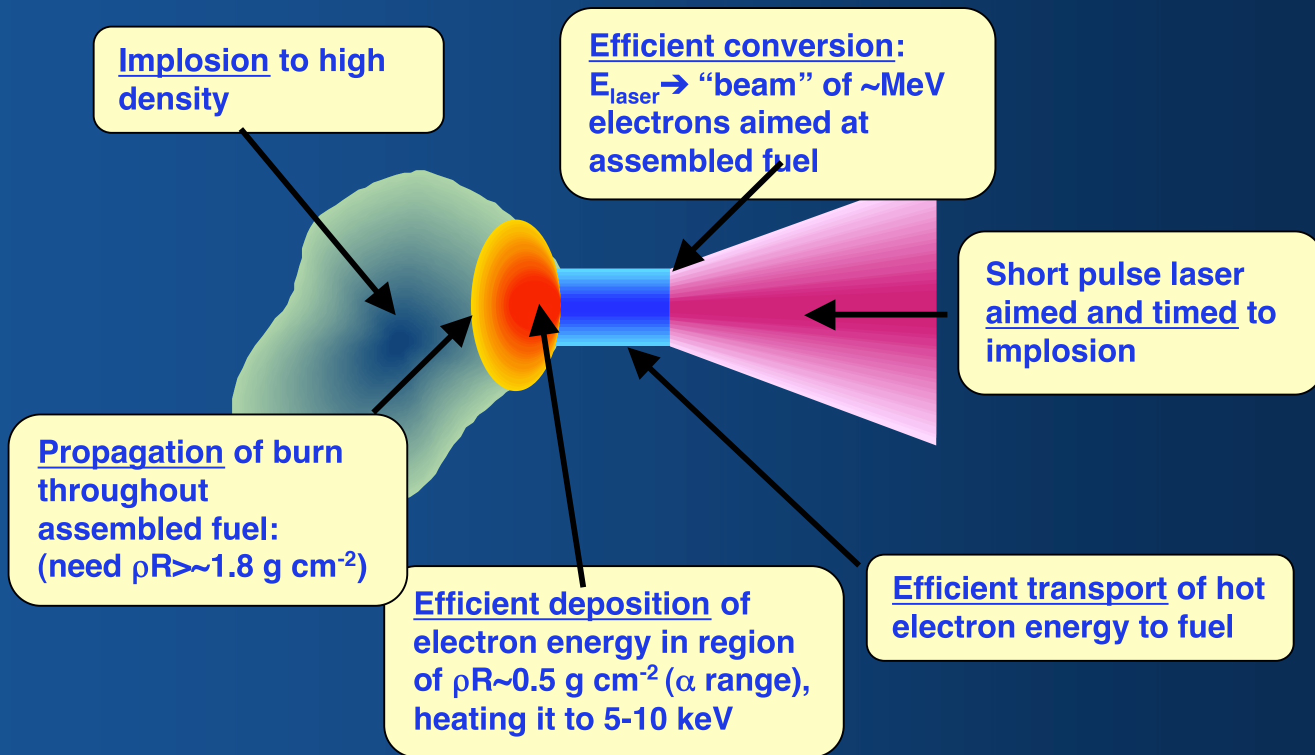
Status of Fast Ignition Research

E. Mike Campbell



Fusion Power Associates
September 27-28, 2006
Washington, DC

UR LLE · FSC · OHIO STATE · UCSD · MIT · UNIVERSITY OF CALIFORNIA Department of Applied Science, UCD · GENERAL ATOMICS

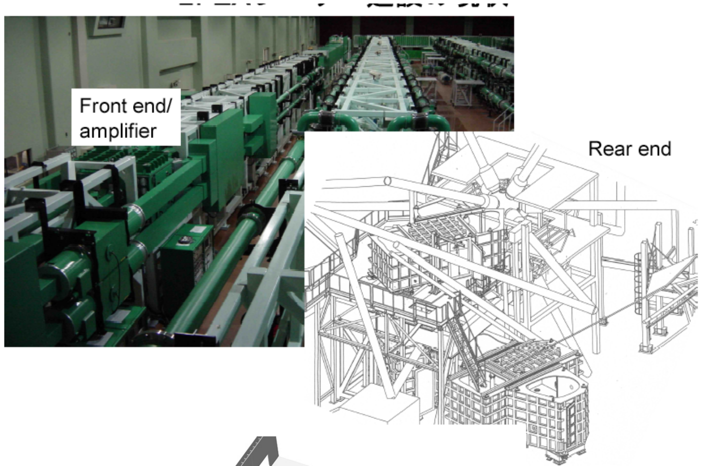
Fast Ignition: Science of the "Extreme"-
High Energy Density Physics and Fusion

- **University (OSU,UCD,UCSD,UR,UNR, UCLA), National laboratory (LLNL), industry (GA) research partnership**
  - 21 refereed publications published/accepted in '06,
  - Dedicated issue on Fast Ignition in Fusion Science and Technology, April 2006
- **Strong International Collaboration (Osaka, RAL)**
  - Osaka, Rutherford Appleton Lab
- **Heavily leveraged and positioned to take advantage of NNSA investment in lab facilities (Omega-EP, Z/PW,NIF and smaller facilities (Titan, Trident Upgrade) as they become available**

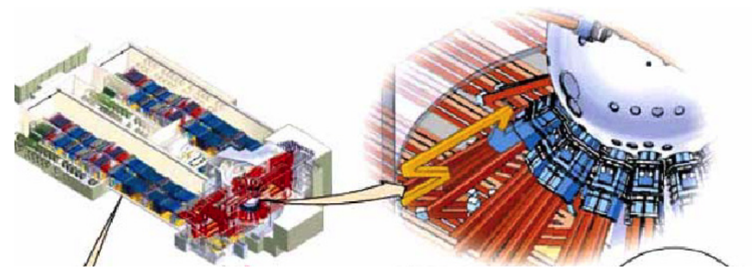
Fast Ignition presents a realistic opportunity to demonstrate Q>0.1 within 5 years and ignition and burn (Q>1) within a decade

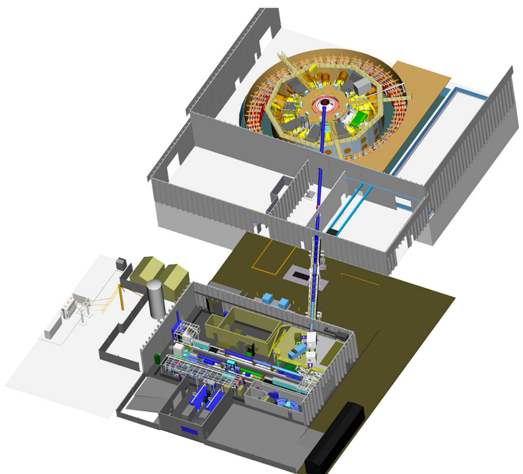
New Facilities under construction will allow FI physics to be explored under relevant conditions

FIREX-1

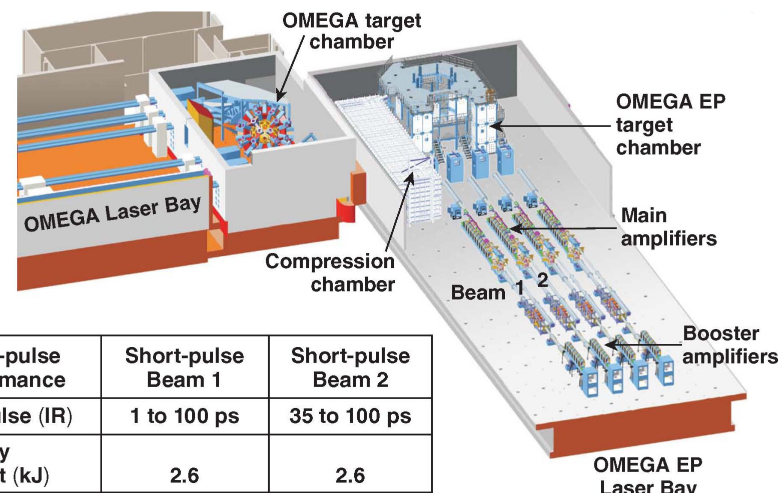


NIF/ARC





ZR and Petawatt



Short-pulse performance	Short-pulse Beam 1	Short-pulse Beam 2
Short pulse (IR)	1 to 100 ps	35 to 100 ps
IR energy on-target (kJ)	2.6	2.6
Intensity (W/cm^2)	6×10^{20}	$\sim 4 \times 10^{18}$
Focusing	> 80% in 20 μm	> 80% in 40 μm

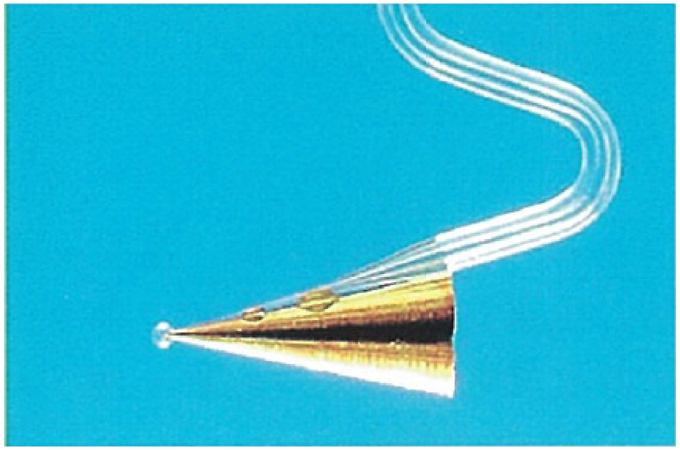
G5546q

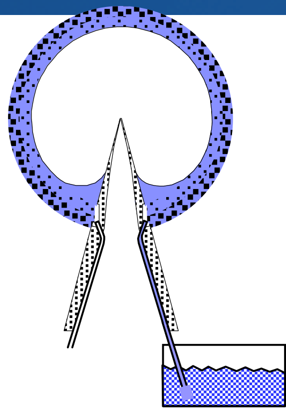
Omega-EP

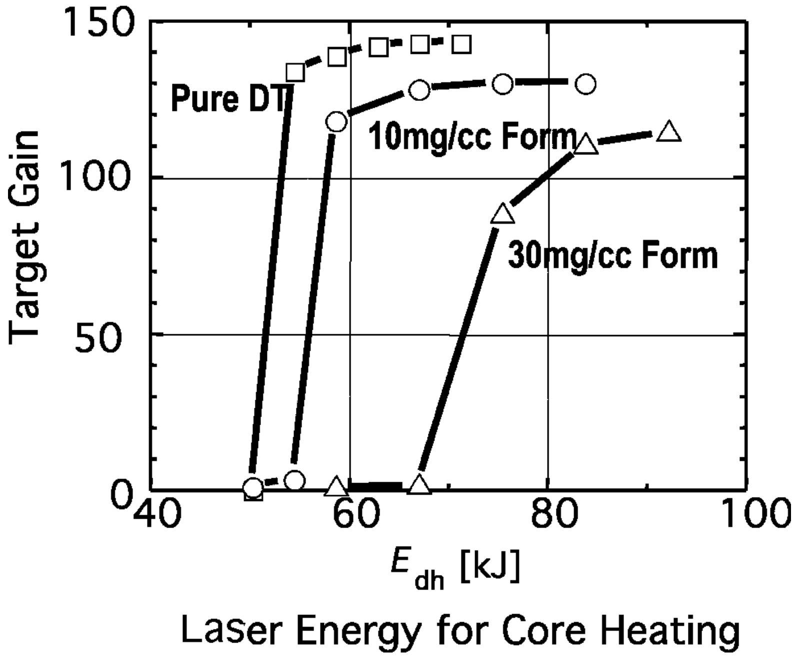
FI benefits from international R&D efforts

- **Reentrant cones cause potential problems with beta layering.**
- **DT surface can be formed by filling foam**
  - Previous cryo-foam experience at ILE

ILE cryo-target



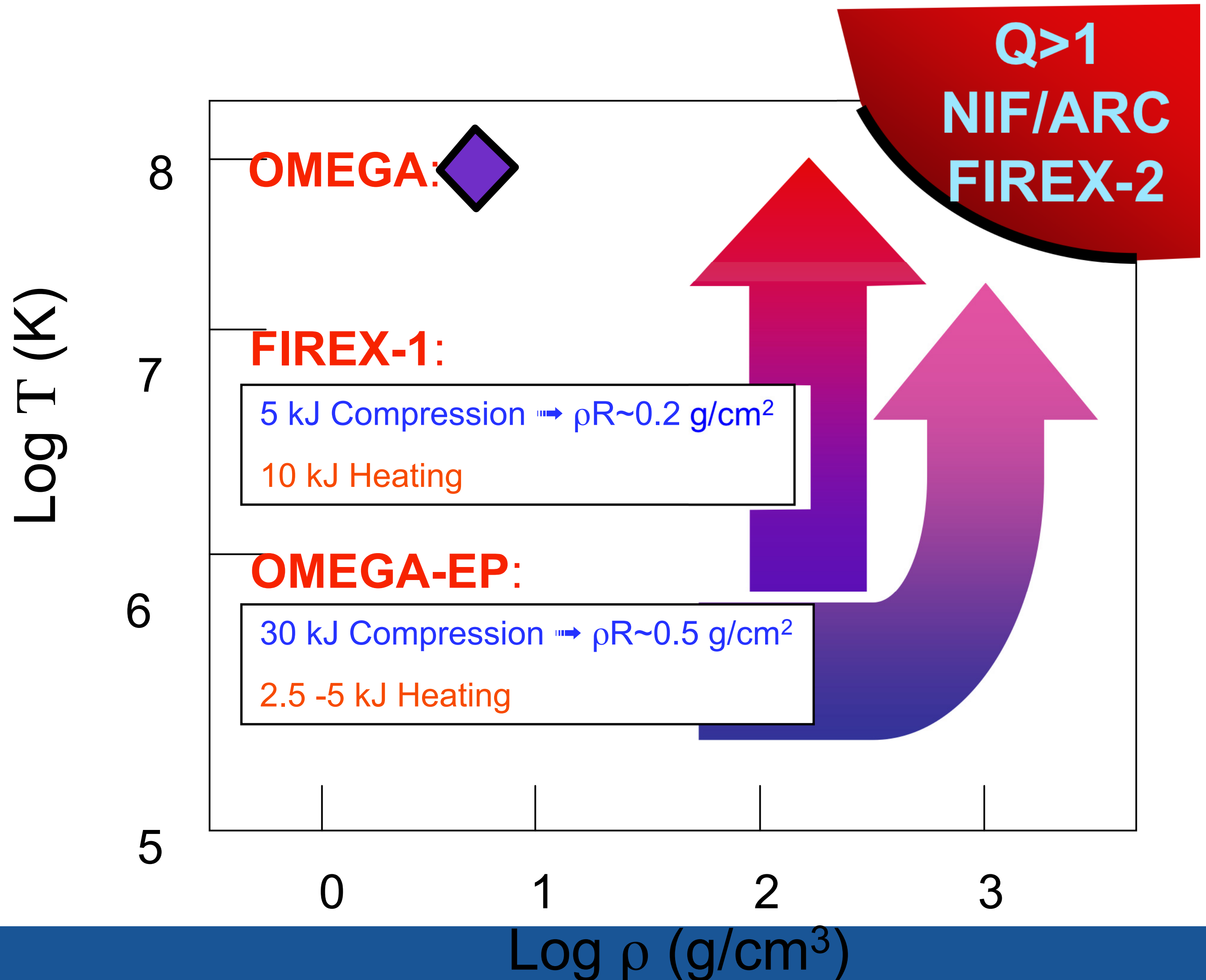




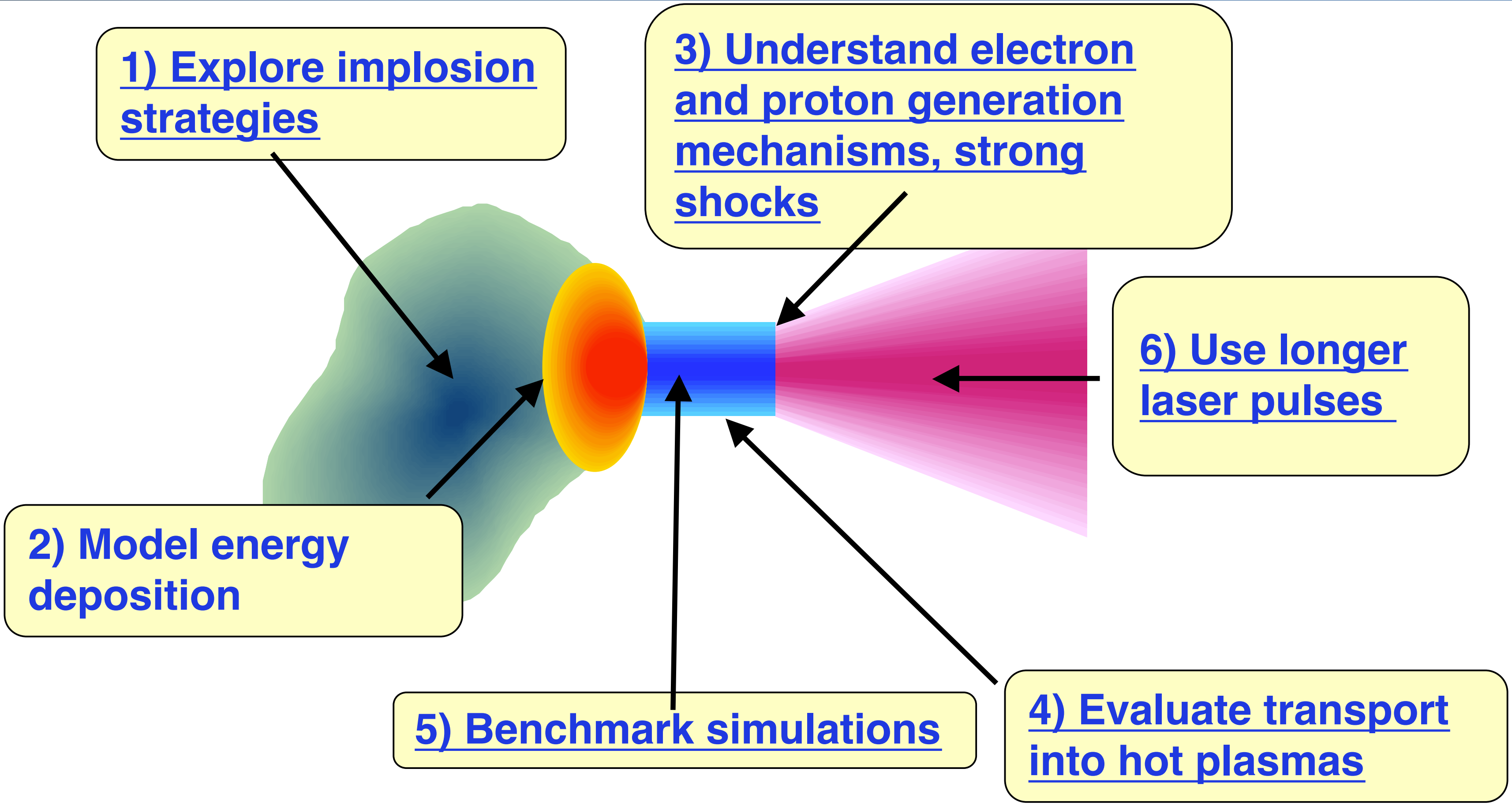
FI Relevant conditions will be available with new facilities that will come on line in next 3 years

- ***Omega EP*** **has FI exploration as one justification and could demonstrate Q 0.1-0.5**
- **FI is a principal justification for *FIREX I***
- **Initial analysis indicated high gain possibility with less than full *NIF* capability - possibly available in FY12**
- ***Challenge is to be ready*** **-- an ignition/gain experiment in 2012 on NIF requires successful sub ignition on Omega EP/FIREXI with a target that performed as modeled with numerical simulation**

Omega-EP and FIREX-I are complementary facilities.



Until "integrated facilities" become available, research is focused on individual components, diagnostic development, and code validation



And prepare for more integrated work on EP/FIREX1

1) Design targets to optimize fast ignition requirements

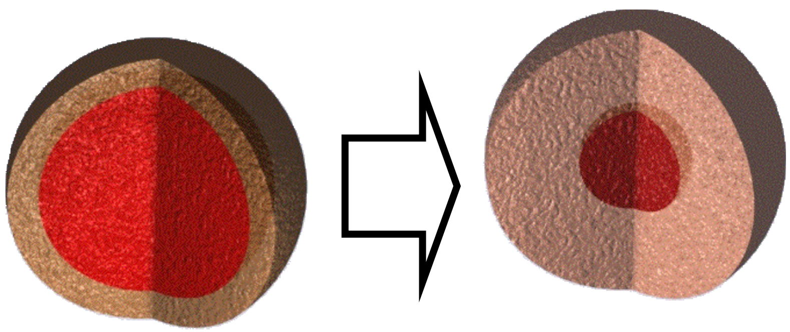
Optimize with Low adiabat, low velocity, implosion

- **Assembled fuel is nearly uniform**
  - Hot spot is <10% of volume
- **Compression energy much lower**
  - 750 kJ to assemble ρR=3 g/cc
- **Dense fuel minimizes ignition energy**
  - 300-400 g/cc

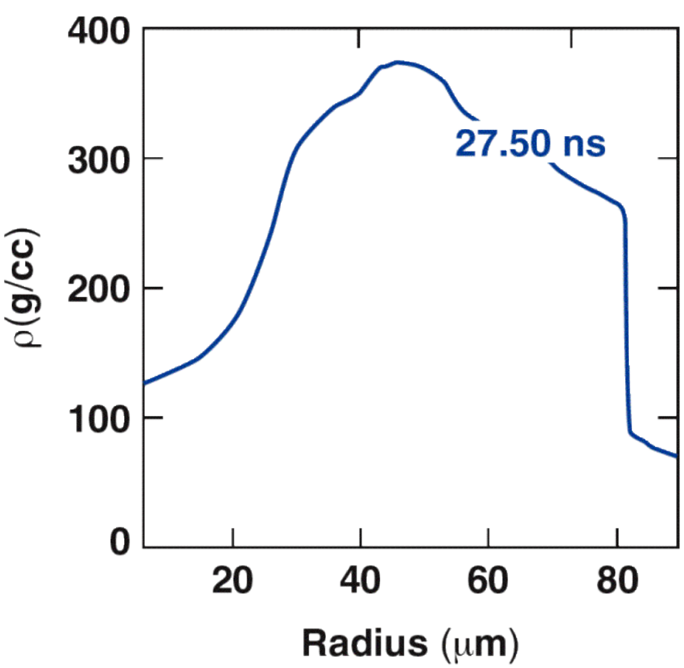
⇒ **Potential for gain >100 within NIF capability**

Fuel density at stagnation

From 1-D

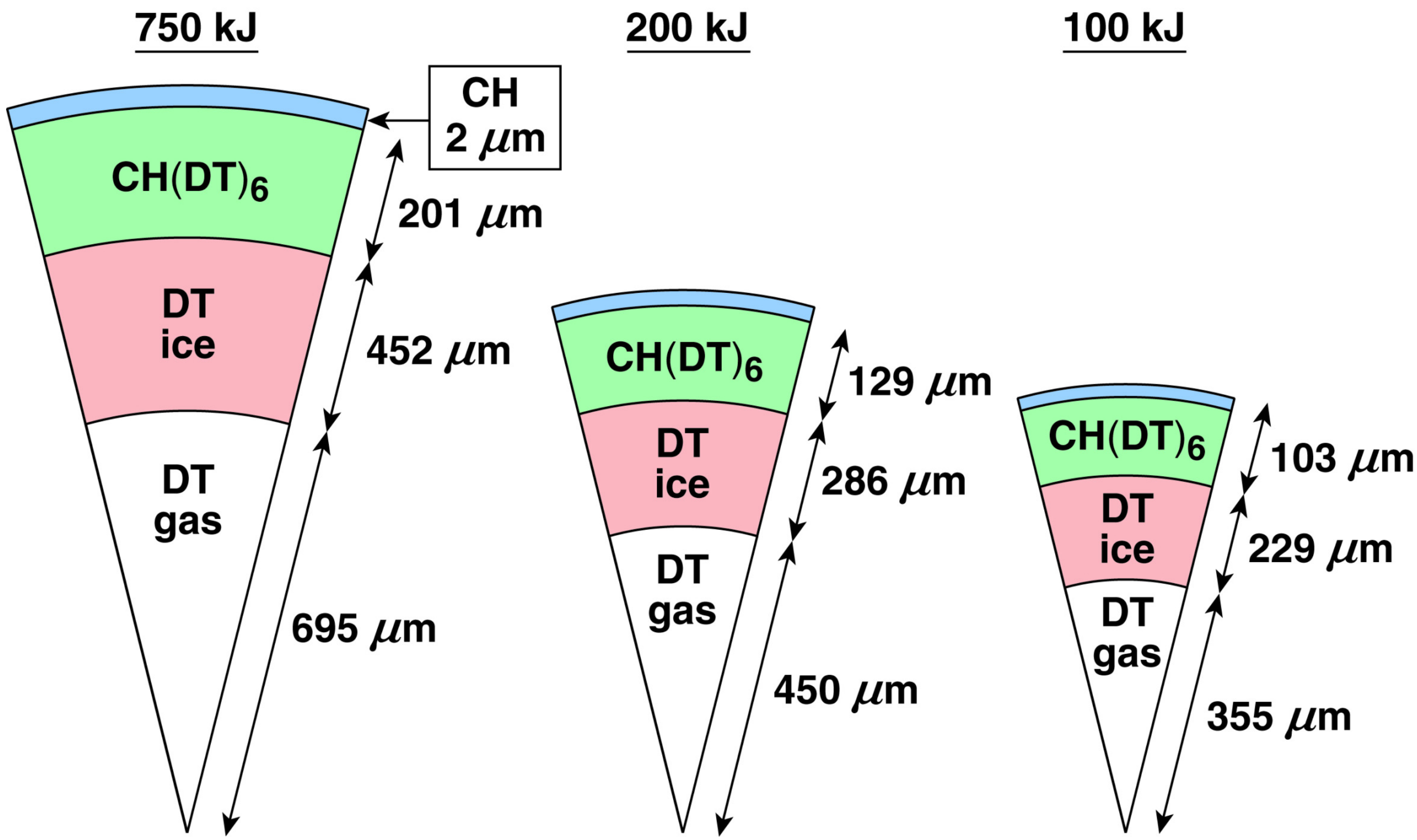


Central Hot spot **Fast ignition**



R. Betti, *Phys of Plasmas* **12**, 110702 (2006)

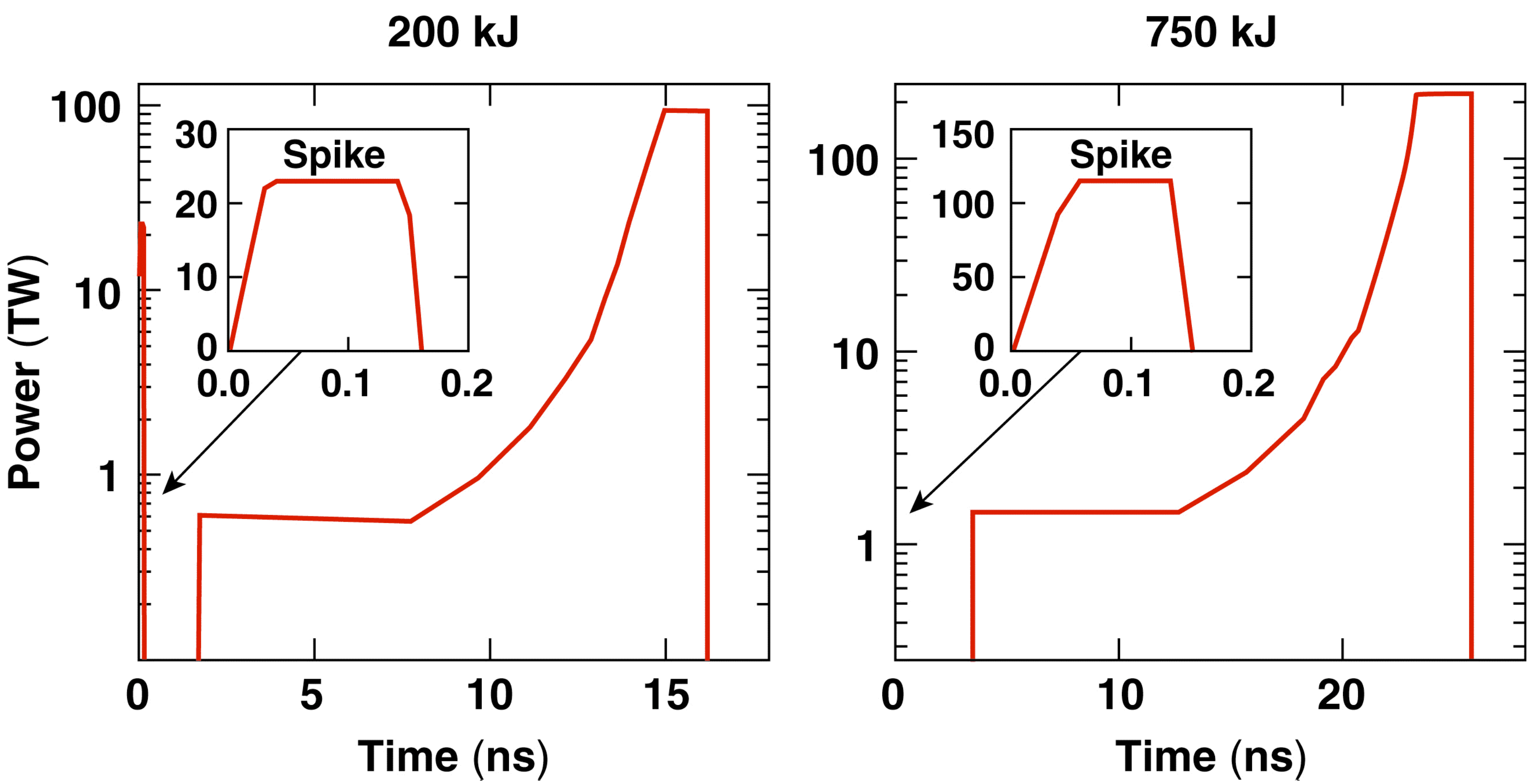
Optimized fast-ignition cryo-targets are thick shells of wetted foam with initial aspect ratio ~2



TC7378

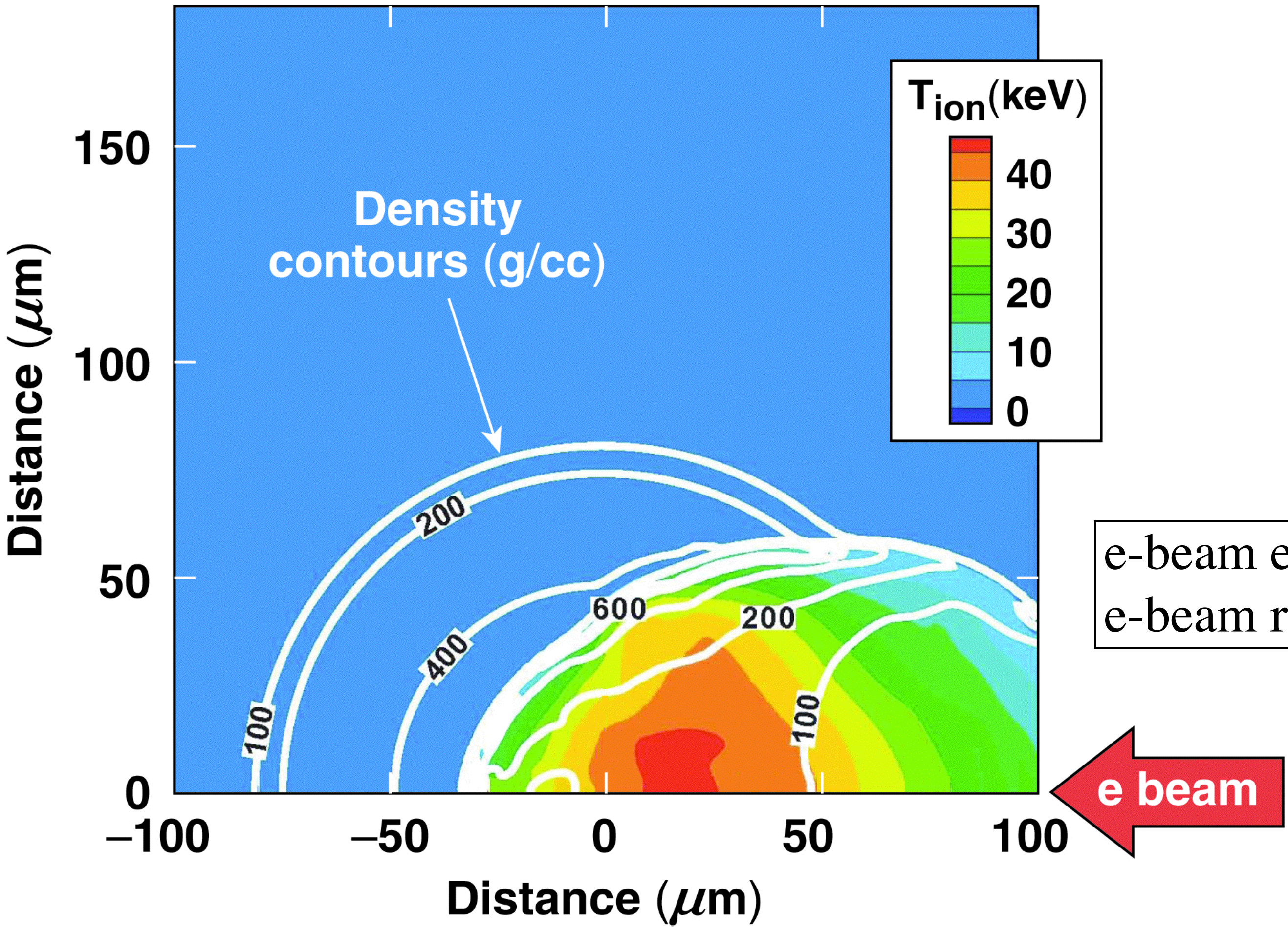
R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005)

Fast-ignition targets require long laser pulses and high contrast ratios (~100) within NIF capabilities



R. Betti and C. Zhou, Phys. Plasmas 12, 110702 (2005)

2-D simulations of the ignition and burn of the dense core by 1-3 MeV electrons have been performed



e-beam energy =15kJ
e-beam radius = 20_m

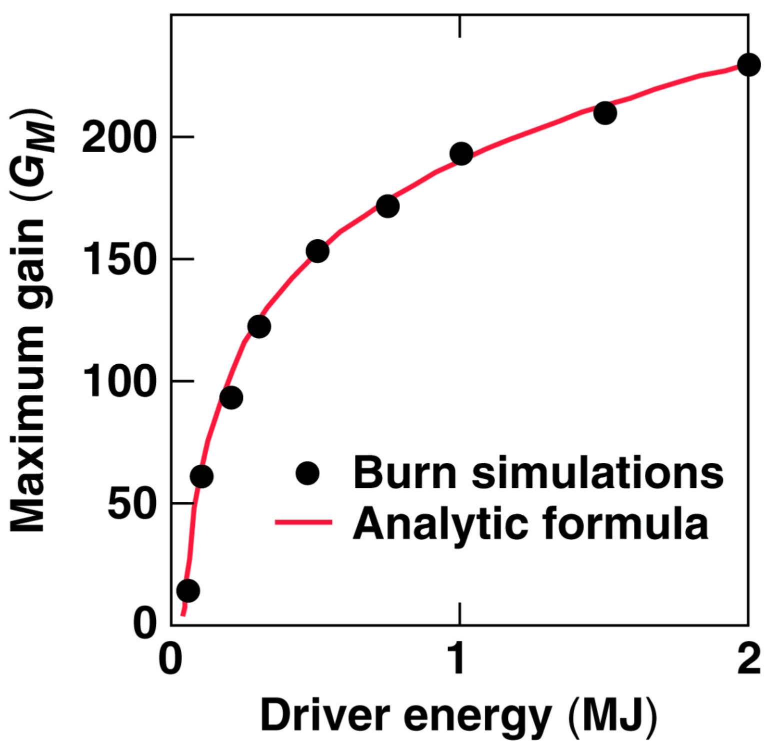
TC7382

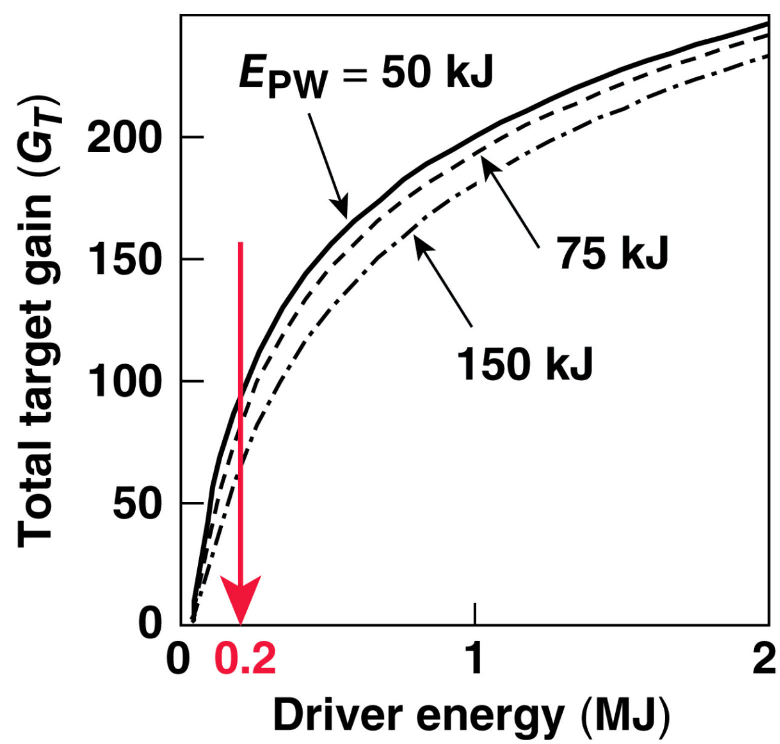
R. Betti, A .Solodov, J. Delettrez, C. Zhou, Phys. Plasmas (to appear in October)

High gains are possible with small drivers with energy as low as 200 kJ

$$G_M = \frac{E_{Fusion}}{E_{Driver}}$$

$$G_T = \frac{E_{Fusion}}{E_{Driver} + E_{Petawatt}}$$



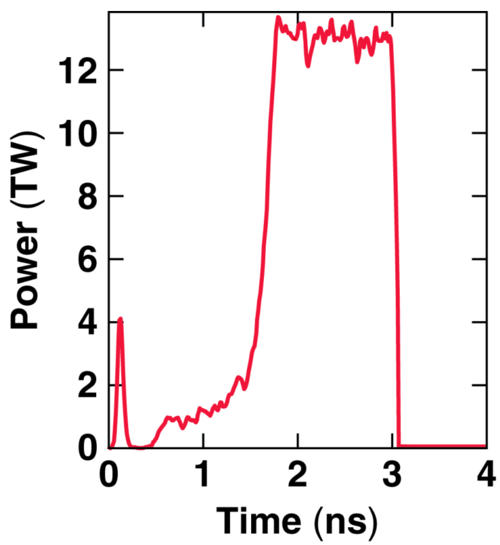


TC7383

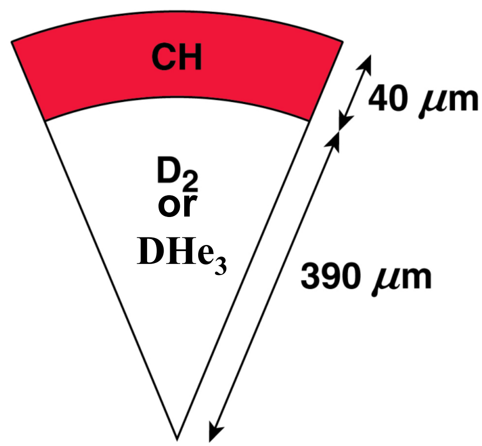
R. Betti, A .Solodov, J. Delettrez, C. Zhou, Phys. Plasmas (to appear in October)

Low-adiabat, low-V_i implosions of CH targets are used to study fuel assemblies on OMEGA

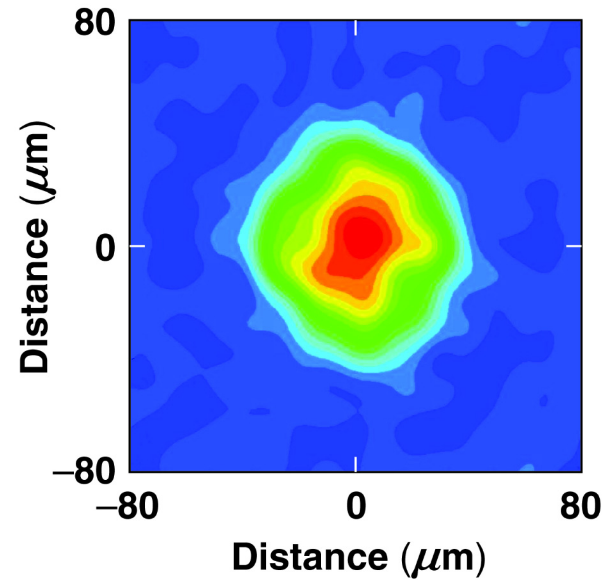
Laser pulse



Target



Core X-ray image



E_L H20kJ, ± H 1.3, V_i H 2 • 10^7 cm/s

C. Zhou, W. Theobald, R. Betti, C. Stoeckl, D. Meyerhofer, C. Sangster (submitted to Phys. Plasmas)

The measured maximum ρR during the burn exceeds $0.2 g/cm^2$ in agreement with 1D predictions

The ρR is measured through the downshift of the proton spectrum

Maximum ρ*R during burn*	Measured (g/cm^2)	Simulation (g/cm^2)
ρR_{max} DHe_3 fill, 33 atm.	0.238	0.246
ρR_{max} DHe_3 fill, 25 atm.	0.244	0.264

→This assembly can stop 3MeV electrons for 2ρR.
→Simulations show that empty CH shells reach $0.5 g/cm^2$ and can stop up to 5MeV electrons for 2ρR.

C. Zhou, W. Theobald, R. Betti, C. Stoeckl, D. Meyerhofer, C. Sangster (submitted to Phys. Plasmas)

2) Transverse scattering modifies e^- beam

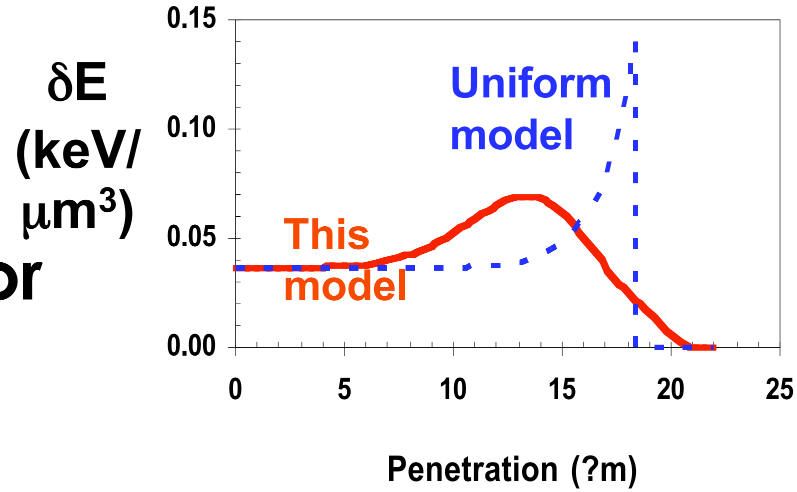
- Classic Coulomb scattering
- Insensitive to screening models

⇒ Propagation distance is blurred

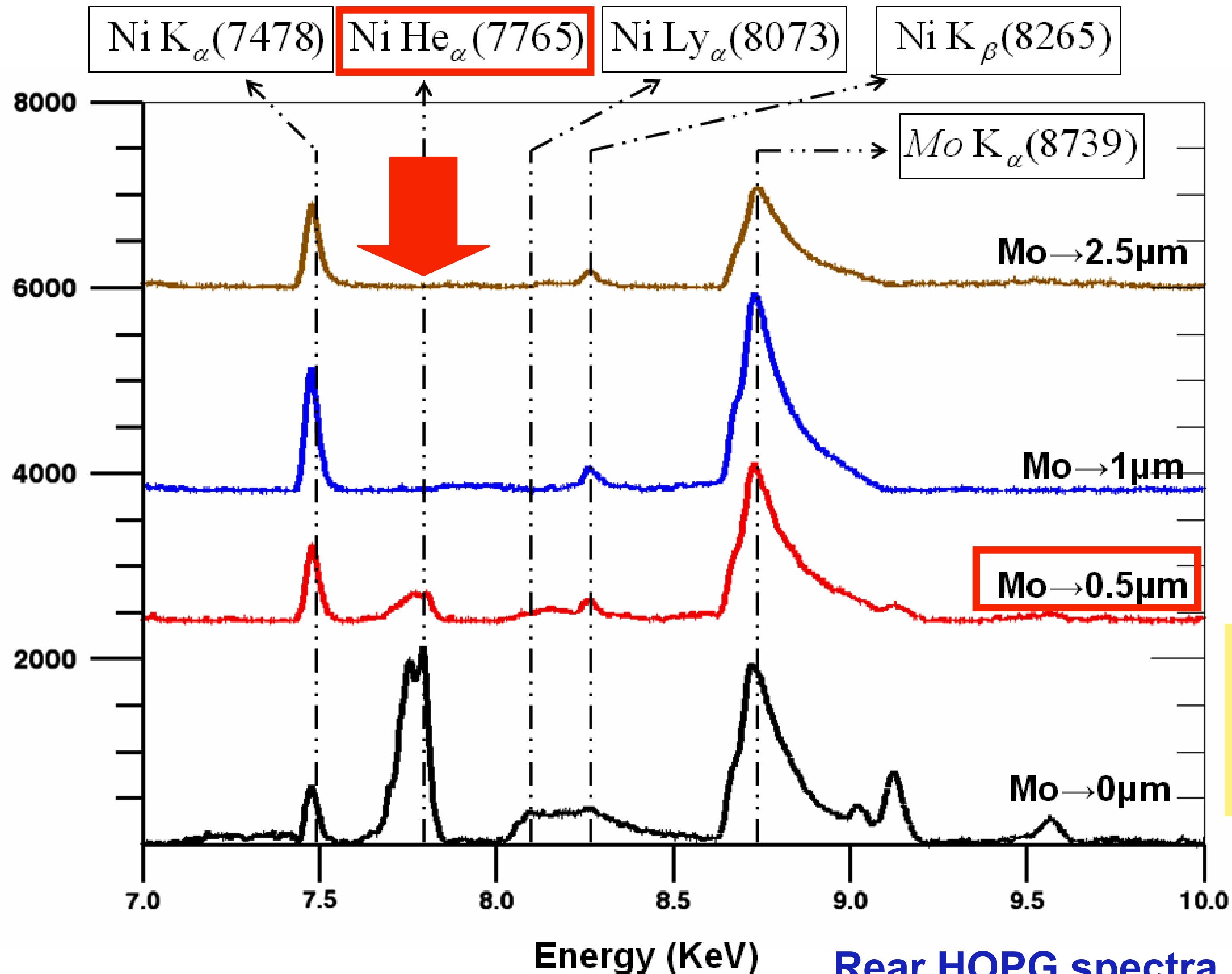
⇒ Spreading less important for larger beam diameter

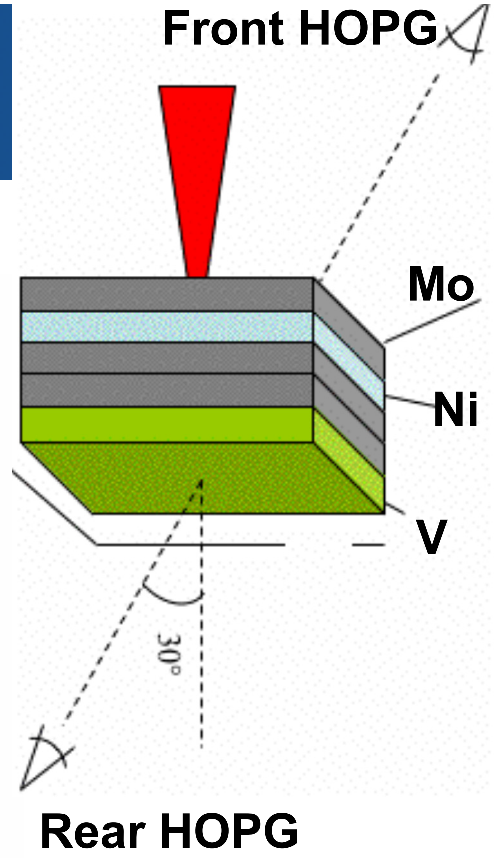
Calculated energy deposition with depth

20 μm dia e^- beam,
T_e = 5 keV,
ρ= 300 g/cc



3) K-shell spectra show super hot thin layer near laser/plasma interface



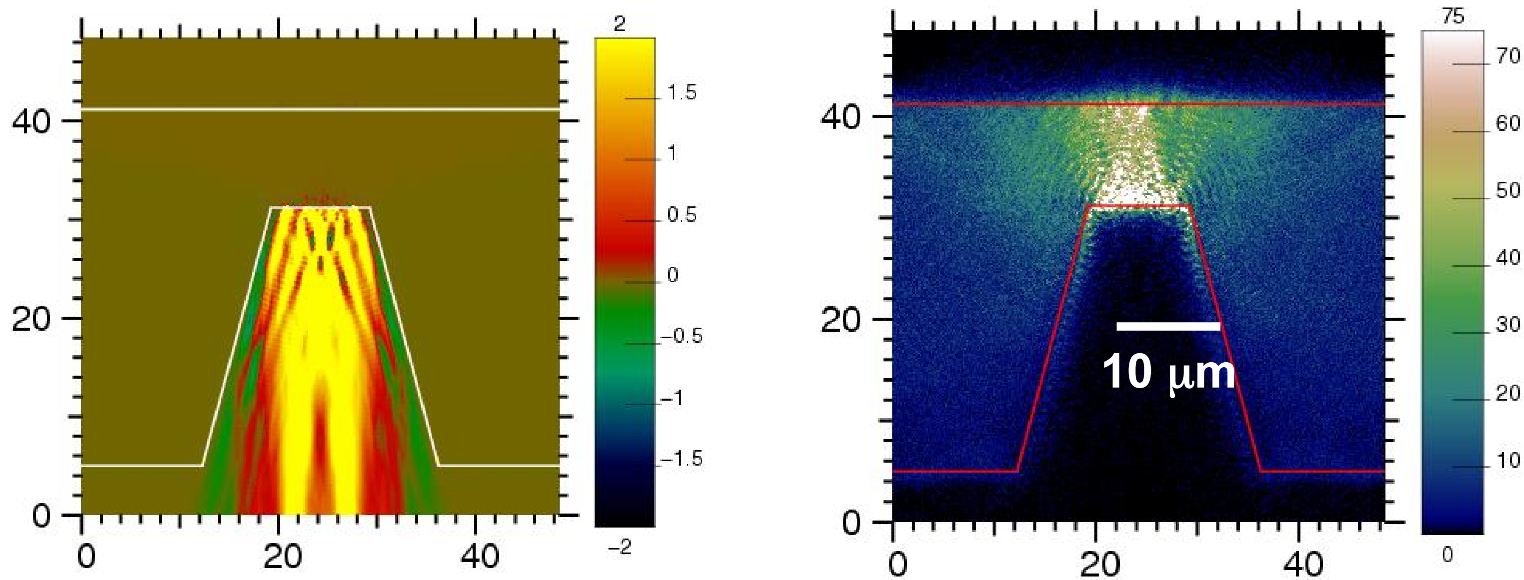


Ni Heα and Lyα disappear under >0.5µm Mo

Rear HOPG spectra

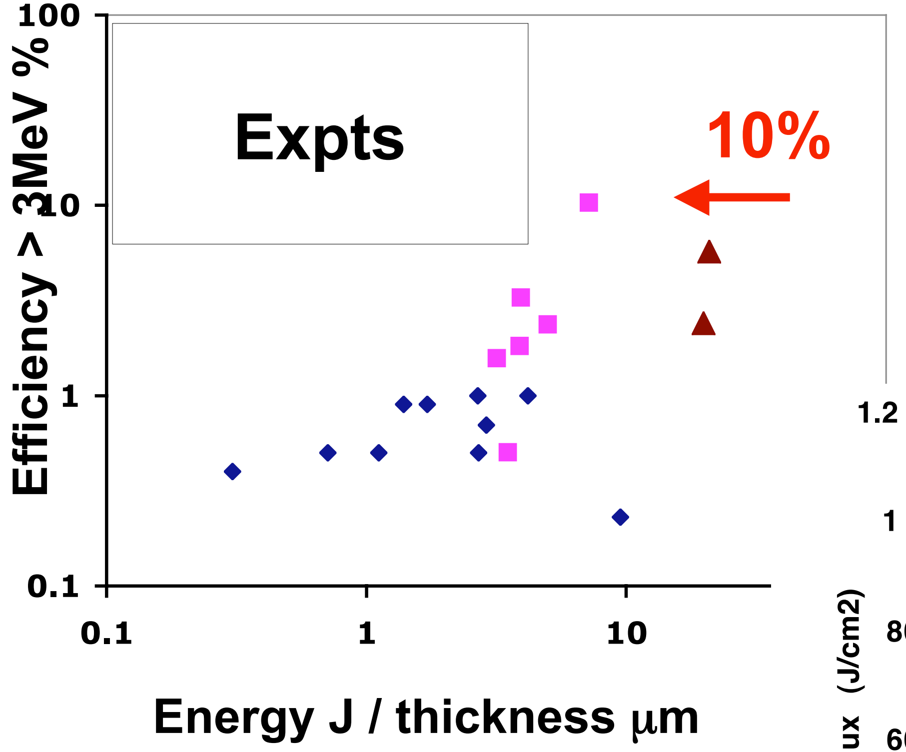
3) Cone geometry plays a role in electron production

- PIC modeling gives guidance
- Experiments with cones are difficult and expensive - current plan to use oblique target as surrogate



e.g.Interaction studies in progress e.g. using Zohar B 2D subscale model

3) Experiments and modeling suggest ways to obtain >15% laser to proton energy conversion needed for FI

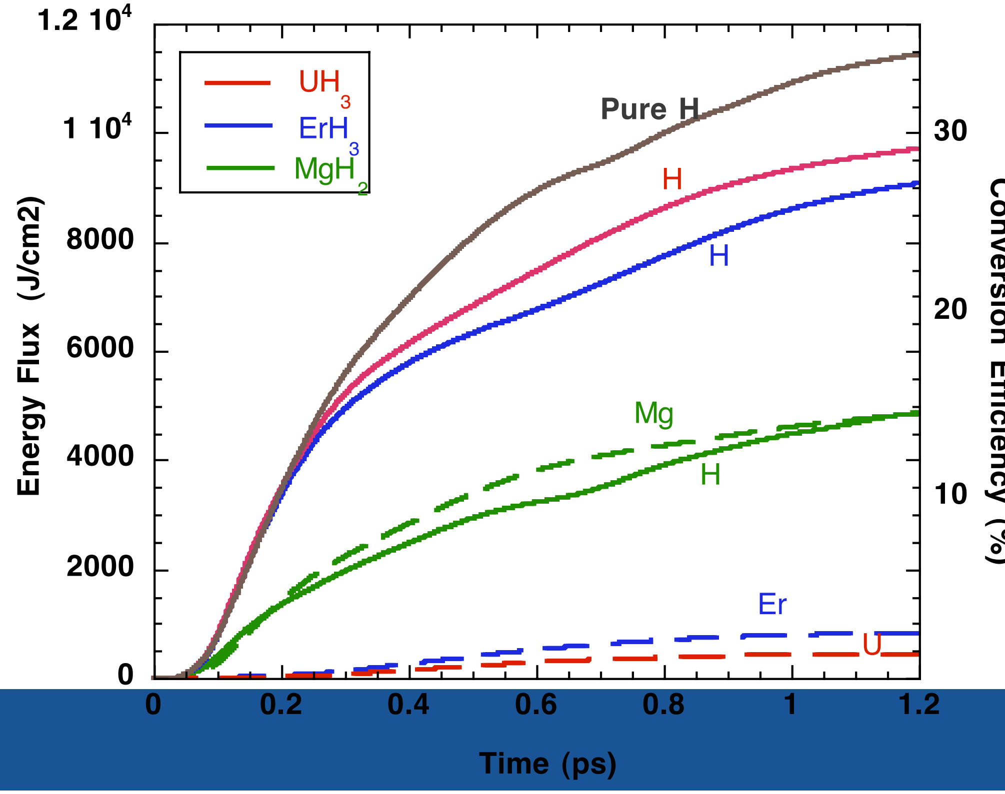


•Adsorbed layer experiment efficiency reaches 10%

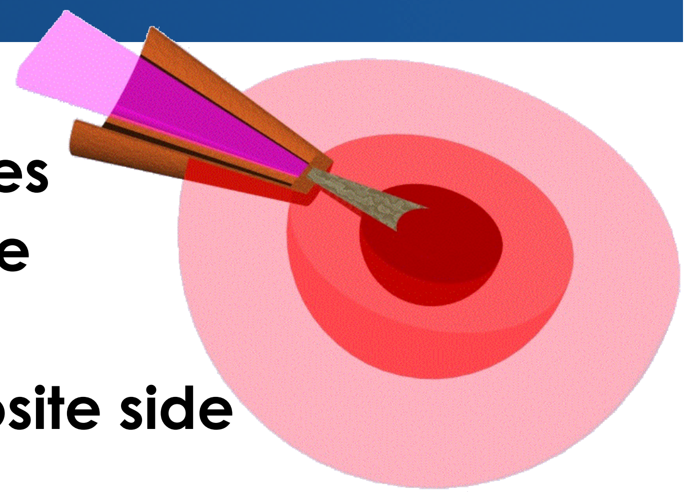
•1D LSP model shows ErH_3 hydride layer almost equiv to pure H

•Tests on Titan laser in progress

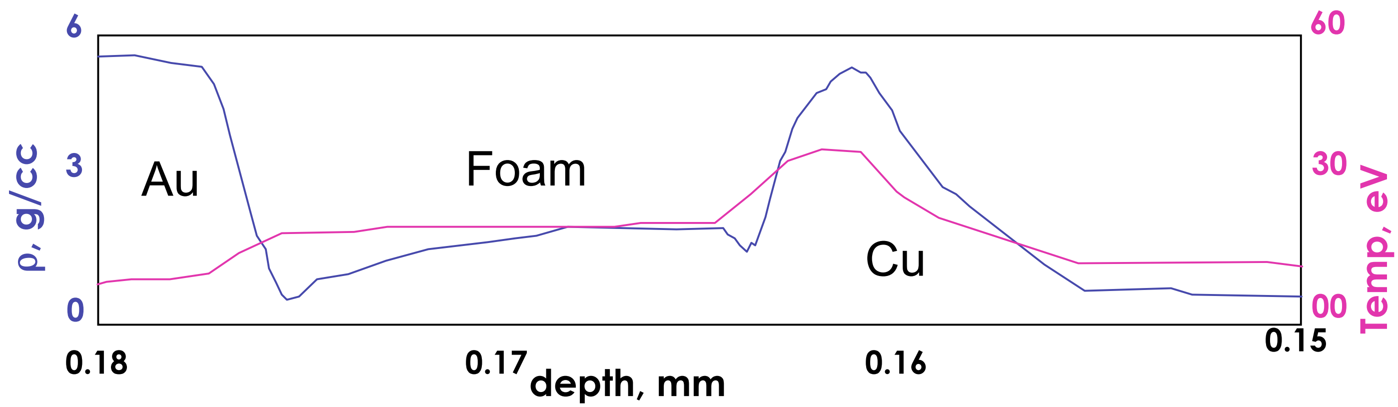
1000 Ang hydride on 5 μm Au
Thot = Edrift = 880 keV

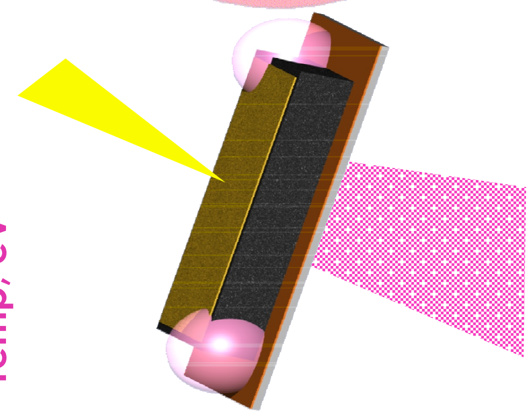


4) Shock compressed foam simulates FI cone tip



- Replace sphere and cone with flat plates
- Long pulse accelerates Al/Cu flyer plate
- Compresses foam to ~1 g/cc
- Shock wave penetrates Au foil on opposite side





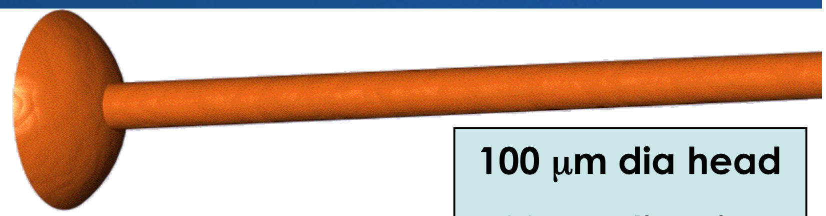
- Electrons generated in Au cross the Au/interface and are counted in Cu

Experiments underway at Titan (LLNL)

5) Comparing simulations to expt

Objective is to perform an experiment that can be accurately modeled

- **Nail target size limited by pointing accuracy and beam size**
- **Must account for modification by prepulse**
- **Heating and current flow can be compared to simulations**

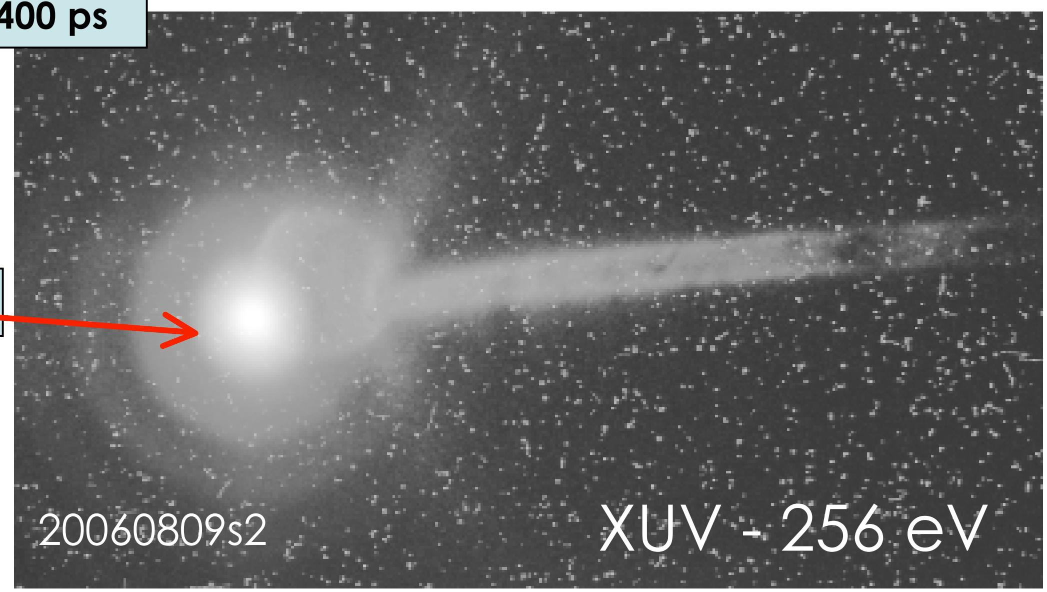


100 μm dia head

20 μm dia wire

10^{14} w/cm^2 400 ps

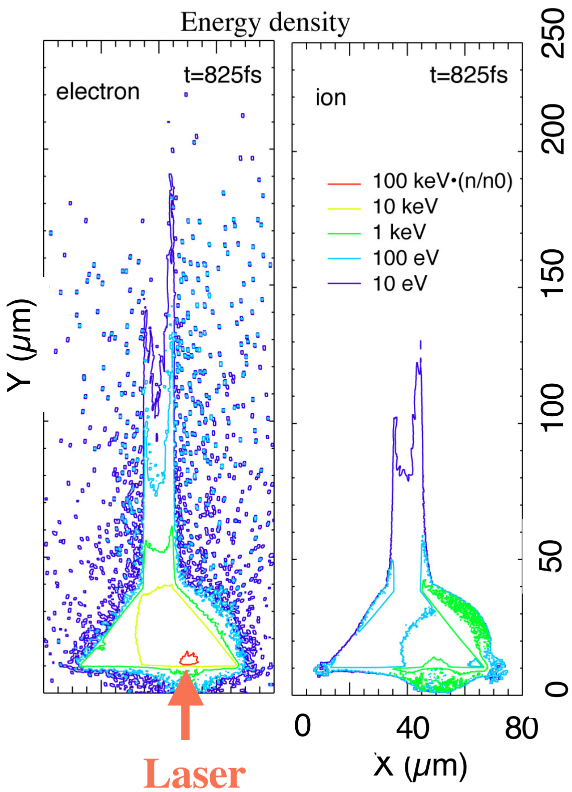
500 J, 1 ps



5) Initial simulations give differing results - work in progress

PICLS

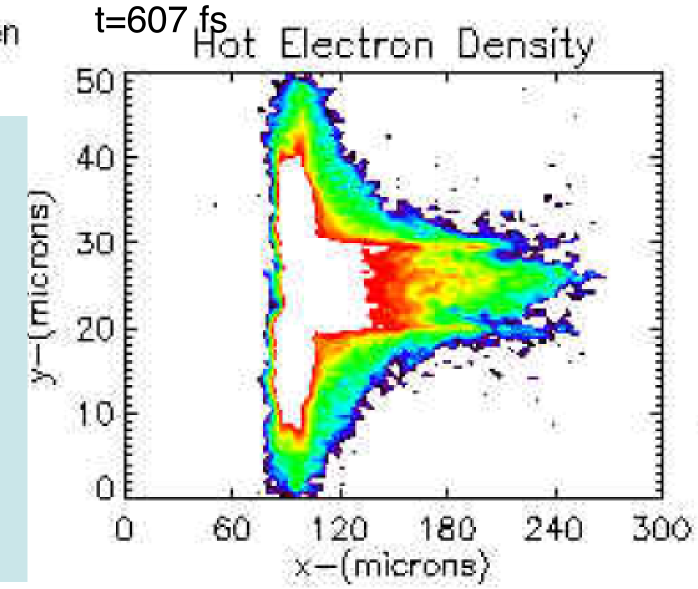
Energy Density



e-PLAS

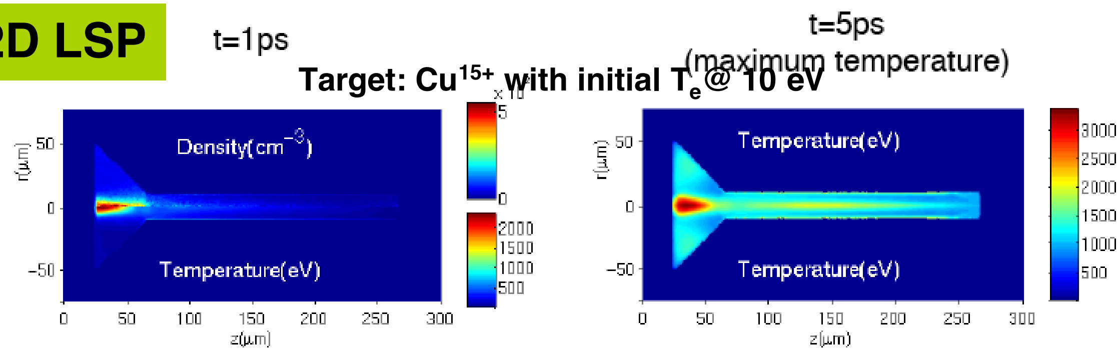
Most of hot electrons remained in the nail head (peak density:2e22 cm^{-3}).

Exponentially decay to 1e20 cm^{-3} from x=90 to 260 μm)
Some surface current flow along the wire surface.



2D LSP

Target: Cu^{15+} with initial T_e@ 10 eV



Energy localization inside the nail head.
STRONG SURFACE CURRENT ALONG THE WIRE.

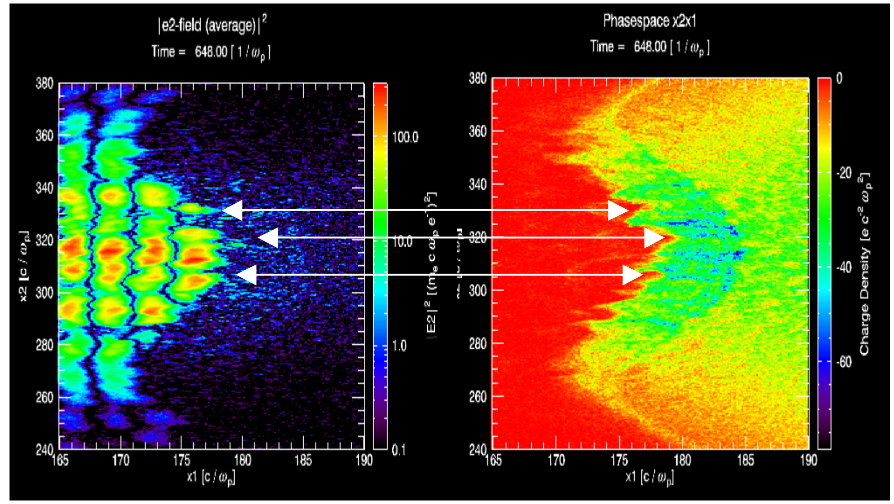
Energy localization inside the nail head
Hot electrons mainly propagating along the axis.
Some currents flow along the wire surface.

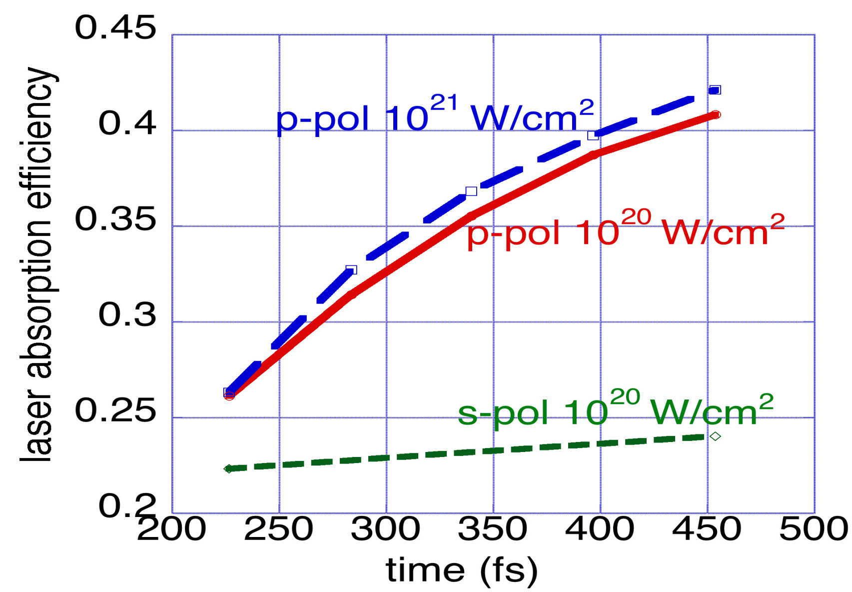
Y. Sentoku, UNR R. Mason, M.-S. Wei, UCSD, A. Solodov, LLE

6) Simulations show absorption increasing w pulse length

- **High laser intensity ripples plasma critical surface**
- **Absorption increases as critical surface ripples.**
  - Additional heating for p-pol as $E \cdot \nabla n \neq 0$
- **Electron current increases with time**

⇒ **Improved coupling for the 10s of ps needed for fast ignition**





Summary

- **Multi-institutional research team has been formed and is working well**
- **“ignition” approaches include**
  - Electron driven
  - Proton driven
  - High velocity impact
  - shock
- **Present experiments are limited**
  - Current facilities allow generation of small hot plasmas
  - New diagnostics are being developed
- **Research is focused on evaluation of “component” phenomena with combined experiments and simulation**

- **An integrated evaluation of FI awaits facilities nearing completion**
  - Integrated code packages
  - Integrated experiments
  - Target fab