Fast Ignition Review

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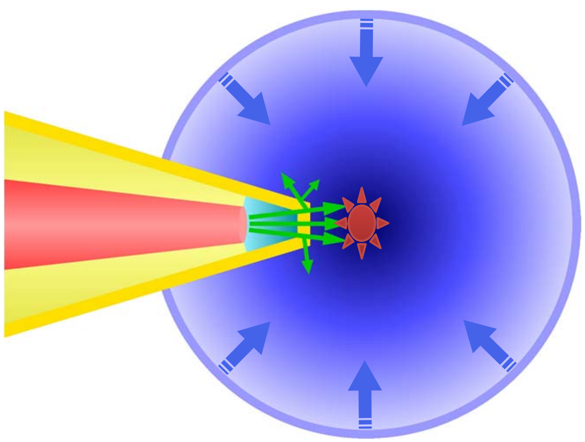

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Fast Ignition Review

I. Promise of Fast Ignition (FI)

II. The Reality of FI: Issues

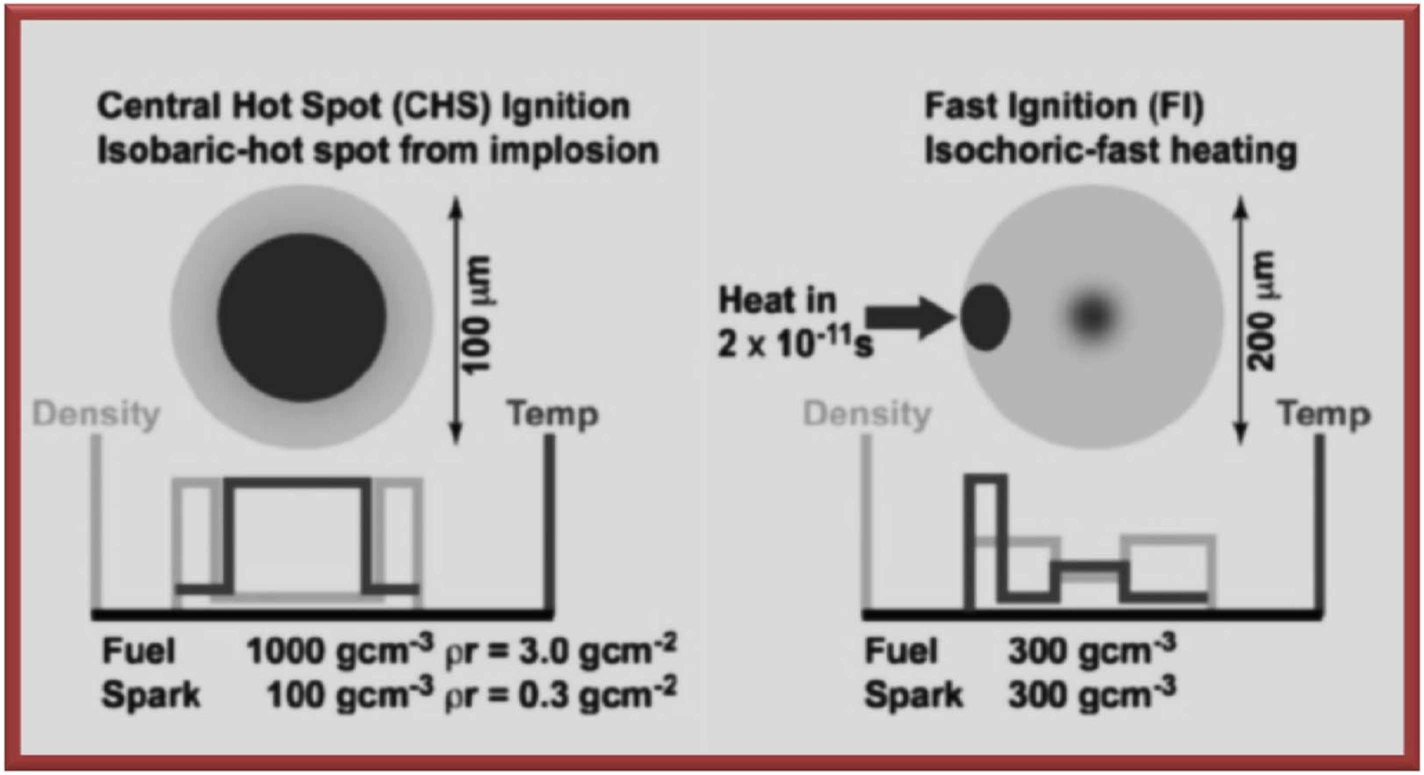
III. Focused Efforts on Issues Yield Progress

IV. Current Aggressive Efforts on Divergence

V. Forward Leaning: Plans, Milestones, Metrics

VI. Summary & Conclusions

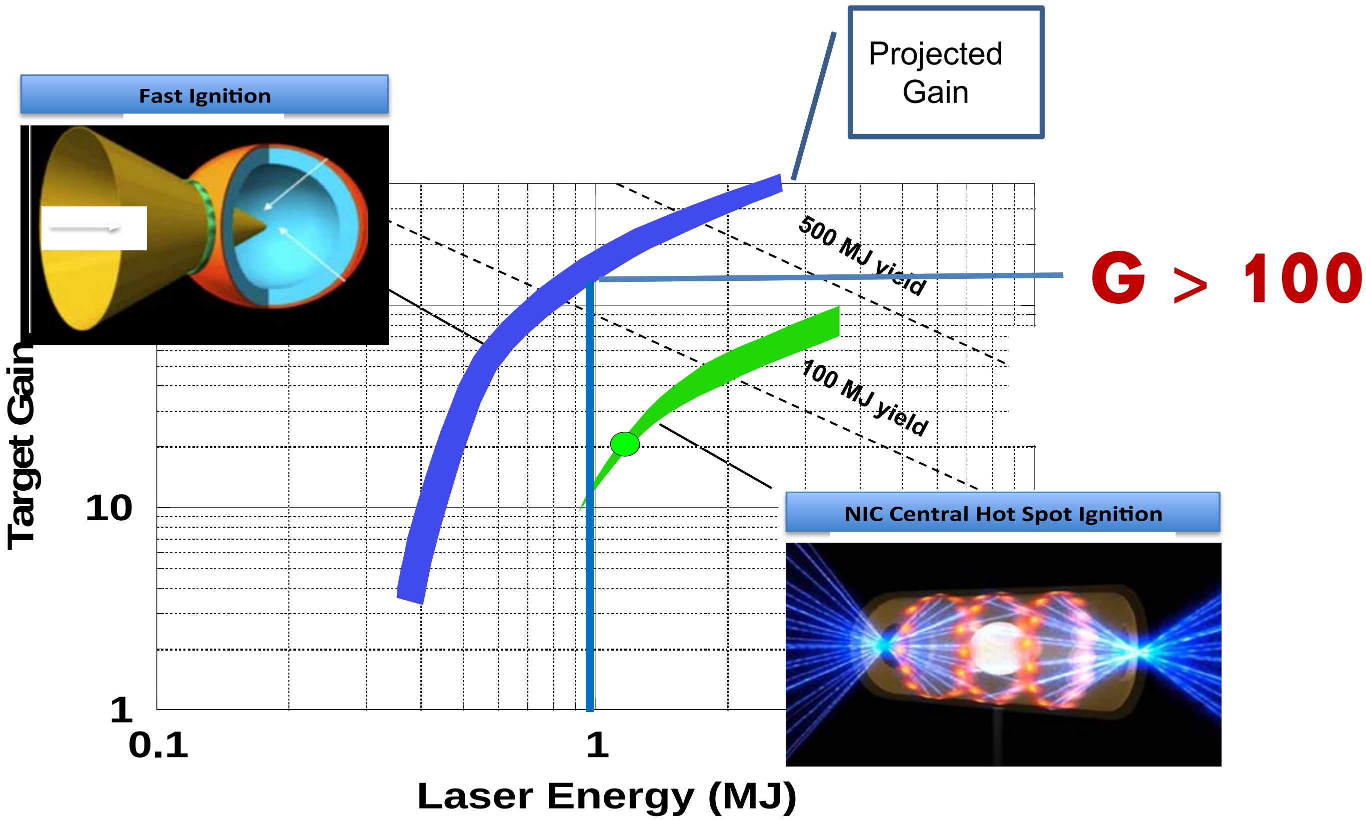
"CHS" vs "FI"



Central Hot Spot (CHS) Ignition
Isobaric-hot spot from implosion
100 μm
Density
Temp
Fuel 1000 gcm-3 ρr = 3.0 gcm-2
Spark 100 gcm-3 ρr = 0.3 gcm-2
Fast Ignition (FI)
Isochoric-fast heating
Heat in
2 x 10-11s
200 μm
Density
Temp
Fuel 300 gcm-3
Spark 300 gcm-3

FI Potentially Has Advantages over CHS

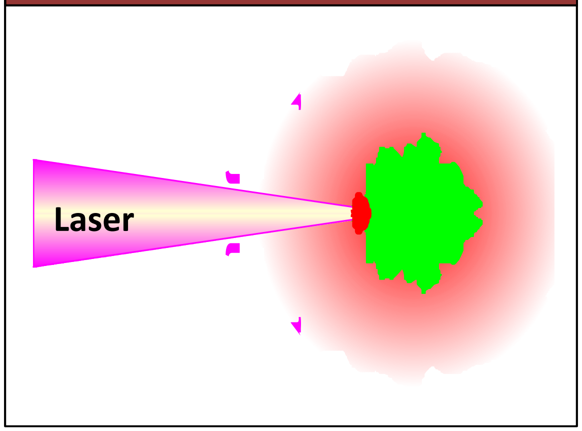
FI is conceived as a "2nd Generation Scheme" for ICE



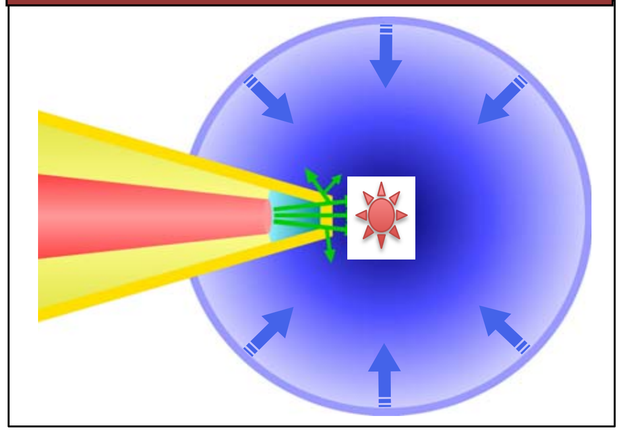
A Gain ~100 at a compression energy of 1MJ is ideal for IFE

Ignition Schemes in FI

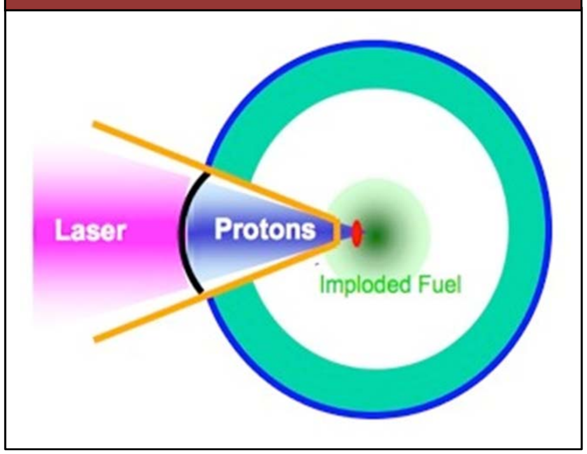
Electrons (hole-boring)



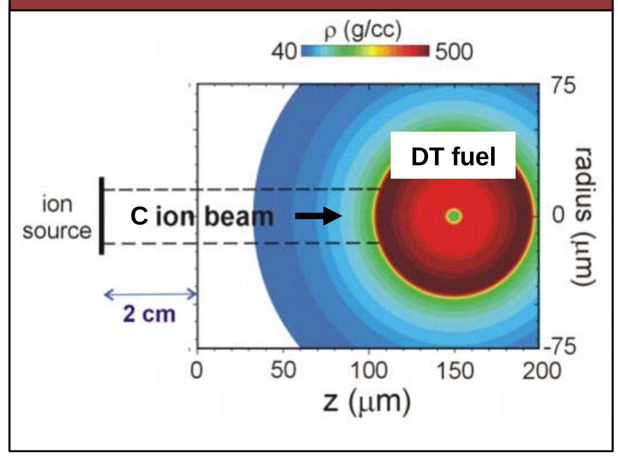
Electrons (cone-guided)



Protons



Ions

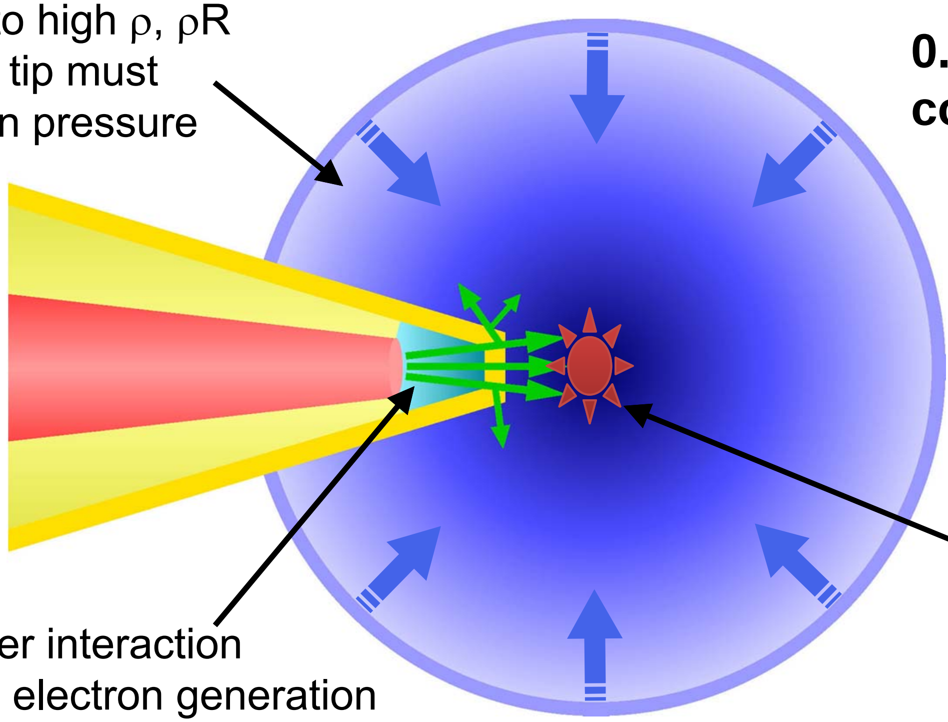


Principle Steps in Cone- Guided FI

1. Compress DT fuel to high ρ, ρR around cone tip; cone tip must survive Gbar implosion pressure

0.5-1.5 MJ, 20ns compression drive

100-200 kJ, 20 ps ignitor pulse



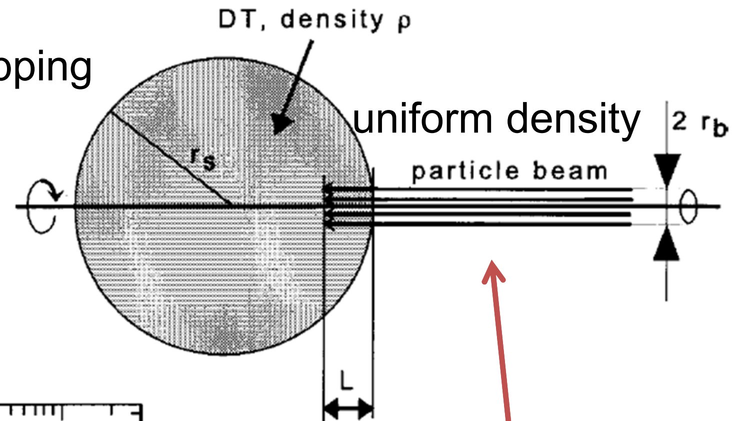
3. Relativistic electron transport in HED plasmas; collective transport, filamentation, core heating & burn

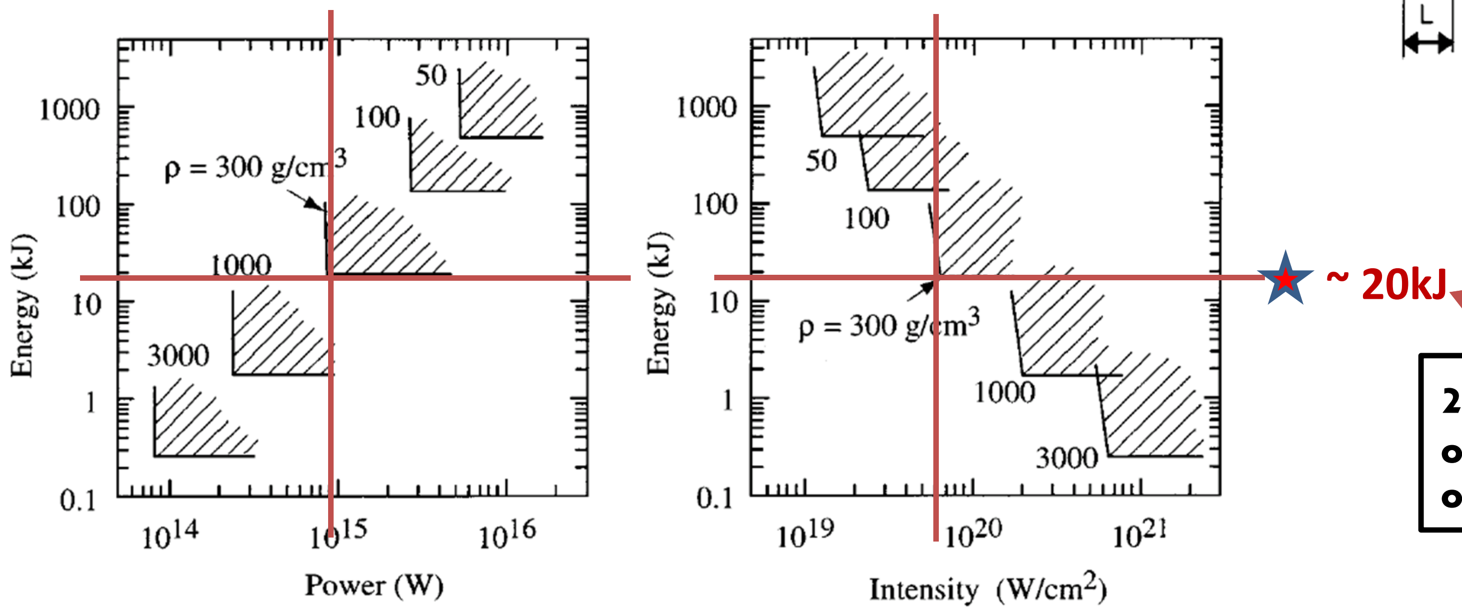
2. Relativistic laser interaction ($I>10^{20}$ W/cm^2) & electron generation

No code capability currently exists that can model this physics self-consistently; FI program is developing ability to link codes

Min. Ignition Energies (Atzeni 1999)

- Ignition requirement is ρr_h <1.2g/cm^2, $T_h \geq 12$ keV
- **Parallel beam of particles** with constant stopping power and range are injected into DT sphere
- Pulse Length Required: ~20 psec (@300g/cm^3)

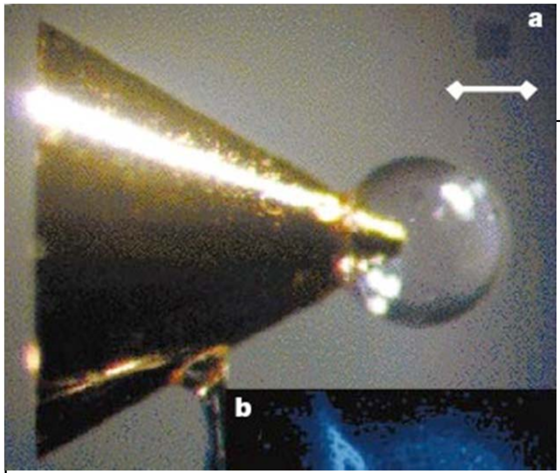
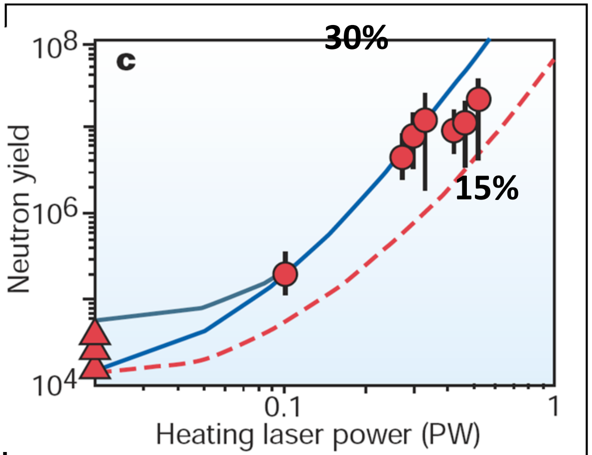




20 kJ Ignition depends on this spatial input of energy

First Hot Electron Yield Enhancement

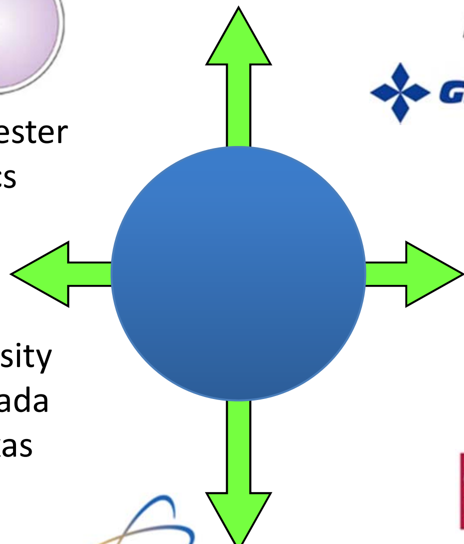
Gekko XII (2002)

Gekko XII Laser Facility	CD shell + Au cone	Neutron yield
		
❑ 2.5 kJ, 1.2 ns flat top pulse, 2ω compression ❑ 350 J, 0.5 ps ignitor pulse	❑ 7 μm CD shell, 500 μm diameter ❑ Imploded core reaches ~ 50-100 g/cm^3 and 30-50 μm diameter	❑ 1000x increase in neutron yield with ignitor pulse ❑ Temp increase from 400 eV to 800 eV

Many Active FI Programs World-wide

US FI Programs

Electron FI



University of Rochester
General Atomics
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MIT
UCSD
Ohio State University
University of Nevada
University of Texas
ILSA
LLNL

Intl. FI Programs

Rutherford Appleton Lab
LULI
Universita di Roma
Imperial College, UK
University of York, UK
Queens Univ., Belfast
CEA, France
IST, Lisbon
UPM, Madrid, …

ILE, Osaka University

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Reality of FI: Issues

Issues:

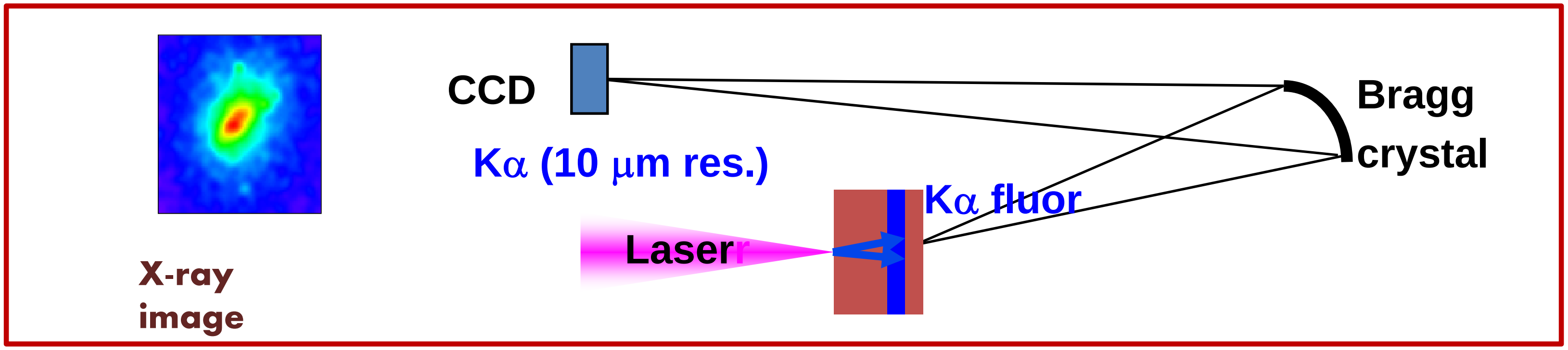
❖SCIENTIFIC

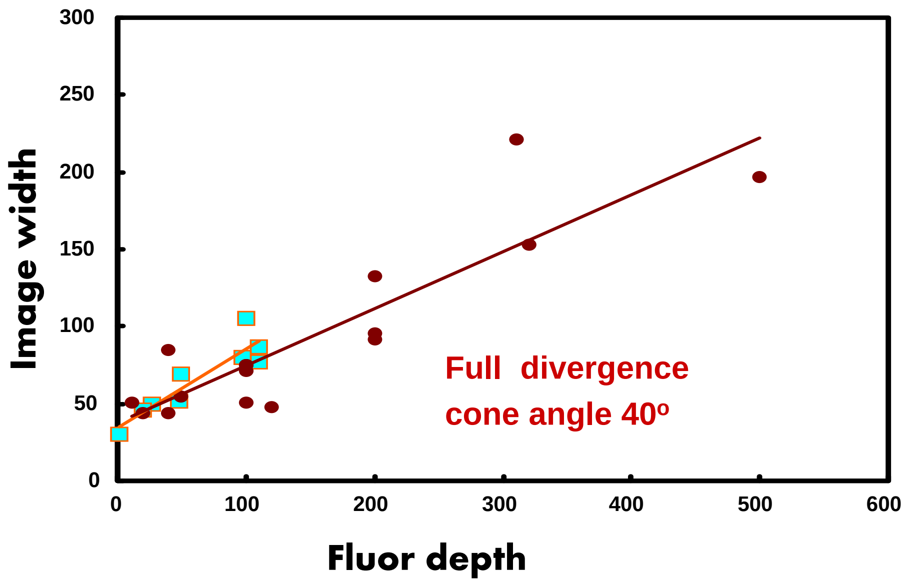
- Divergence of hot electrons
- Compression of Target with Cone

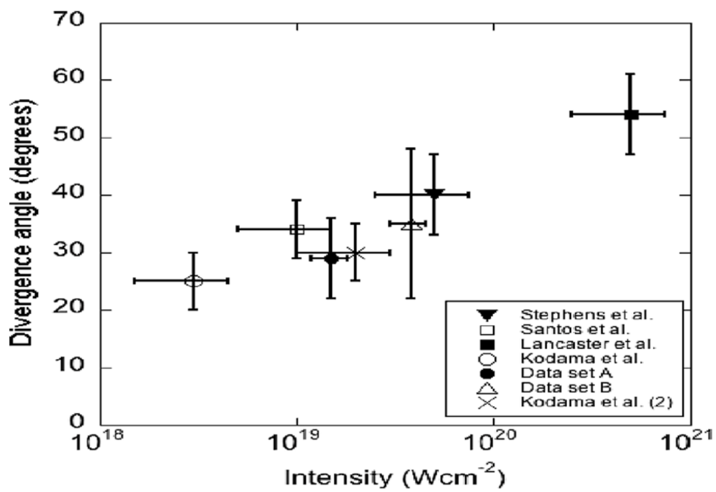
❖TECHNOLOGY

- Facilities
- Target Fabrication
- Ignition Laser Driver

Science Issue: Electron Divergence







Divergence depends weakly on Intensity

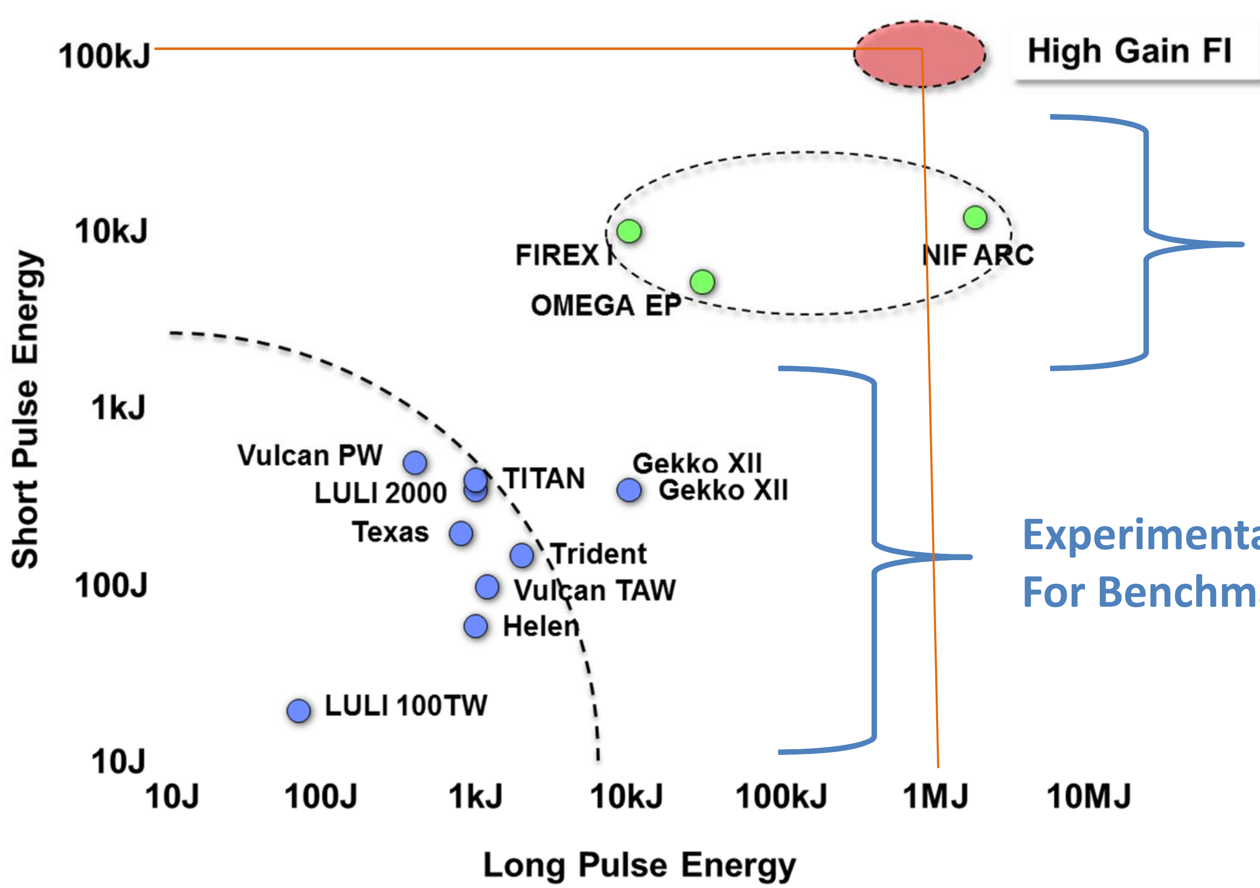
Full Scale FI Modeling shows large angles

PIC LPI followed by hybrid charge transport calculations predict that the average divergence angle in hot DT is 52^0:

Because of this large divergence, the "point design" is pushed towards having the hot electron source as close to the compressed core as possible. Under any reasonable cone-core offset scenario, the modeling result is that the ignition energy required jumps from ~20kJ for collimated electrons to well over 200kJ.

As we discuss below, control of the hot electron divergence is the major physics and technology issue confronting FI

Technology Issue: Facilities

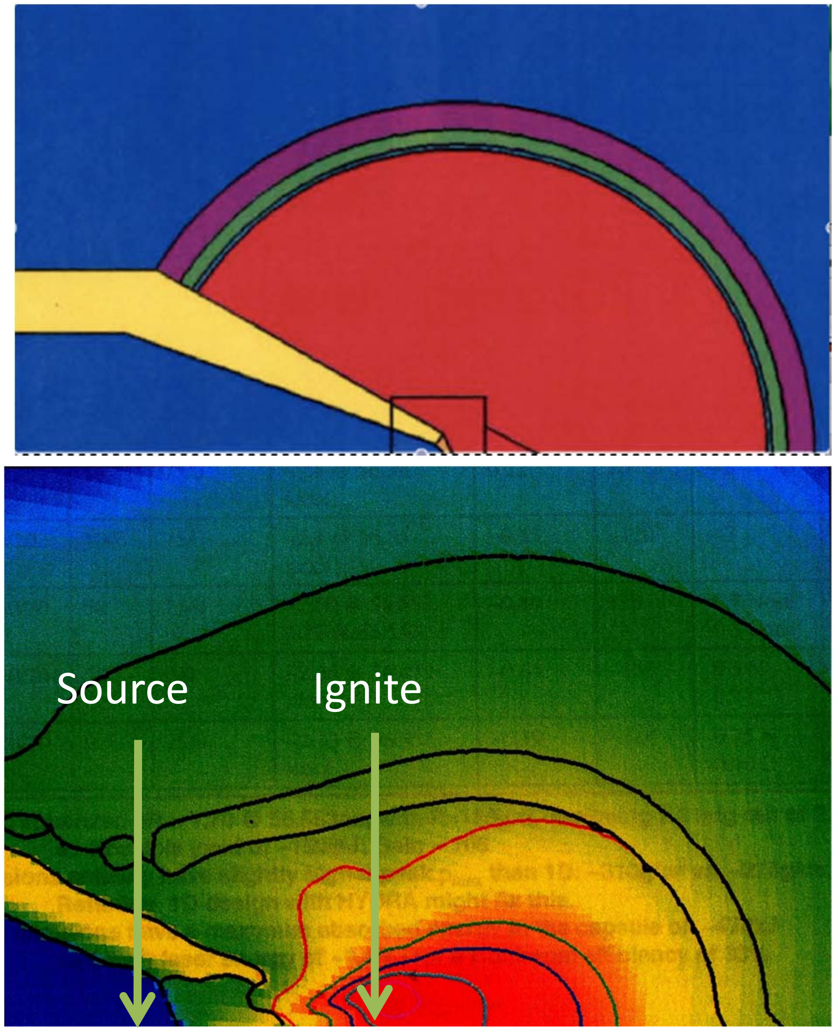


1 MJ Compression
100 kJ Ignition

Sub-Ignition
Experimental
Facilities

Experimental Facilities
For Benchmarking Codes

Science Issue: 2D Hydro Design



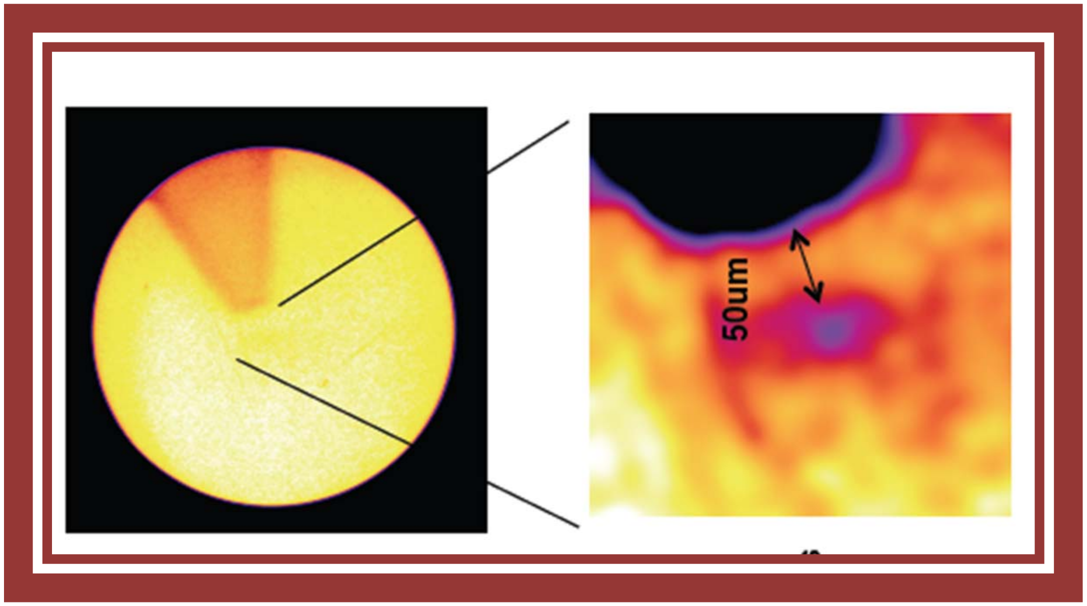
INDIRECT DRIVE

- **DT mass = 2.75 mg**
- **Peak density 310 g/cc**
- **Drive 1.4 MJ**
- **Gain =106**
- **Stand off 110 μ of cone tip from core**

Science Issue: Cone Target Compression

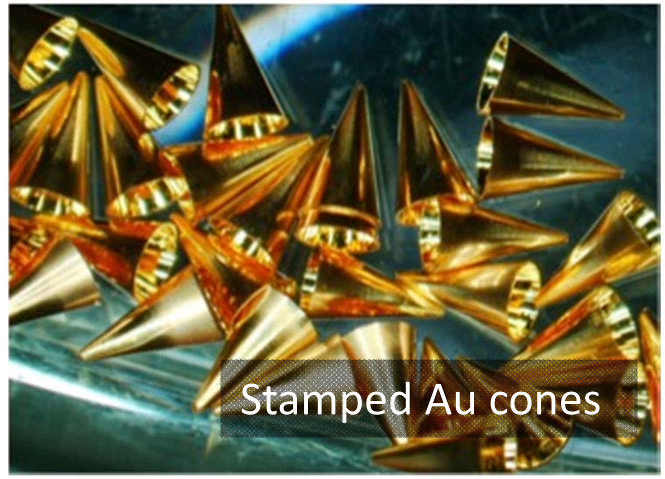
OMEGA-EP BACKLIT IMPLOSION

- **EP-Backlight Compton Radiography @ 100 keV**
- **Empty CD Shell, 40μ thick**
- **Reentrant Cu Cone**
- **$\rho R \sim 180 mg/cm^2$**

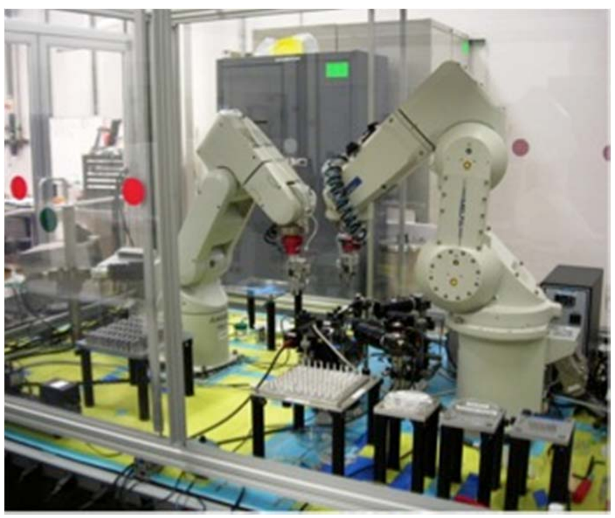


Technology Issue: Cones (current GA)

- **High Z metal parts**
- **Foam-lined plastic shells**
- **Robotic assembly**
- **LIFE (indirect drive) targets: costed @$0.30/target delivered**


Stamped Au cones


4 mm dia foam DVB shells




Cone shell targets assembled with ±10 um accuracy

Technology Issue: Ignition Laser

Full Scale short-pulse laser driver

- ***Energy TBD (at least 100kJ)***
- ***Pulse Length 20psec***
- ***Possible 2w conversion***
- ***High Contrast ratio***
- ***Wall-Plug Efficiency***

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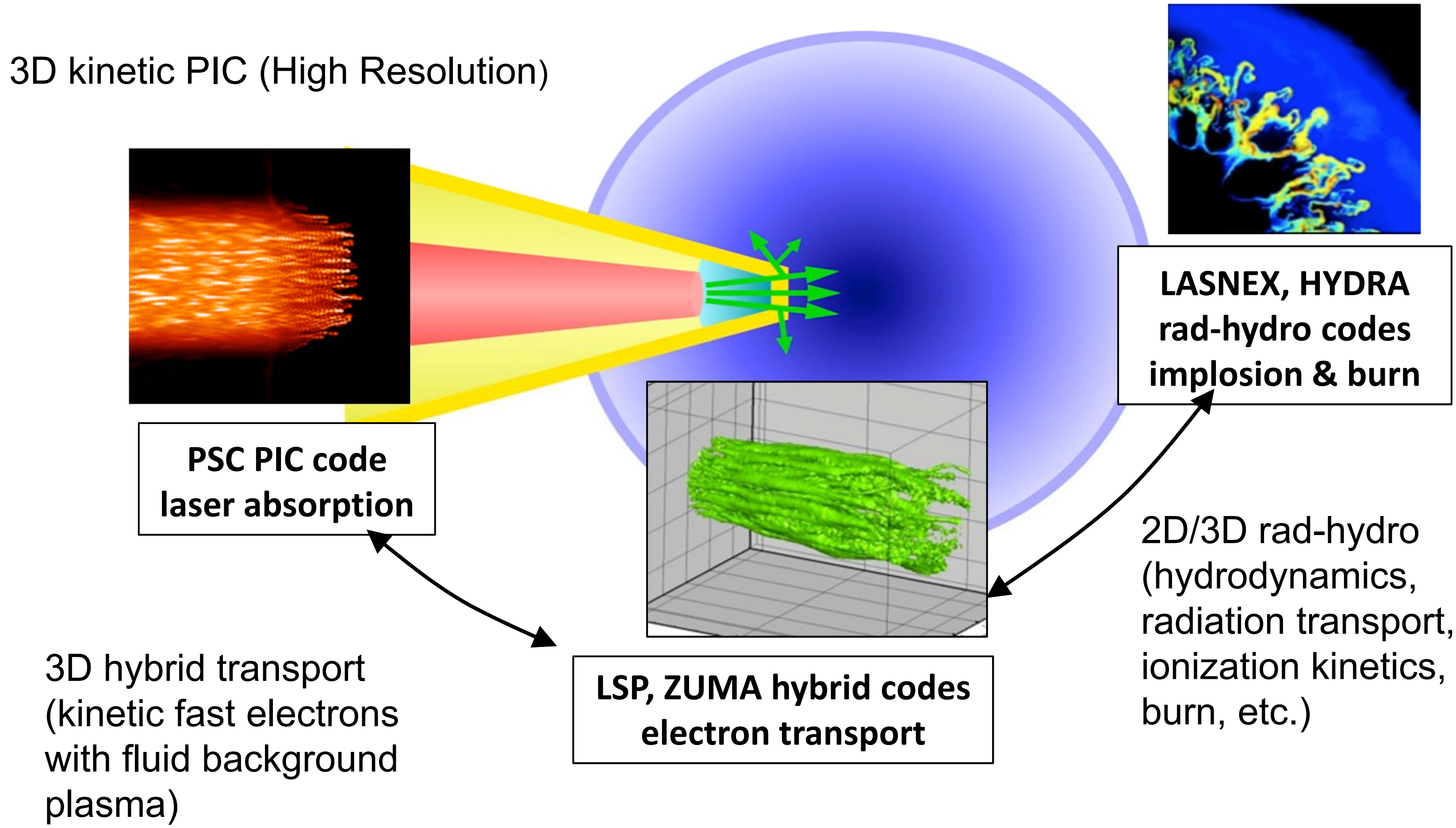
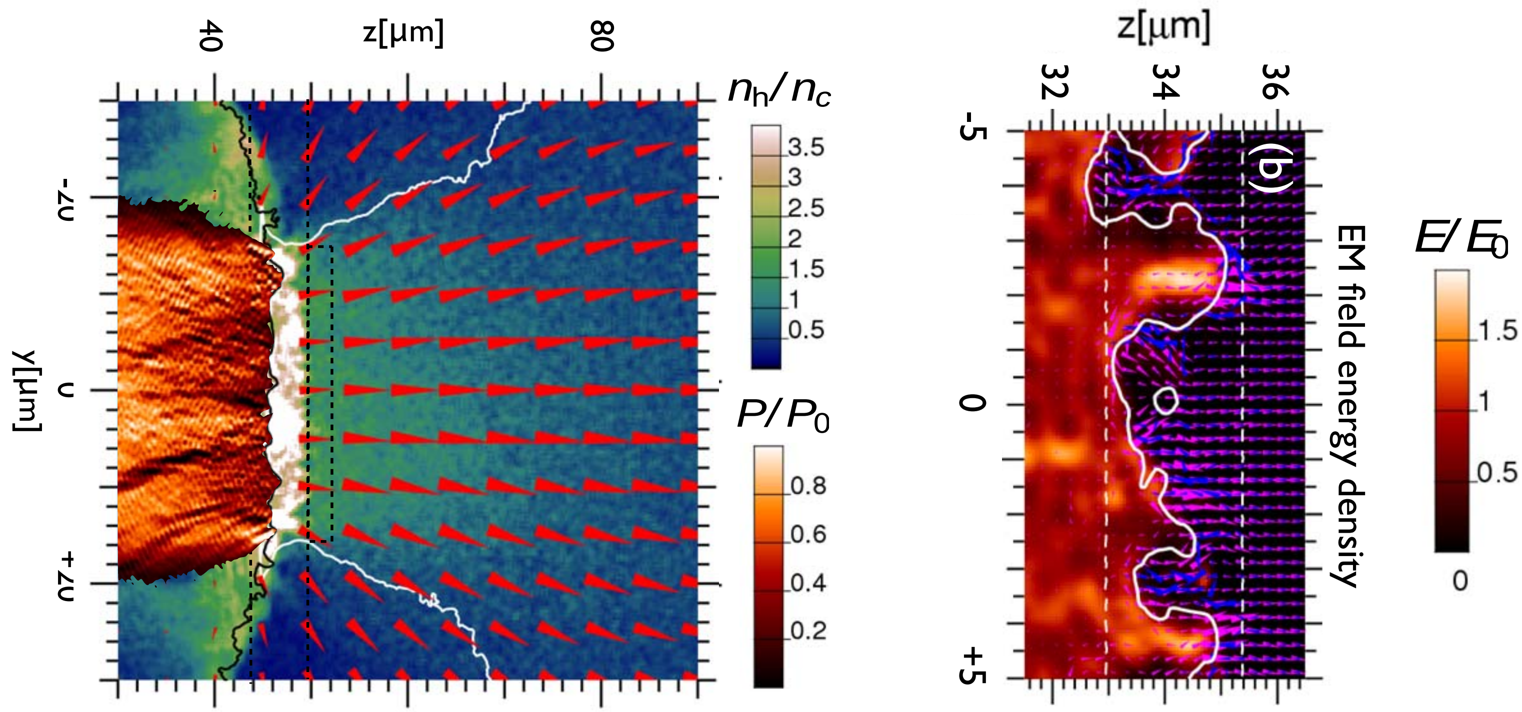
Focused Efforts: Advanced Modeling



Focused Efforts: Advanced Modeling

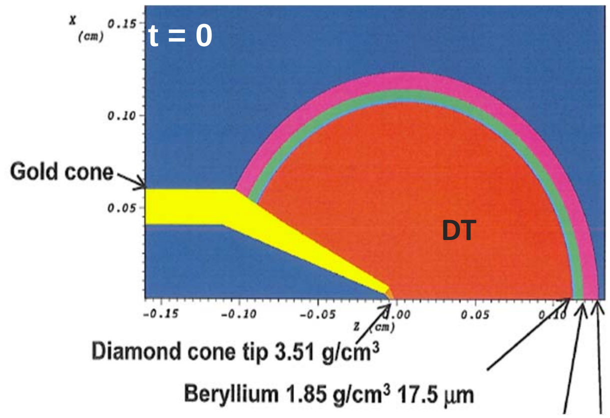
- 200kcpu-h @2048 cpus on ATLAS
- Simulate 40 μm diameter laser pulse for 2 ps duration
- I=1.4x10^{20} W/cm^2, 120x160 μm box, 50 cells/μm, 32e+32i ppc

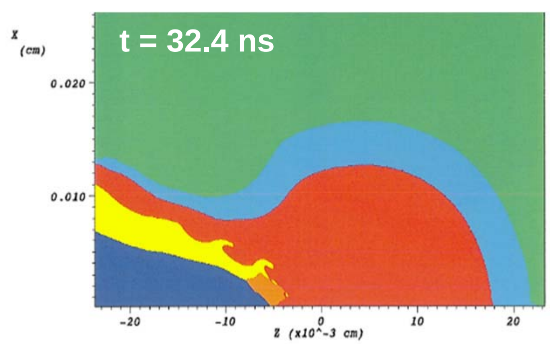


- These simulations provide the first realistic electron source distributions for subsequent transport calculations

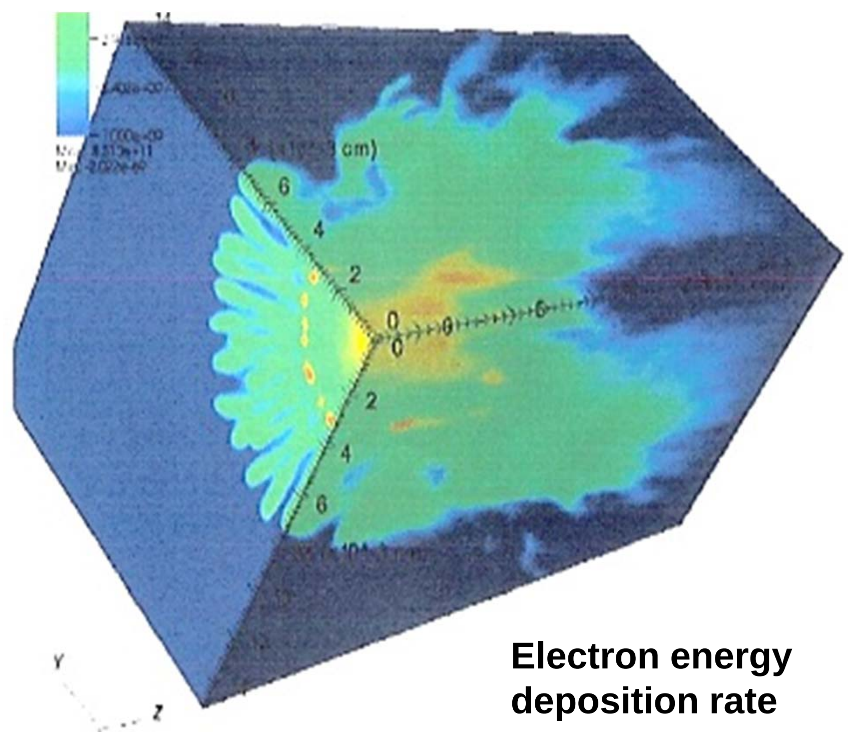
Focused Efforts: Advanced Modeling

- 3D simulation initialized with axisymmetric profiles at beginning of electron pulse
- 47.7 million zones in HYDRA mesh with 100 million IMC photons run on 1024 processors
- 36 millions zones in Zuma mesh – 1 µm resolution on each mesh



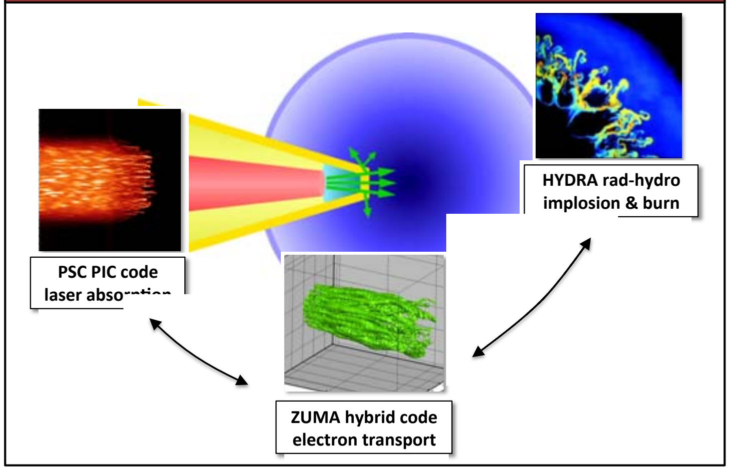


Fully integrated 2D/3D capsule implosion, core heating and burn simulations

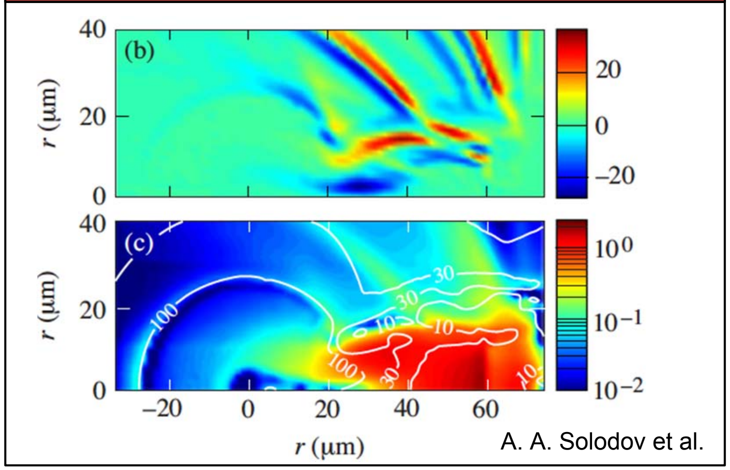


Many Groups Contribute to Modeling

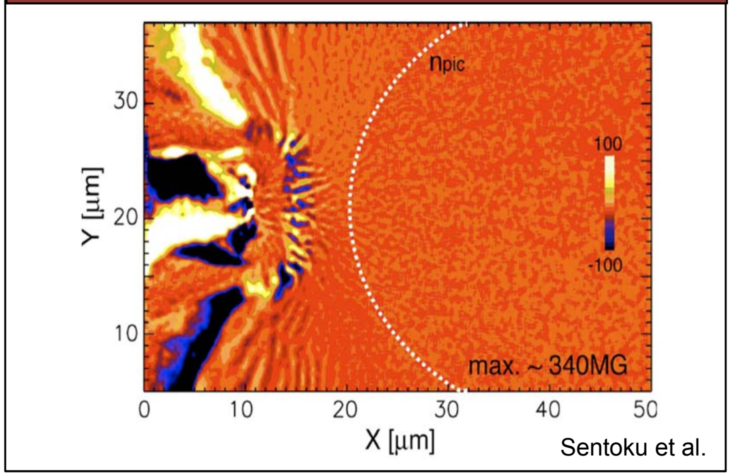
PSC-ZUMA-HYDRA (LLNL)



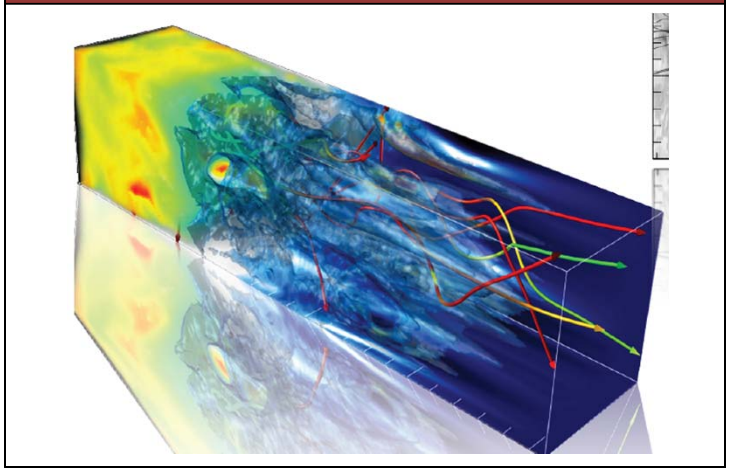
LSP (Voss, LLE, OSU, UCSD)



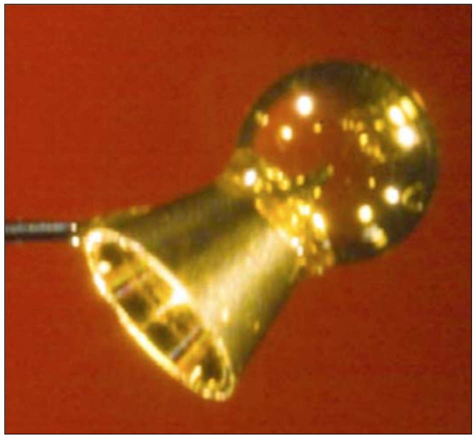
PICLS (UNR,Reno)

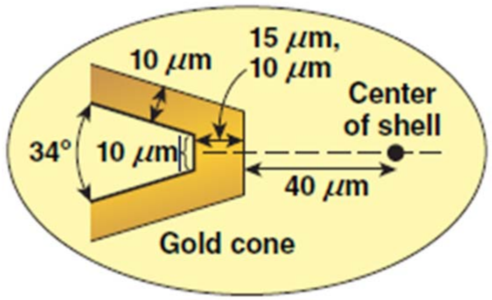


OSIRIS (ULCA/IST)



Fast Electron Core Heating at OMEGA EP

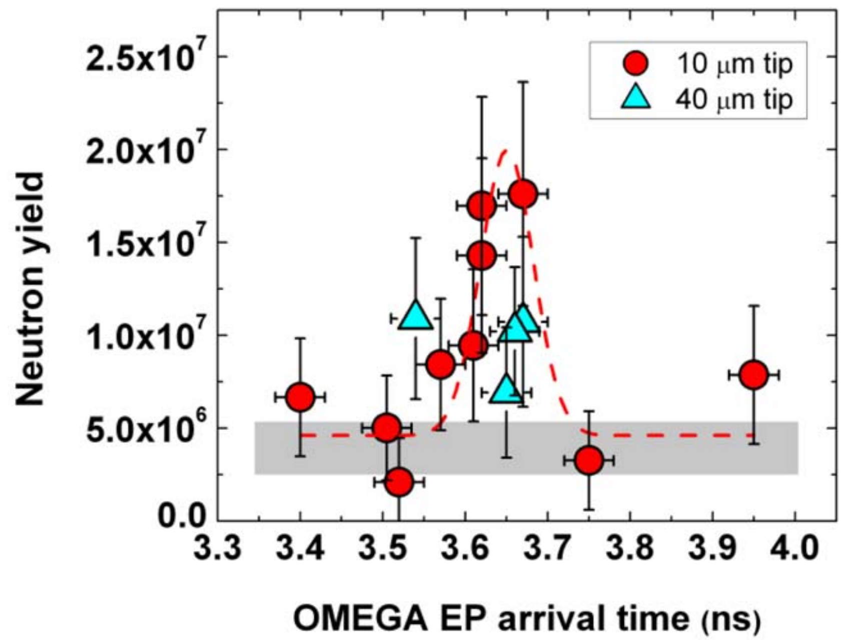




Shell material	CD
Shell diameter	~870 μm
Shell thickness	~40 μm

Implosion

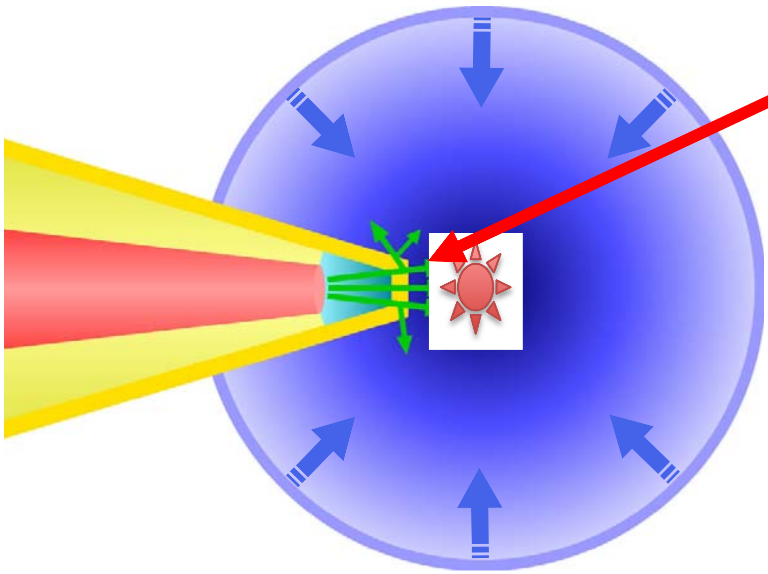
Energy	~20 kJ (54 beams)
Wavelength	351 nm
Pulse shape	Low-adiabat, $\alpha \approx 1.5$
Pulse duration	~3 ns
Implosion velocity	~2×10^7 cm/s



Demonstration of fast electron core heating under well understood conditions

Fast Ignition Review

Control of Hot Electron Divergence



Whether fast electron FI is viable depends on what happens to the hot electrons in this region

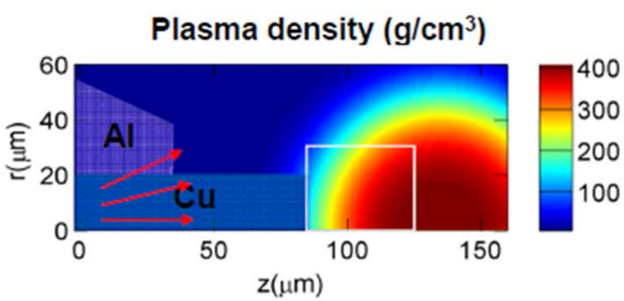
If they leave the cone tip collimated, a point design with ignition energies <100kJ Is likely

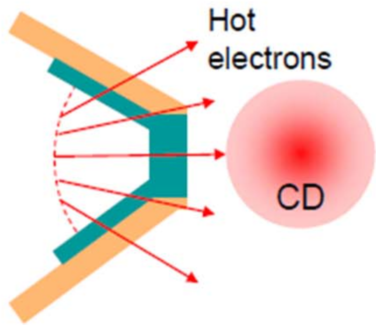
If they leave the cone tip spread into 2π NO reasonable point design is possible

TWO DIRECTIONS FOR MODELING AND DESIGN:

- External Magnetic Fields
- Self-generated Resistive Magnetic Fields

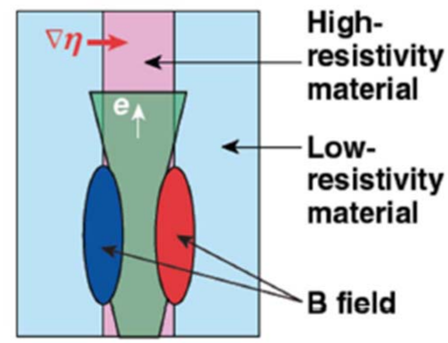
Divergence: Applied B Fields

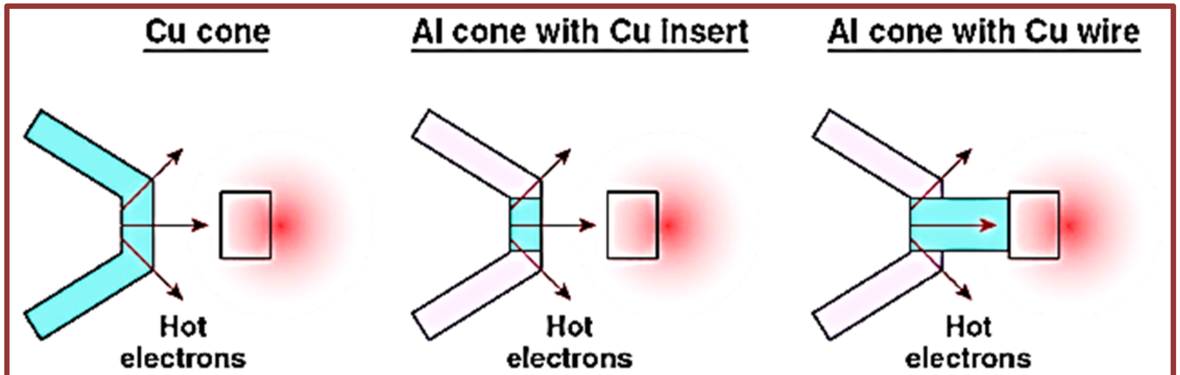




$$\frac{\partial \vec{B}}{\partial t} = \eta \nabla \times \vec{j}_h + \boxed{\nabla \eta \times \vec{j}_h}$$

Electron collimation by B fields generated by resistivity gradients*





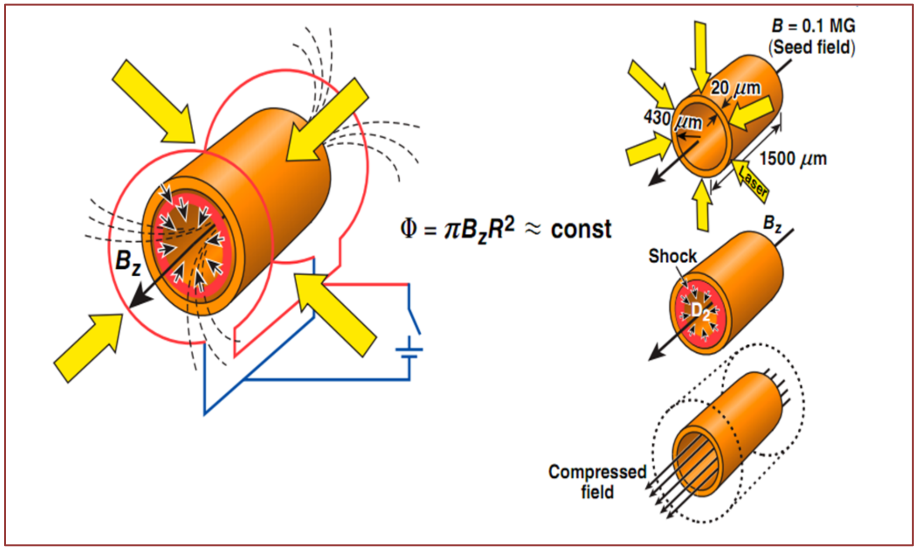
Energy coupled to the "ignition region"		
2.7 kJ (7%)	4.5 kJ (11%)	18 kJ (45%)

Energy of Input Electrons = 40 kJ

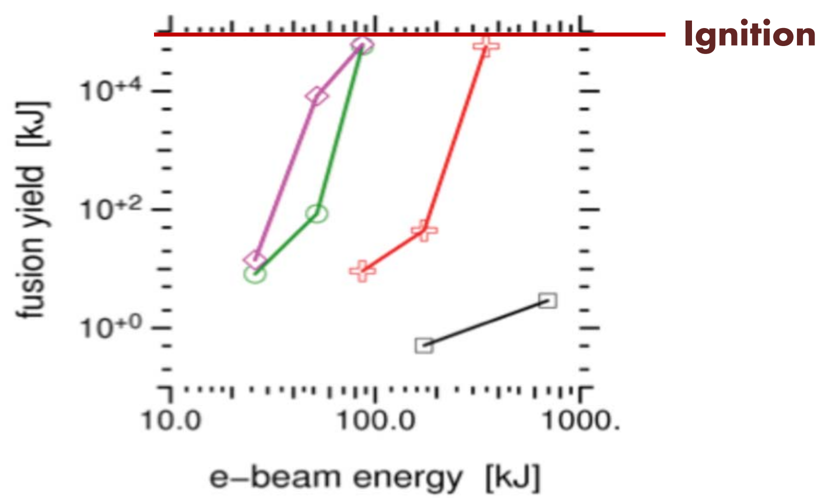
Divergence: Applied B Fields

External magnetic field amplified by compression

$$\boxed{B_{final} = B_{seed}\,(R_{initial}/R_{final})^2}$$



Place target in seed field of 0.05 MG; during implosion the core will effectively compress the field region by ~30 yielding B during hot electron transport ~50 MG

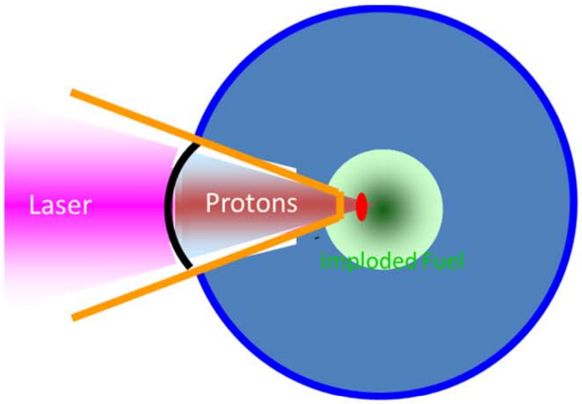


Color	Bz0 [MG]
Black	0
Red	10
Green	30
Magenta	50

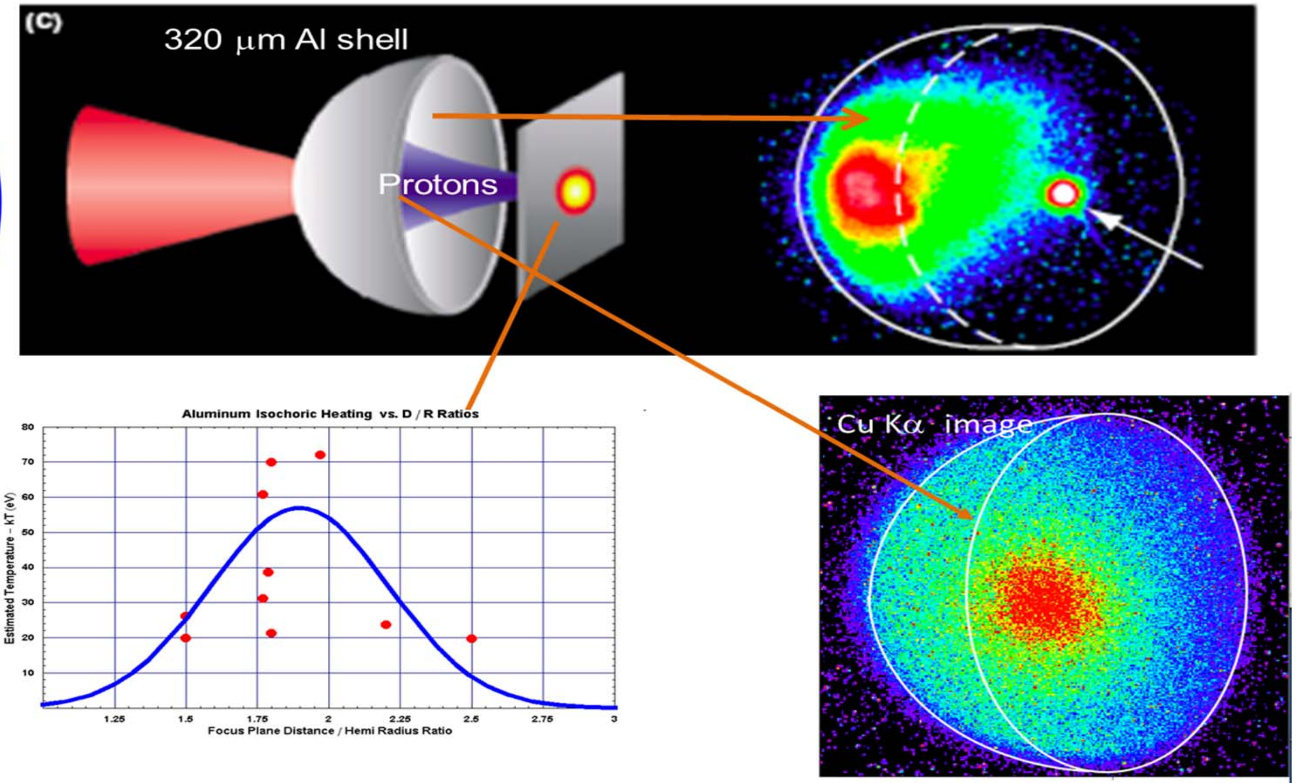
48 micron spot at 0.53 μm on 450 g/cc >Atzeni opt. 27 μm

If details of $B_{initial}$ configuration can be worked out, FI at 100 kJ appears possible

Proton FI Concept

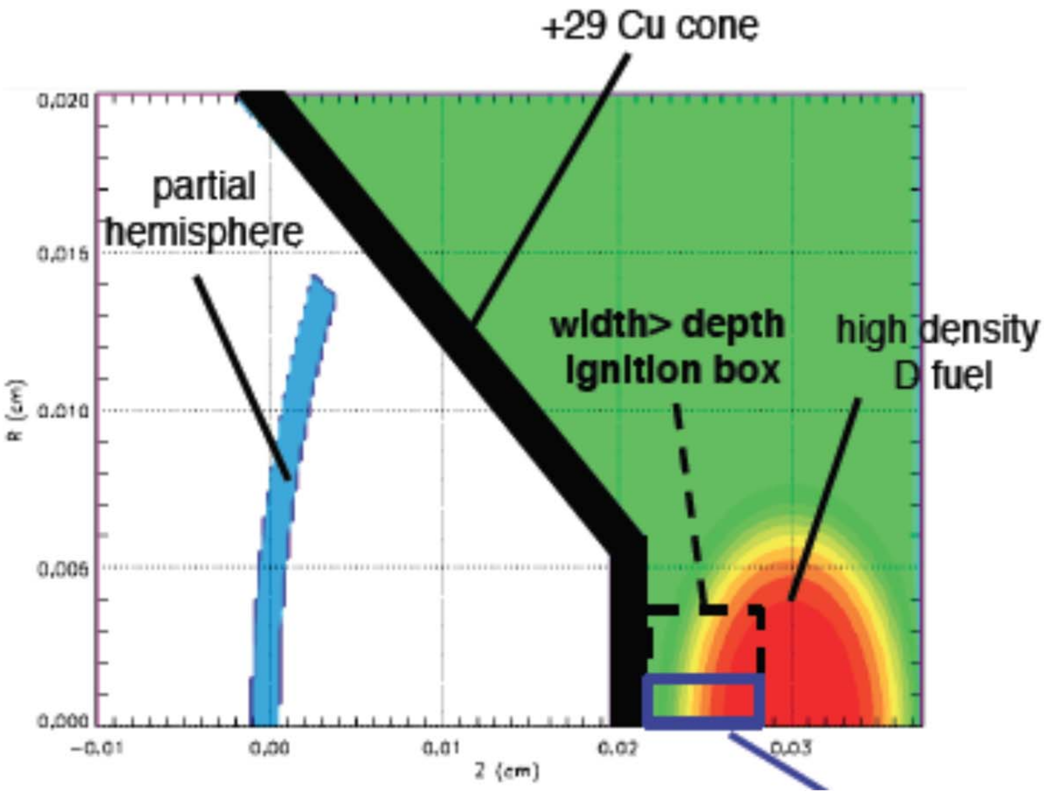


Proton FI
Shell-in-cone



Experimental Demonstration
Foscused Proton Isocoric Heating

Proton FI Concept



LSP Set up for Proton FI

Proton FI has only recently been subjected to the same level of scrutiny as electron FI

Potential:

- **Laser : elec eff. ~80%**
- **electron : proton eff. ~30%**
- **Proton frac in hot spot ~30%**
- **Laser energy for ignition ~180kJ**
- **Requires, e.g 2x1020 Wcm-2 on 200 μ diameter for 4 ps at 1.06 μ**

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Going Forward: Short Term Objectives

CODE DEVELOPMENT

- Integration PIC with Hydro 3D/2D
- EOS and Ionization, material properties in transport codes

MODELING

- Long Pulse (Hydro—cone suvival)
- Short Pulse LPI (prepulse), Direct Comparison to Experiment
- Direct Support of Point Design Effort

EXPERIMENT:

- Electron Generation and Transport at EP Conditions
- 1ω vs 2ω Dependence of LPI (pre-pulse effects)
- Direct Experiment/Full Scale Modeling (Benchmark)

Going Forward: Milestones and Metrics

FIVE YEAR METRICS:
- "HARD" Point Design from Fully Integrated Modeling
- Sub-Critical Integrated Tests on Omega-EP
- Full Scale Hydro compression on NIF

TEN YEAR METRICS:
- Design, Construction and Test of Modules for Ignition Laser
- Test at Full Scale Compression (NIF) → Sub-Ignition (NIF_ARC)
- Capsule Design Realized on Production Scale

TWENTY YEAR METRIC:
- Design, Construction of FI-IFE Power Plant

SUMMARY AND CONCLUSIONS

✓Fast Ignition continues to hold great promise for IFE

Fundamentals of intrinsic high gain and relaxed target specs are significant and worthy of intense research efforts

✓Initial implementation of FI concepts, ones that encouraged speculation of problem-free development, were overly optimistic

Nearly 10 years of International Effort has led to paths for solutions to problems; only in the last 3 years have we seen the computational and experimental capabilities to analyze FI issues competently

✓Fast Ignition research draws from and leverages 50 years of NNSA investment

Computational and Laser Facilities needed for advances are in place; NIF and Omega-EP (both existing) will validate core heating and compression prior to any high gain demonstration

✓Fast Ignition research has a large, scientifically vigorous academic base that feeds NNSA's workforce

FI research gave birth to HEDP science in many universities world-wide

Bibliography

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