e. pure Cu targets)
- 10 μm Cu tracer layer (no good signal with thinner Cu)

Kα imager with X-ray CCD

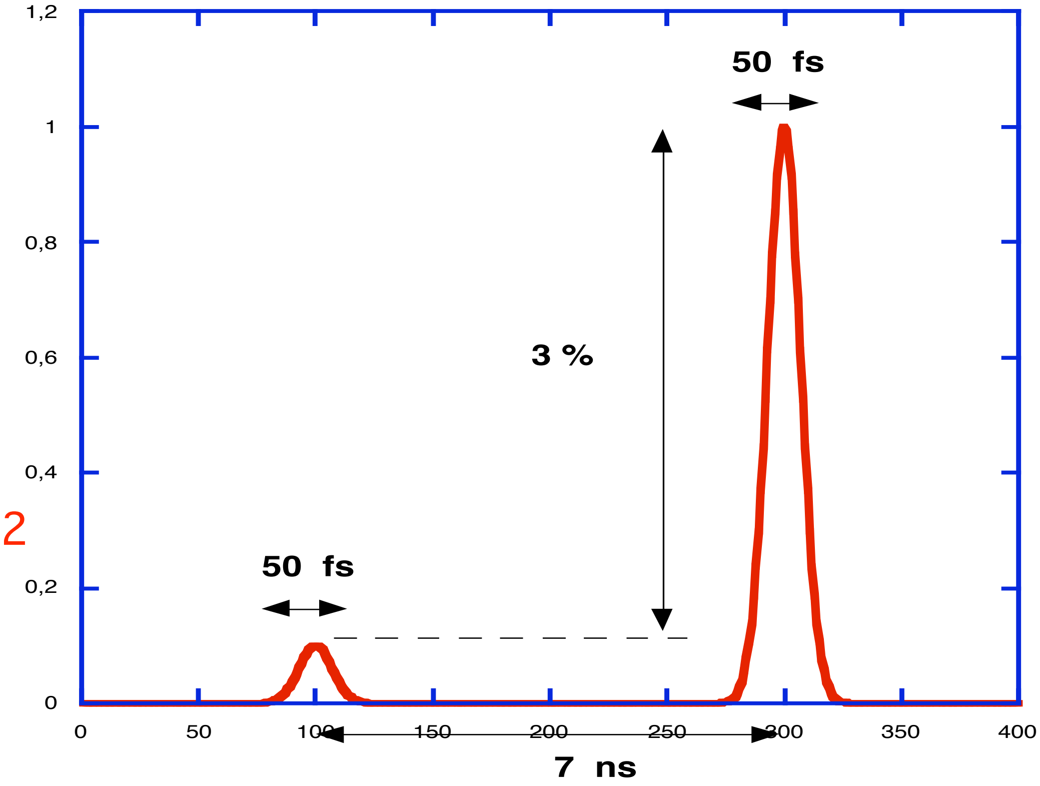




Spherically bent quartz crystal 211
2d = 3.082 Å; Ø = 3 cm
R = 380 mm; Magnification ≈ 4

Pre-pulse problem

1 to 3 % of laser energy was contained in a prepulse



I~10^{19} W/cm^2

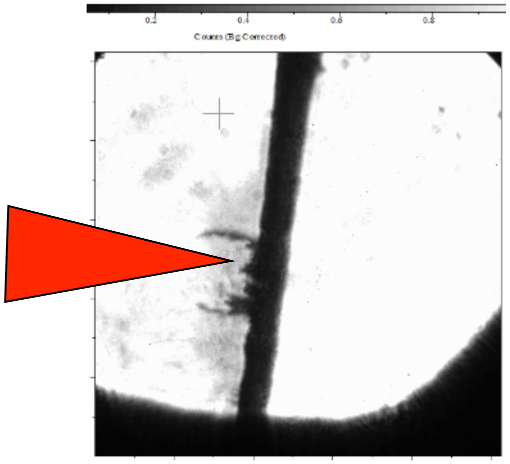
I~10^{17}W/cm^2

Laser energy 6 J @ 50 fs; Focal spot ~ 60 μm

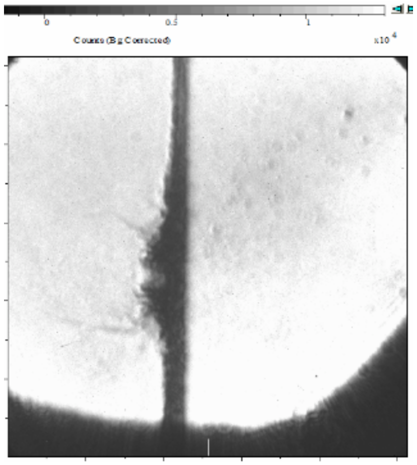
Main pulse interacts with plasma created by prepulse

Does the target survive?

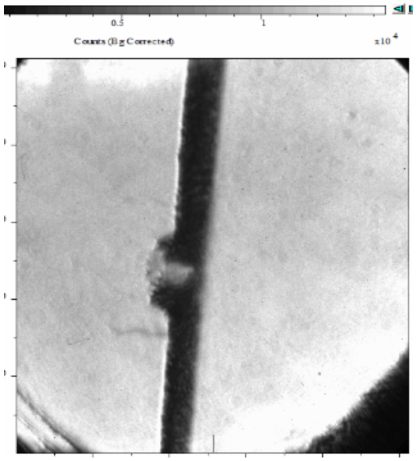
Shadowgraphy images



25 μm Cu, 0 ps, 4.2 J



25 μm Cu, 250 ps, 4.35 J



25 μm Cu, +100 ps, 3.4 J

Targets 25 μm Cu are not drilled through

Signals come from prepulse

Typical fast electron energy

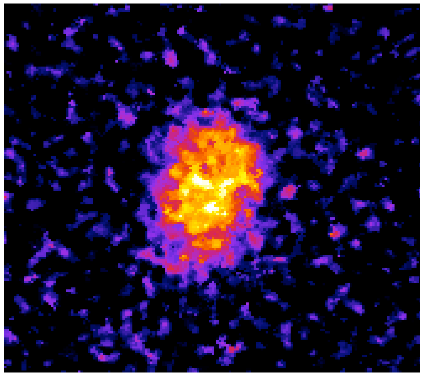
The energy of fast electrons is ≈ 150 keV using the scaling law by Beg et al. [Phys. Plasmas, **4**, 447 (1997)]

$$T_{hot} \approx 100 \text{ keV } (I\,\lambda^2)^{1/3}$$

λ in μm ; I in units of 10^{17} W/cm^2

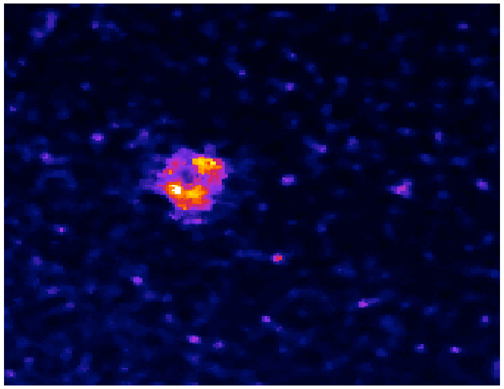
Typical Kα images

Cu
10 μm



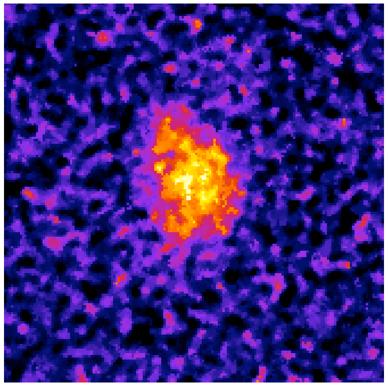
E = 7.3 J

Cu
35 μm



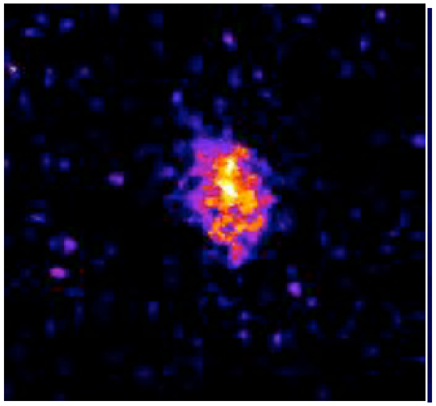
E = 4.7 J

Al 15 μm



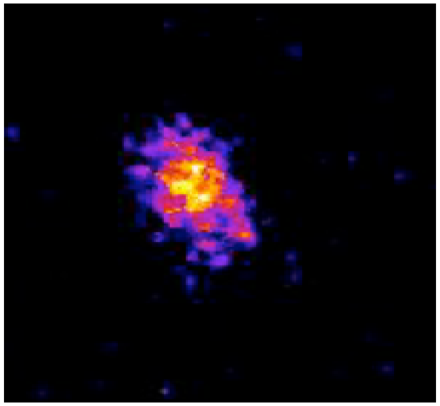
E = 6.6 J

CH 15 μm



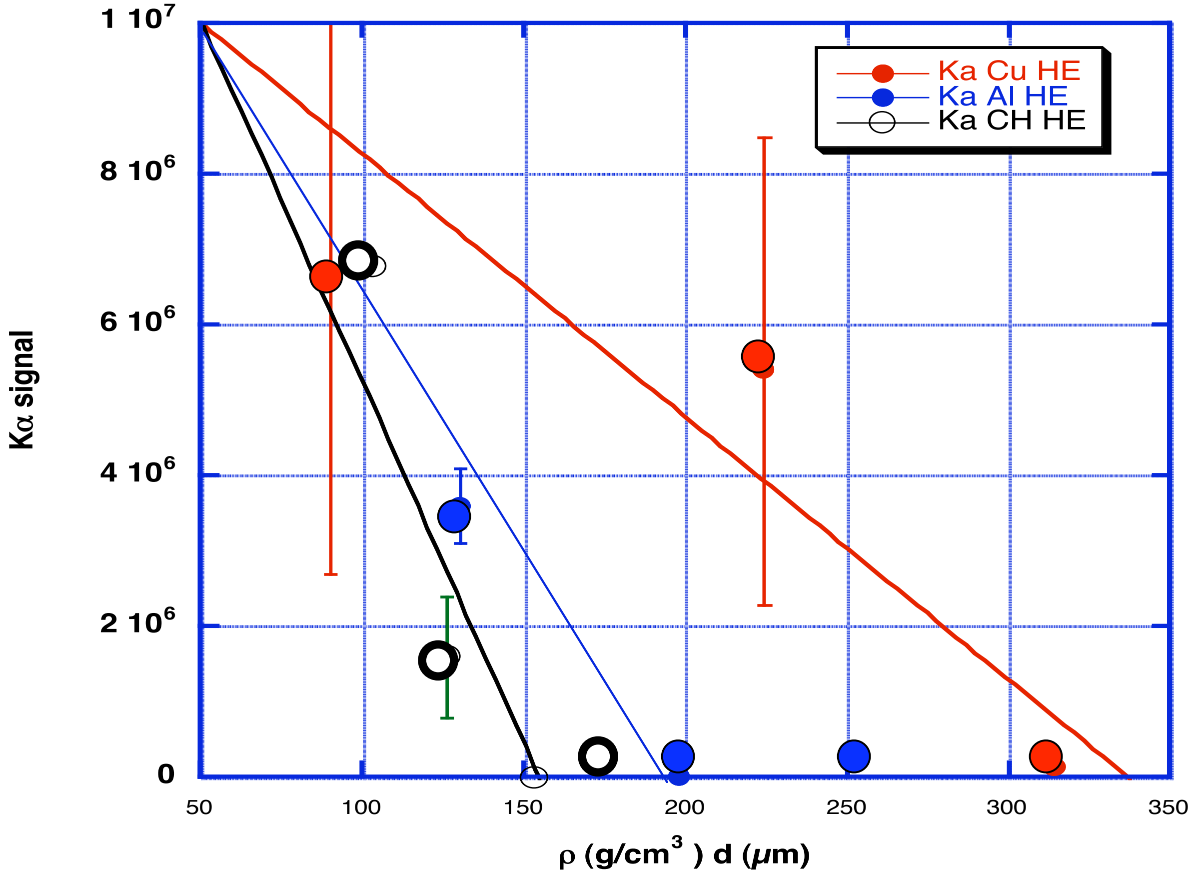
E = 2.1 J

Cu 10 μm



E = 2.9 J

Kα signal vs total crossed mass



High energy shots only (E > 3 J)

Penetration ranges (distances where the signal reduces to 0.5)

CH 0.005 g/cm^2 50 μm

Al 0.0075 g/cm^2 28 μm

Cu 0.014 g/cm^2 16 μm

Tabulated data

Collisional Penetration Ranges for 150 keV

Cu 0.043 g/cm^2 --> exp 0.014 g/cm^2

Al 0.037 g/cm^2 --> exp 0.0075 g/cm^2

CH 0.026 g/cm^2 --> exp 0.005 g/cm^2

(http://physics.nist.gov/PhysRefData/Star/Text/contents.html)

What is the origin of the difference? (a factor ≈ 3-5)

Electrical inhibition?

$z_o\ (\mu m) = 3\ \ 10^{-3}\ (kT_{fast})^2\, \sigma_6\ /\ I_{17}$

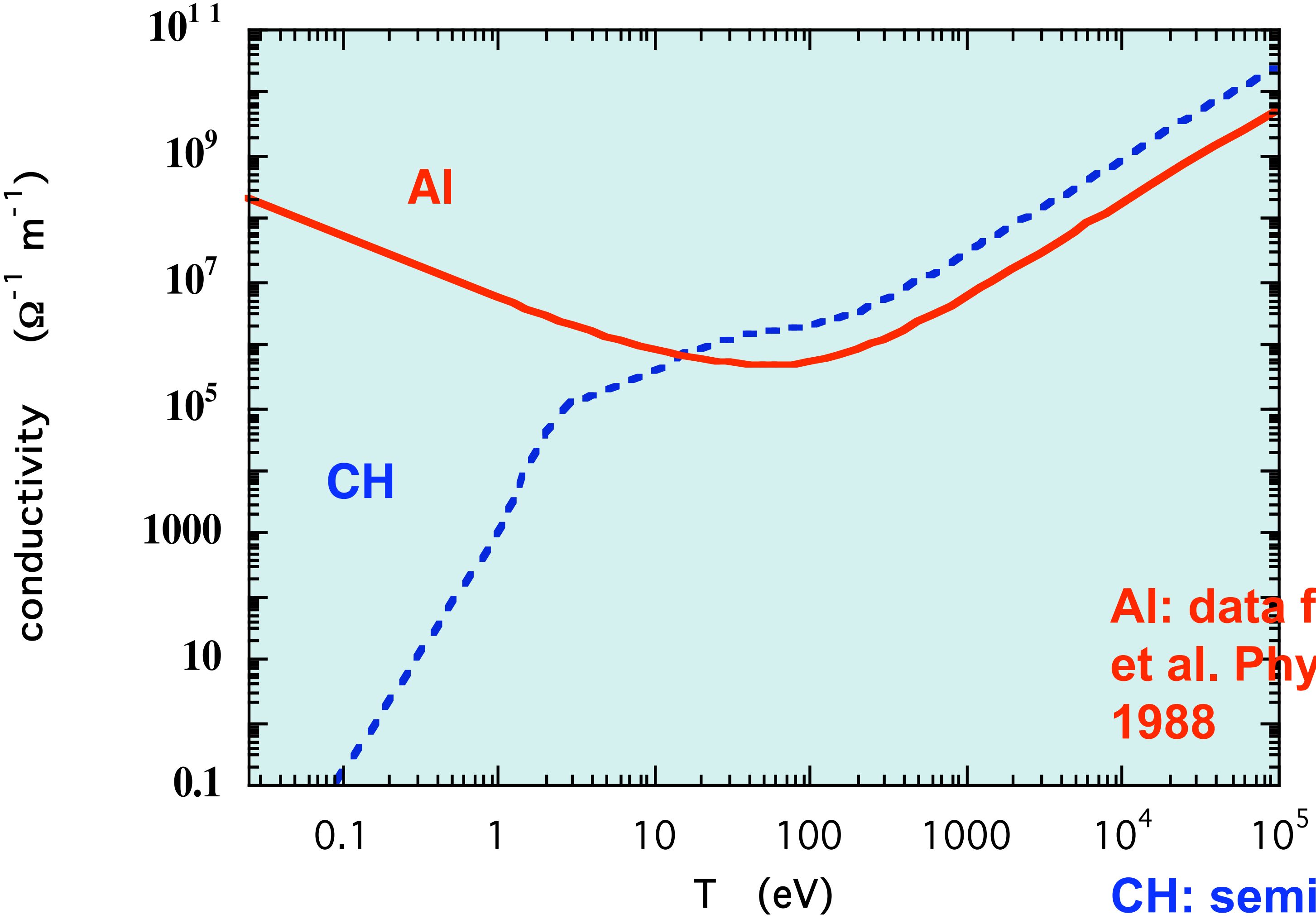
σ = 59.6 10^6 for Cu and 37.8 10^6 for Al

We find large numbers (800 μm or 0.2 g/cm^2 for Al)

No Electrical Inhibition?

And what about plastics?

Problem - calculation of σ



Al: data from H.Milchberg et al. Phys. Rev. Lett. 1988

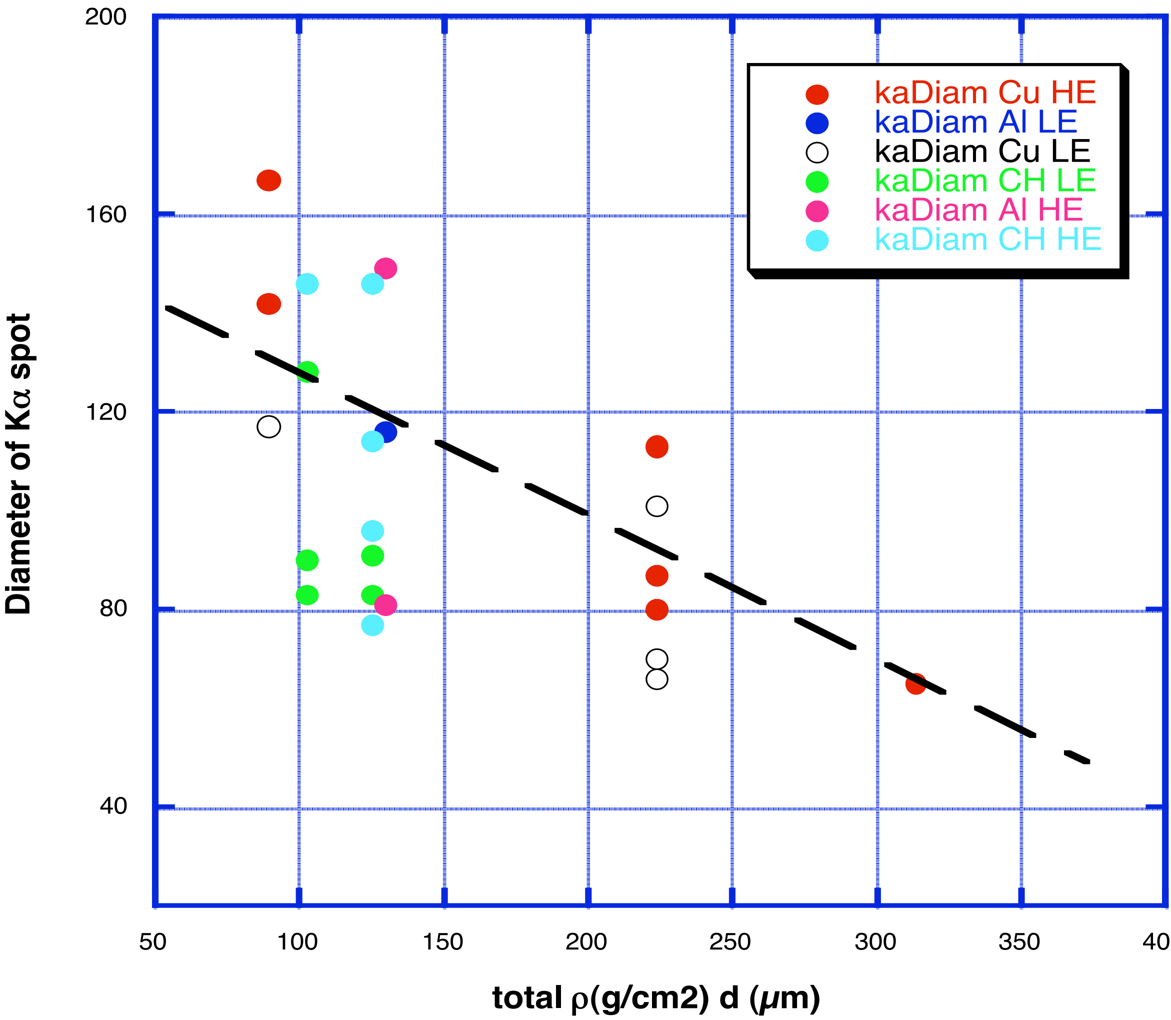
CH: semiclassical model with ionization from Sesame tables

Problem - calculation of σ

The value z_o = 0.2 g/cm^2 for cold Al (σ = 37.8 10^6 (Ω m)$^{-1}$) implies that we get the experimental value 0.0075 g/cm^2 for $\sigma \approx 1.4\ 10^6$ or a temperature T ≈ 5eV.

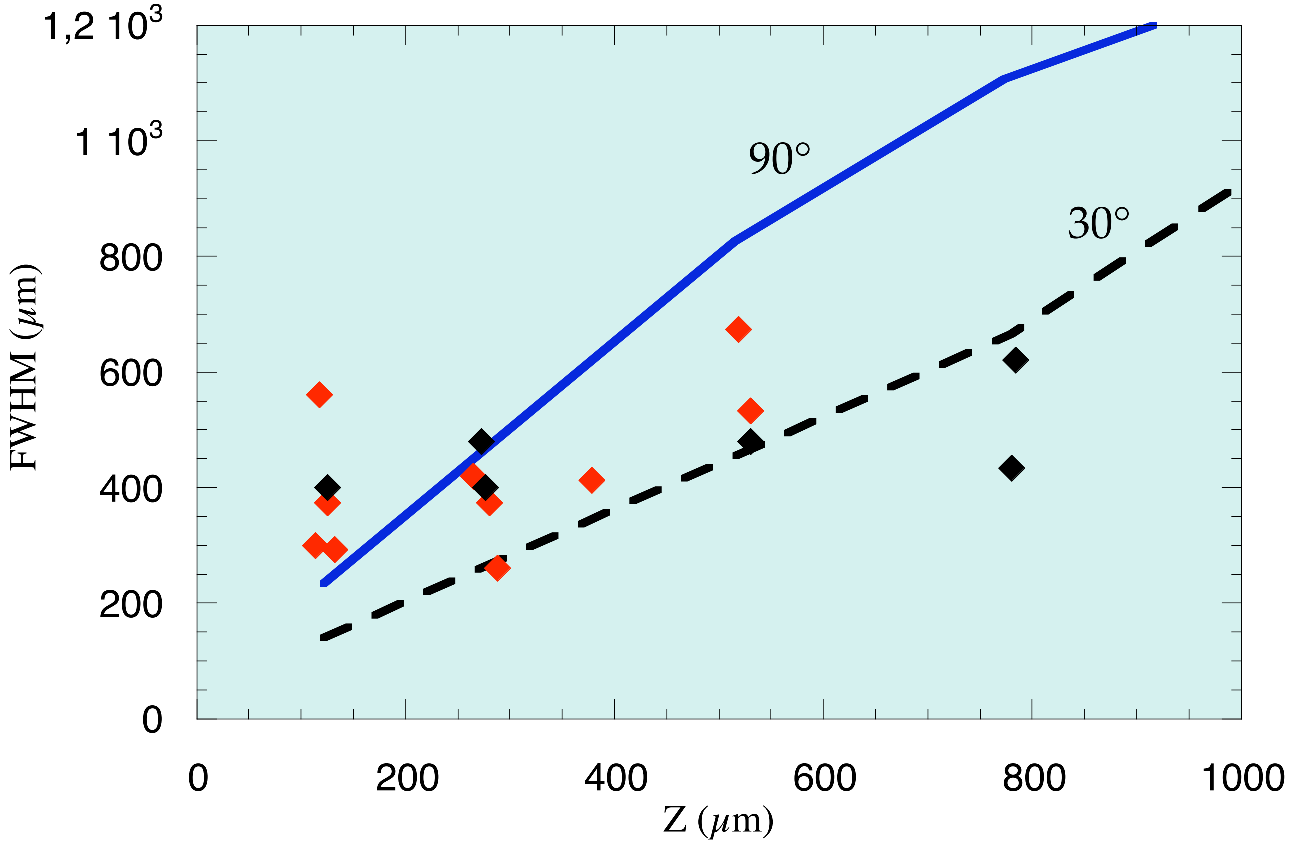
At the same temperature $\sigma \approx 2\ 10^5$ (Ω m)$^{-1}$ for CH giving z_o = 0.001 g/cm^2 in the same range of experimental data (0.005 g/cm^2) while collisional penetration was 0.026 g/cm^2

Kα source size vs crossed mass



The Kα spot size diminishes as target thickness increases

Comparison with previous works



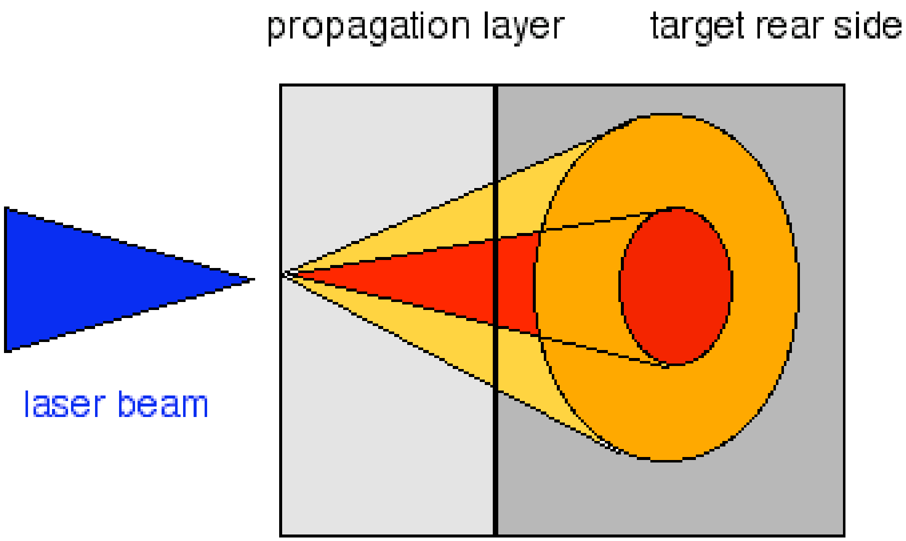
Wharton et al.

PRL 81, 5 (1998)

Measured x-ray source size vs CH thickness, compared with simulation for e-beam with 30° and 90° half-cone angles

Effect of self-pinching due to magnetic fields?

Possible alternative explanation



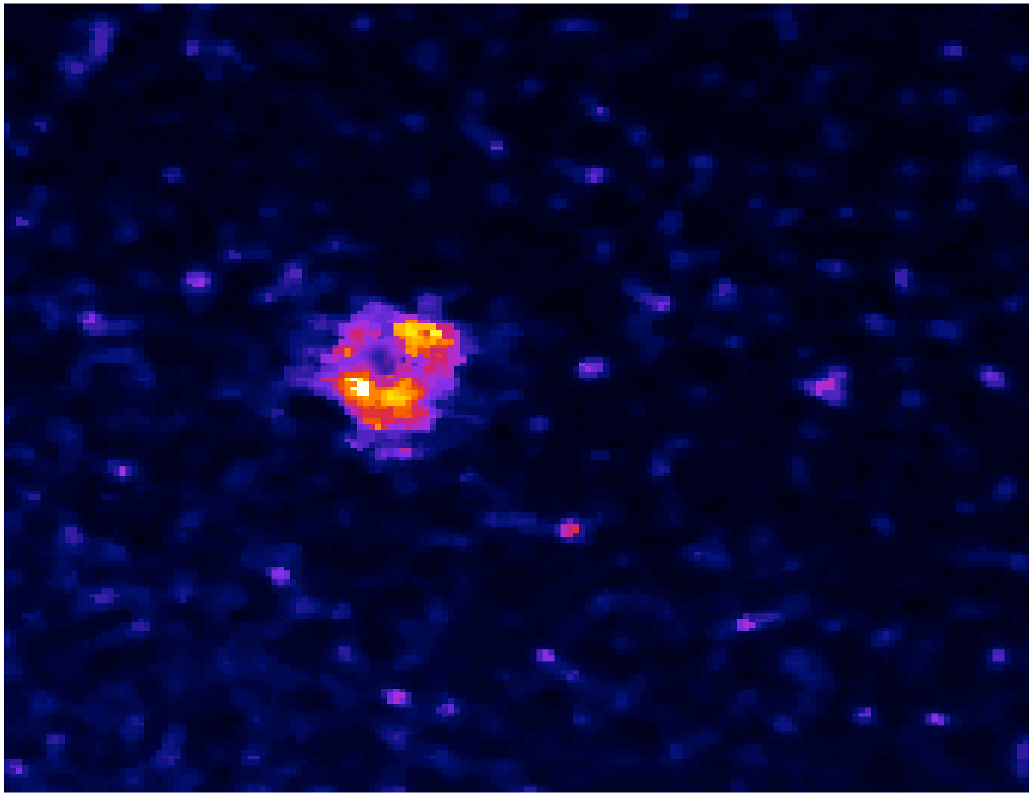
Fast electrons are produced with an angular distribution g(Θ) and an energy distribution f(E).

The smaller the energy, the larger the angle (??)

For small thickness, we observe the effect of large Θ, as thickness is increased we see the effect of larger energies (lower energies electrons have been already stopped) and smaller Θ.

Our data clearer: Kα spot diminishes instead of remaining constant

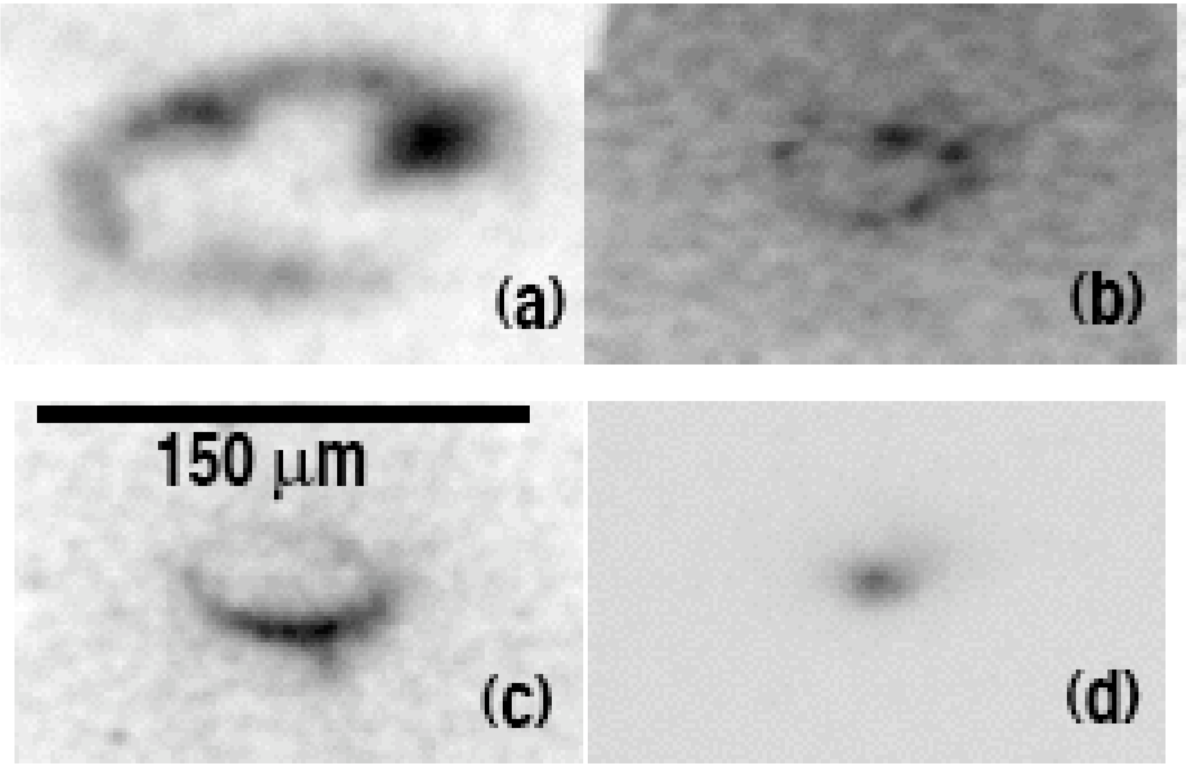
Annular propagation



Cu 35 μm

E = 4.7 J

Comparison with previous works



J. A. Koch, et al. “Experimental measurements of deep directional columnar heating by laser generated relativistic electrons at nearsolid density” Phys. Rev. E 65, 016410 (2001)

FIG. 1. X-ray pinhole images of thin diagnostic layers buried in CH targets. (a) is from an Al layer, buried 15 µm under the front surface and (b) from a Au layer at a depth of 50 µm. (c) is from a Au layer at a depth of 100 µm, viewed from the back of the foil. In contrast, (d) shows the solid spot emitted by a solid Au film viewed from the front.

Comparison with previous works

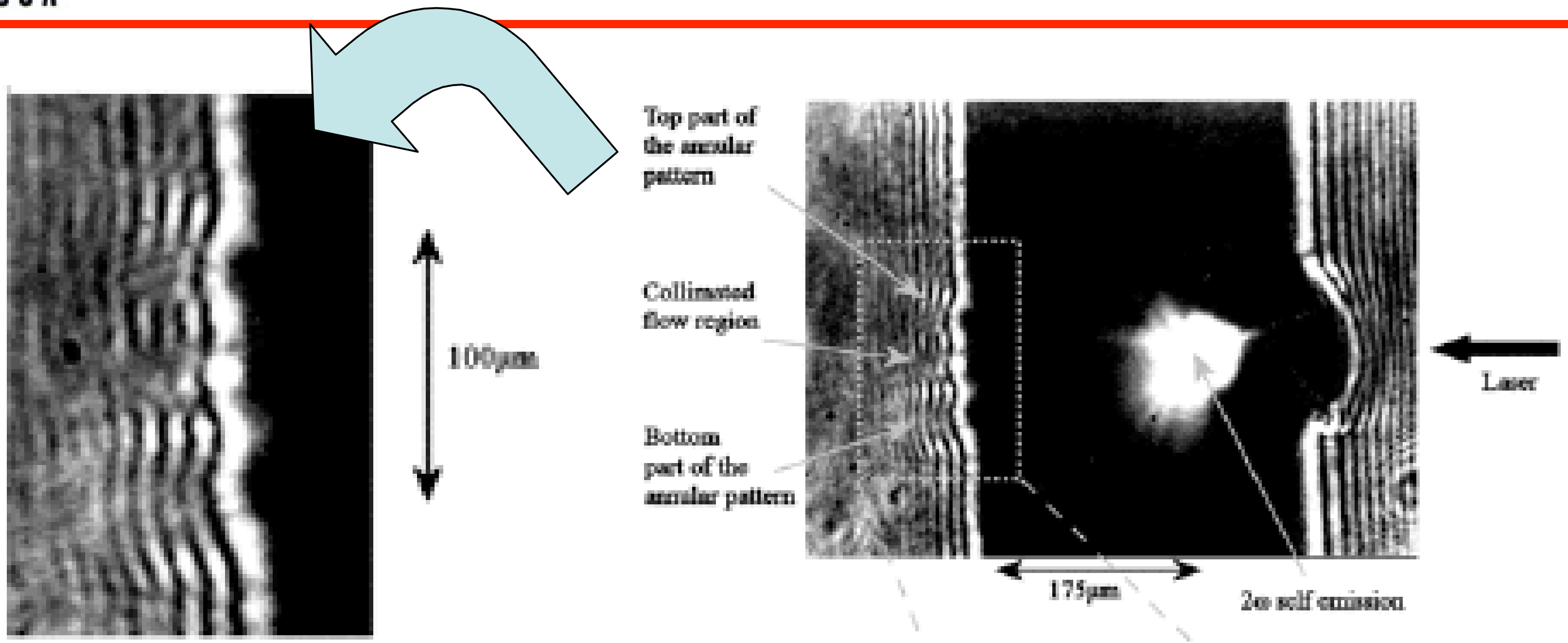


Figure 2. A 50TW laser pulse on a 175μm thick mylar target, corresponding to an intensity of 2×10^{19} $\mathrm{Wcm^{-2}}$ within the focal spot. The heated plasma on the rear surface of the target exhibits a central heated region surrounded by an annular structure with a total divergence angle of 20°.

P. A. Norreys, et al. “Observation of annular electron beam transport in multi-TeraWatt laser-solid interactions” Plasma Phys. Control. Fusion, 48, N. 2 (February 2006)

Conclusions

First experiment realized with the new XL-III 350 TW fs laser facility Academy of Sciences Beijing China

- Prepulse problem ⇒ low fast electron energy
- No match with collisional predictions
- Significant electric inhibition, background temperature ≈ 5 eV
- Spot size decreases with thickness (effect of angular/energy distribution?)
- Annular propagation at large distances. Role of self generated magnetic fields?

Clear experimental data show effects previously observed only at higher laser intensity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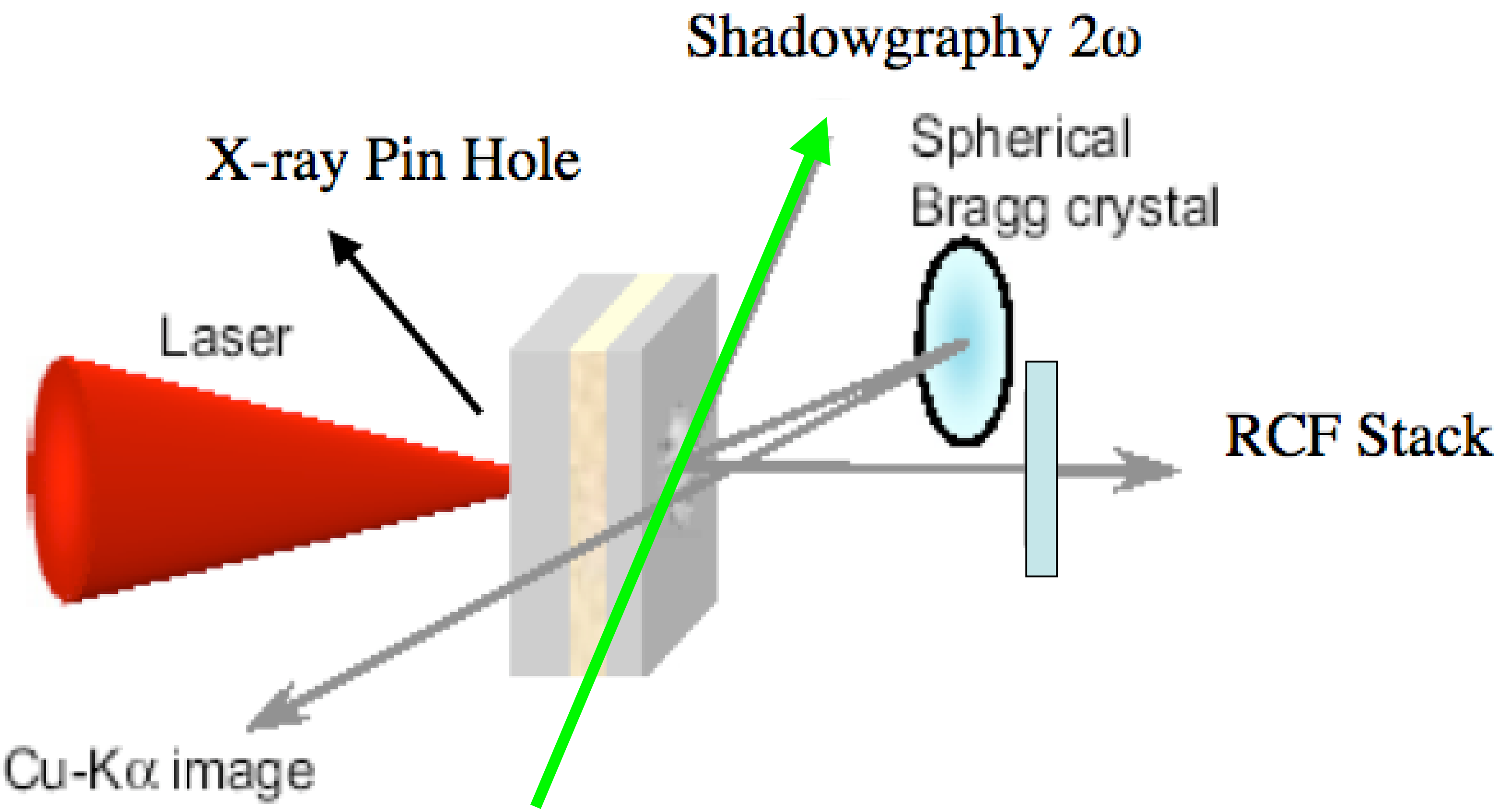
Thank you !!

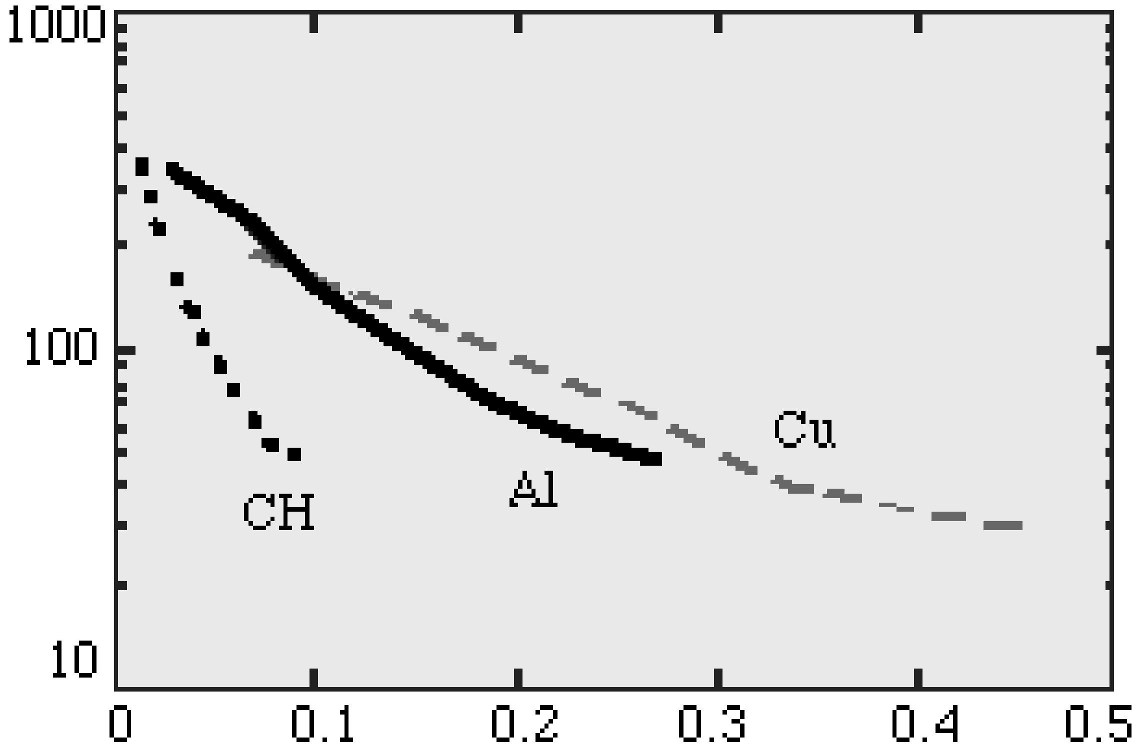
Experimental set-up, summary



We are looking for information about:

- Penetretion range
- Fast electron beam geometry

Comparison with previous works



$\exp(-R/R_o)$

Our results in agreement with Key et al. [Phys.Plasmas, 5, 1966 (1998)]. At larger laser intensity and fast electron energy 640 keV, they got:

0.032 g/cm^2 for CH ⇒ 320 microns
0.1 g/cm^2 for Al ⇒ 370 microns
0.195 g/cm^2 for Cu ⇒ 220 microns

Comparison with previous works

Collisional stopping power in the non-relativistic regime

$$\frac{dE}{dx} = \frac{K}{\rho m v^2}\ln(..) \quad \Rightarrow \quad x \propto E^2$$

Electrical Penetration Range (Bell's law)

$$z_o = 3 \; 10^{-3} \, (kT_{fast})^2 \, \sigma_6 \, I_{17}^{-1} \; \mu m,$$

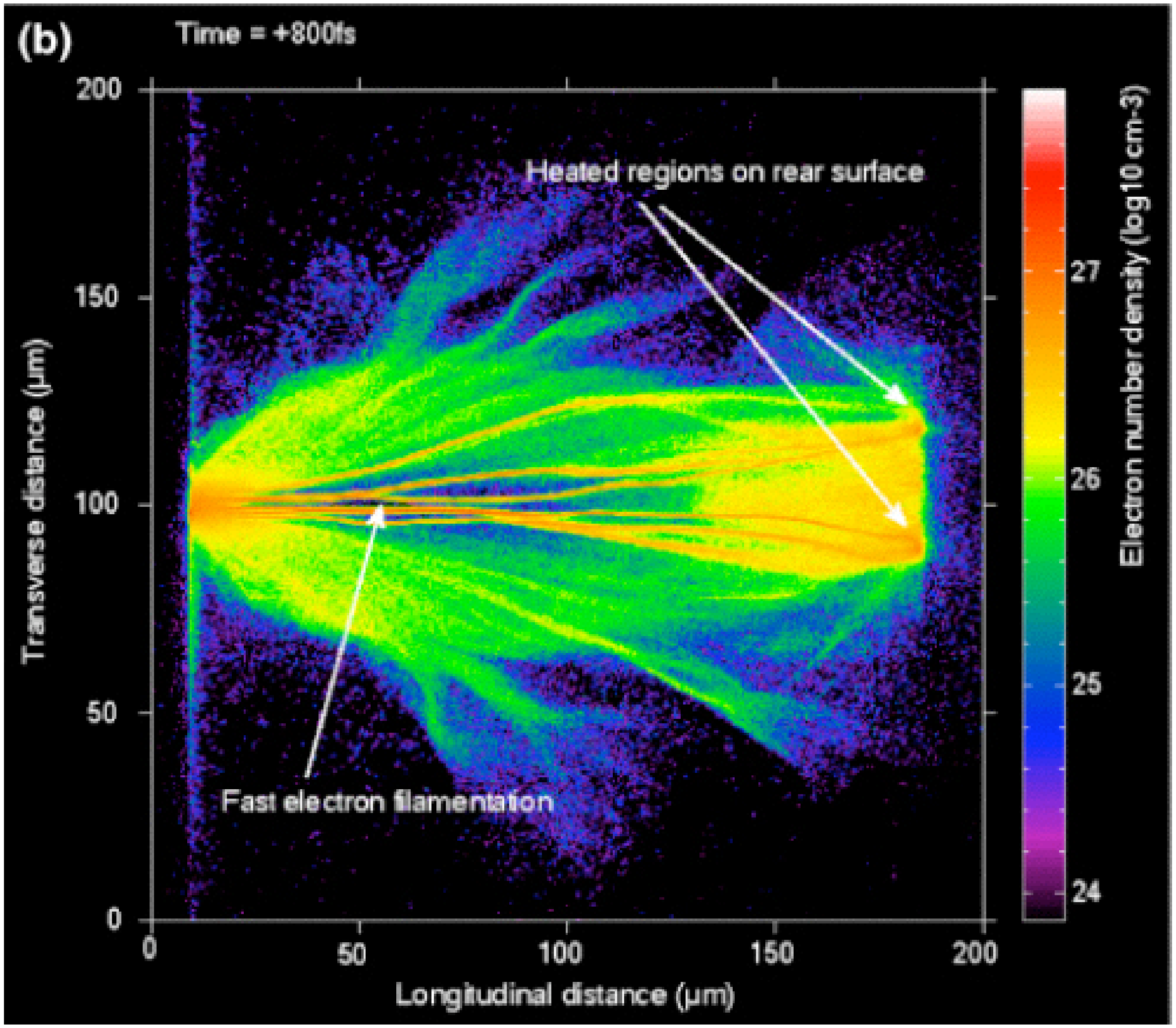
Now

$$\left(\frac{150\ keV}{640\ keV}\right)^2 = 0.055$$

320 μm for CH ⇒ 18 μm (measured 50 μm)
370 μm for Al ⇒ 20 μm (measured 28 μm)
220 μm for Cu ⇒ 12 μm (measured 16 μm)

Agreement is fair (we have large error bars)

Self-generated magnetic-field effect?



Fast electron number density given by LSP 800 fs after the fast electron beam was injected at the target front surface for an intensity of 6 10^{19} W/cm^2.