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Divergence control and fast electron transport in laser solid interaction

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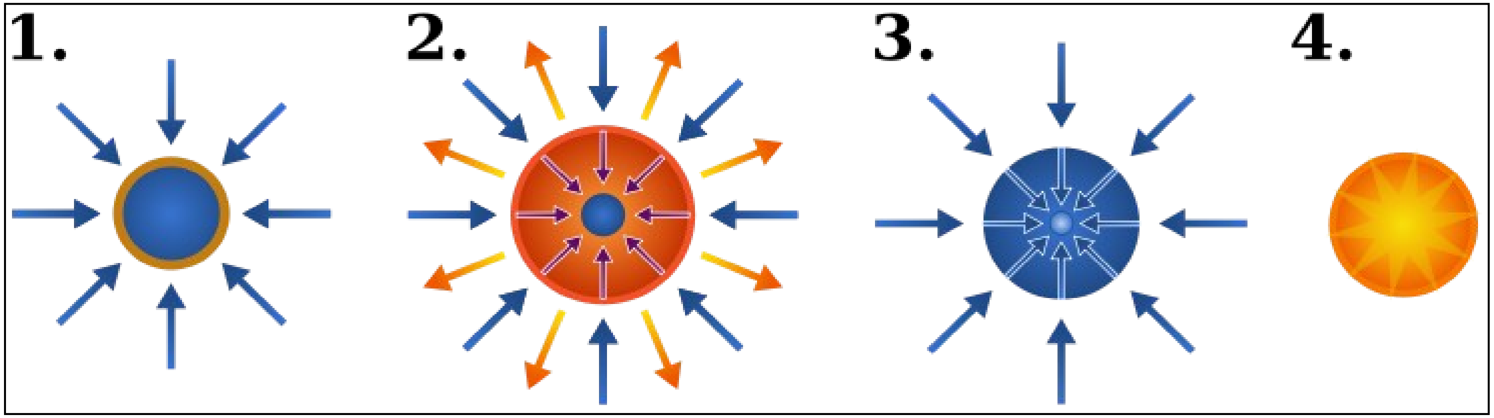
Laser Driven Fast Electron Collimation by Magnetic Fields from Z Boundary Targets

LASER for five decades, a milestone looms in the world of laser fusion

Outline

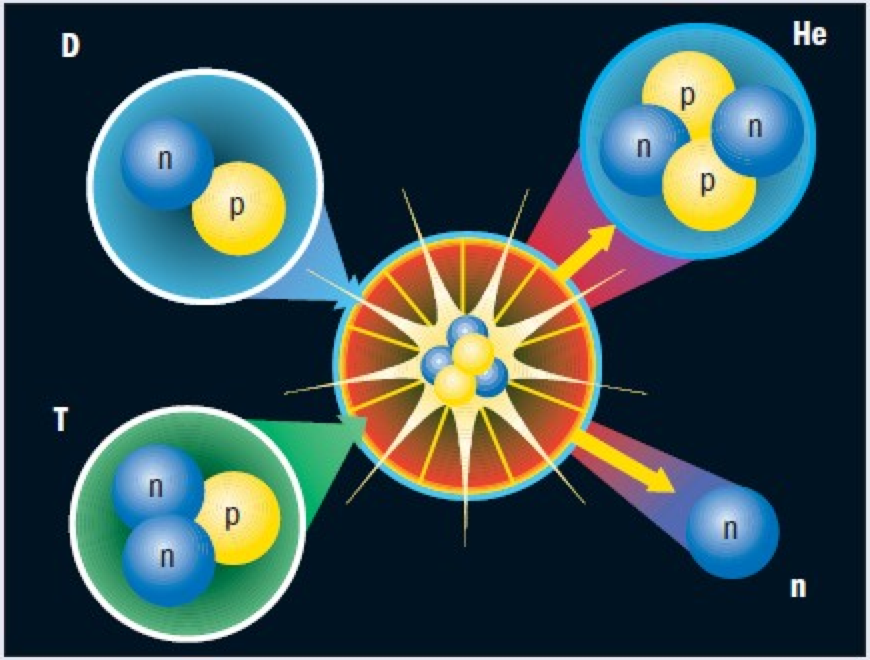
- Inertial Confinement fusion
- Concept of fast ignition
- Electron beam- transport and divergence issues
- Beam collimation ideas - targets and experiments
- Z - boundary target – Results
- Fast electron transport using double pulse

Energy production: Laser driven thermonuclear fusion



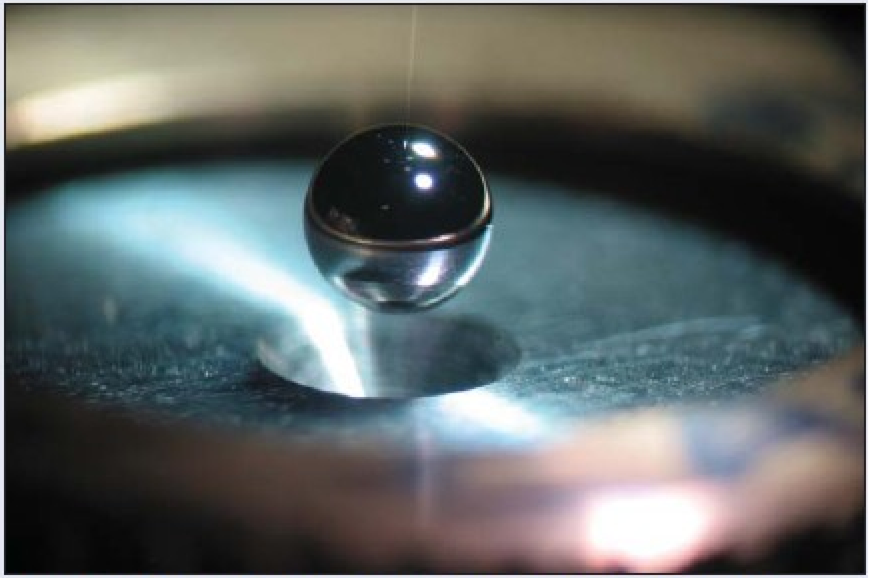
1. Laser beams or laser-produced X-rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope. 2. Fuel is compressed by the rocket-like blowoff of the hot surface material. 3. During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000 ˚C. 4. Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.

1 Getting it together



In a nuclear-fusion reaction, molecules of deuterium and tritium – isotopes of hydrogen with one and two neutrons, respectively – combine to produce helium and an energetic neutron.

2 On target

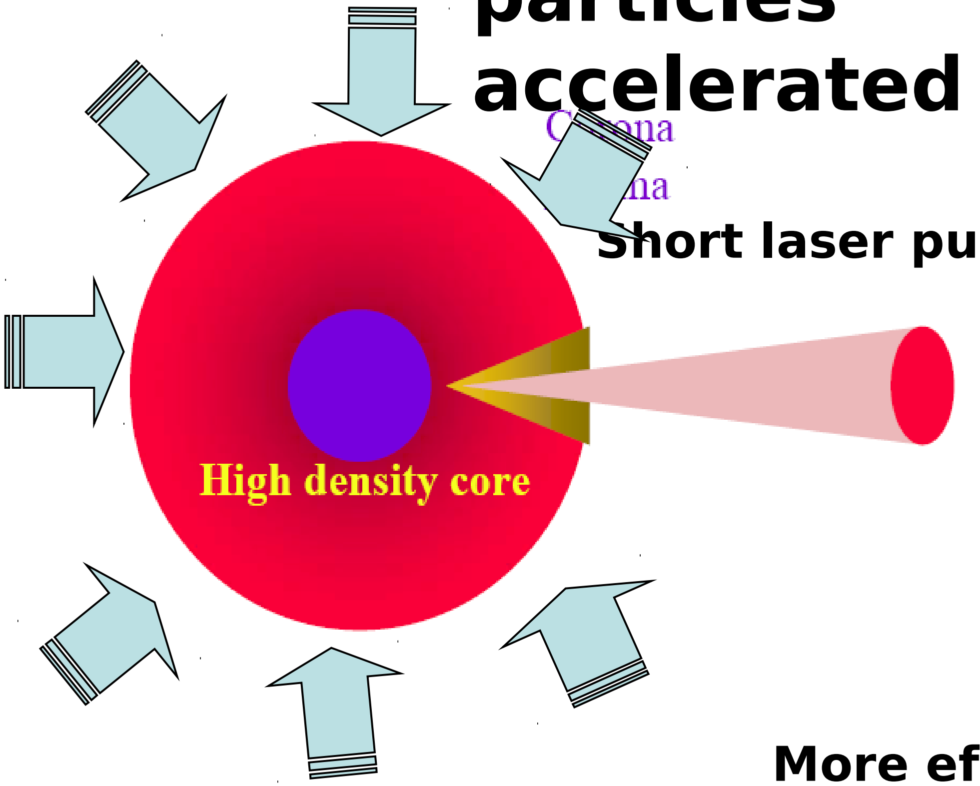


The fuel pellets used in laser fusion are ball-bearing-sized hollow spheres made of beryllium (shown here), plastic or high-density carbon. The pellets must be extremely round, with a very smooth surface, since any irregularity will cause the laser beam to transfer energy to the fuel unevenly.

$$^{2}\mathrm{D}+{}^{3}\mathrm{T} \rightarrow {}^{4}\mathrm{He}(3.5\mathrm{MeV})+\mathrm{n}\ (14.1\mathrm{MeV})$$

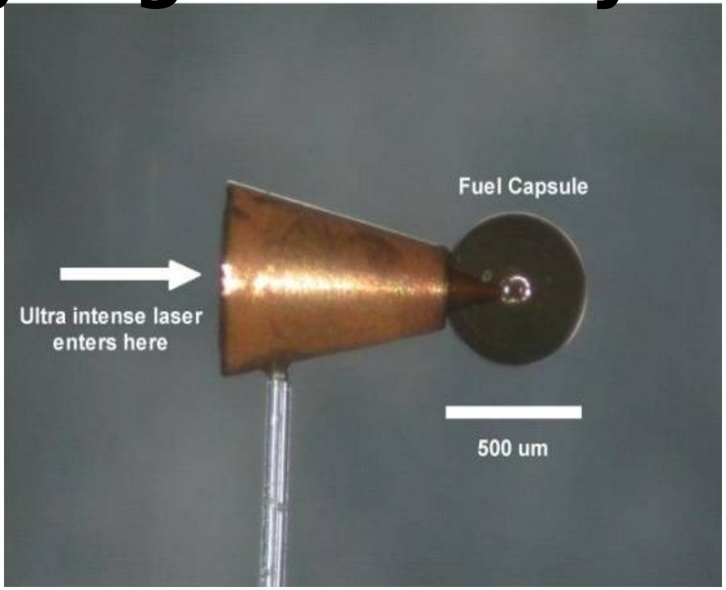
Direct drive and Indirect drive

Fast Ignitor approach employs particles accelerated by high intensity las



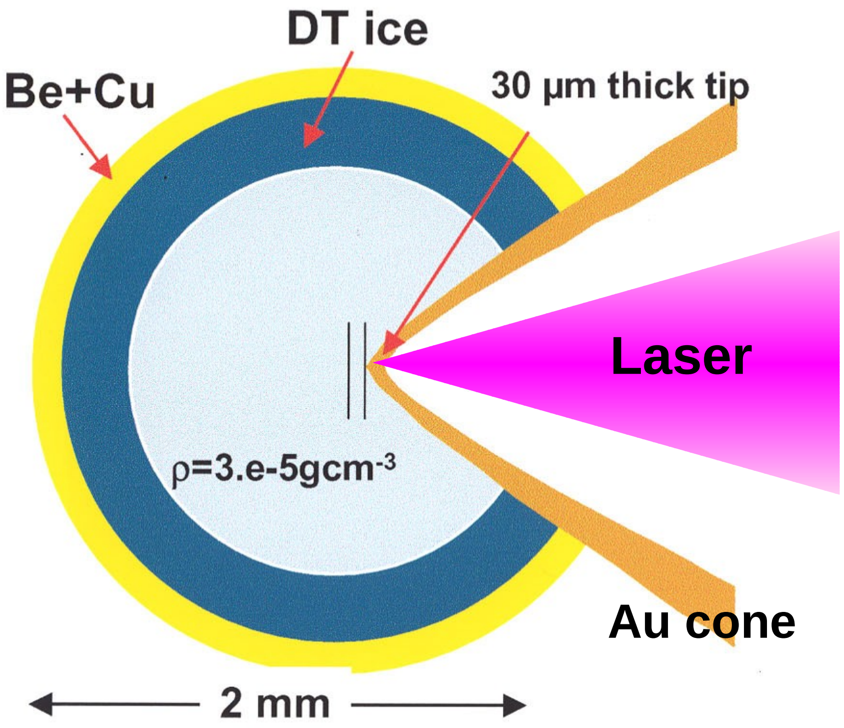
Short laser pulse

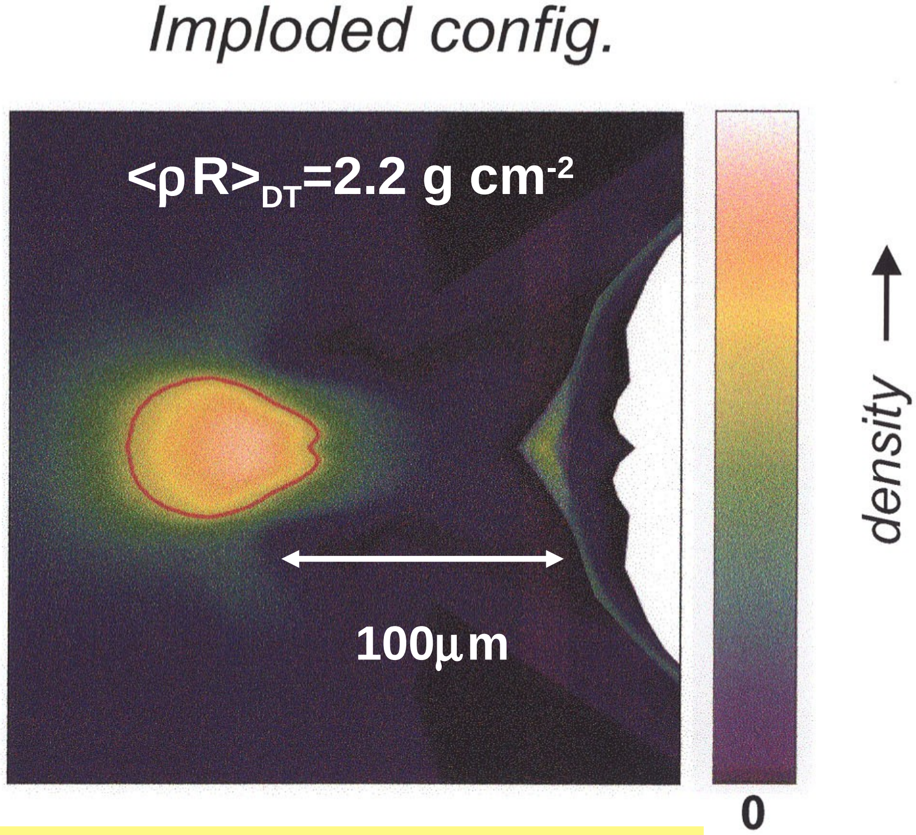
Long pulses



More efficient and more promising for “
energy production

The cone coupled FI concept provides a clear path for the laser with the electron source close to the ignition spot

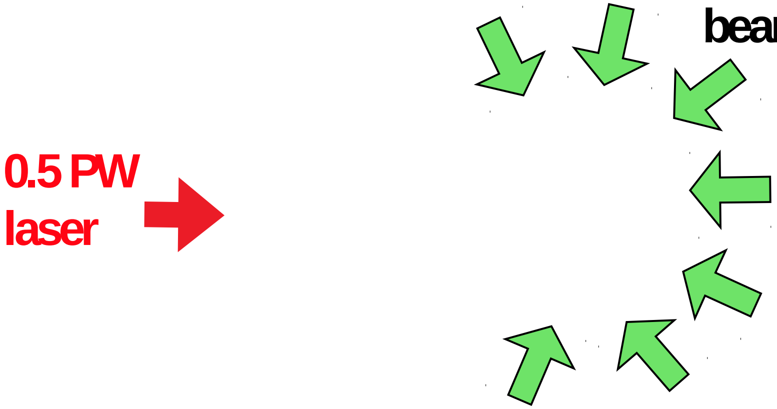




Radiation - hydro simulations are well developed for ICF and allow hydro--design optimization for FI

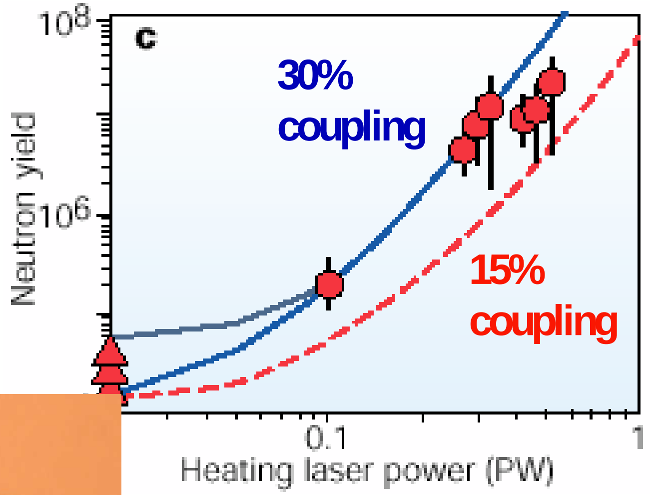
The first cone coupled fast ignition experiment at the Gekko laser in Japan gave very encouraging results

Gekko "Cone" implosion

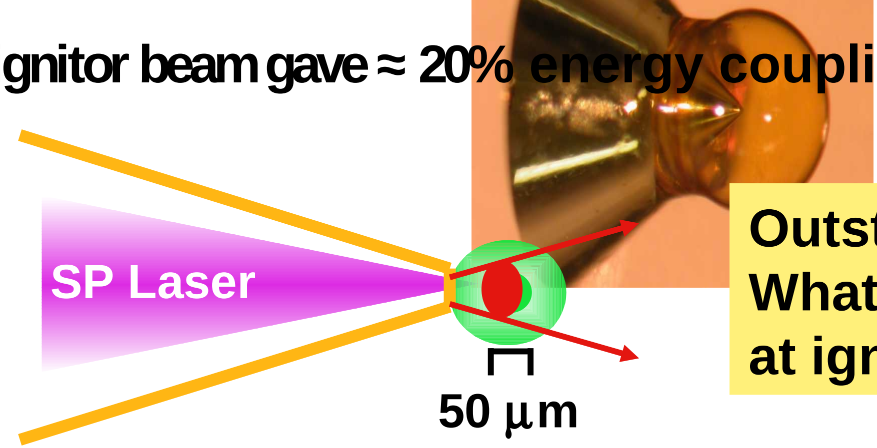


- 1000x increased DD neutrons

R Kodama et.al. Nature 412(2001)798 and 418(2002)933.



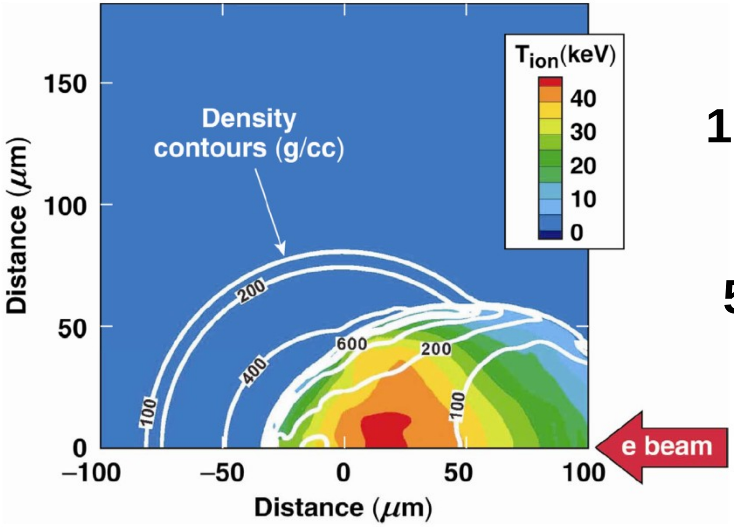
- 0.5PW ignitor beam gave ≈ 20% energy coupling to imploded CD

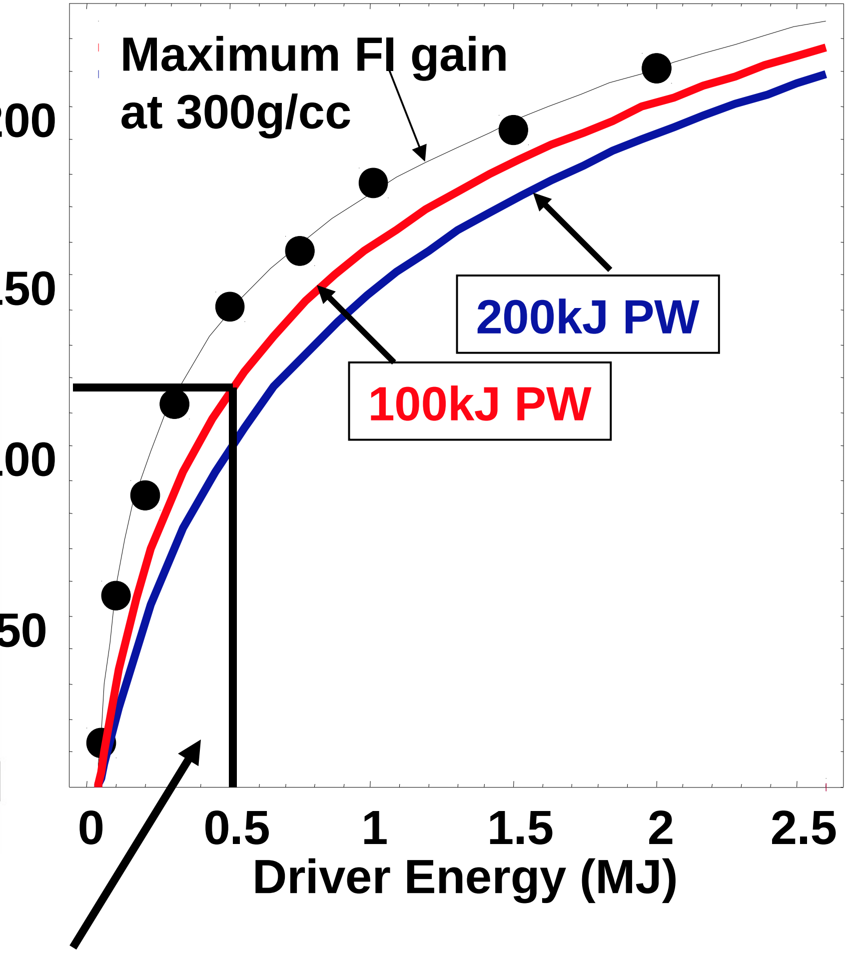


Outstanding question for FI is What coupling is the efficiency at ignition scale ?

Fast Ignition - Modelling

2D simulations of ignition and burn by 15kJ, 2MeV, 20µm, 15ps e-beam

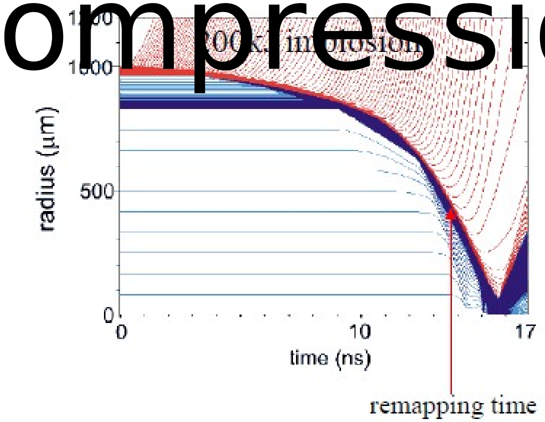


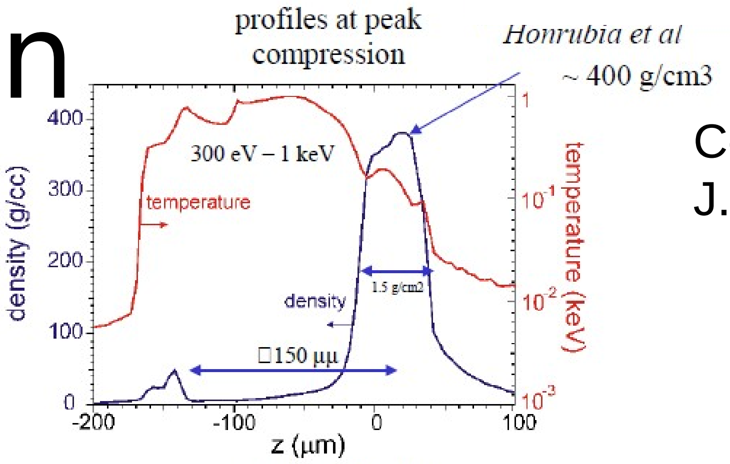


>100x gain with 500kJ driver is attractive for IFE

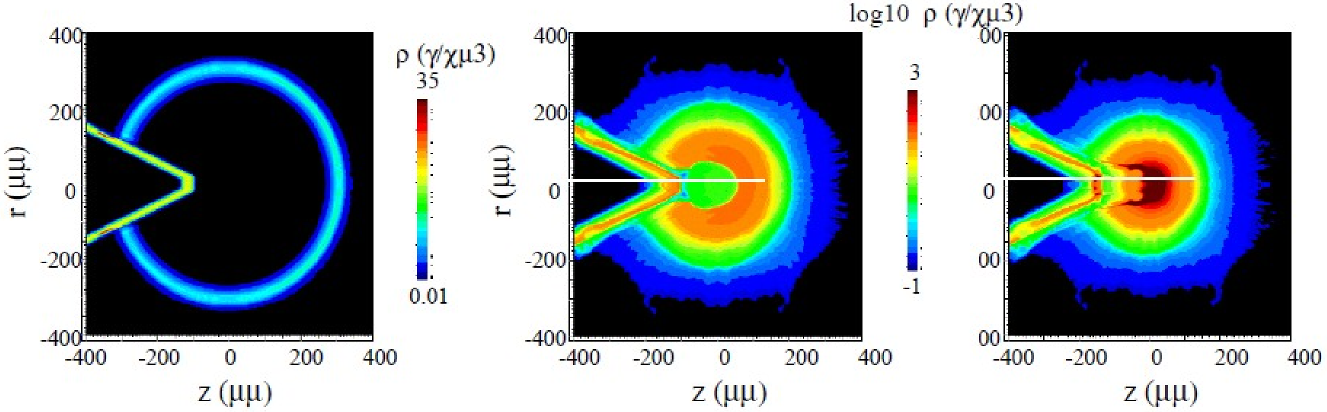
e.g. R. Betti, A.A. Solodov, J.A. Delettrez, C. Zhou, Phys. Plasmas 13, 100703 (2006)

Simulations of fuel compression

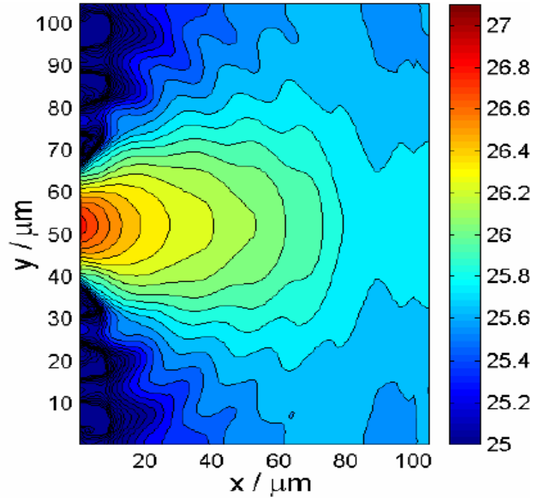




Courtesy J.Honrubia



Divergence- related to B-field and intensity

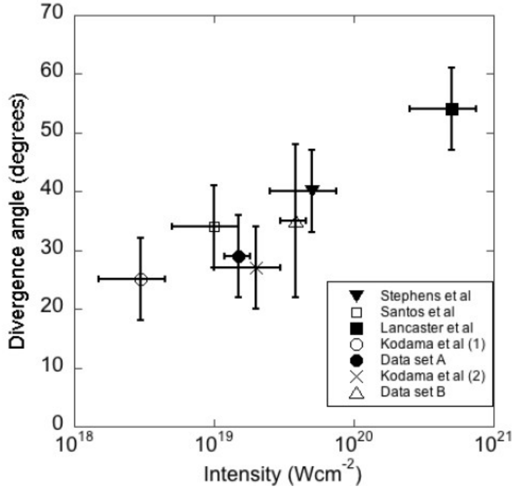


➢ Electron beam transport for laser generated electron beams is highly divergent.

➢**B** field is therefore very weak

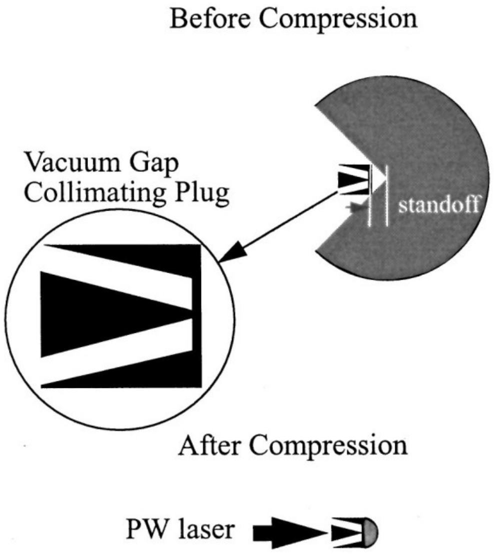
➢Results in a spray of electrons

➢Beam divergence also depends on intensity {J.S.Green et al., Phys.Rev.Lett.100,015003(2008)}



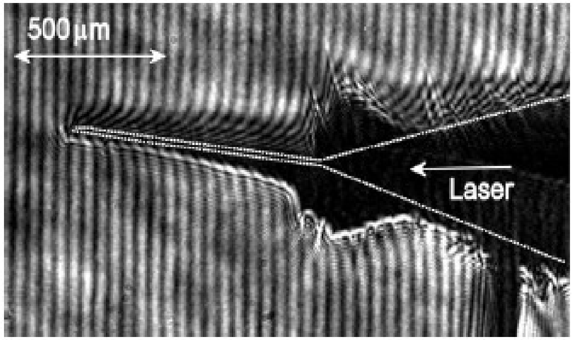
Beam collimation Ideas

1. *"Collimation of Petawatt generated relativistic electron beams through solid density matter"* R.B.Campbell et al., 10,4169(2003)

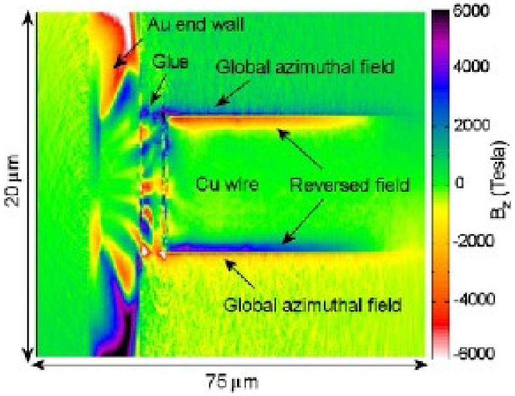


2a. "*Plasma devices to guide and collimate MeV electrons*" R.Kodama et al., Nature (London) 432(7020), (1005) 2004.

2b. "*Surface heating of wire plasmas using laser irradiated cone geometries"* – Nature physics 3, 853 (2007)



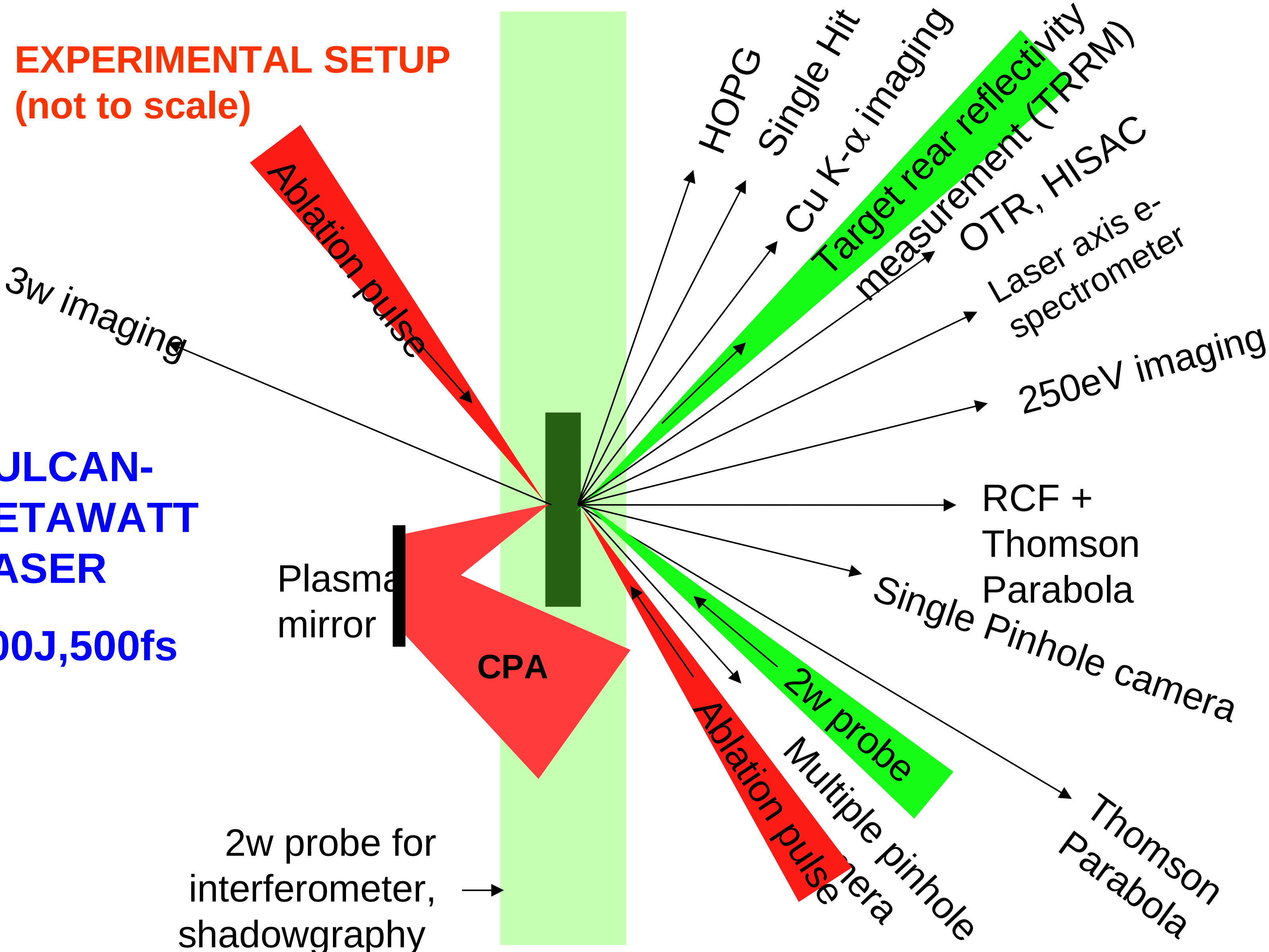
Cone wire plasma expansion 400 ps after plasma expansion



2D-LSP simulation of the magnetic field at the cone- wire interface

ELECTRON TRANSPORT EXPERIMENTS

EXPERIMENTAL SETUP
(not to scale)



VULCAN-
PETAWATT
LASER

500J,500fs

HOPG

Single Hit

Cu K-α imaging

Target rear reflectivity measurement (TRRM)

OTR, HISAC

Laser axis e- spectrometer

250eV imaging

RCF +
Thomson
Parabola

Single Pinhole camera

Thomson
Parabola

Multiple pinhole
era

2w probe

Ablation pulse

Ablation pulse

3w imaging

Plasma
mirror

CPA

2w probe for
interferometer,
shadowgraphy

Experimental set up and theory

HOPG crystal

X-ray Pinhole

Laser

Target

Image plate

Plasma mirror

Al/Fe/Al

Parabola

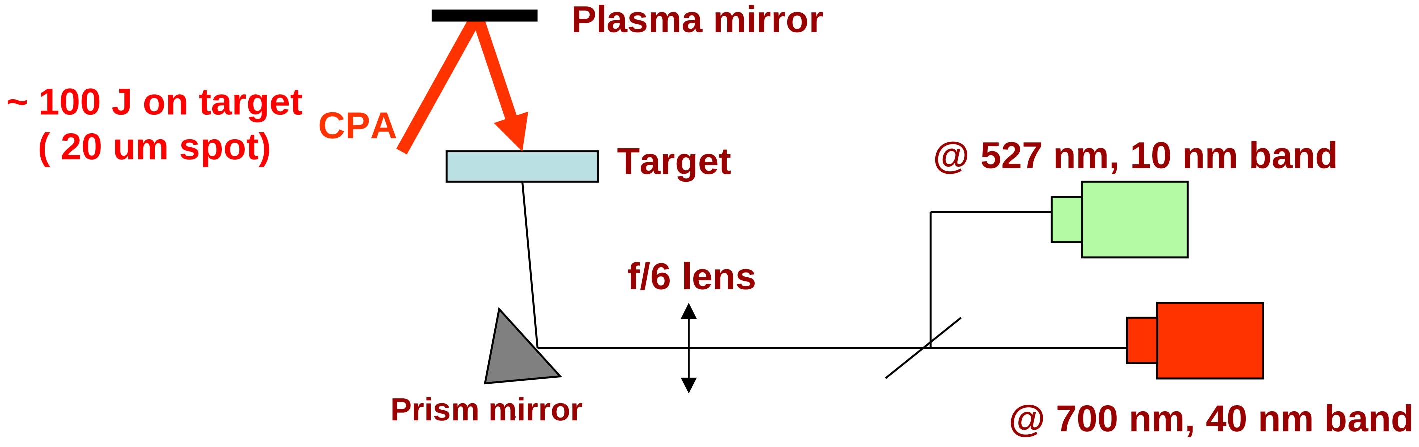
Vulcan TAP LASER I ~ 10^{20}W/cm^2
Pulse duration ~ 500 fs

$$\frac{\partial B}{\partial t} = \eta \nabla \times j + \left(\nabla \eta\right) \times j.$$

I. First term - B acts to push the fast electrons towards regions of higher fast electron density

II. Second term- pushes fast electrons towards higher resistivity

Setup and targets



Plasma mirror

~ 100 J on target
(20 um spot)

CPA

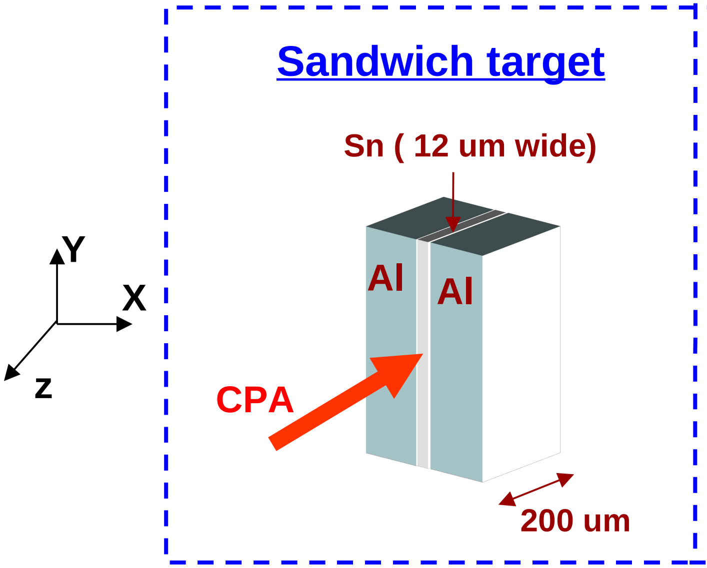
Target

@ 527 nm, 10 nm band

f/6 lens

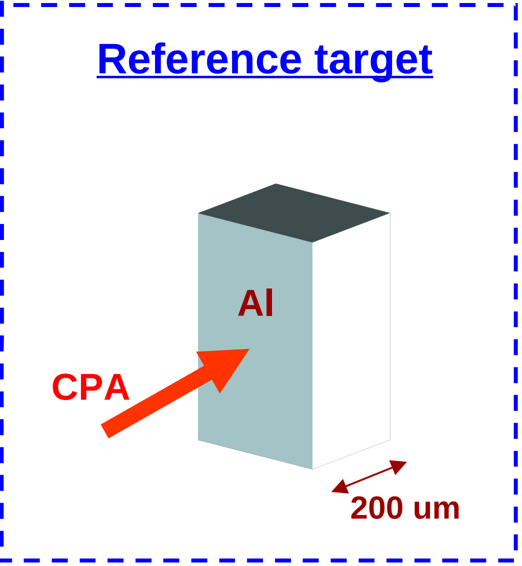
Prism mirror

@ 700 nm, 40 nm band



Sandwich target

Sn (12 um wide)



Reference target

Alluminum (Al)

At. No = 13

R_{elec} = 2.5 [10^8 Ωm^{-1}]

Tin (Sn^{50})

At. No = 50

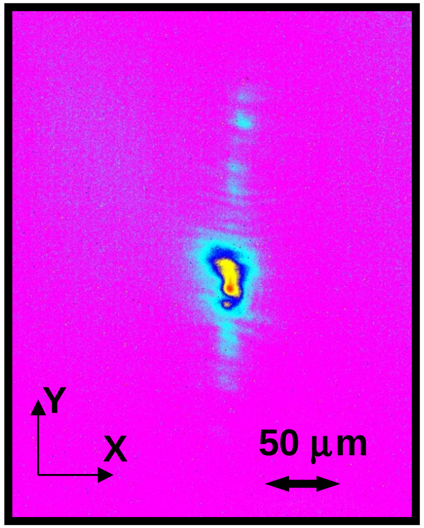
R_{elec} = 11 [108 Ωm-1]

Target Rear surface: lapped (~ 100 nm rms) + Au coated

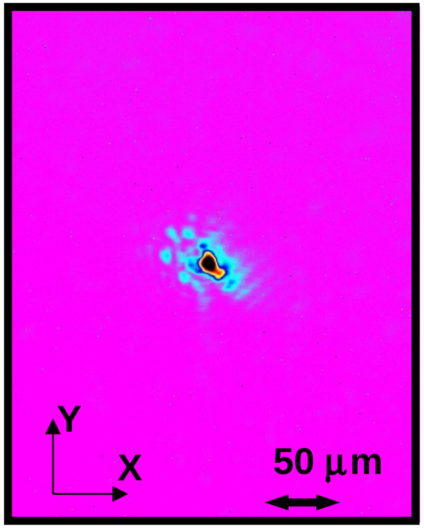
Time integrated images of rear surface optical emission

S. Kar et. al., PRL, 20,133045

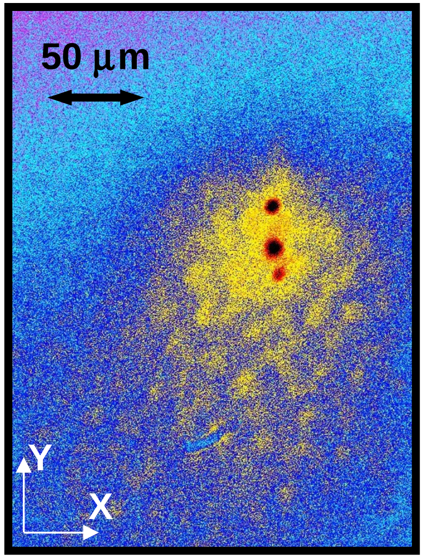
Sandwich Target



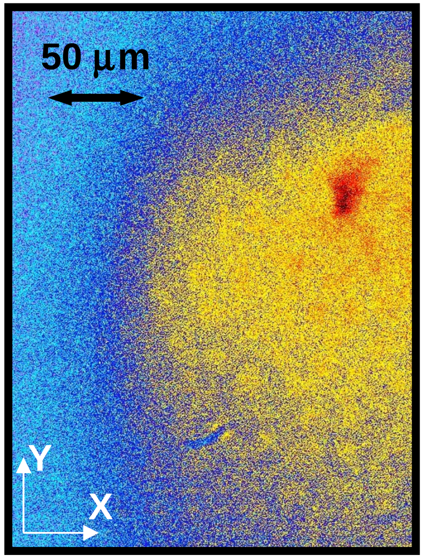
@ 527 nm
Coherent OTR



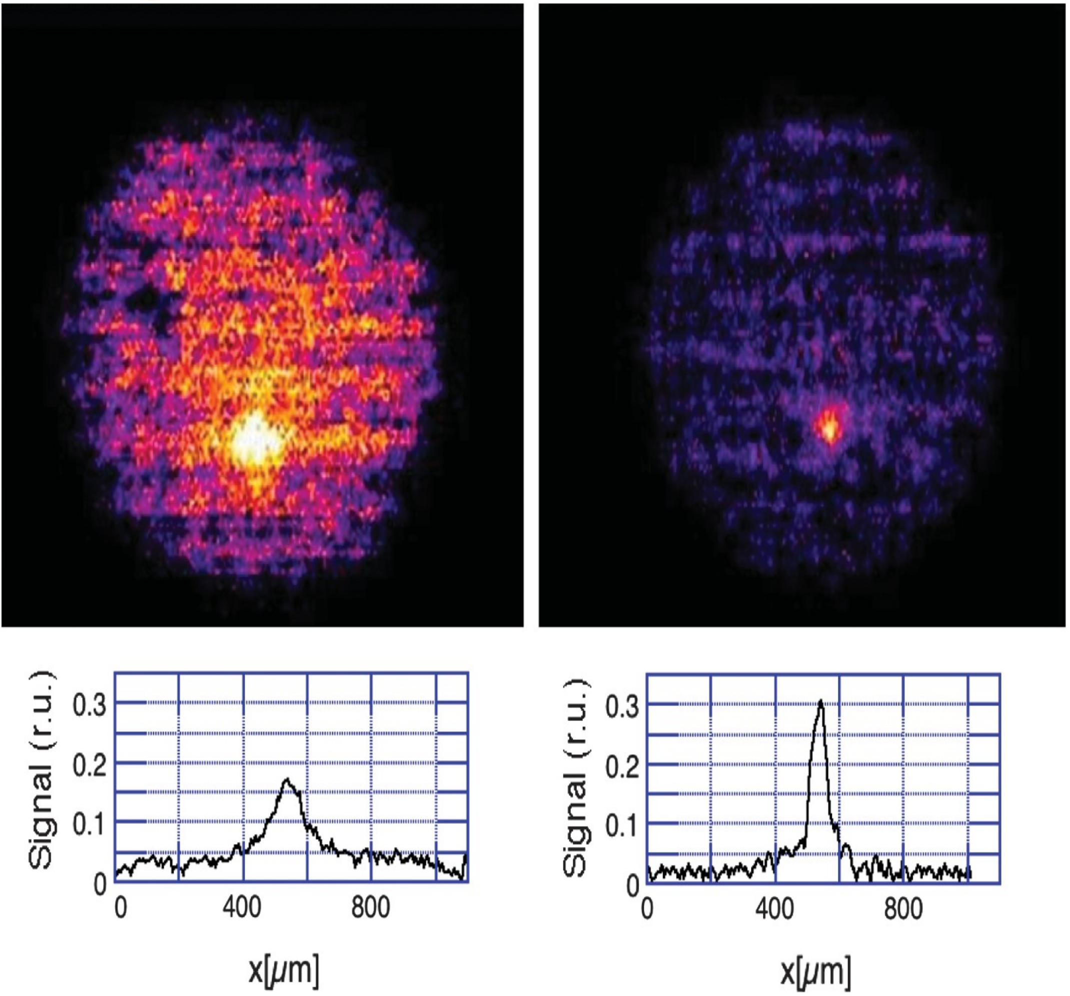
Reference Target

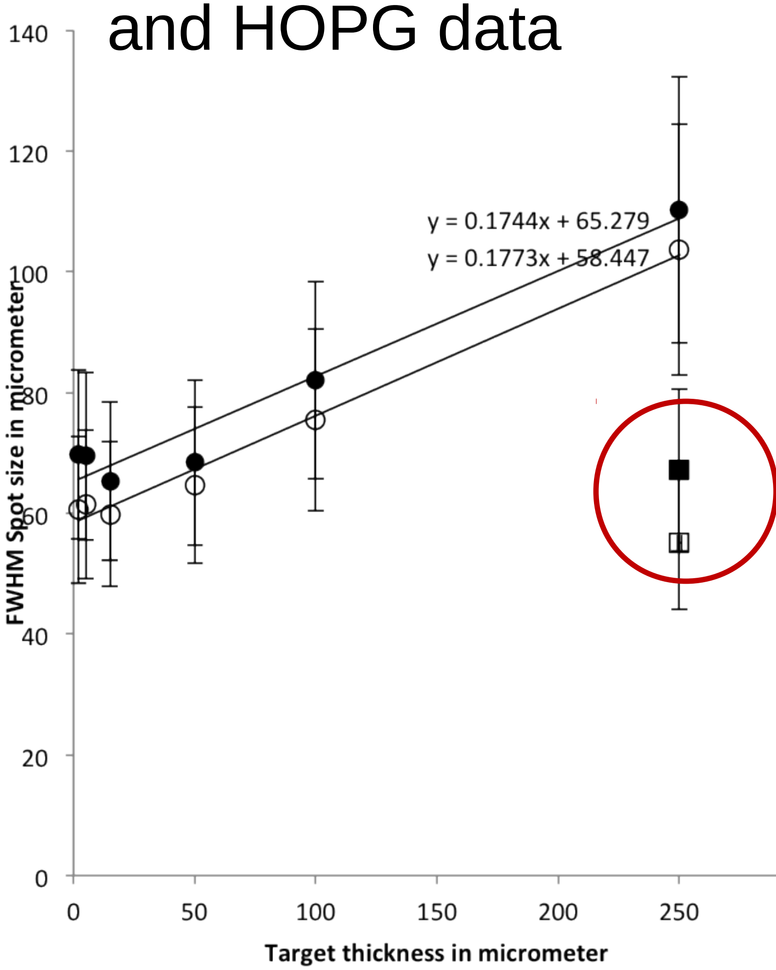


@ 700 nm
Incoherent OTR
+
Planckian emission



Spot sizes measured from Cu-K α Pinhole and HOPG data

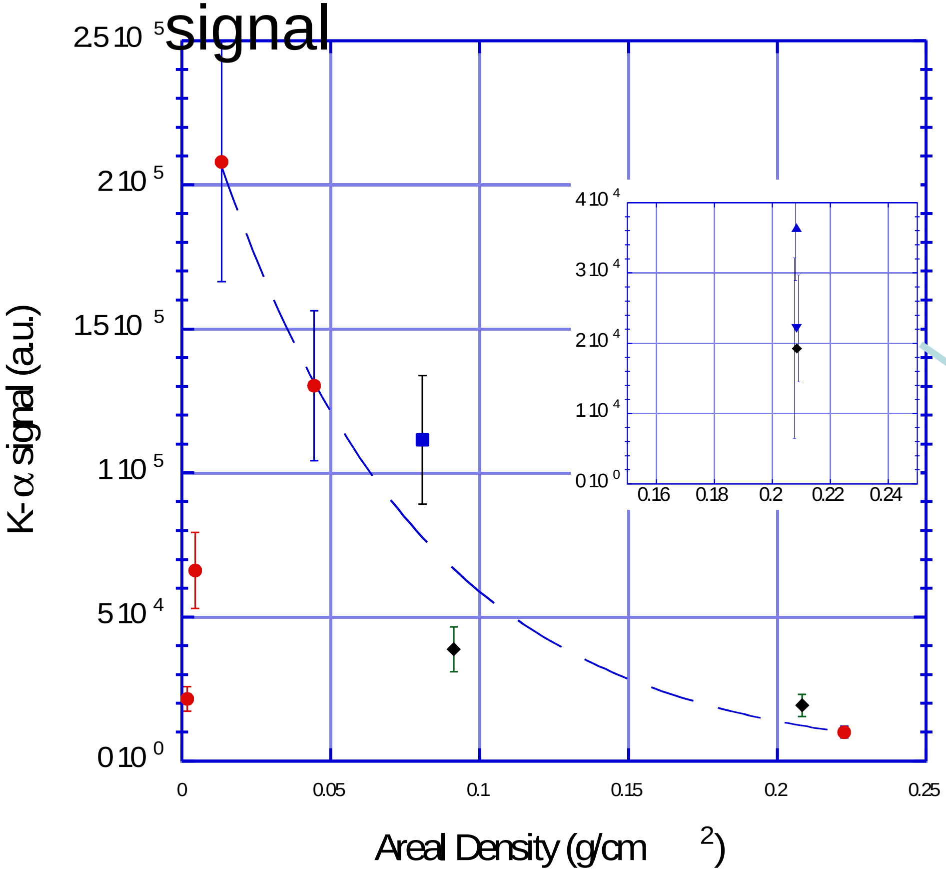




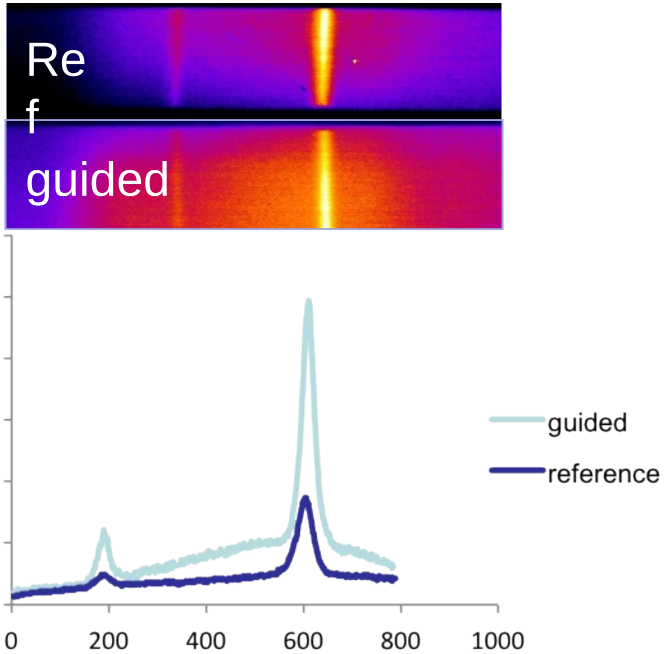
B.Ramakrishna et al.,
(Phys.Rev.Lett. **105**, 135001 (2010)

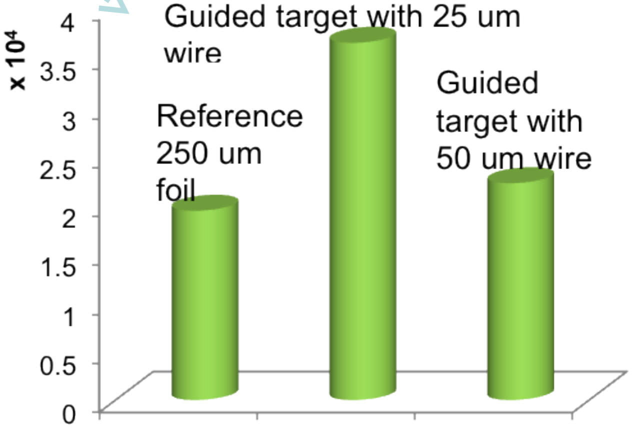
Queen's University Belfast

HOPG K-α Integrated signal



Data follows the simulation trend by Salzmann et al.,





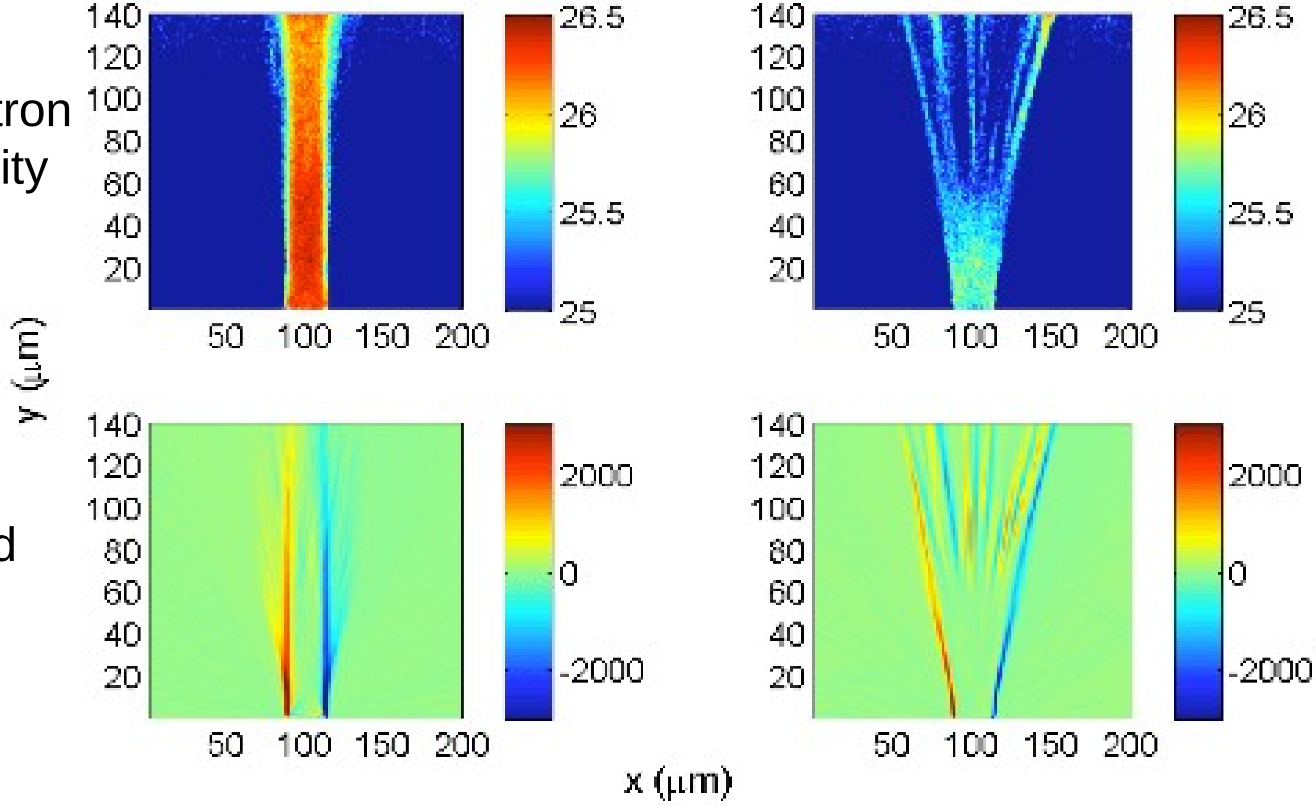
Simulations

GUIDED

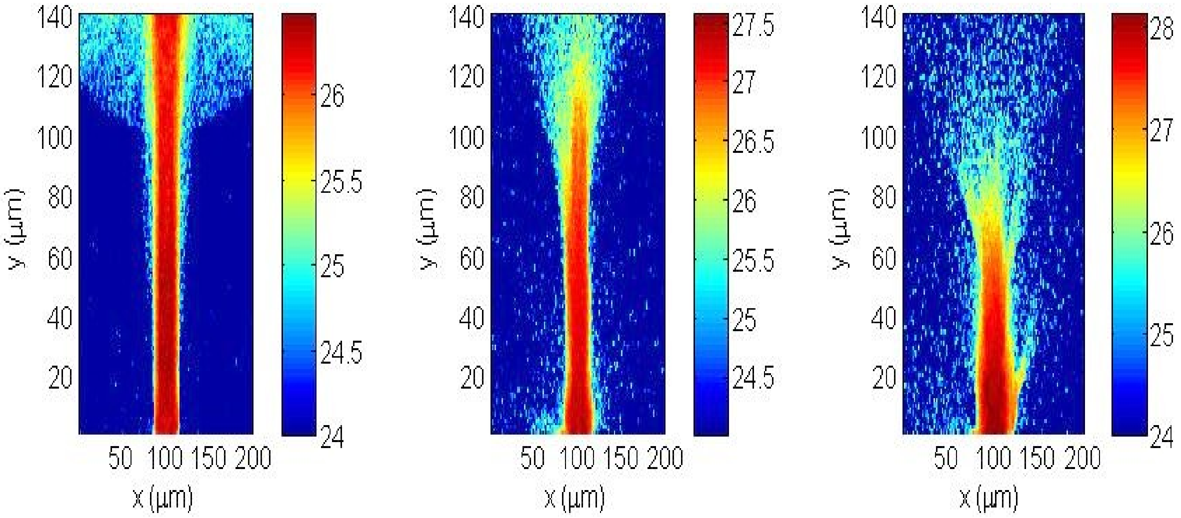
UNGUIDED

Electron density

B_Z field

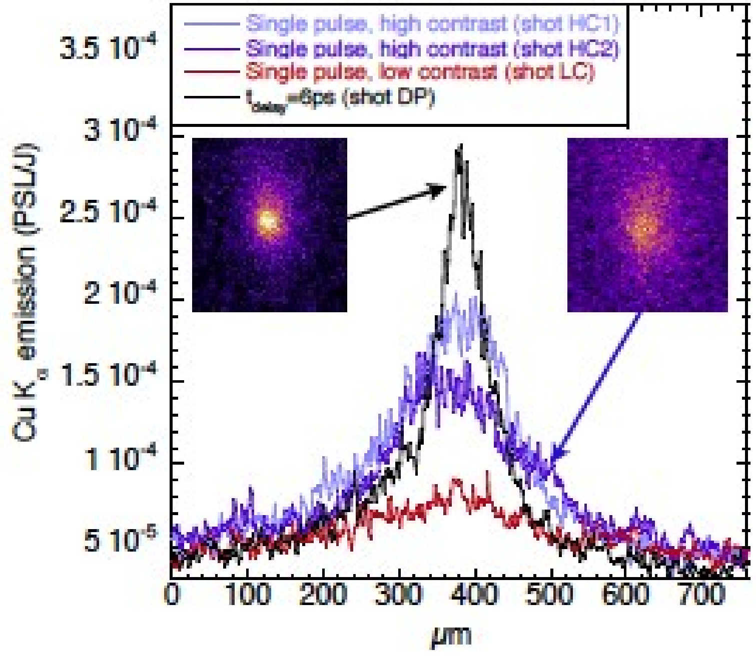


Simulations

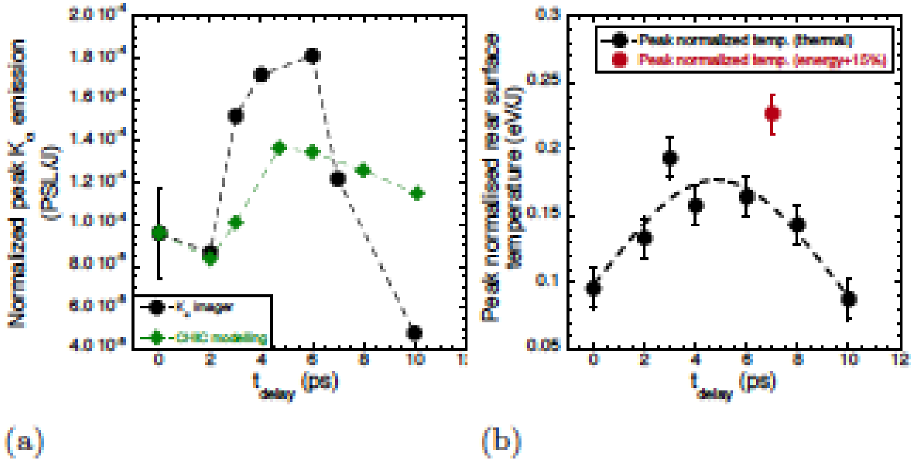


Fast electron density distribution (on logarithmic scale, top images) at 1.5 ps obtained from ZEPHYROS code for Fe/Al guiding-targets with 25µm Fe core for temperatures of 9 MeV (left), 3 MeV (centre) and 1 MeV (right). Colour bar is in units of $\log(N_e[m^{-3}])$. All three cases show clear confinement of the electron beam to the Fe core despite electron being injected with a full cone angle of 60°. The confinement is clearly robust with respect to variations in hot electron temperature. Note that the range of the electrons is substantially reduced compared to single particle ranges by collective stopping (~80µm rather than ~400µm for 1 MeV electrons)

Double pulse experiments

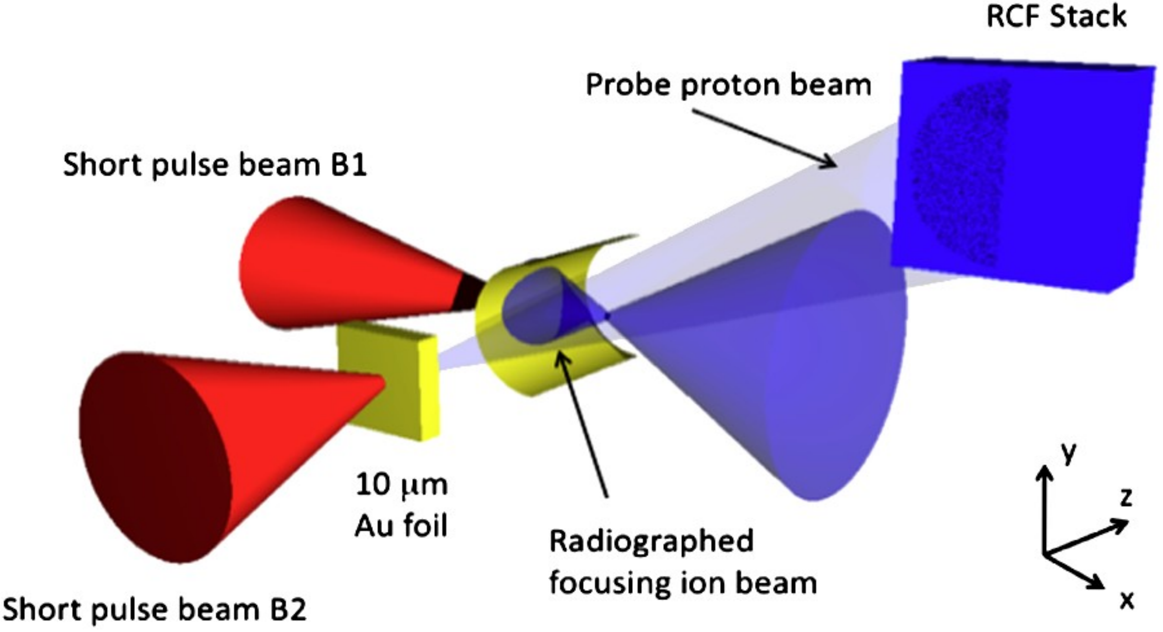


Robbie Scott et al., PRL accepted



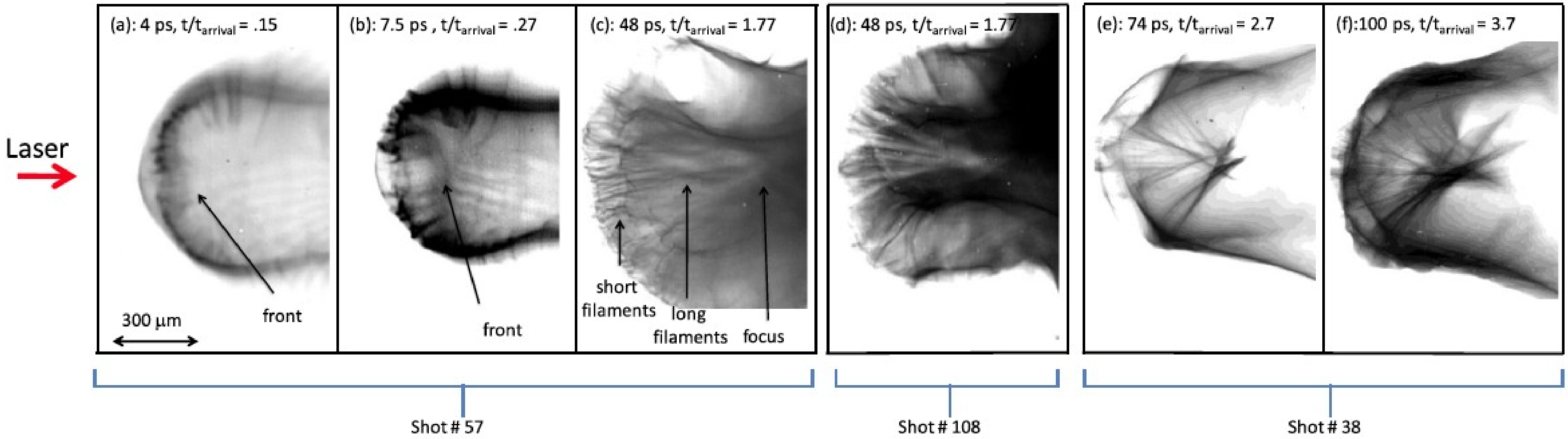
Two Intense laser pulses (ratio1:10) (delay 6 ps) on 75umAl/10um Cu @ peak intensity of 10^{20} W/cm^2

Recent Filamentation experiments-1

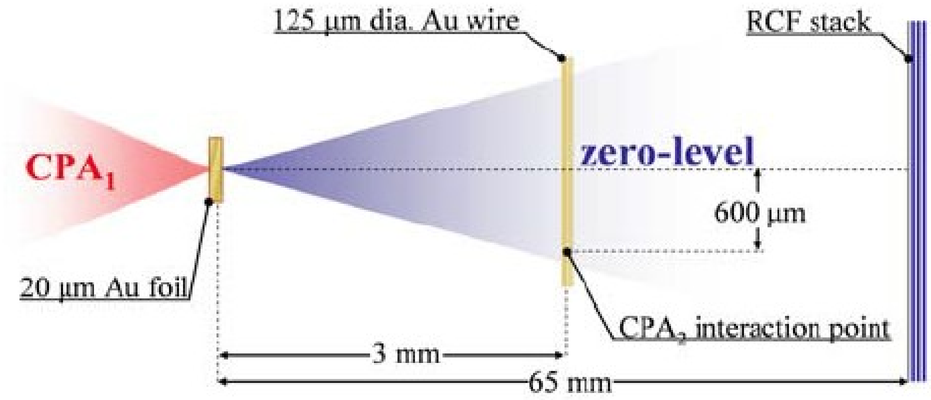


All this, resulting here in the observed beam size of 30 μm, is detrimental to the proton fast ignition scheme which would require
10–20 μm beam to minimize the required igniter energy

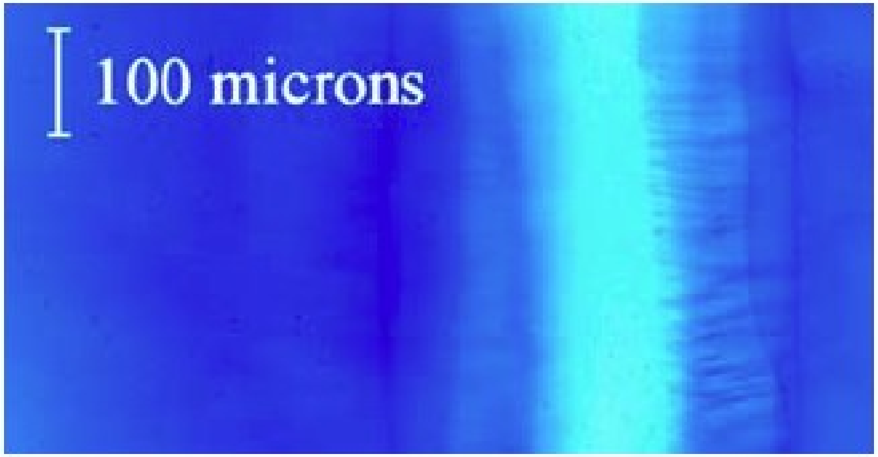
J Fuchs PRL 2012

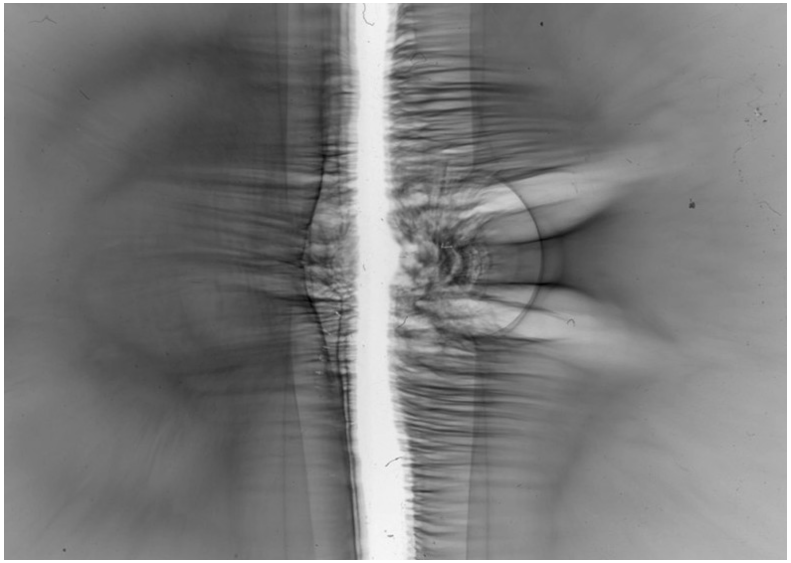


Recent Filamentation experiments-2

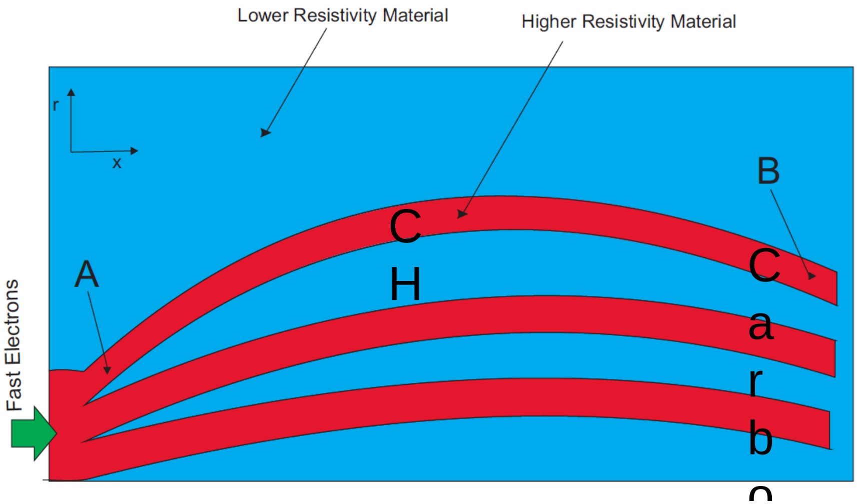


K Quinn, L Romagnani, B Ramakrishna etal., PRL Accepted





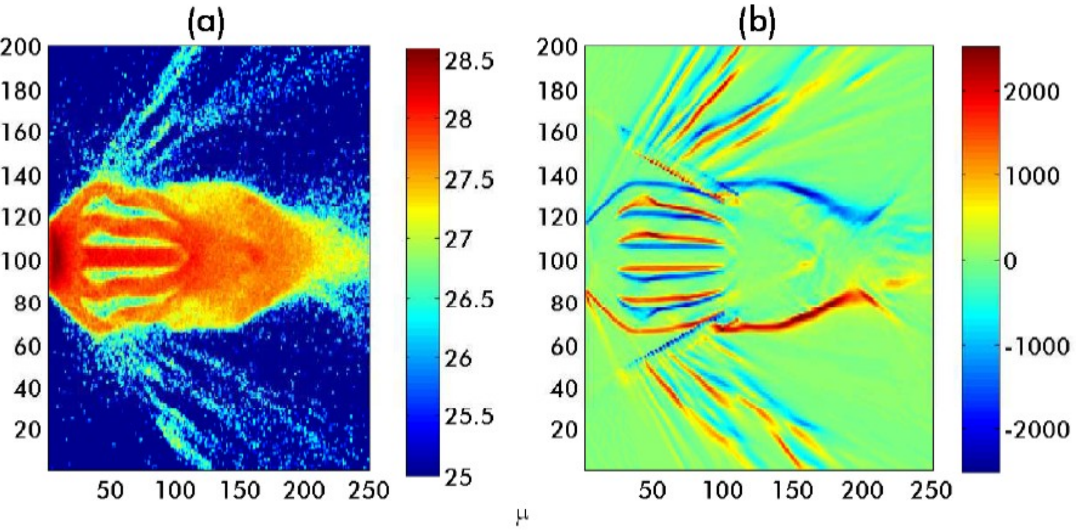
Simulated Targets – Reduced Filamentation



Target based on B Ramakrishna PRL 2010

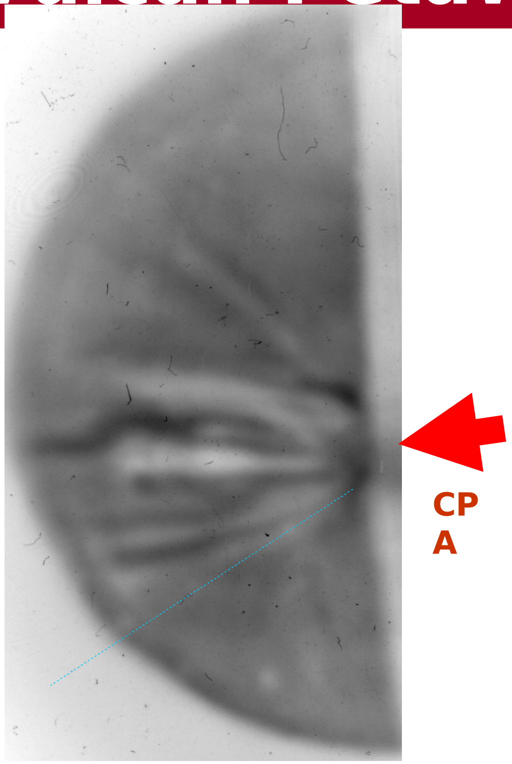
PRL Alex Robinson etal.,

It was shown that a relatively simple structure could still produce a remarkable focussing effect in tests relevant to Fast Ignition conditions (20 kJ, 18 ps). In this test, 27% of the injected fast electron energy was deposited in a specified ignition volume

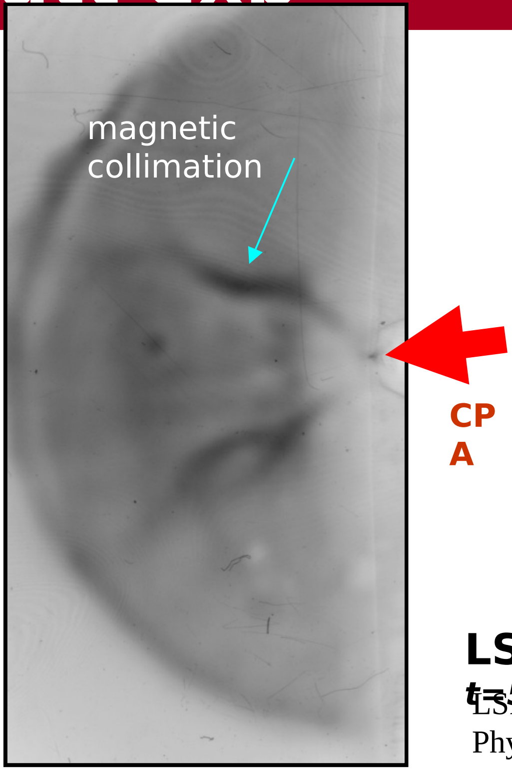


$$\frac{\partial \mathbf{B}}{\partial t} = \eta \nabla \times \mathbf{j}_{fast} + \nabla \eta \times \mathbf{j}_{fast}$$

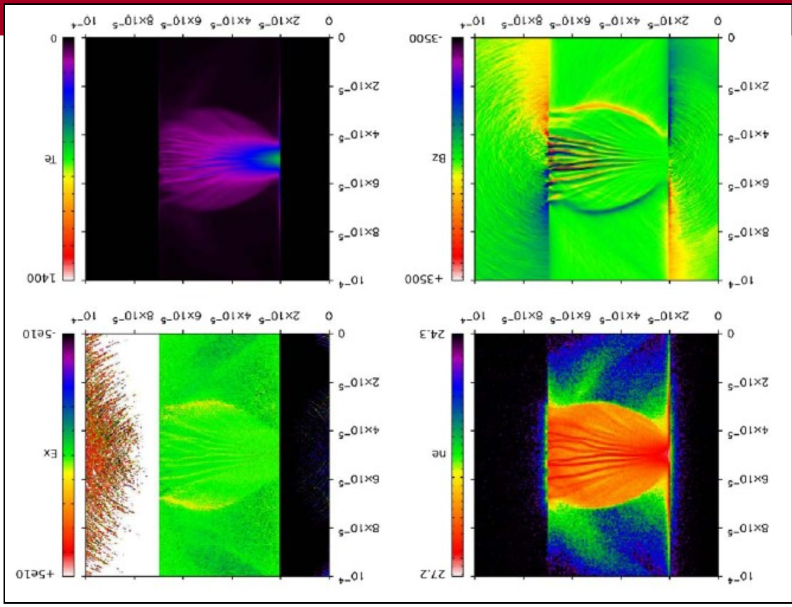
Electron transport in Foam Targets- Vulcan Petawatt exp



50mg,30%Br n_e= $1.5\text{x}10^{22}$ cm^{-3}



100mg/cc,30%Cl n_e=$3.11\text{x}10^{22}\text{cm}^{-3}$



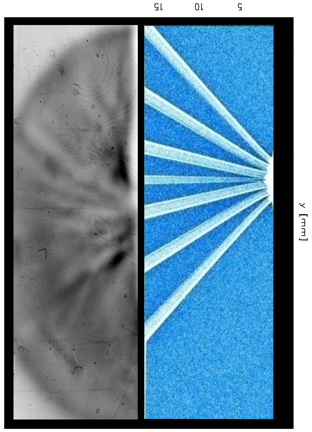
LSP simulations showing Te ,Bz, Ex, Nhot at t=500fs

LSP Simulations from Evans.R.G, High Energy Density Physics,2,35,(2006)

Filamentation occurs possibly due to Weibel instability.

The magnetic field is azimuthal around the fast electron beam and acts to collimate it.

$$\frac{\partial B}{\partial t} = -\nabla \times E = \nabla \times (\eta J_{fast})$$



3D-Patricle tracing simulation

B. Ramakrishna et al., Astrophysics and space science, **322**, 161 (2009)

Conclusions

- A technique for collimating a beam of fast electrons to 50 µm is illustrated.
- Higher design flexibility for fast ignitor approach.
- No significant loss in transport efficiency.
- The scheme has credibility to solve many issues behind the success of ICF and will make a landmark for HIPER.

THANK YOU