Fast Ignition: the Good, the Bad and the Ugly

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High Energy Density Physics Research

- High intensity laser matter interactions
  - Relativistic electron transport in solid and warm dense targets
  - Proton production, conversion efficiency and focusing
  - Modeling with EPOCH, LSP, PICLS, and ZUMA codes

- Mono-energetic ion beams with ultra-intense lasers

- Shock Ignition

- Z-pinches
  - Staged Z-pinch for fusion
  - Supersonic jets and collisionless shocks
  - Liner physics

- X-pinches
  - Point projection radiography
  - Laser cut x-pinches as rep. rate source
  - Intense source for x-ray diffraction

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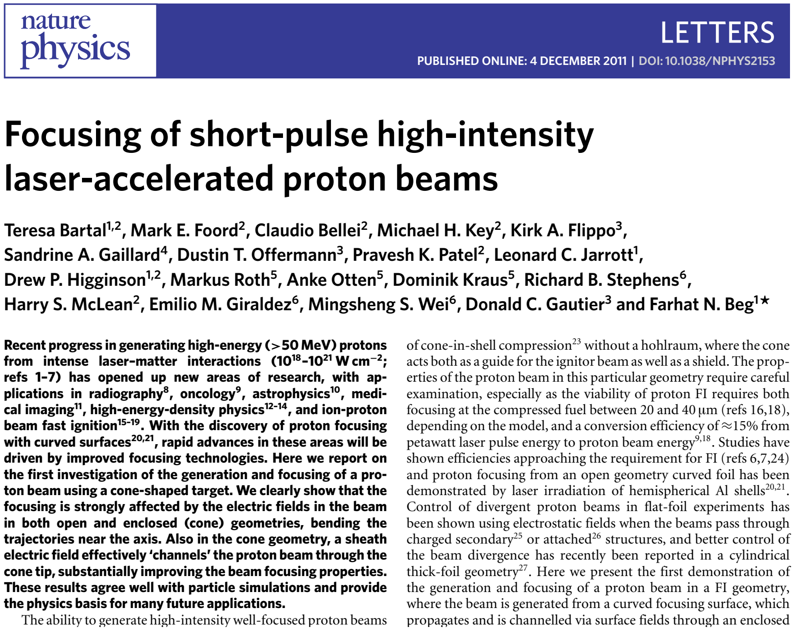

nature physics | LETTERS
PUBLISHED ONLINE: 4 DECEMBER 2011 | DOI: 10.1038/NPHYS2153

Focusing of short-pulse high-intensity laser-accelerated proton beams

Teresa Bartal[1,2], Mark E. Foord[2], Claudio Bellei[2], Michael H. Key[2], Kirk A. Flippo[3],
Sandrine A. Gaillard[4], Dustin T. Offermann[3], Pravesh K. Patel[2], Leonard C. Jarrott[1],
Drew P. Higginson[1,2], Markus Roth[5], Anke Otten[5], Dominik Kraus[5], Richard B. Stephens[6],
Harry S. McLean[2], Emilio M. Giraldez[6], Mingsheng S. Wei[6], Donald C. Gautier[3] and Farhat N. Beg[1]★

Recent progress in generating high-energy (>50 MeV) protons from intense laser–matter interactions (10^{18}–10^{21} W cm^{-2}; refs 1–7) has opened up new areas of research, with applications in radiography[8], oncology[9], astrophysics[10], medical imaging[11], high-energy-density physics[12–14], and ion-proton beam fast ignition[15–19]. With the discovery of proton focusing with curved surfaces[20,21], rapid advances in these areas will be driven by improved focusing technologies. Here we report on the first investigation of the generation and focusing of a proton beam using a cone-shaped target. We clearly show that the focusing is strongly affected by the electric fields in the beam in both open and enclosed (cone) geometries, bending the trajectories near the axis. Also in the cone geometry, a sheath electric field effectively 'channels' the proton beam through the cone tip, substantially improving the beam focusing properties. These results agree well with particle simulations and provide the physics basis for many future applications.

The ability to generate high-intensity well-focused proton beams of cone-in-shell compression[23] without a hohlraum, where the cone acts both as a guide for the ignitor beam as well as a shield. The properties of the proton beam in this particular geometry require careful examination, especially as the viability of proton FI requires both focusing at the compressed fuel between 20 and 40 μm (refs 16,18), depending on the model, and a conversion efficiency of ≈15% from petawatt laser pulse energy to proton beam energy[9,18]. Studies have shown efficiencies approaching the requirement for FI (refs 6,7,24) and proton focusing from an open geometry curved foil has been demonstrated by laser irradiation of hemispherical Al shells[20,21]. Control of divergent proton beams in flat-foil experiments has been shown using electrostatic fields when the beams pass through charged secondary[25] or attached[26] structures, and better control of the beam divergence has recently been reported in a cylindrical thick-foil geometry[27]. Here we present the first demonstration of the generation and focusing of a proton beam in a FI geometry, where the beam is generated from a curved focusing surface, which propagates and is channelled via surface fields through an enclosed

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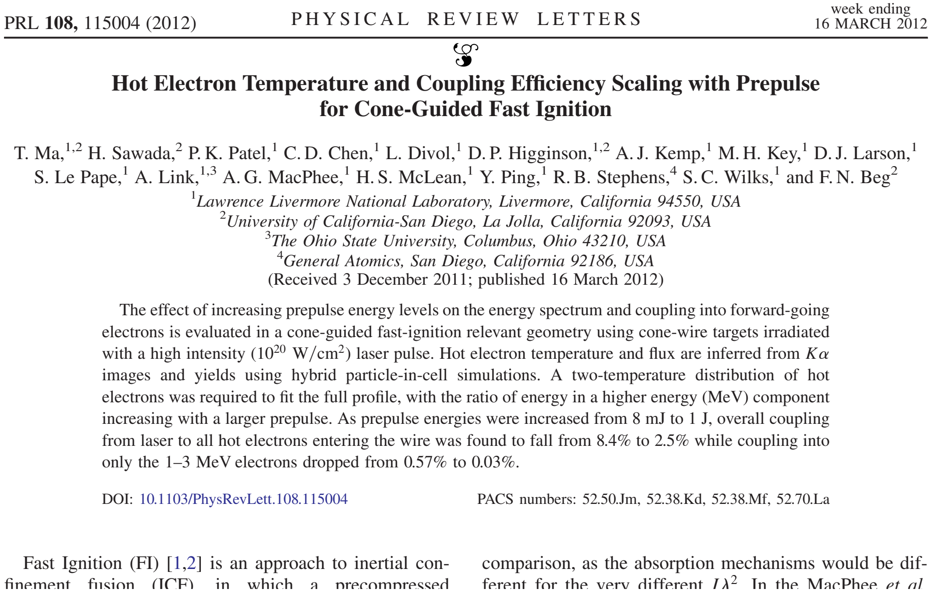

PRL **108,** 115004 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

Hot Electron Temperature and Coupling Efficiency Scaling with Prepulse for Cone-Guided Fast Ignition

T. Ma,[1,2] H. Sawada,[2] P. K. Patel,[1] C. D. Chen,[1] L. Divol,[1] D. P. Higginson,[1,2] A. J. Kemp,[1] M. H. Key,[1] D. J. Larson,[1]
S. Le Pape,[1] A. Link,[1,3] A. G. MacPhee,[1] H. S. McLean,[1] Y. Ping,[1] R. B. Stephens,[4] S. C. Wilks,[1] and F. N. Beg[2]
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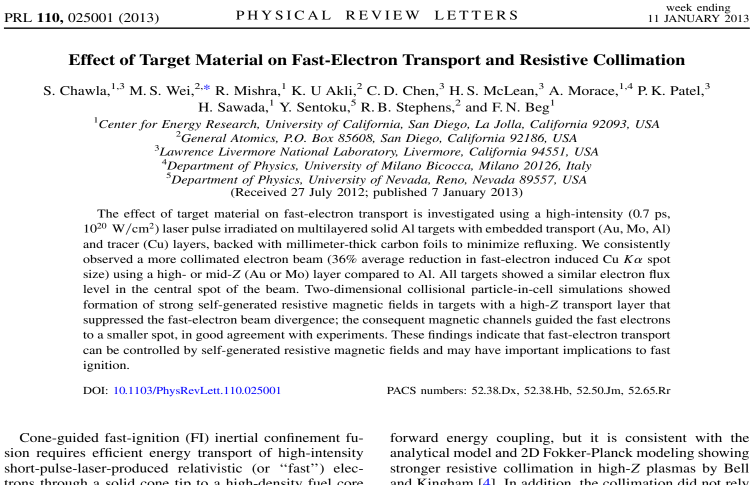
(Received 3 December 2011; published 16 March 2012)

The effect of increasing prepulse energy levels on the energy spectrum and coupling into forward-going electrons is evaluated in a cone-guided fast-ignition relevant geometry using cone-wire targets irradiated with a high intensity (10^{20} W/cm^2) laser pulse. Hot electron temperature and flux are inferred from $K\alpha$ images and yields using hybrid particle-in-cell simulations. A two-temperature distribution of hot electrons was required to fit the full profile, with the ratio of energy in a higher energy (MeV) component increasing with a larger prepulse. As prepulse energies were increased from 8 mJ to 1 J, overall coupling from laser to all hot electrons entering the wire was found to fall from 8.4% to 2.5% while coupling into only the 1–3 MeV electrons dropped from 0.57% to 0.03%.

DOI: 10.1103/PhysRevLett.108.115004 PACS numbers: 52.50.Jm, 52.38.Kd, 52.38.Mf, 52.70.La

Fast Ignition (FI) [1,2] is an approach to inertial confinement fusion (ICF) in which a precompressed comparison, as the absorption mechanisms would be different for the very different $I\lambda^2$. In the MacPhee *et al.*



PRL **110,** 025001 (2013) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2013

Effect of Target Material on Fast-Electron Transport and Resistive Collimation

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(Received 27 July 2012; published 7 January 2013)

The effect of target material on fast-electron transport is investigated using a high-intensity (0.7 ps, 10^{20} W/cm^2) laser pulse irradiated on multilayered solid Al targets with embedded transport (Au, Mo, Al) and tracer (Cu) layers, backed with millimeter-thick carbon foils to minimize refluxing. We consistently observed a more collimated electron beam (36% average reduction in fast-electron induced Cu $K\alpha$ spot size) using a high- or mid-Z (Au or Mo) layer compared to Al. All targets showed a similar electron flux level in the central spot of the beam. Two-dimensional collisional particle-in-cell simulations showed formation of strong self-generated resistive magnetic fields in targets with a high-Z transport layer that suppressed the fast-electron beam divergence; the consequent magnetic channels guided the fast electrons to a smaller spot, in good agreement with experiments. These findings indicate that fast-electron transport can be controlled by self-generated resistive magnetic fields and may have important implications to fast ignition.

DOI: 10.1103/PhysRevLett.110.025001 PACS numbers: 52.38.Dx, 52.38.Hb, 52.50.Jm, 52.65.Rr

Cone-guided fast-ignition (FI) inertial confinement fusion requires efficient energy transport of high-intensity short-pulse-laser-produced relativistic (or "fast") electrons through a solid cone tip to a high-density fuel core forward energy coupling, but it is consistent with the analytical model and 2D Fokker-Planck modeling showing stronger resistive collimation in high-Z plasmas by Bell and Kingham [4]. In addition, the collimation did not rely

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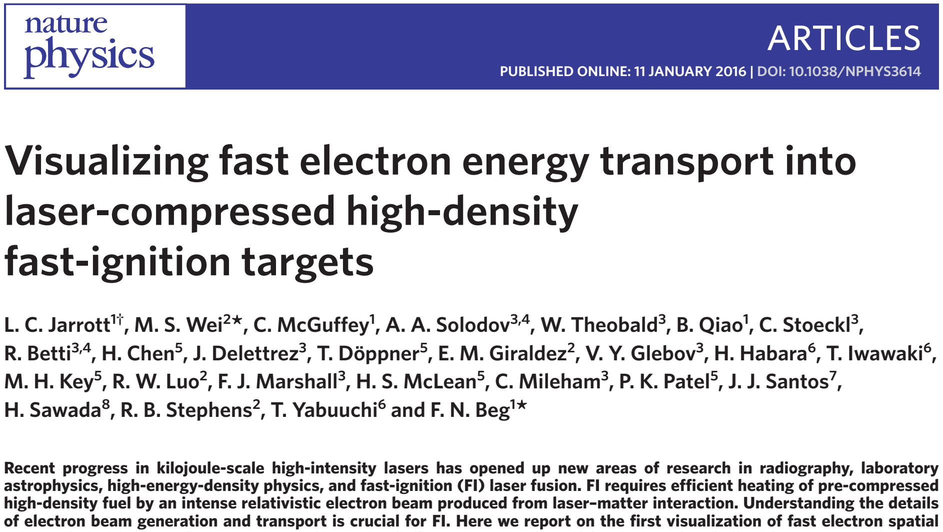


nature physics | ARTICLES
PUBLISHED ONLINE: 11 JANUARY 2016 | DOI: 10.1038/NPHYS3614

Visualizing fast electron energy transport into laser-compressed high-density fast-ignition targets

L. C. Jarrott[1†], M. S. Wei[2]★, C. McGuffey[1], A. A. Solodov[3,4], W. Theobald[3], B. Qiao[1], C. Stoeckl[3],
R. Betti[3,4], H. Chen[5], J. Delettrez[3], T. Döppner[5], E. M. Giraldez[2], V. Y. Glebov[3], H. Habara[6], T. Iwawaki[6],
M. H. Key[5], R. W. Luo[2], F. J. Marshall[3], H. S. McLean[5], C. Mileham[3], P. K. Patel[5], J. J. Santos[7],
H. Sawada[8], R. B. Stephens[2], T. Yabuuchi[6] and F. N. Beg[1]★

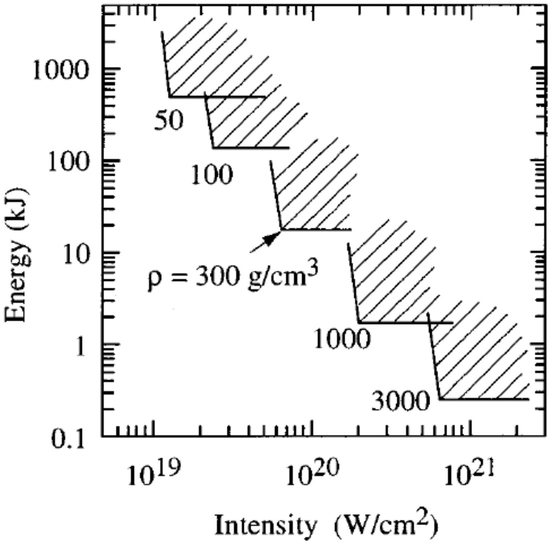
Recent progress in kilojoule-scale high-intensity lasers has opened up new areas of research in radiography, laboratory astrophysics, high-energy-density physics, and fast-ignition (FI) laser fusion. FI requires efficient heating of pre-compressed high-density fuel by an intense relativistic electron beam produced from laser-matter interaction. Understanding the details of electron beam generation and transport is crucial for FI. Here we report on the first visualization of fast electron spatial

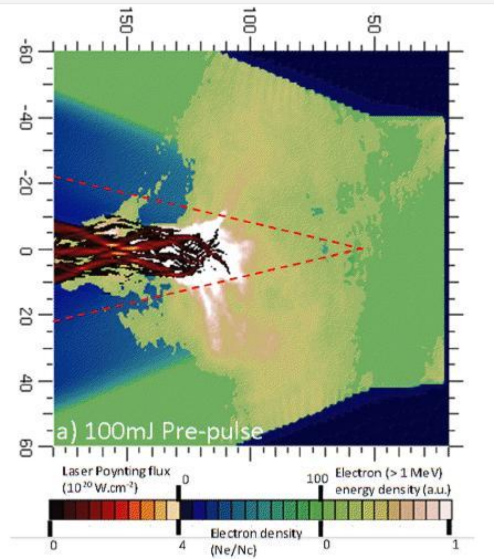
Outline

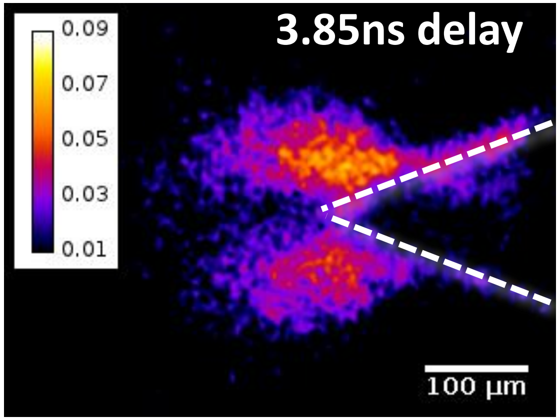

THE
GOOD


THE
BAD


AND THE
UGLY

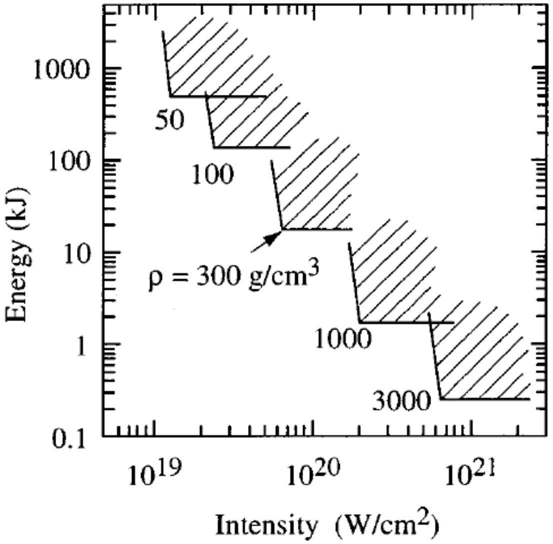

Energy (kJ)
1000
100
10
1
0.1
50
100
ρ = 300 g/cm3
1000
3000
10^19
10^20
10^21
Intensity (W/cm2)


150
100
50
-60
-40
-20
0
20
40
60
a) 100mJ Pre-pulse
Laser Poynting flux (10^20 W.cm^-2)
0
4
Electron density (Ne/Nc)
0
100
Electron (> 1 MeV) energy density (a.u.)
0
1

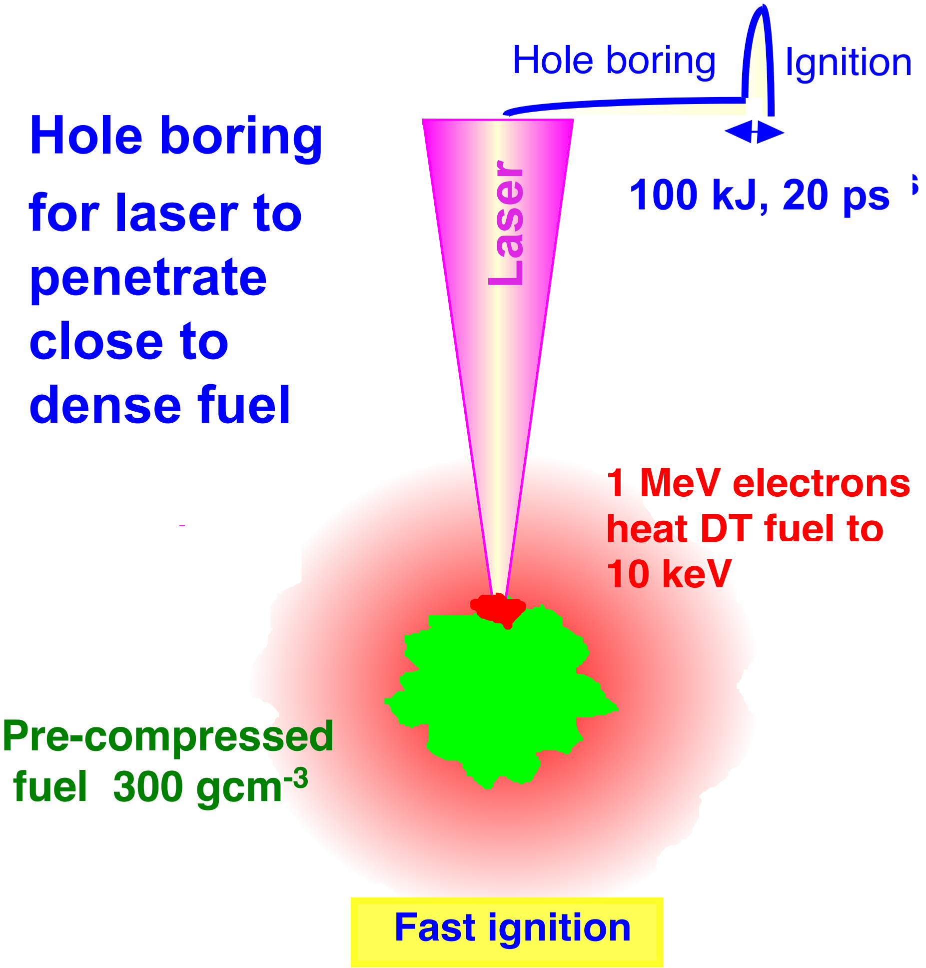

0.09
0.07
0.05
0.03
0.01
3.85ns delay
100 µm

Outline


THE
GOOD


1000
100
10
1
0.1
Energy (kJ)
50
100
ρ = 300 g/cm^3
1000
3000
10^{19}
10^{20}
10^{21}
Intensity (W/cm^2)

Fast Ignition is an advanced ICF concept

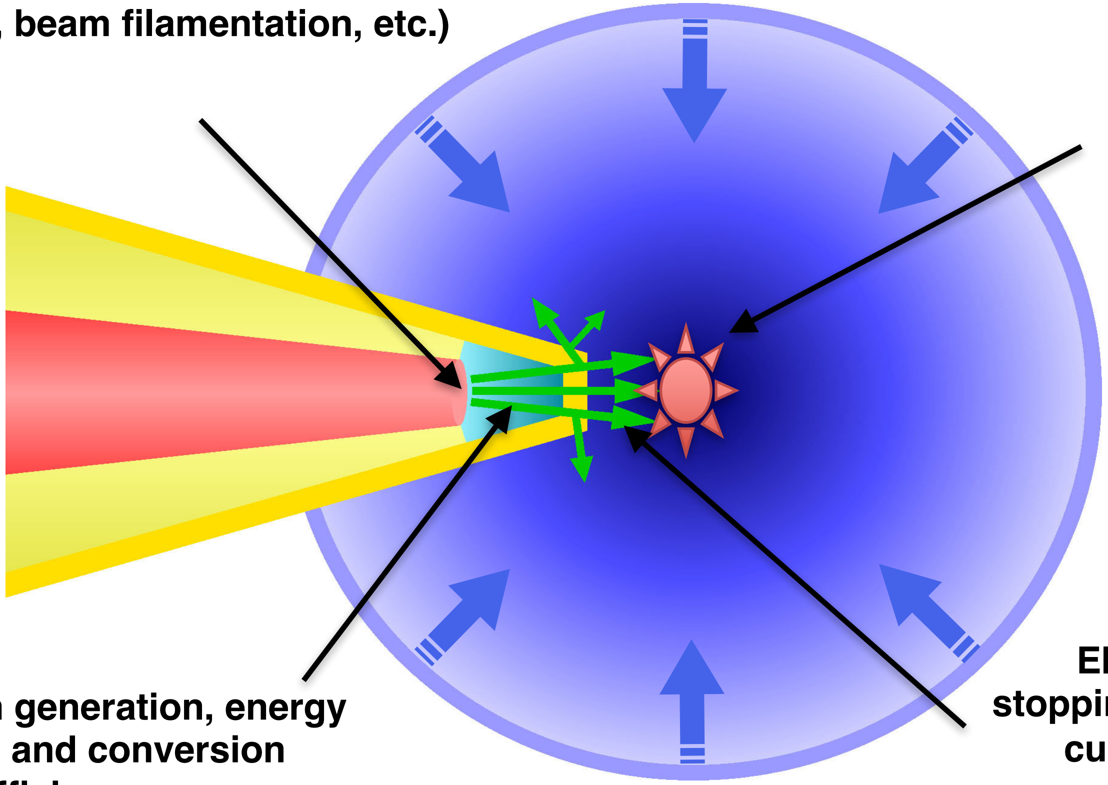


Hole boring for laser to penetrate close to dense fuel

- **Laser hole boring and heating by laser generated electrons was the first FI concept**
- **1MeV electron range = ignition hot spot ϕ**
- **Absorption of intense laser light produces forward directed electrons**
- **e-beam temperature scales as kT~ $(I\lambda^2)^{0.5}$**
- **kT≈1 MeV for λ=1μm laser at 5×10^{19} Wcm^{-2}**

M Tabak, S Wilks et al. Phys. Plasmas1,1626 (1994)

Fast Ignition involves challanging short pulse laser matter interactions



High intensity laser propagation through plasma (relativistic self-focusing, beam filamentation, etc.)

Courtesy: Prav Patel. LLNL

Achieving high fuel compression in asymmetric implosion

Fast electron generation, energy spectrum and conversion efficiency

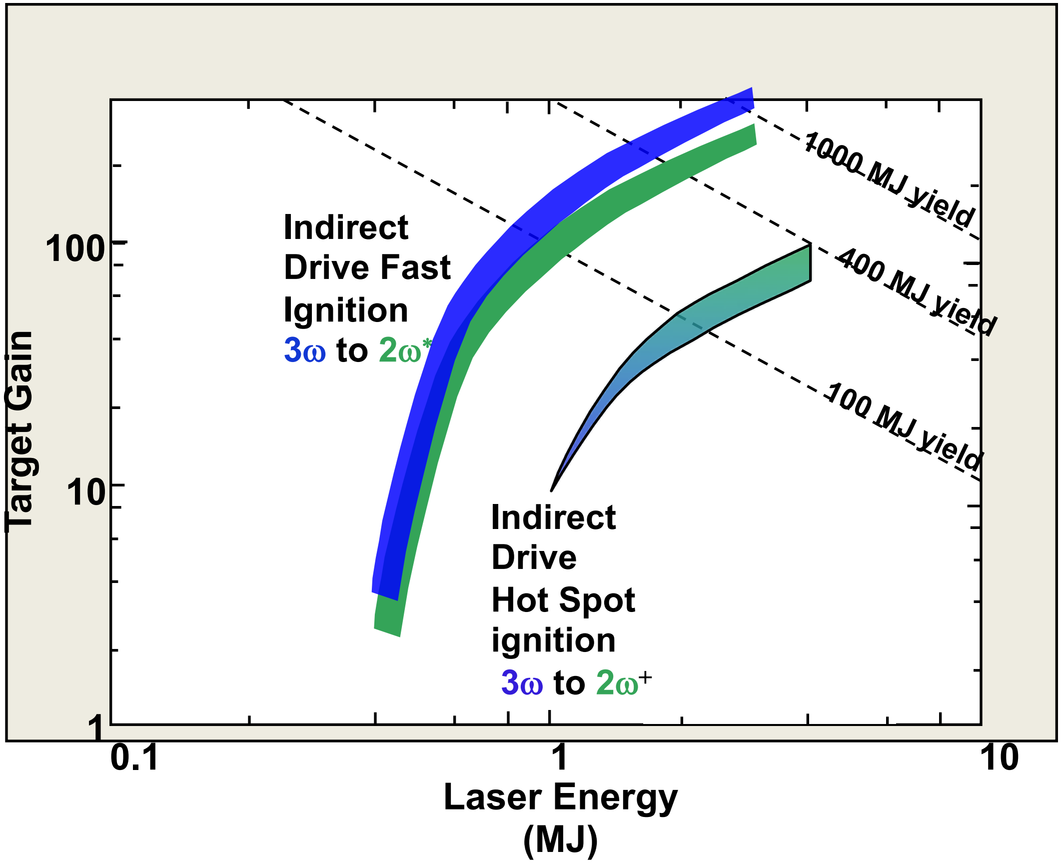
Electron transport and stopping in dense plasma (high currents, B-fields, beam instabilities)

- **Fast Ignition physics is extremely challenging as it encompasses ICF, relativistic laser interaction, charged particle beam transport, and high energy density science**

S. Atzeni, POP 8, 3316 (1999)

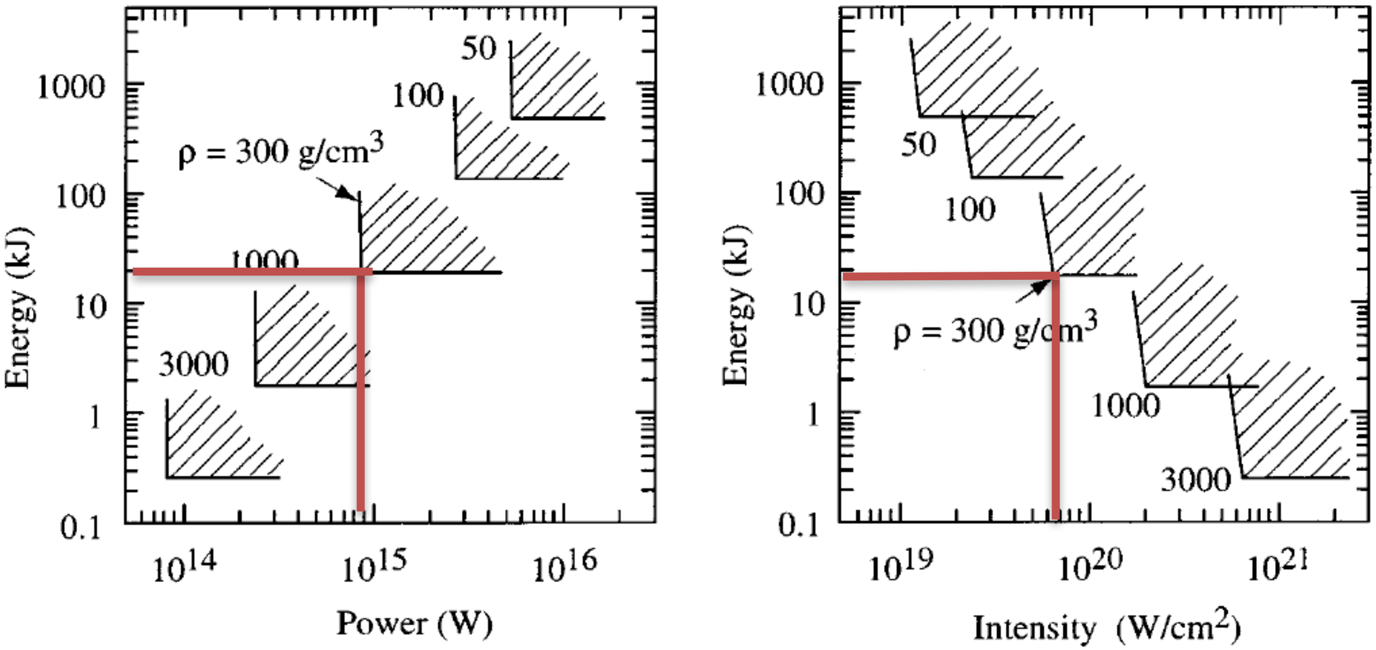
Why Fast Ignition?

* M. Tabak et. al., Fusion Science and Technology v 49 2006



- Higher gain and lower ignition threshold
- Less stringent symmetry requirement
- Stand off distance is challenging

Atzeni examined the requirements for FI with an arbitrary particle beam



$$E_{ign} = 140\left(\frac{\rho}{100\,g/cm^3}\right)^{-1.85} kJ$$

$$I_{ig} = 6.8\times10^{19}\left(\frac{\rho}{300\,g/cm^3}\right)^{0.95} W/cm^2$$

$$P_{ig} = 8.7\times10^{14}\left(\frac{\rho}{300\,g/cm^3}\right)^{-1} W$$

S. Atzeni, Phys. Plas. 8, 3316 (1999)

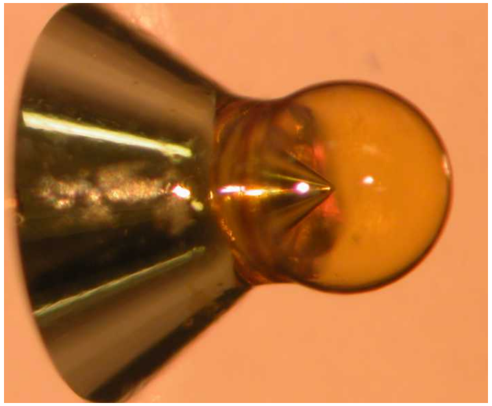
- **Ignition requirement:** $\rho r_h \geq 0.5 g/cm^3, T_h \geq 12 keV$
- **Parallel beam of particles was injected into uniform density sphere**
- **18-20 kJ beam energy is sufficient for ignition for the beam parameter**
  - **pulse length < 20 ps**
  - **beam intensity ~ 6-8x10^{19} Wcm^{-2} (radius ~ 20 μm)**

Results from first integrated fast ignition experiment in Japan were encouraging

Gekko XII Laser Facility

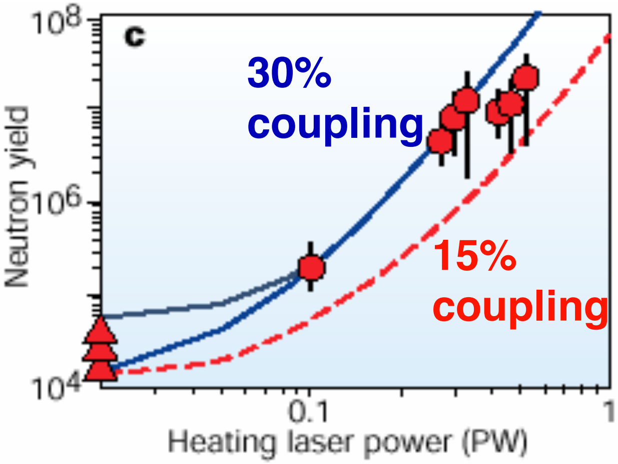
- 2.5 kJ, 1.2 ns flat top pulse, 2 w compression
- 350 J, 0.5 ps ignitor pulse

Au cone + CD shell



- 7 μm CD shell, 350 μm dia Imploded core

Neutron yield



- 1000x increase in neutron yield
- Temp. increase from 400 eV to 800 eV

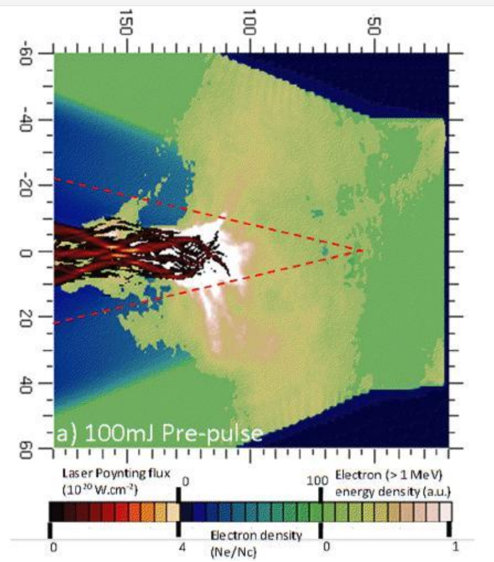
R Kodama *et al*., Nature 412, 798 (2001) .

- 50 μm blob was formed 50 μm from tip of the cone (density ~ 50 g/cc)
- Ignitor beam gave ≈ 20% energy coupling to imploded CD

Experimental data could not be reproduced and several physics issues were identified including the laser prepulse, source divergence, and spectrum among others

Outline


THE
BAD

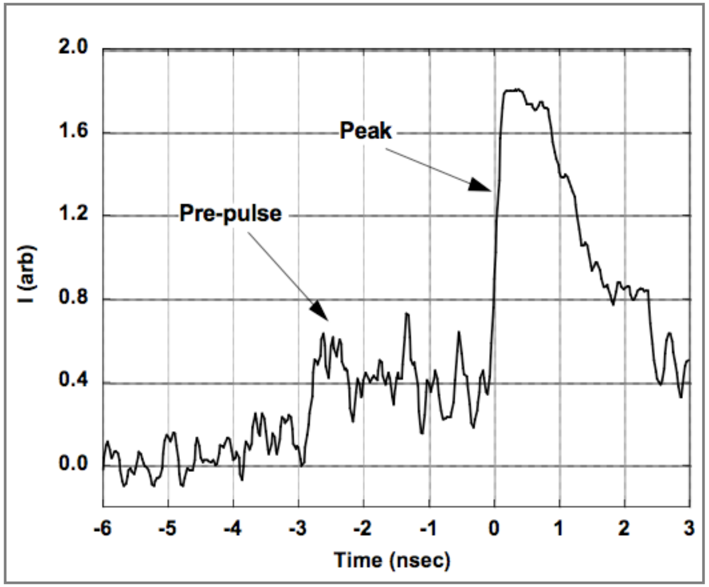

150
100
50
-60
-40
-20
0
20
40
60
a) 100mJ Pre-pulse
Laser Poynting flux (10^20 W.cm^-2)
0
4
0
100
Electron (> 1 MeV) energy density (a.u.)
Electron density (Ne/Nc)
0
1

Laser prepulse can significantly modify the laser solid interaction

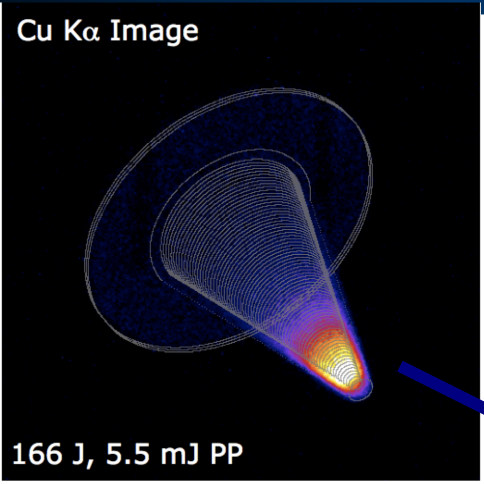
Energy contrast levels for a FI-scale laser will be ~10^{-5} (i.e., 100 kJ laser = ~100 mJ – 1 J prepulse energy)

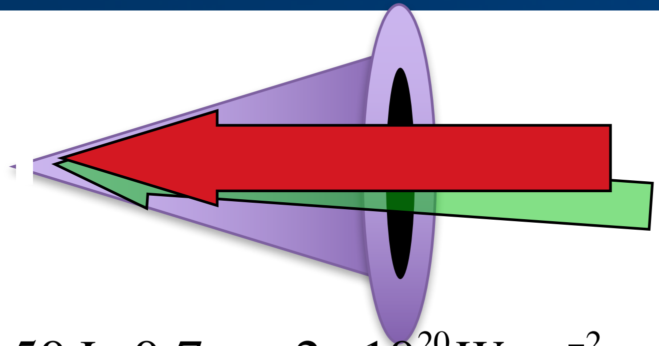
- Current typical contrast levels for short pulse lasers is ~ 10^{-5} – 10^{-7}
- These intrinsic prepulse levels are lower than what is expected at full scale, but many experiments have created artificial prepulses at relevant levels
- The prepulse can form a substantial preformed plasma in front of the solid target which severely affects the interaction of the main laser with the target

Prepulse trace from the Titan laser

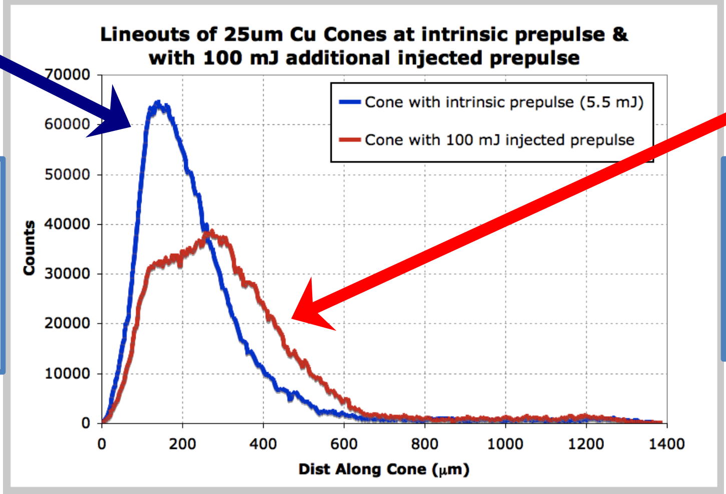


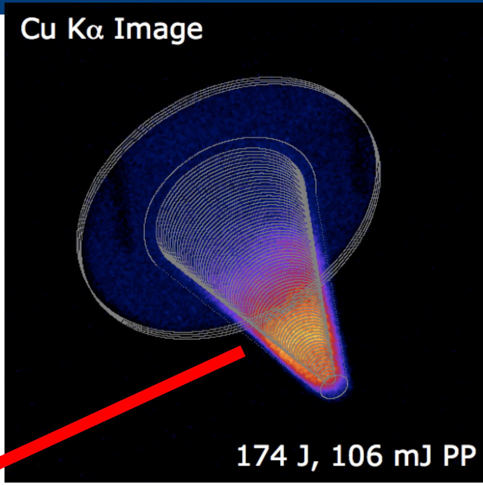
Increasing prepulse level into the stand-alone cone gives a large region of electron heating





$150J\,,\,0.7ps,\,2\times10^{20}Wcm^{-2}$





- Well defined peak 50 μm from the tip
- Emission decreases sharply over 200 μm

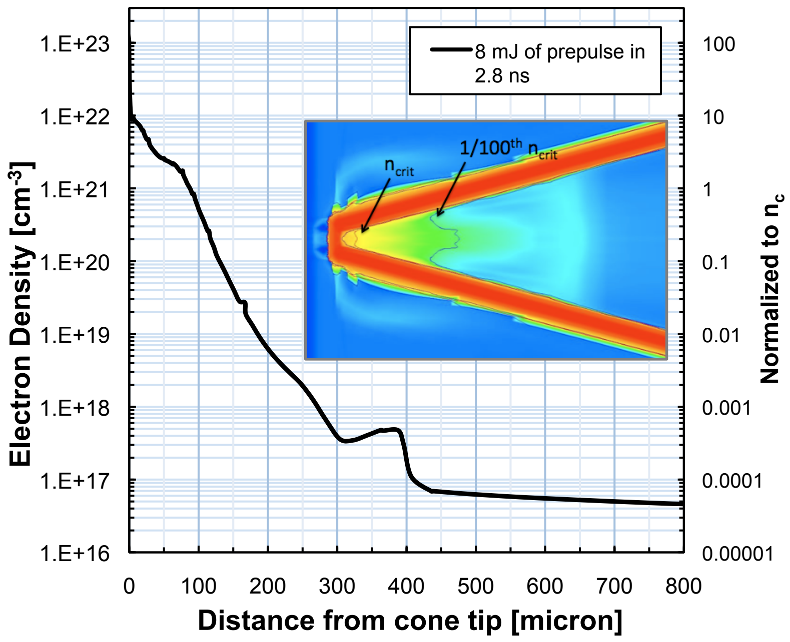
- Emission distributed broadly 200 μm from cone tip
- Extends further 500 μm from cone tip

- Total integrated Kα yield is near-identical in both cases
- Peak hot electron density is 2x higher in intrinsic pp case

Observation is consistent with preplasma filling the cone and hot electron source away from tip of the cone

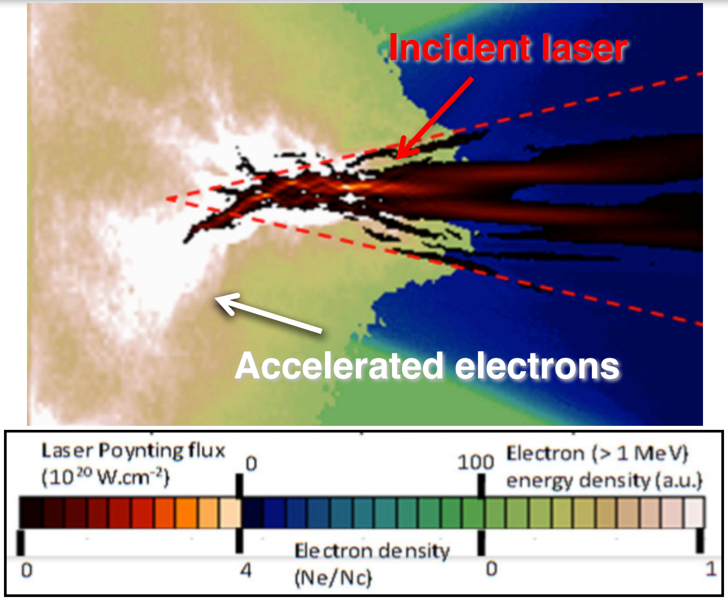
Preplasma in cone decreases fast electrons coupling to the cone tip

Preplasma from Titan



- Prepulse creates large scale preplasma critical density pushed back 88μm from initial tip.

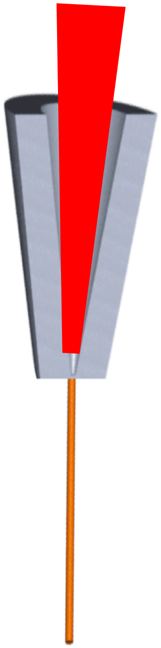
Interaction surface is pushed back[]



- Preplasma causes laser to filament and accelerates electrons away from cone tip.
- Electrons may get lost in the cone walls and leave the cone at large angle

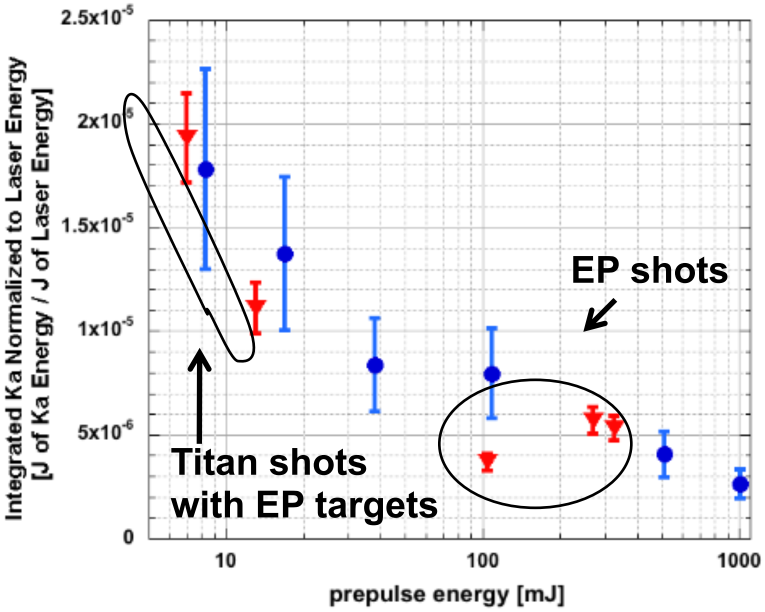
A. MacPhee *et al.*, PRL104, 055002 (2010)

Preplasma in cone significantly affects the energy coupling to the wire

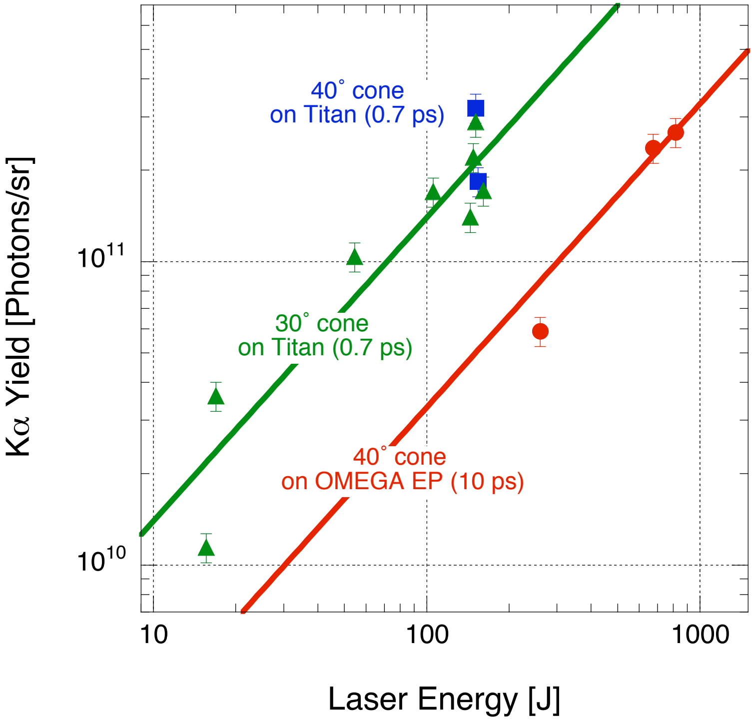


T. Ma et al., *Phys. Rev. Lett.*, 108 (11), (2012)

$$800J, 10ps, 5\times10^{18}Wcm^{-2}$$

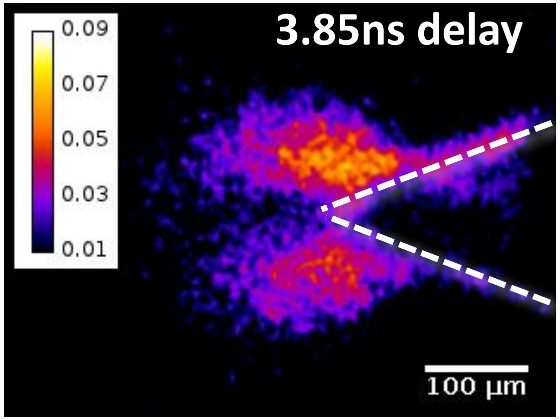


T. Yabuuchi et al., *New Journal of Physics* 15, 015020 (2013)

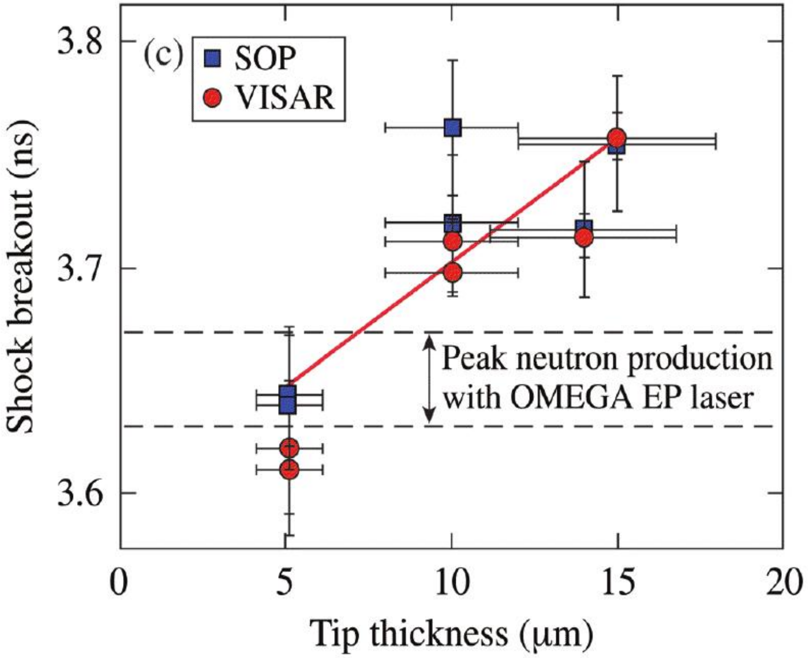


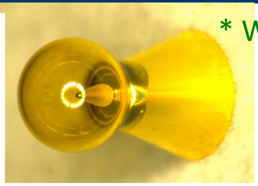
- **Extreme case of OMEGA EP prepulse with 350 mJ energy was used.**
- **Laser coupling into the wire changes linearly with the laser energy**
- **Coupling is similar with two different angles cones**

AND THE UGLY



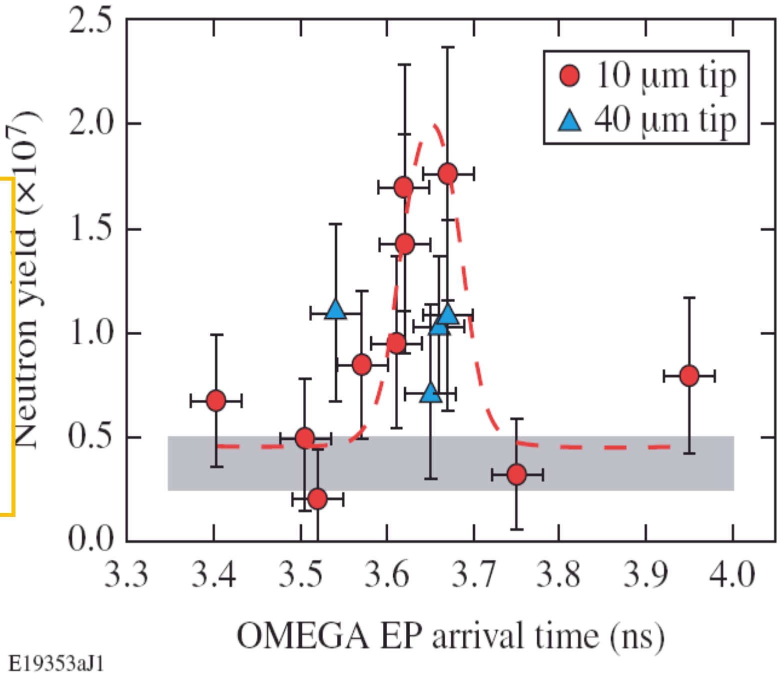
Integrated Fast Ignition heating experiments rely on neutron yield measurement to infer energy coupling





CD shell:
40 µm thick,
OD 870 µm
Au cone:
34° opening
15 µm thick
10 µm tip dia.

* W. Theobald et al., Phys. Plasmas 18, 056305 (2011)

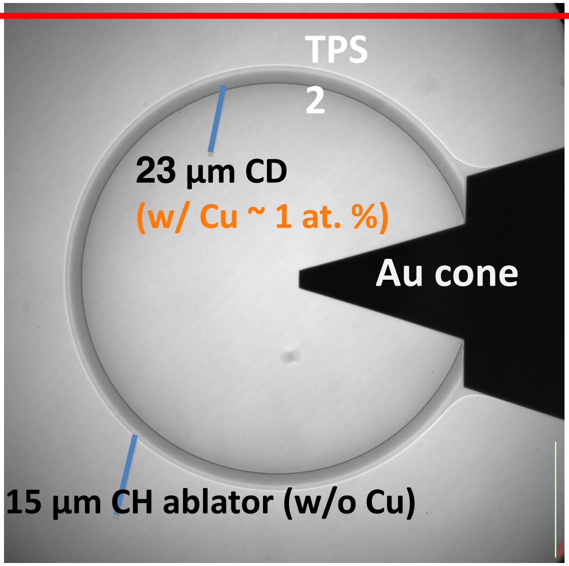


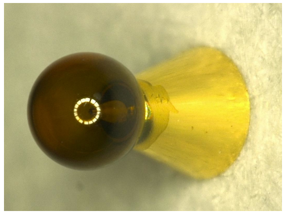
- 18 kJ OMEGA UV driver pulse compresses the shell and 1kJ OMEGA-EP injected into cone at cone-tip
- Varied delay between driver beams and ignition beam to observe enhancements in neutron yield
- Enhancement in neutron yield with short pulse injection

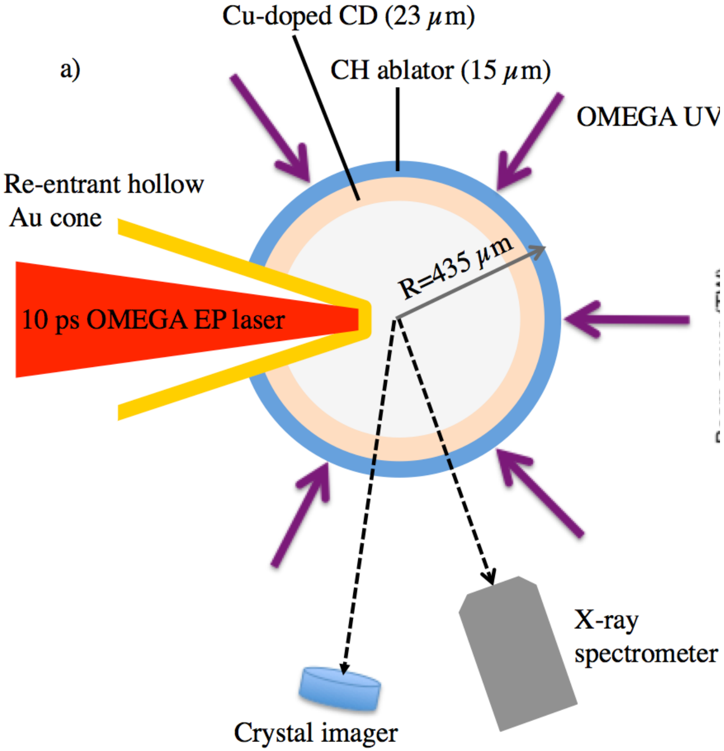
What are the core issues for lower coupling?

CD shell with Cu dopant is used to characterize EP laser produced fast electron transport

X-ray radiography image of
Cone-in-(Cu-doped) CD shell target

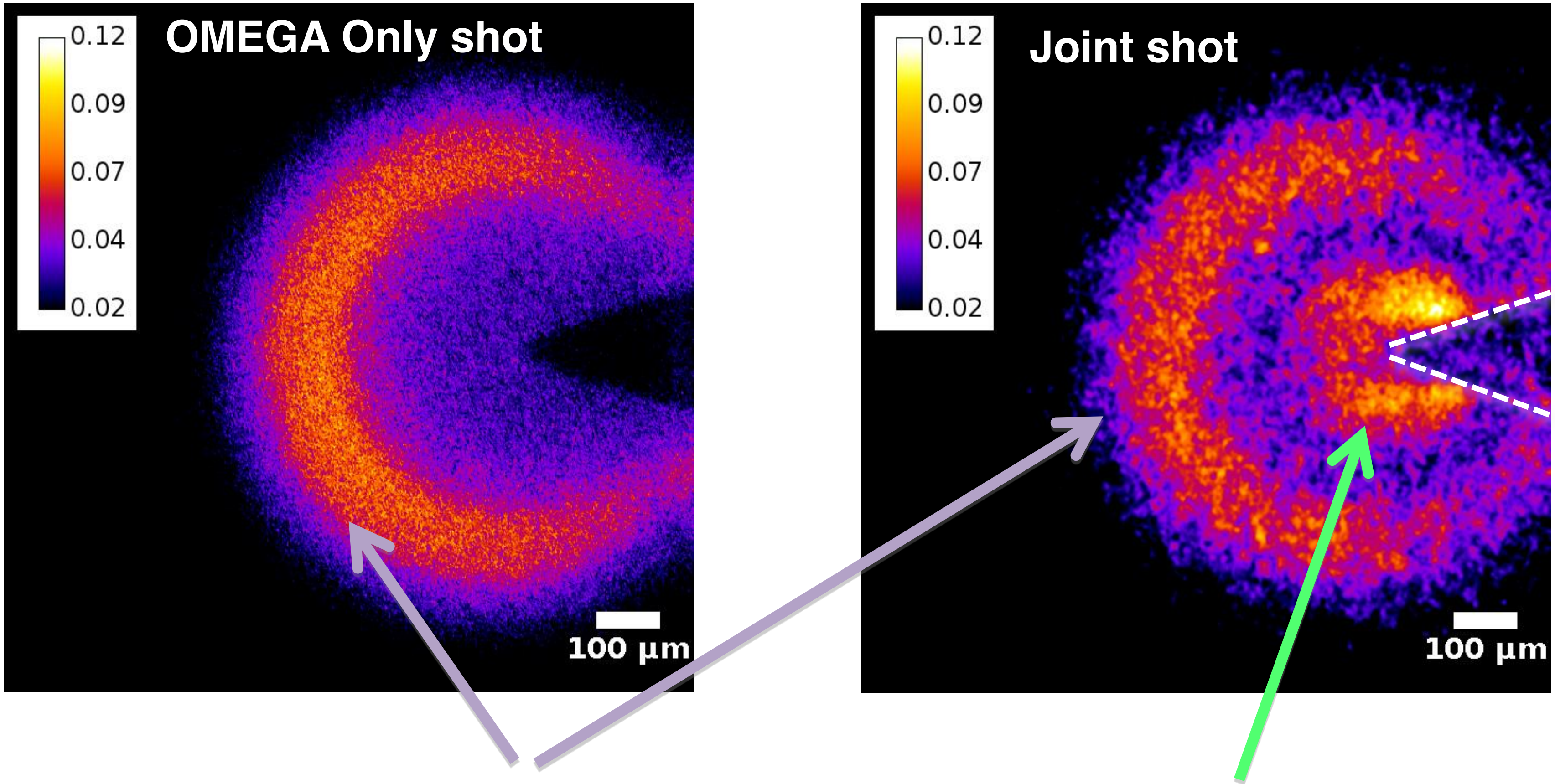






- **Cu-doped CD shell has similar outer diameter and same mass as previous FI CD shell**
- **Characterize EP beam produced fast electron transport with Cu K-shell diagnostics:**
  - **Cu Kα x-ray yield and spatial distribution by a calibrated x-ray spectrometer(ZVH) and a spherical crystal imager (SCI)**

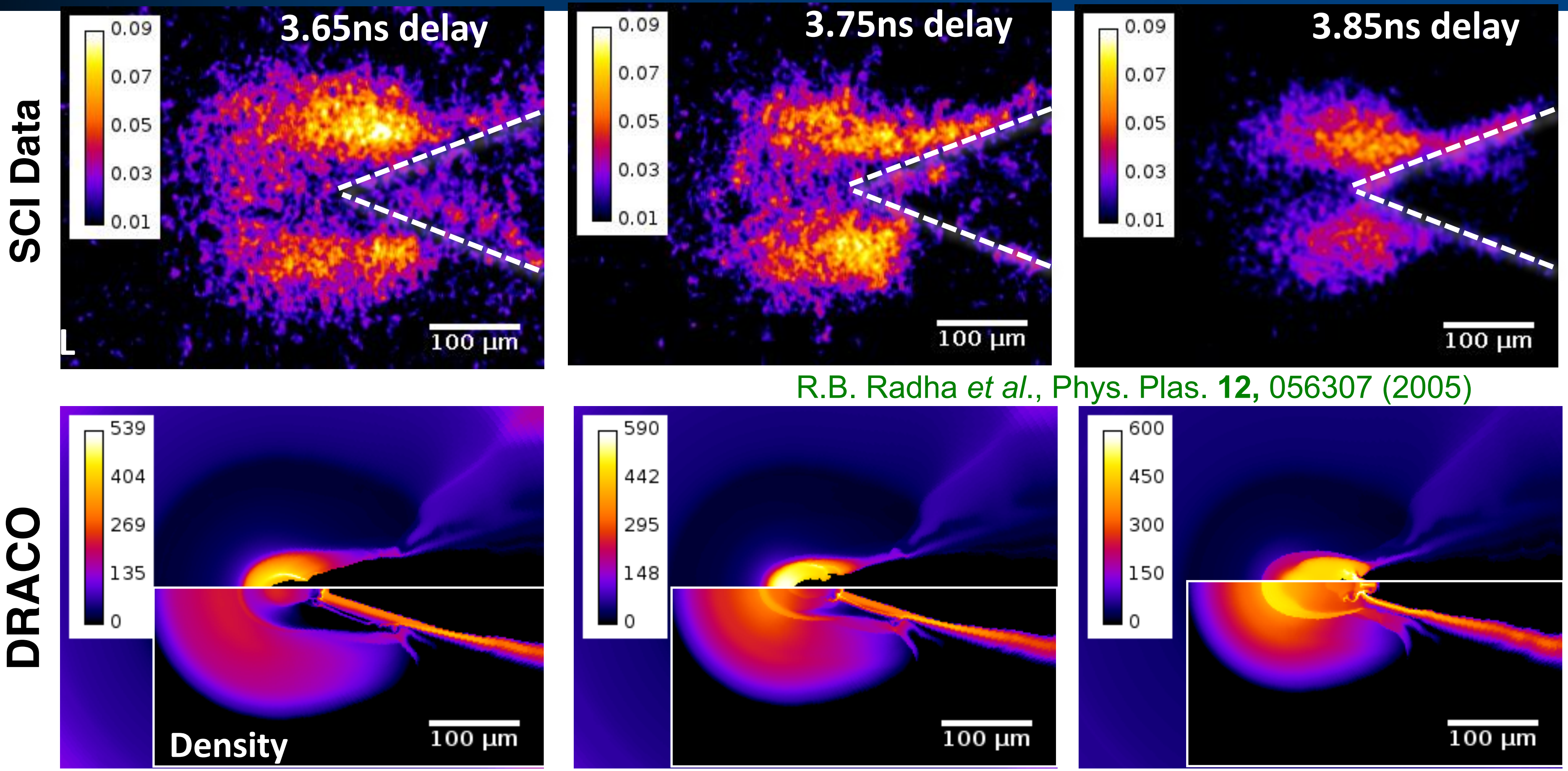
Comparison of SCI from OMEGA-only vs. Joint shots shows spatial distribution of OMEGA EP produced Kα



- **Cu Kα from in-flight shell produced from suprathermal electrons induced by OMEGA**

- **Cu Kα from fast electrons induced by OMEGA-EP in the imploded core**

Measured Kα distribution agrees with density profile predicted by 2D rad-hydro code DRACO

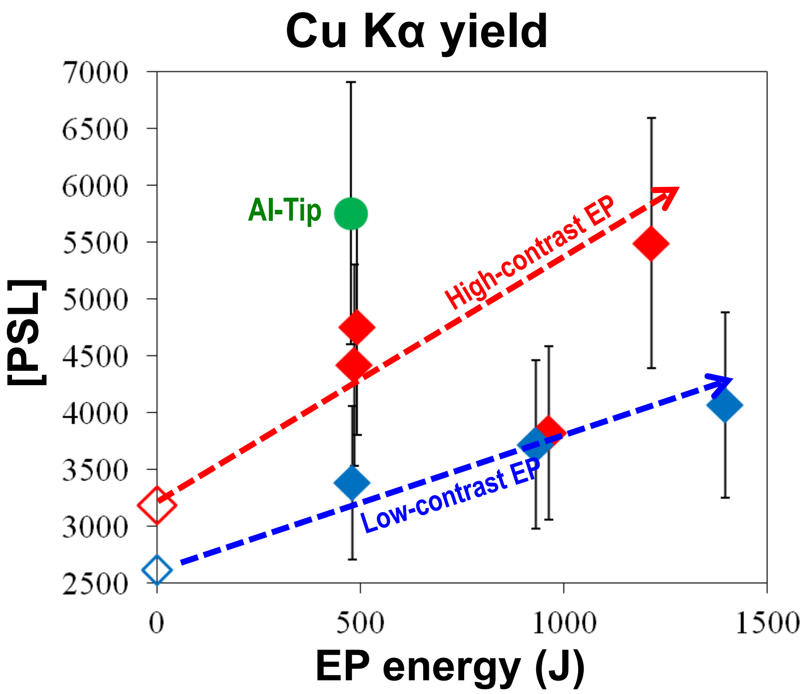


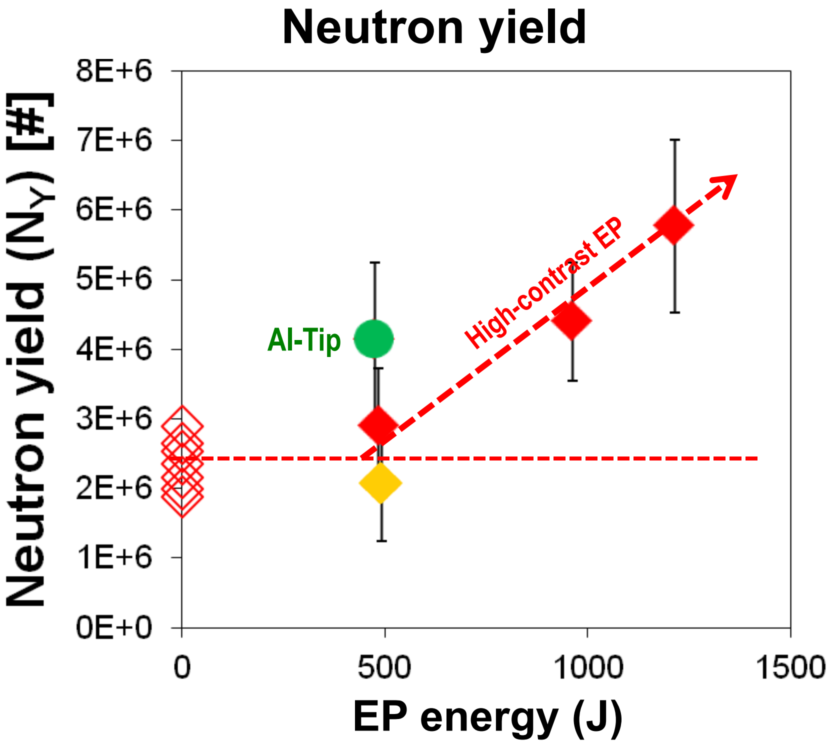
R.B. Radha *et al*., Phys. Plas. **12,** 056307 (2005)

- **Strong correlation of Cu Kα source position with DRACO simulated density**
- **Cu Kα produced as far back as 100um from cone tip**

- **Reduction in Kα signal at cone tip is partially due to heating of the core thereby shifting Cu Kα line out of imaging crystal bandwidth**

Kα and neutron measurements show promising trends with EP energy and high contrast

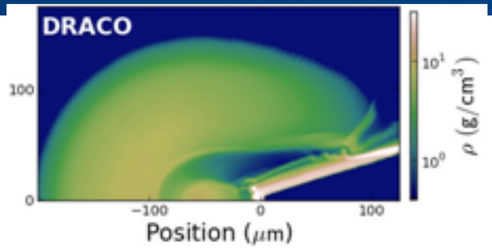




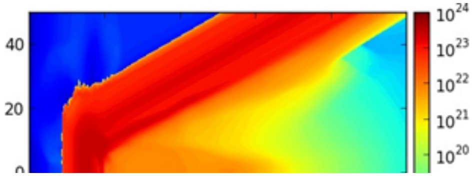
- Established Kα and N_Y scaling with EP energy (intensity) for the first time
- More evidence that high contrast pulses (low preplasma) improve energy coupling

A multi-step simulation approach was taken to model the various stages of integrated Fast Ignition

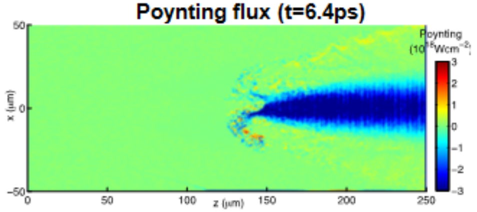
Radiation hydrodynamic (DRACO) simulation of implosion



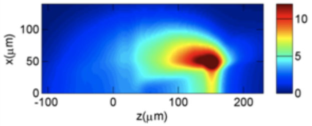
Radiation hydrodynamic (HYDRA) simulation of OMEGA-EP pre-pulse interaction in the Au cone



Particle-in-Cell (LSP) simulation of OMEGA-EP LPI



Particle-in-Cell (ZUMA) simulation of electron transport and deposition

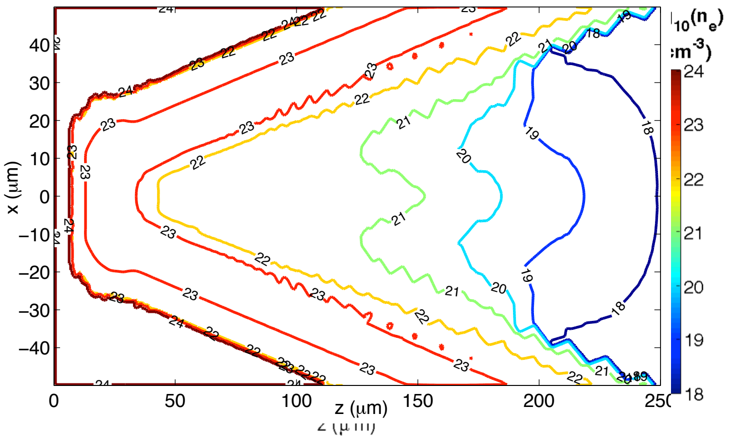


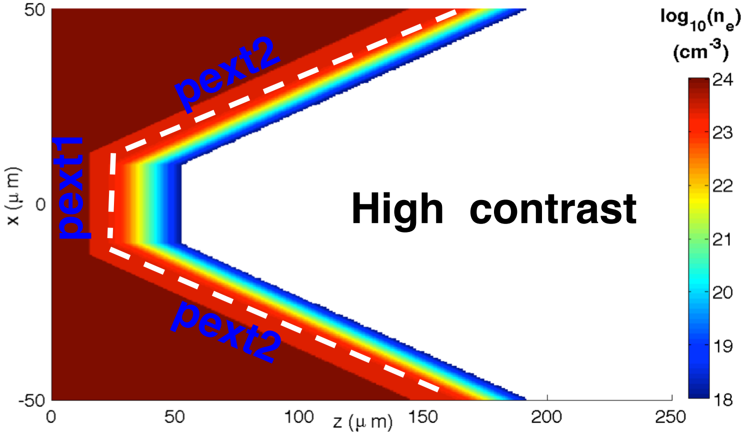
Particle-in-Cell (LSP) simulation of electron transport and deposition

LSP simulations to characterize 10ps laser-plasma interaction and fast electron source for both low- and high- contrast cases

Plasma setup: HYDRA simulation calculated the preplasma conditions (OMEGA EP prepulse), which were initialized into LSP to simulate the LPI including field ionization.

Low-contrast (21mJ,3 ns)

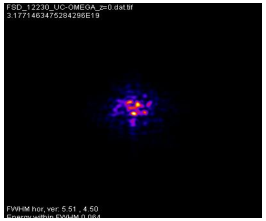




High-contrast (<1mJ) L=2μm is assumed

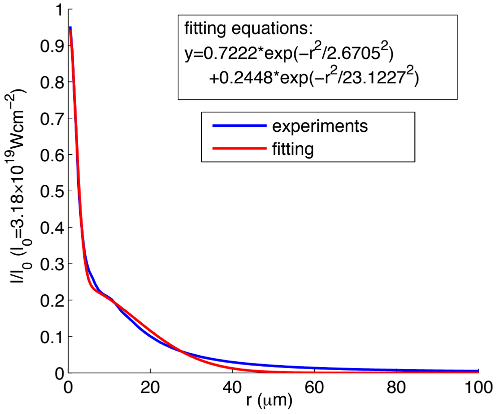
(pext* : extraction plane to diagnose time-integrated hot electron source though the cone tip and wall)

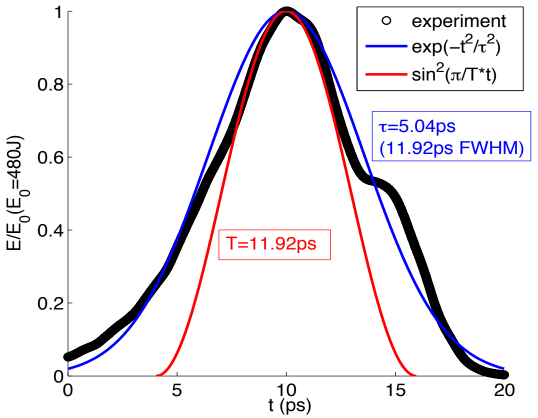
Laser setup: EP 10ps laser focal spot spatial and temporal distributions are fitted well in the simulation.



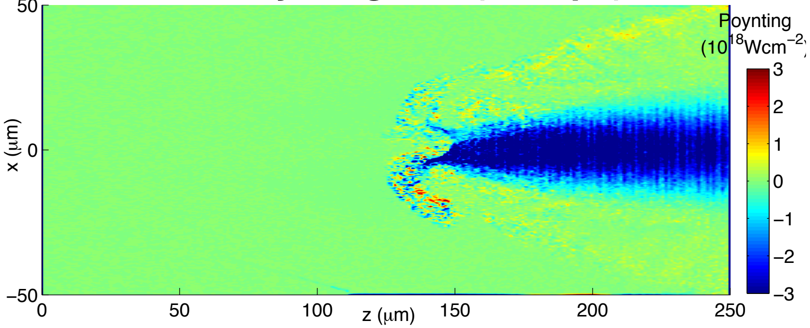
FSD_12230_UC-OMEGA_z=0.dat.tif
3.1771463475284296E19

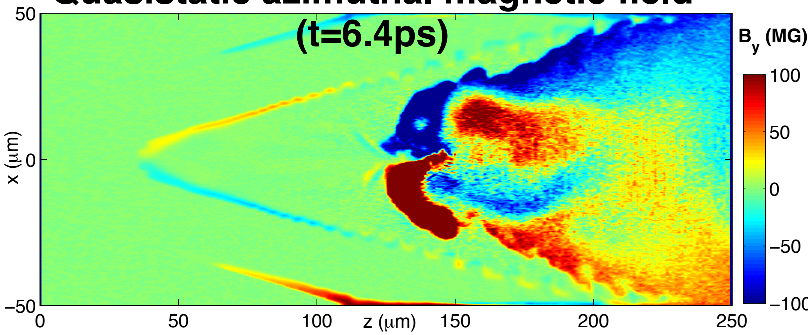
FWHM hor, ver: 5.51 , 4.50
Energy within FWHM 0.064

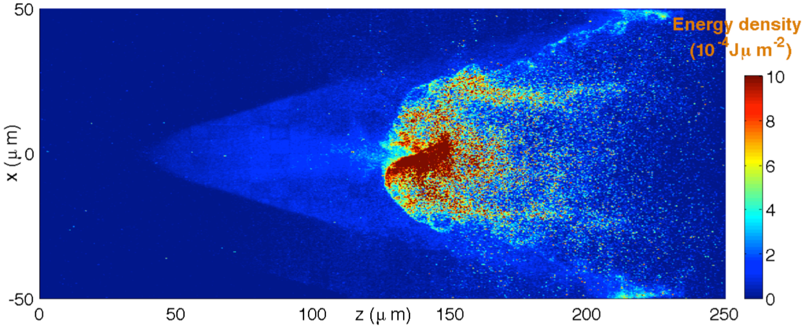


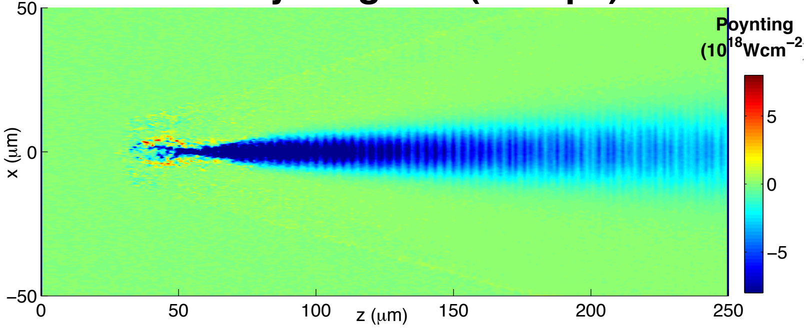


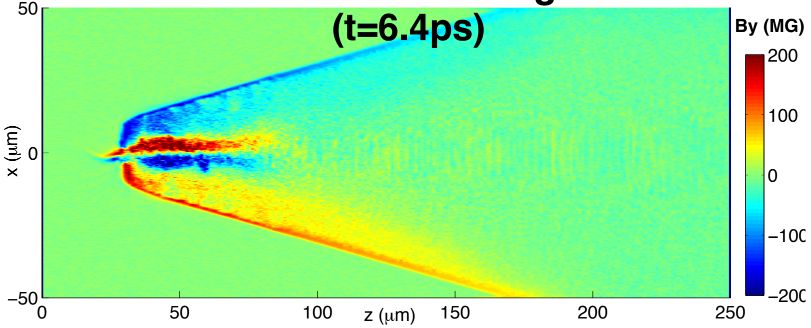
Complex laser filamentation and strong magnetic field generation defines LPI in two cases

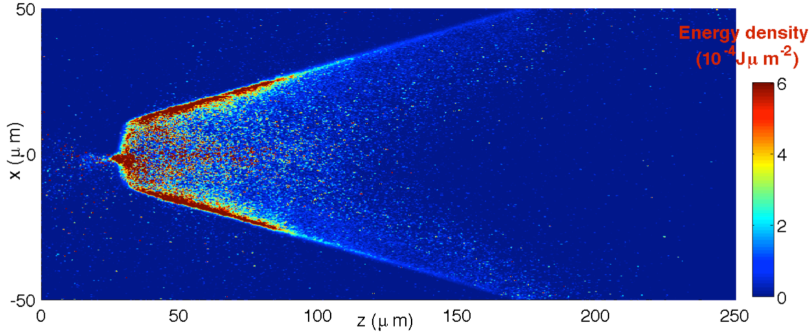

Poynting flux (t=6.4ps)


Quasistatic azimuthal magnetic field (t=6.4ps)


e^- energy density (t=6.4ps)

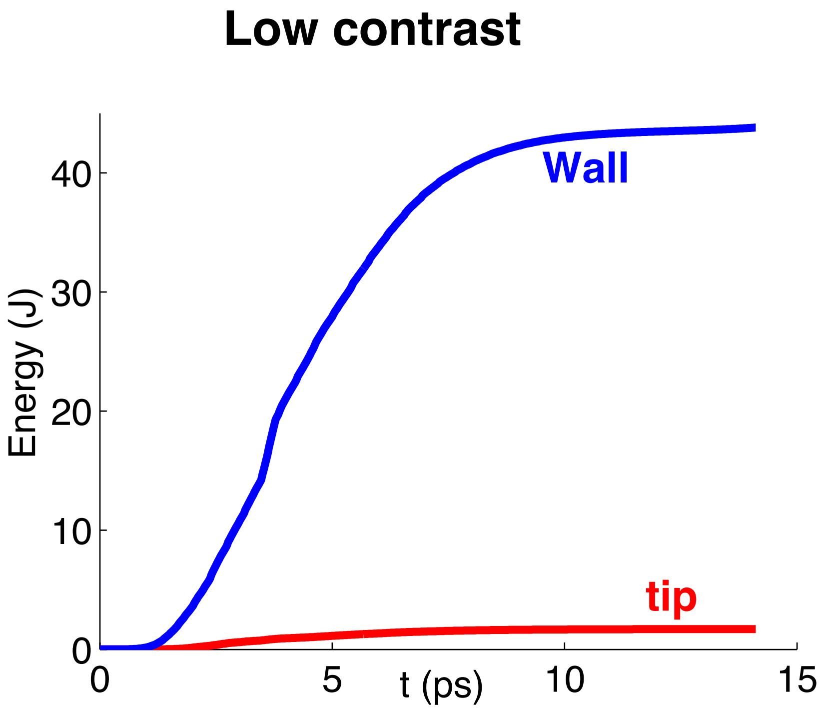

Poynting flux (t=6.4ps)

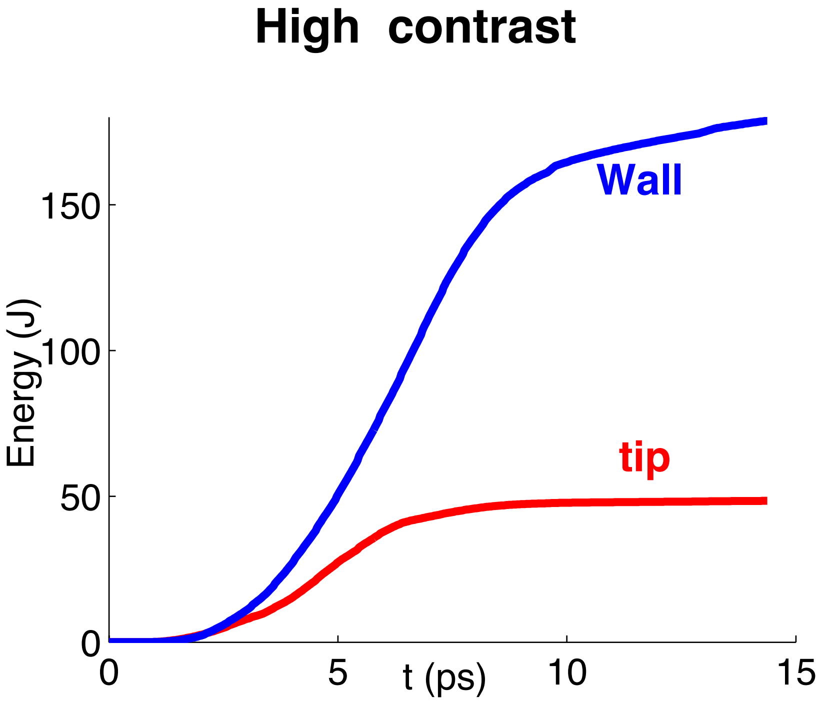

Quasistatic azimuthal magnetic field (t=6.4ps)


e^- energy density (t=6.4ps)

High contrast significantly improved the coupling efficiency from laser to fast electrons that enter into the cone

Laser energy in simulation : 320J





14% of laser energy coupled to fast electrons that enter into cone (wall and tip), among which:

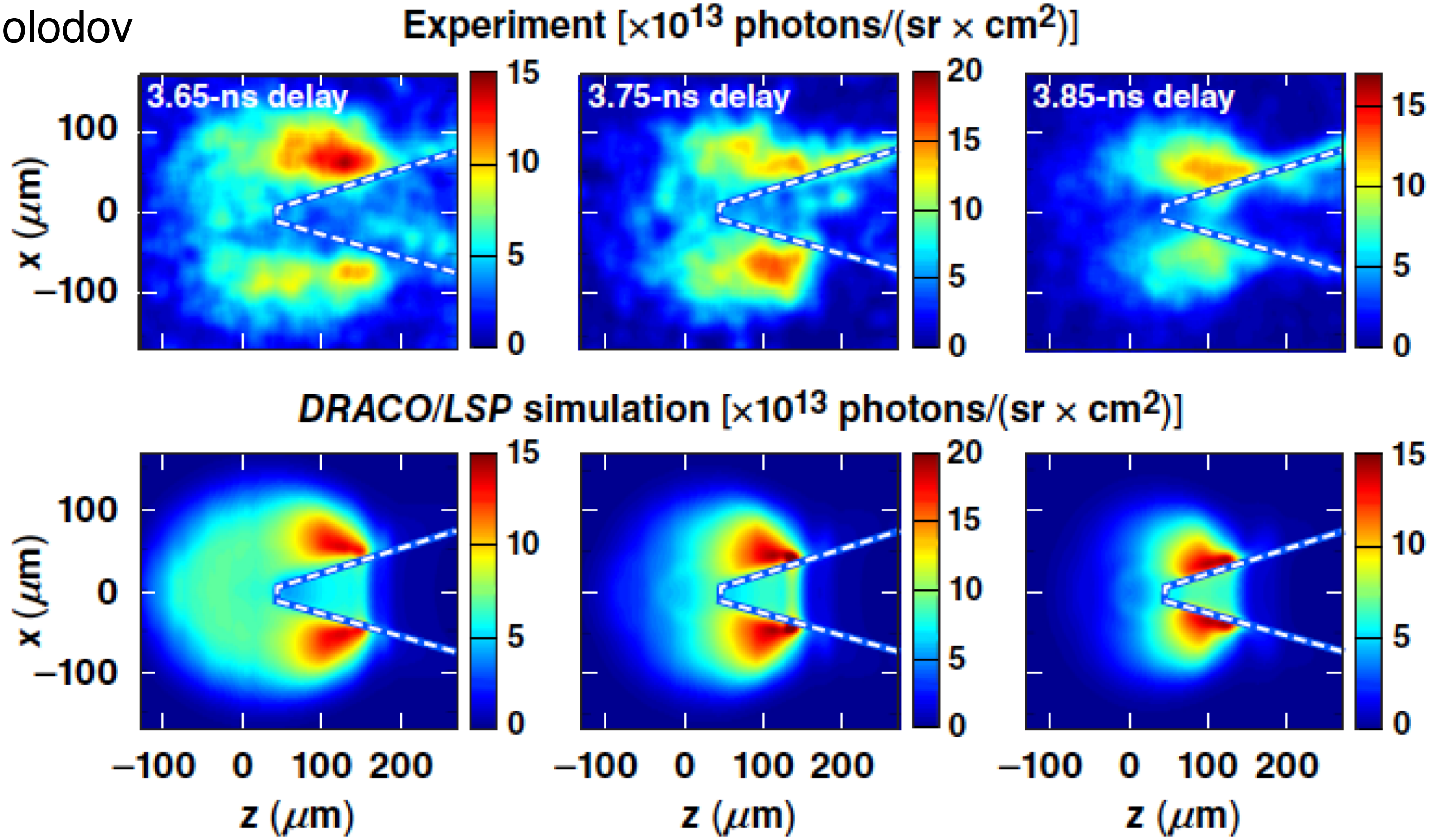
- 13% reach the side walls
- ~1% reach the cone tip

65% of laser energy coupled to fast electrons that enter into cone (wall and tip), among which:

- 45% reach the side walls
- ~20% reach the cone tip

LSP simulations with the PIC simulated electron energy spectrum captures features observed in experiments

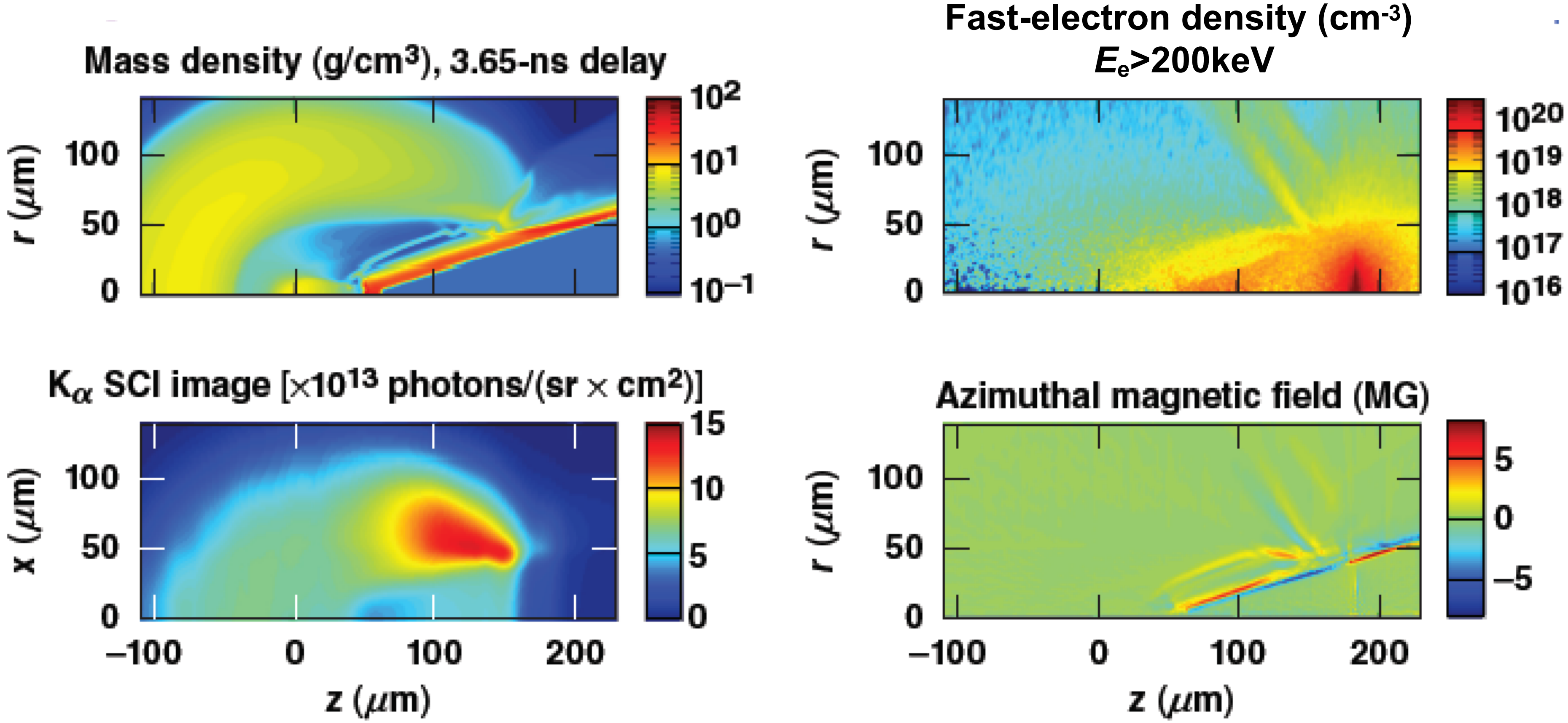
A.A. Solodov



- **Matching the simulated Ka yield with the experiments showing ~3.8 % of the total fast-electron energy (~1.2% laser energy) is coupled to the core ($\rho_{CD} > 1$ g/cm^3)**
  - **Large distance from the source to the core**
  - **Large divergence**
  - **Hard fast-electron spectrum for relatively low *ρr* of the compressed plasma**

Large distance from source to the core and divergence explains the low energy coupling to the core

A.A. Solodov



Mass density (g/cm^3), 3.65-ns delay

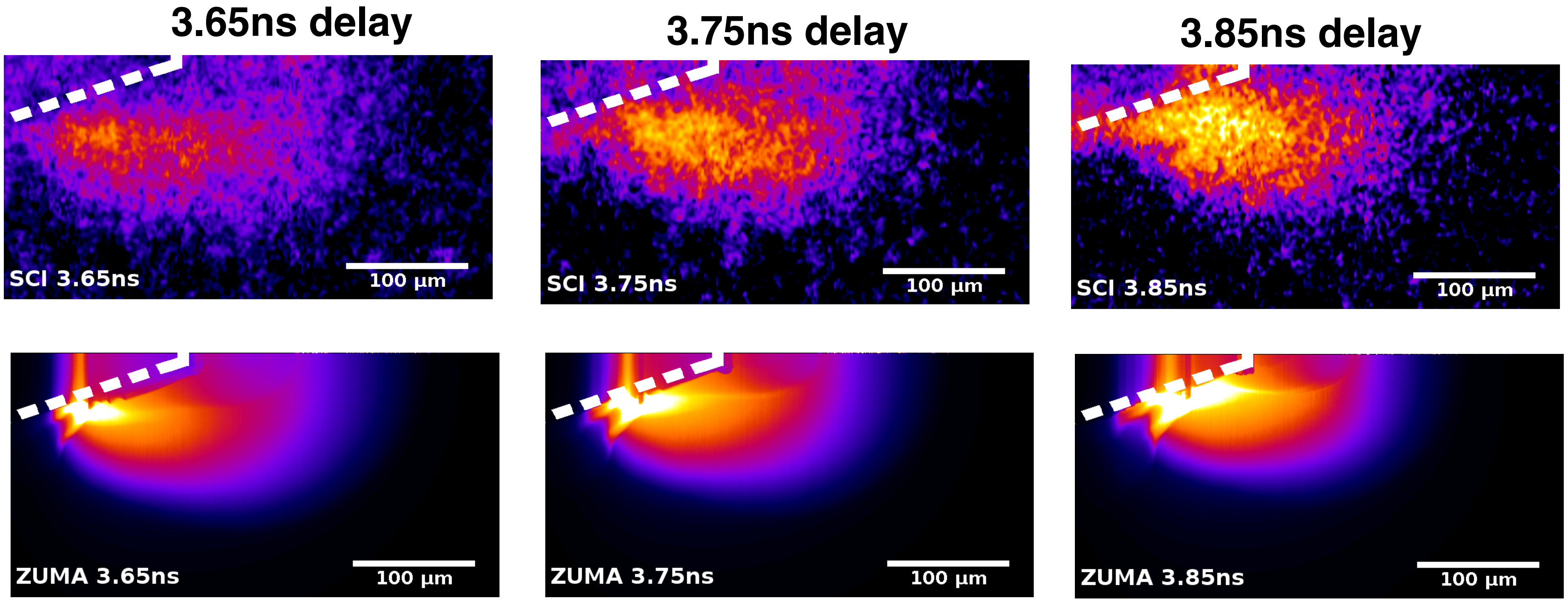
Fast-electron density (cm^{-3}) E_e>200keV

K_α SCI image [$\times 10^{13}$ photons/(sr $\times$ cm^2)]

Azimuthal magnetic field (MG)

- About 3.8 % of the total fast-electron energy is coupled to the core ($\rho_{CD} > 1$ g/cm^3)
- Large distance from the source to the core
- Large divergence

ZUMA simulated Kα spatial distribution is in good agreement with experimentally measured values



3.65ns delay

3.75ns delay

3.85ns delay

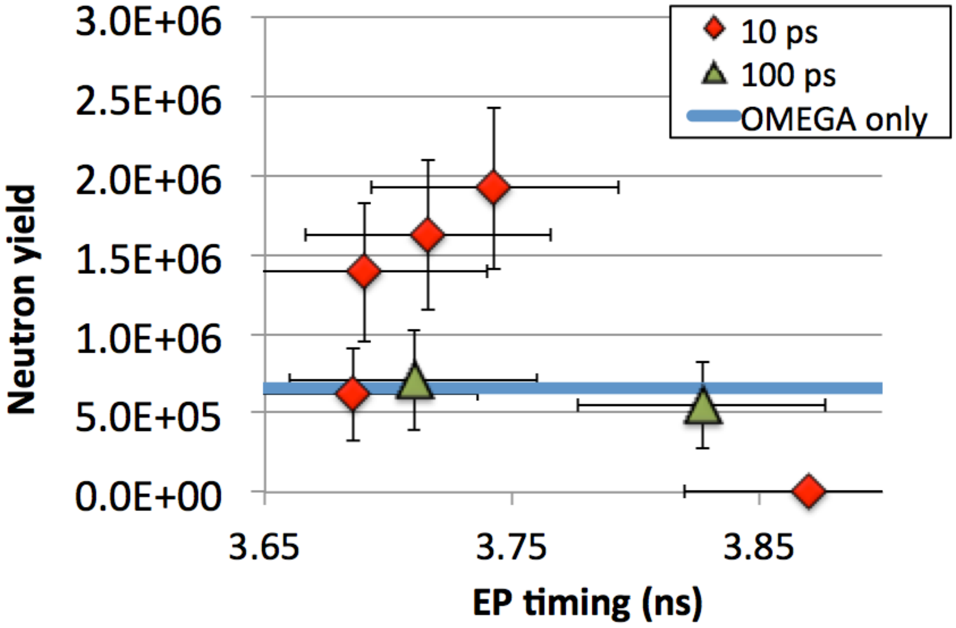
- **Source is injected 100 µm from cone tip**
- **Source divergence 50^o**
- **Lack of Ka signal at cone tip seen in temperature corrected ZUMA output**

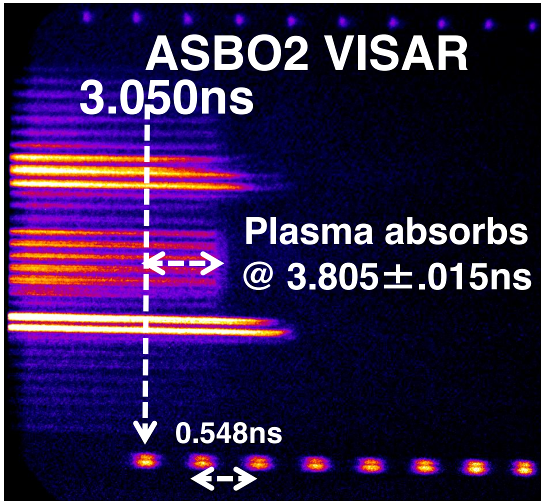
C. Jarrott et al. (to be submitted to Physics of Plasmas)

WHAT IS THE WAY FORWARD?

Experiments with an improved target design

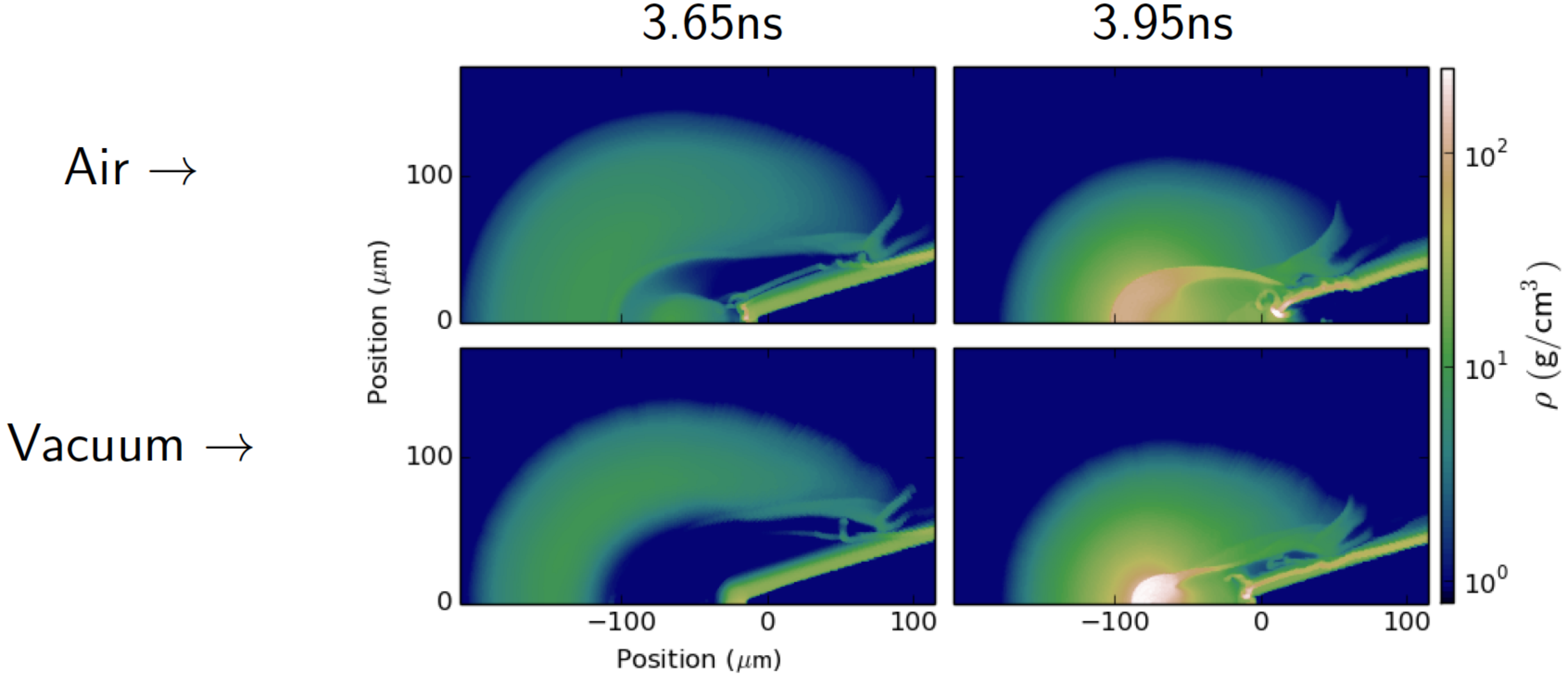
- Cone tip size 40 μm to mitigate preplasma
- Vacuum shell (pre-evacuating the trapped air)
- Measured the cone tip breakout time
    - $t_{breakout}$ ~ 3.8 ns
- Varied OMEGA EP (10 ps pulse) beam energy and timing delay





Optimizing target and implosion to form a denser core* to facilitate fast electron energy coupling

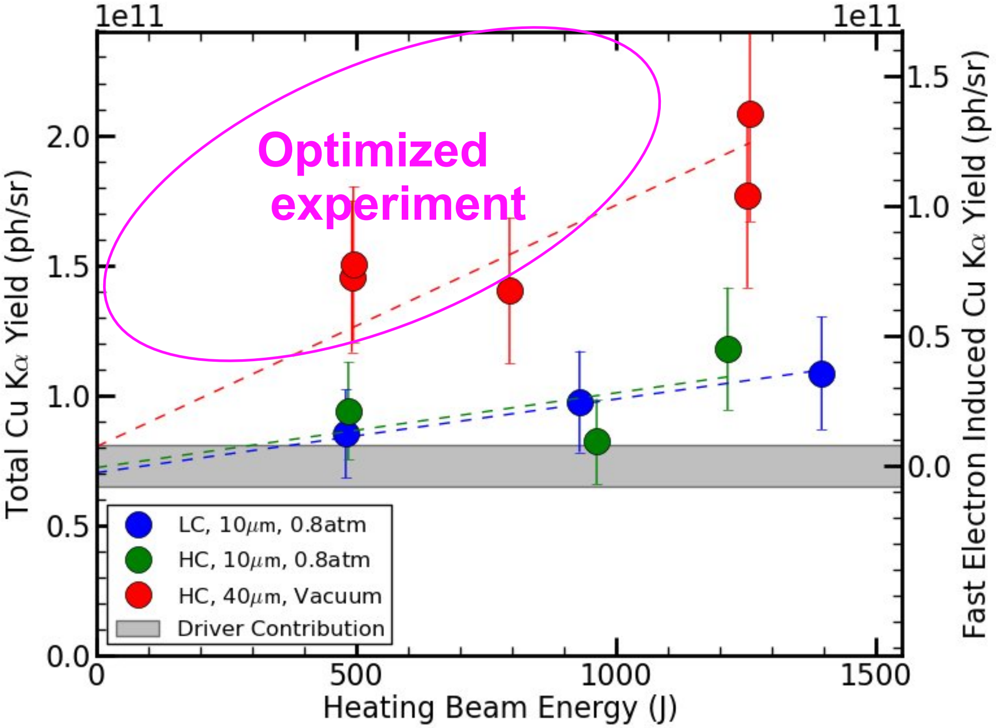
*W. Theobald, A.A. Solodov et al., Nature Communications 5, 5785 (2014)



Gas pressure	ρR_{break} (mg/cm^2)	ρR_{max} (mg/cm^2)
0.8-atm air	80	300
Vacuum	360	600

- **DRACO simulations of implosion with a vacuum shell shows a much delayed cone-tip breakout time and a significant increase in ρR**

Enhanced energy coupling in optimized experiments with 40-um tip cone and vacuum shell



L.C. Jarrott, **Nature Physics (2016)**

- **4X increase in the observed Kα yield and up to 7% laser energy is coupled to the compressed plasma in the optimized experiment**
    - **A denser core stops electrons more effectively**
- **Cu Kα is emitted closer to the cone tip**
- **40 μm tip mitigates preplasma facilitating energy deposition at the tip**

New Ideas

There are several ideas to improve coupling

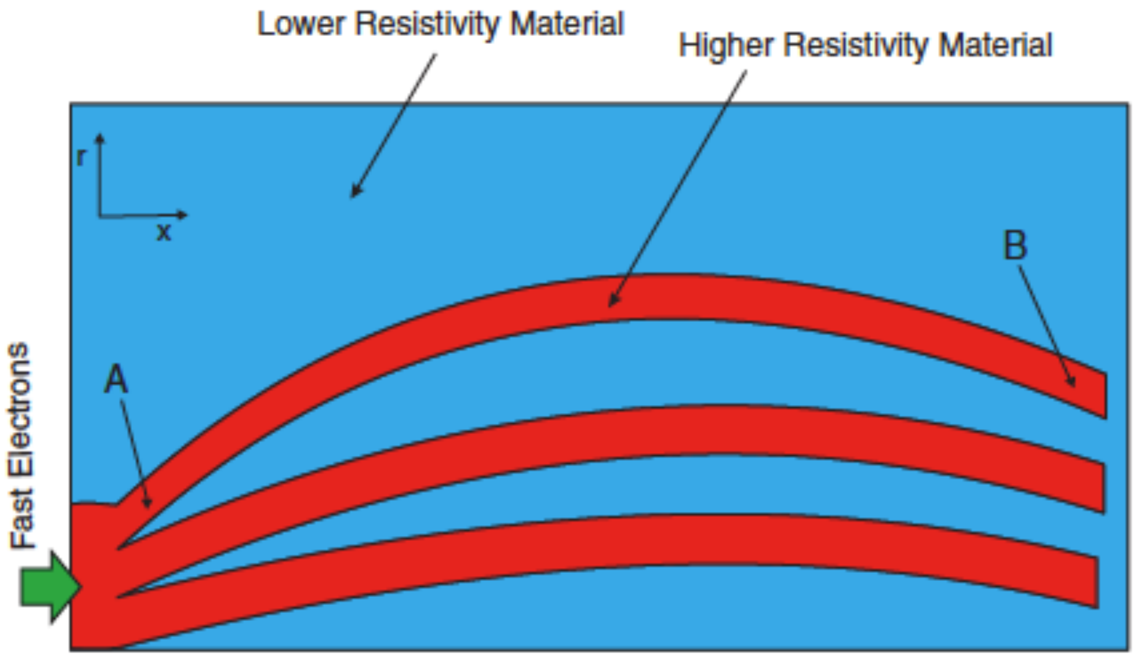
- **Use of protons to ignite the target**
- **Switchyard to mitigate divergence**
- **Resistive collimation of electrons**
- **External magnetic field to mitigate source divergence**
- **Two pulses to collimate beam**

Robinson's switchyard sorts particles by direction and then directs them to a common point beyond the high Z material

- Robinson's switchyard sorts particles by direction and then directs them to a common point beyond the high Z material

- In this concept, resistivity gradient is used to guide the electrons

- Coupling efficiency of 25% can be achieved

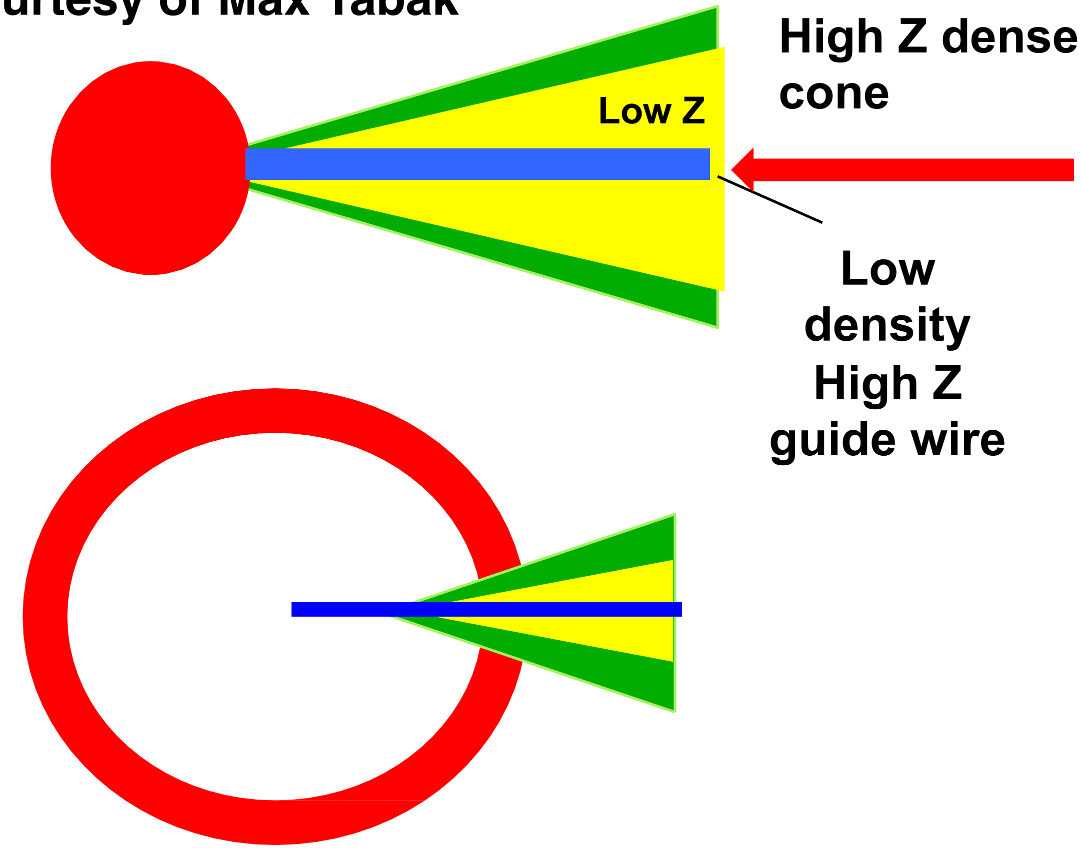


$$\frac{\partial B_z}{\partial t} = -\nabla \times \eta J$$

A. Robinson et al., Phys. Rev. Lett. (2012)

Magnetically guiding can relax constraints on the cone

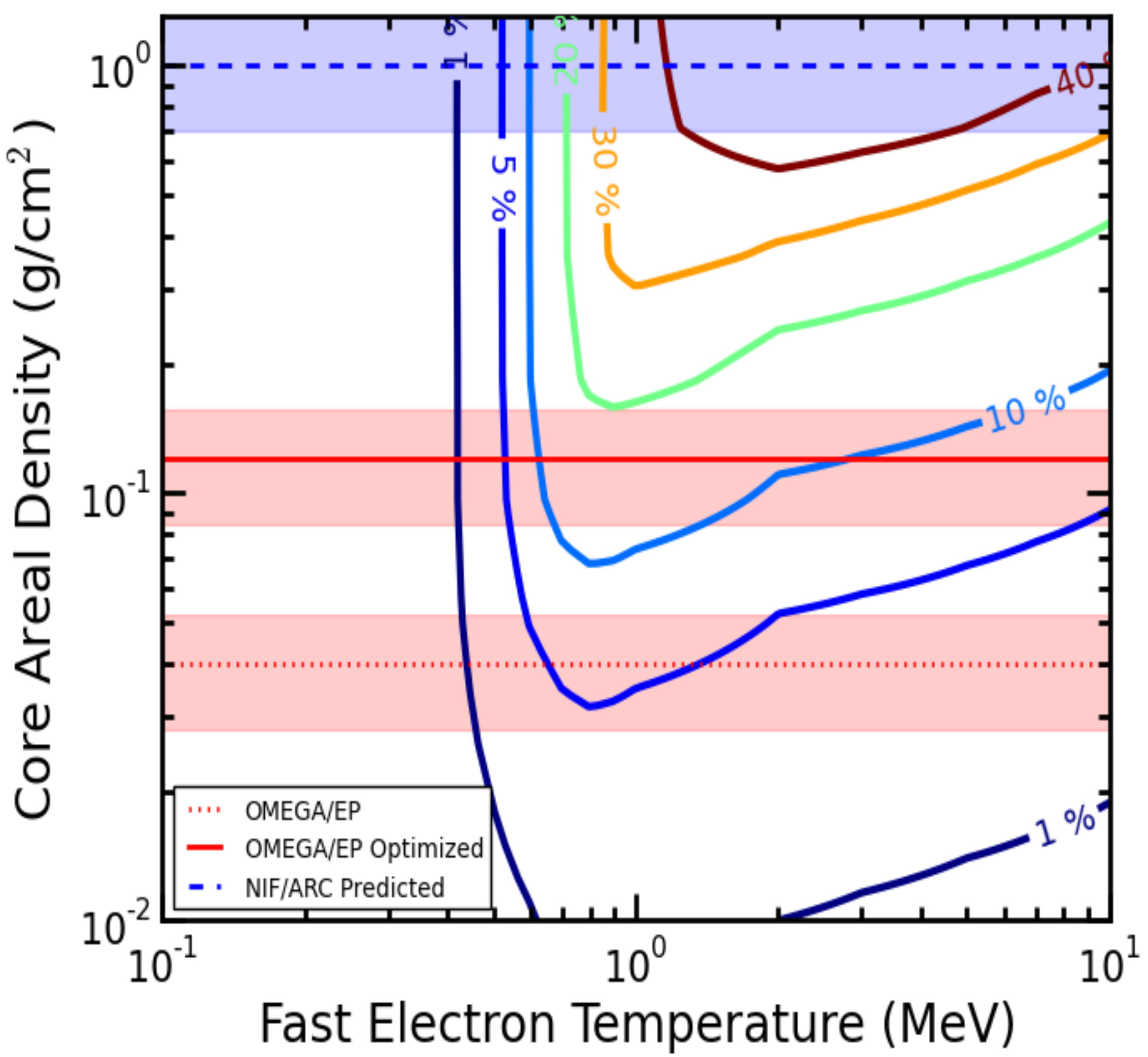
Courtesy of Max Tabak



- Current density ~ 10^{12} A/cm^2
- Current in excess of 100 MA
- Magnetic field in excess of 50 MG

- Guiding may reduce losses to wall due to prepulse
- Can density and Z be low enough that beam is not attenuated in wire?
- With efficient electron transport, the solid angle removed from implosion sphere can be reduced.The implosion will be closer to 1D

Benchmarking the experimental data led to robust prediction of >15% in NIF scale experiments



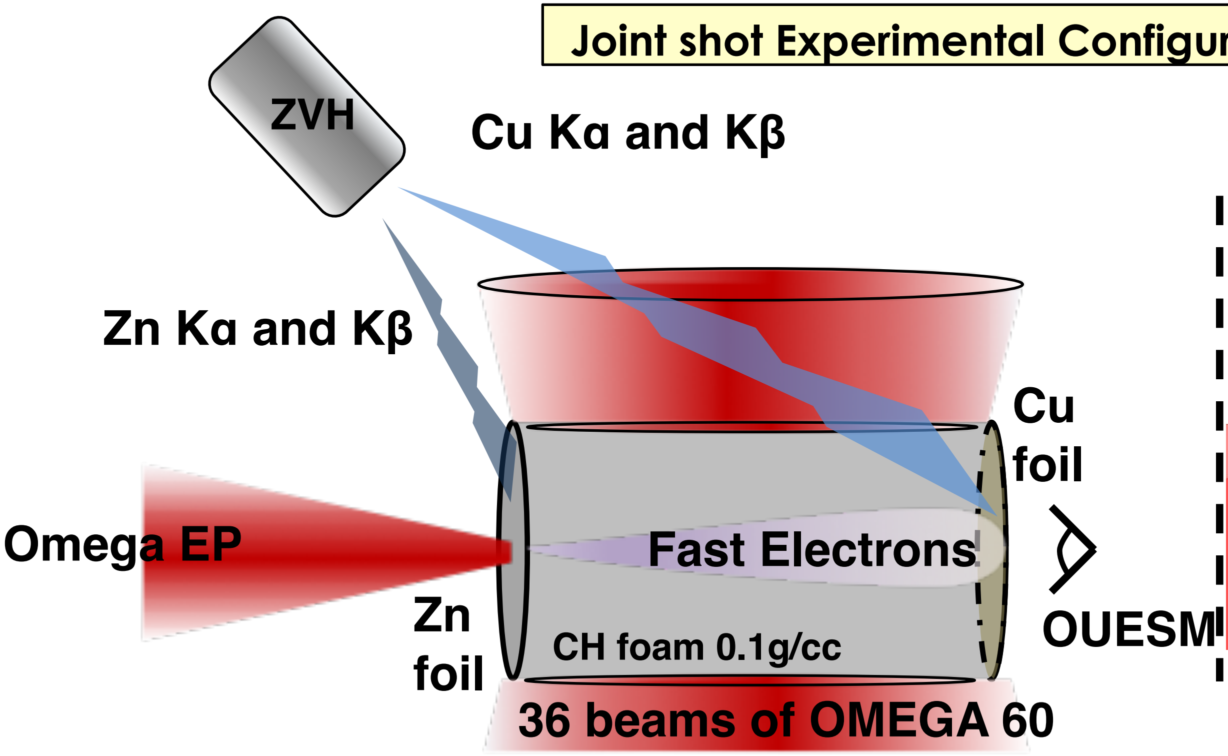
<- NIF/ARC predicted

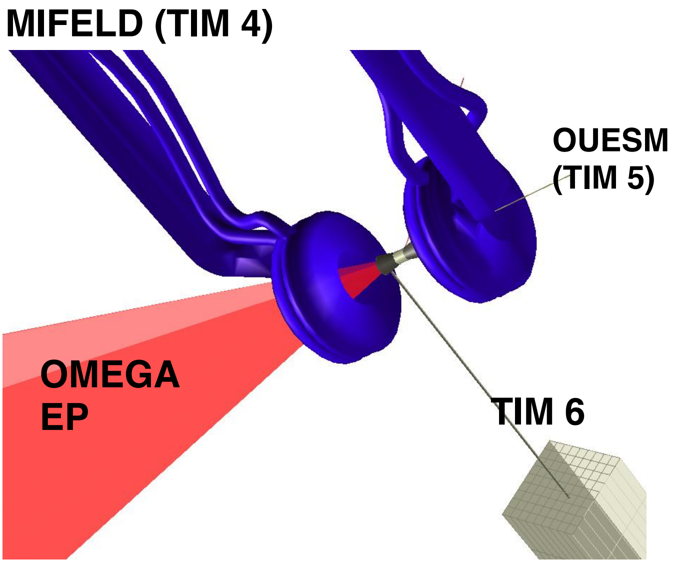
<- OMEGA/EP optimized

<- OMEGA/EP

FAST IGNITION 2.0

Joint shot Experimental Configuration





Summary

- **Fast ignition promises high gain but it involves challenging physics**

- **In recent years, issues with electron source and transport have been identified**
  - Electron source has a large divergence
  - Stand-off distance between electron source and compressed core is significant
  - Electron spectrum needs to match ρr

- **Results with redesigned targets are encouraging**

- **New schemes have been proposed to mitigate source divergence and to improve coupling into the compressed core**

The team

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A.A. Solodov, W. Theobald, C. Stoeckl, C. Mileham, F.J, Marshall, J. Delettrez, R. Betti

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H. Sawada

T. Yabuuchi, H. Habara, T. Iwawaki

J.J. Santos, D. Batani

THANK YOU FOR YOUR ATTENTION