LLNL Fast Ignition Program

Fusion Power Associates

30th Anniversary Meeting and Symposium

Fusion Energy: Status and Prospects

December 2-3, 2009

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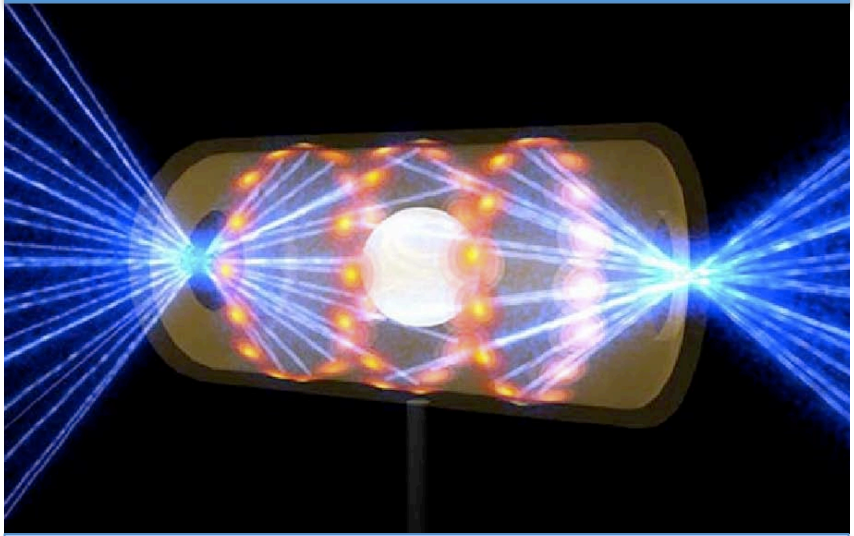
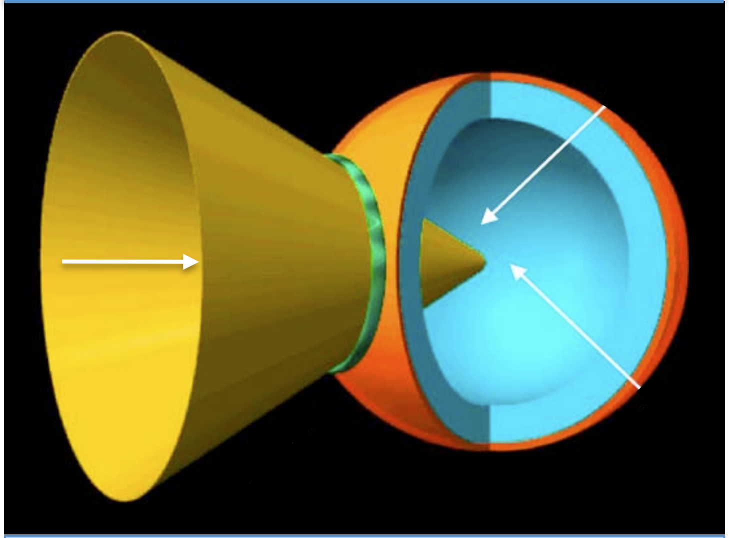
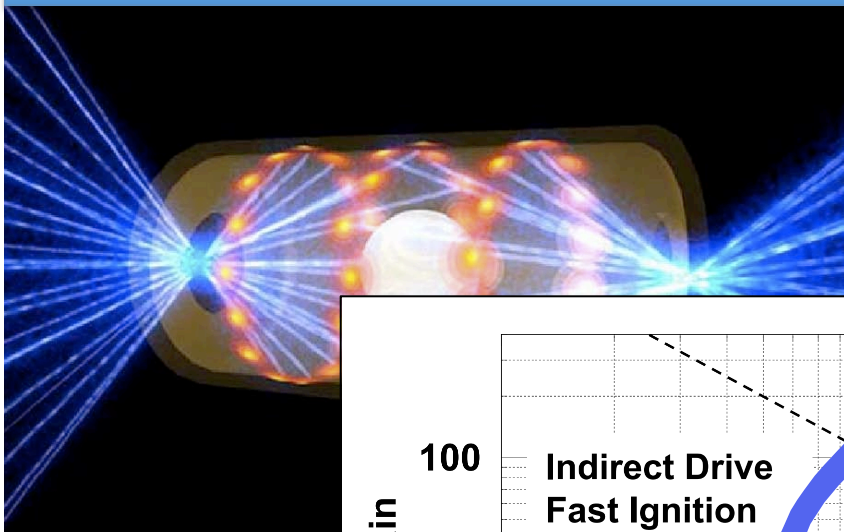
LLNL-PRES-420830

Fast Ignition is an ICF scheme that could provide the high gains desirable for Inertial Fusion Energy

NIC Central Hot Spot Ignition	Fast Ignition
	
Simultaneous compression & heating with 1.3 MJ drive	500 kJ compression + 100 kJ heating pulse

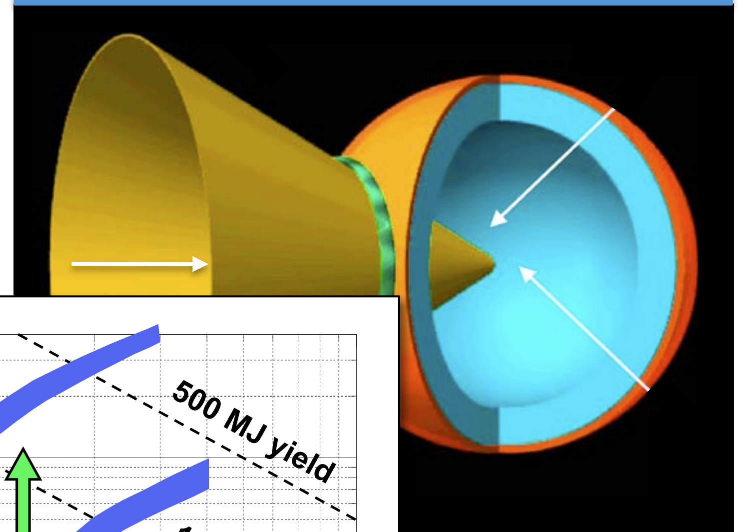
Fast Ignition is an ICF scheme that could provide the high gains desirable for Inertial Fusion Energy

NIC Central Hot Spot Ignition

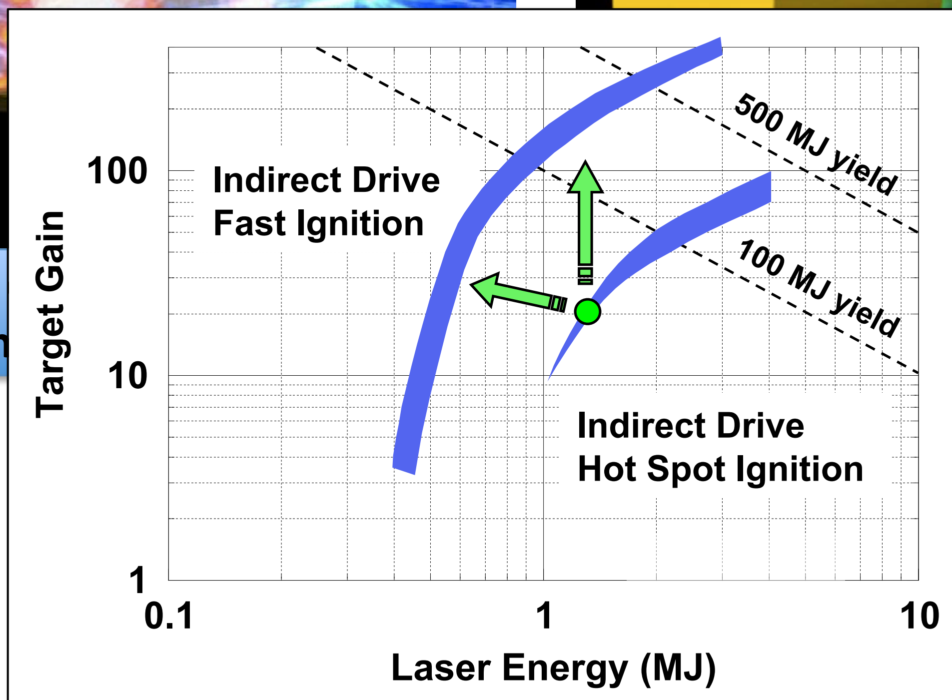


Simultaneous
with

Fast Ignition



sion + 100 kJ
pulse



In FI the core is heated to 10 keV using an intense particle beam generated by an ultrahigh power laser

- Long pulse laser must compress fuel to:

  $\rho \sim 300\ g/cm^3$

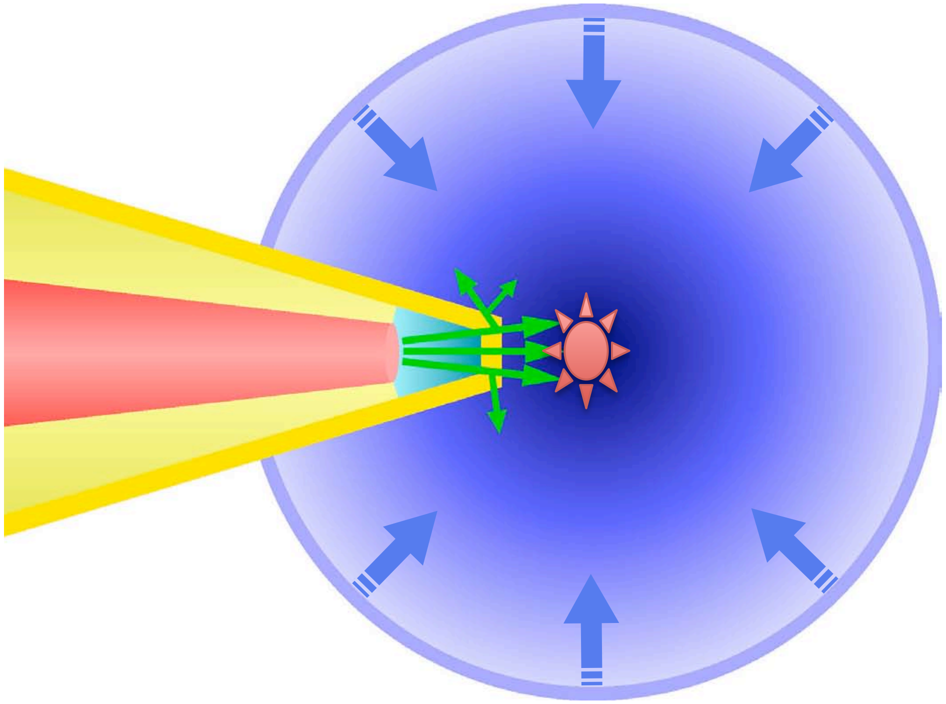
  $\rho R \sim 2\ g/cm^2$

- Short-pulse laser must heat core to 10 KeV:

  Energy ~ 20 kJ

  $\Delta z \sim 40\ \mu m$

  $\tau \sim 20\ ps$

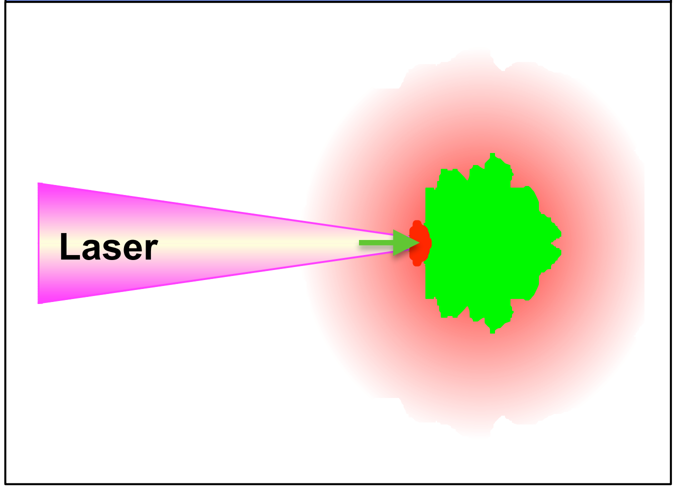


- High-intensity, short-pulse lasers ($I > 10^{19}\ W/cm^2$) incident on a solid target can very efficiently accelerate intense beams of energetic electrons

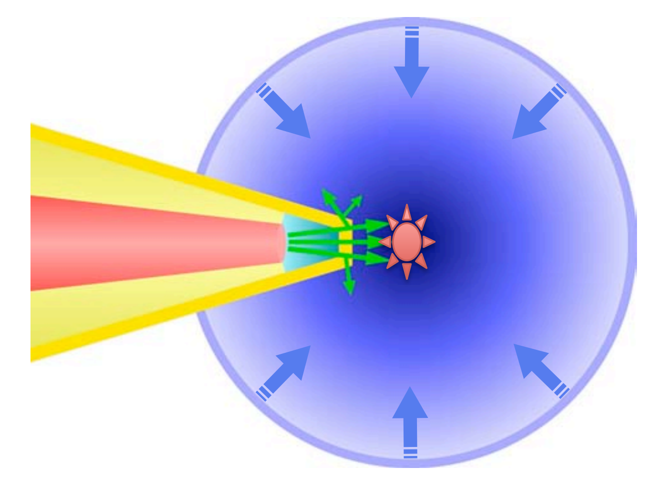
S. Atzeni, POP 8, 3316 (1999)

Several options are being persued for delivering the required particle flux to the core

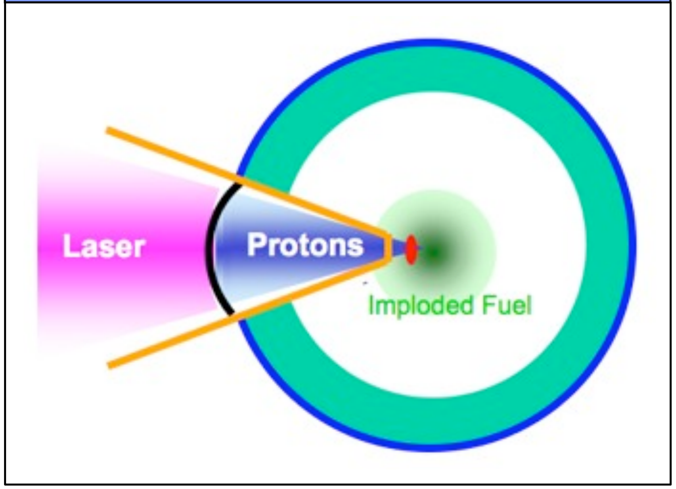
Electrons (laser channeling)



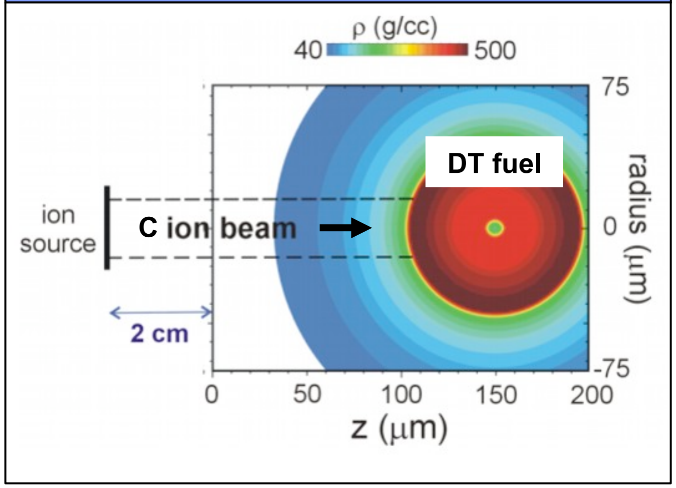
Electrons (cone-guided)



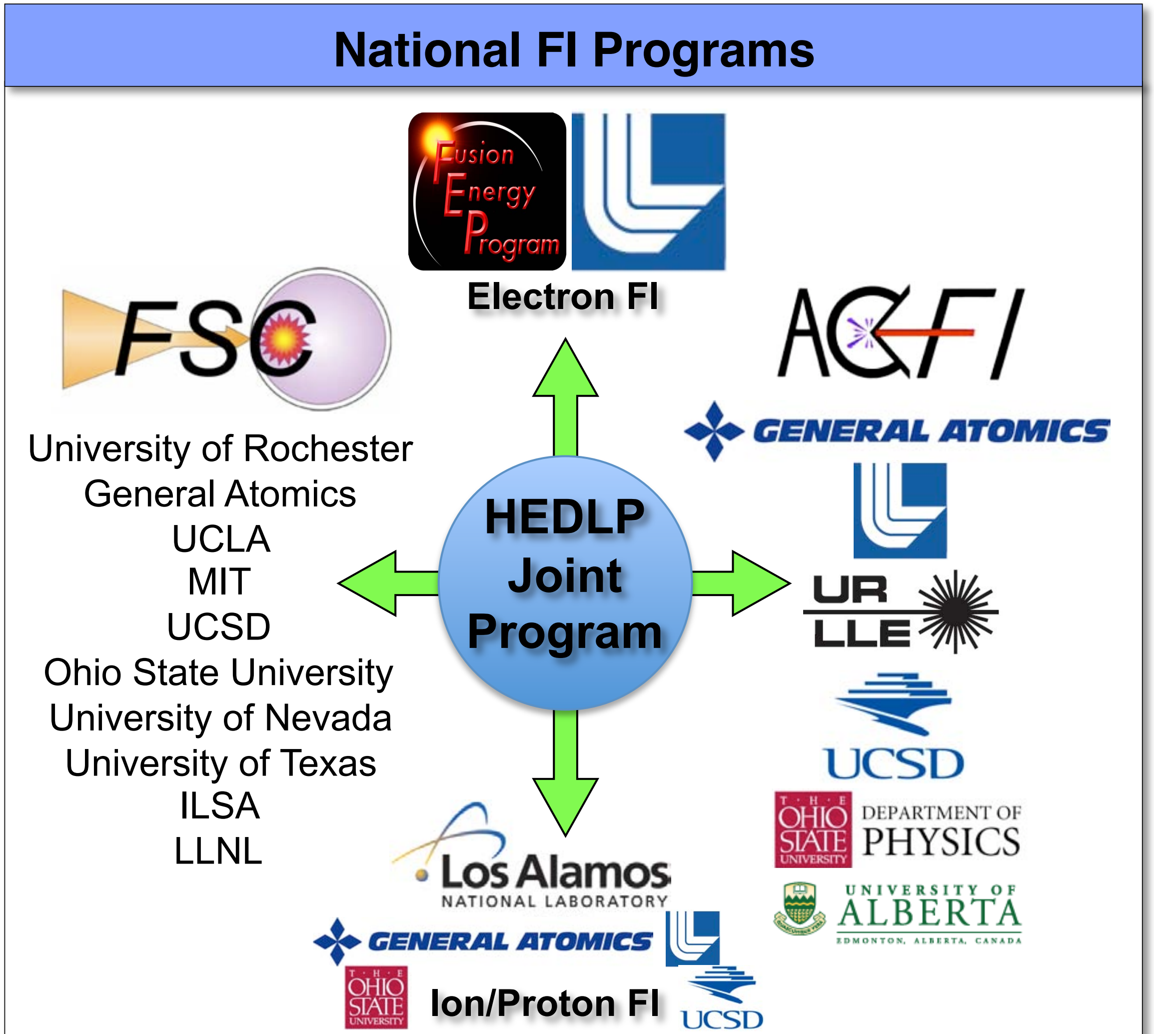
Protons



Ions



Fast Ignition research programs have emerged at numerous universities and national labs across the US



- Fast Ignition in the US has effectively become a co-ordinated national effort

Fast Ignition research programs have emerged at numerous universities and national labs across the US

National FI Programs

Electron FI

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

HEDLP Joint Program

Ion/Proton FI

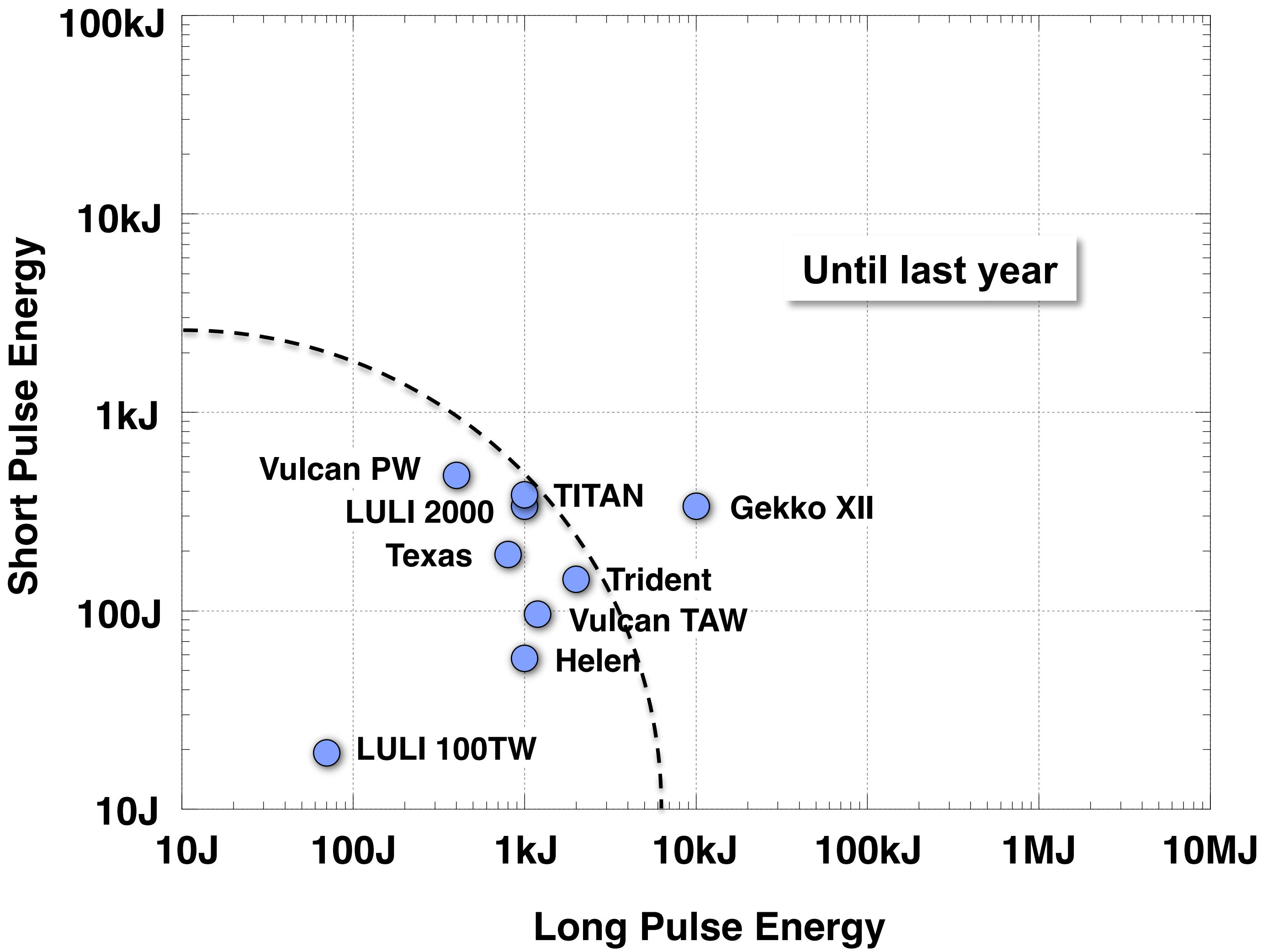
Intl. FI Programs

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

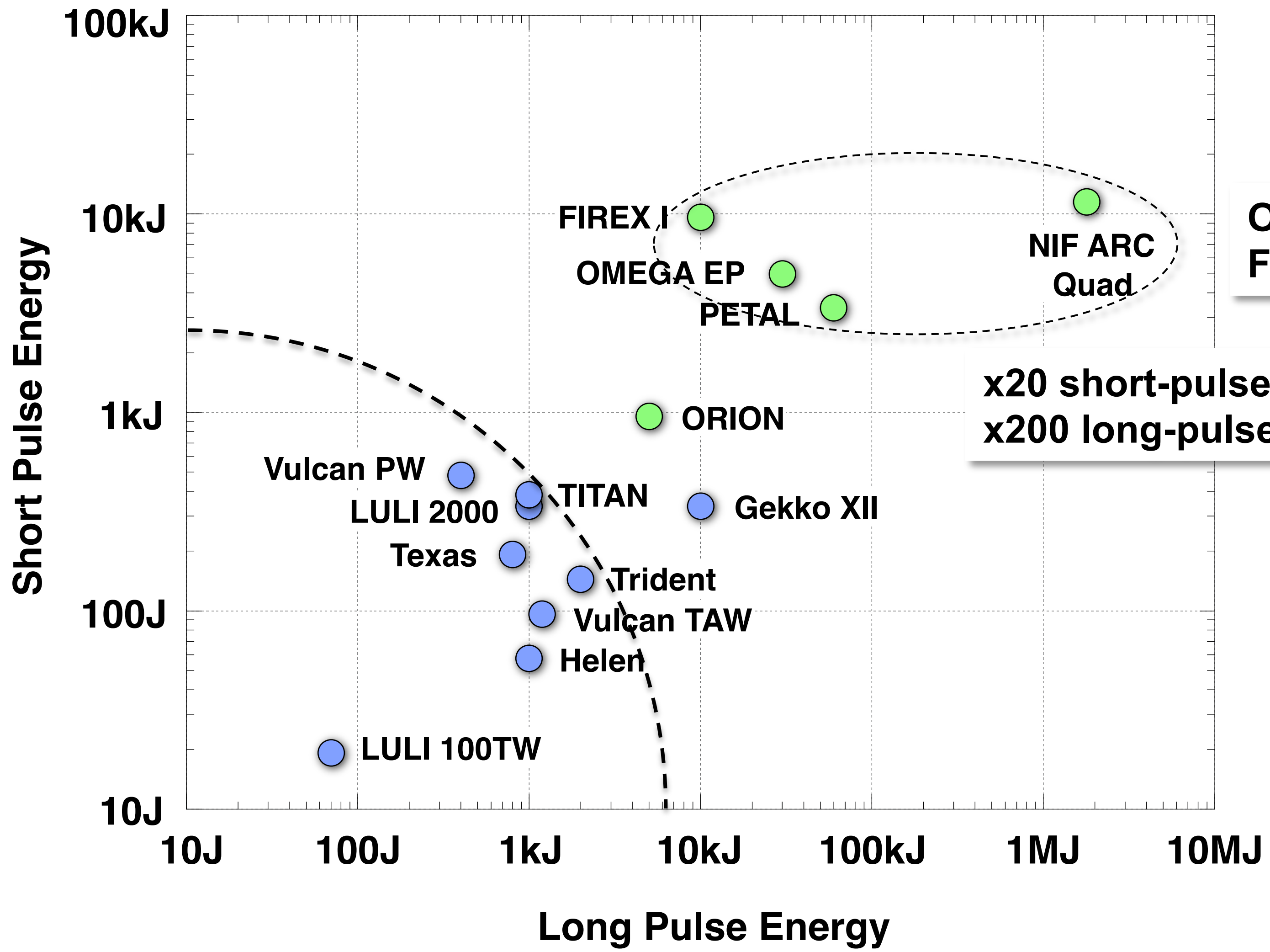
ILE, Osaka University

- Fast Ignition in the US has effectively become a co-ordinated national effort
- There are strong collaborations between the US, Europe, and Japan

A new generation of facilities are coming online capable of integrated tests of fast ignition physics



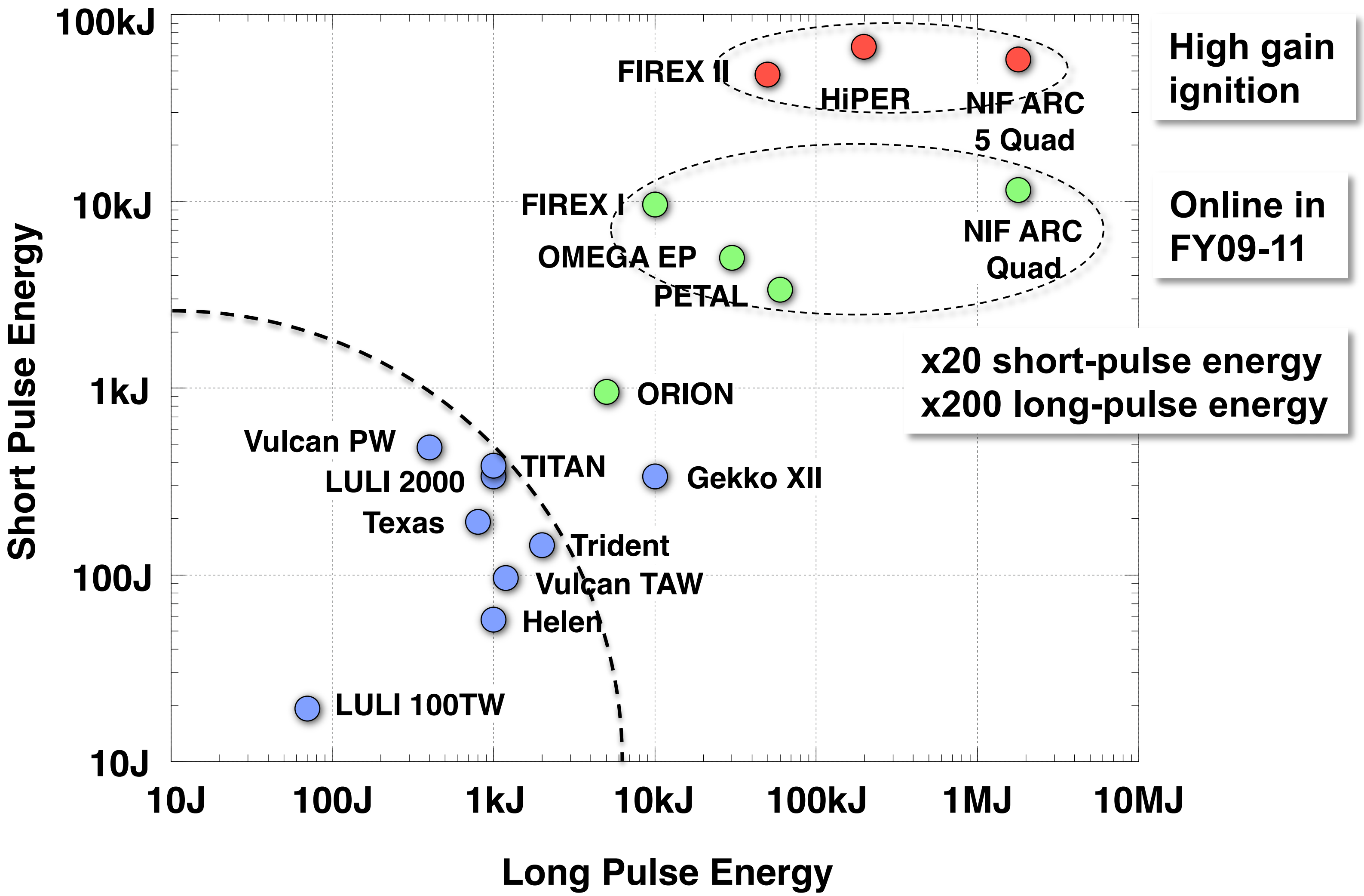
A new generation of facilities are coming online capable of integrated tests of fast ignition physics



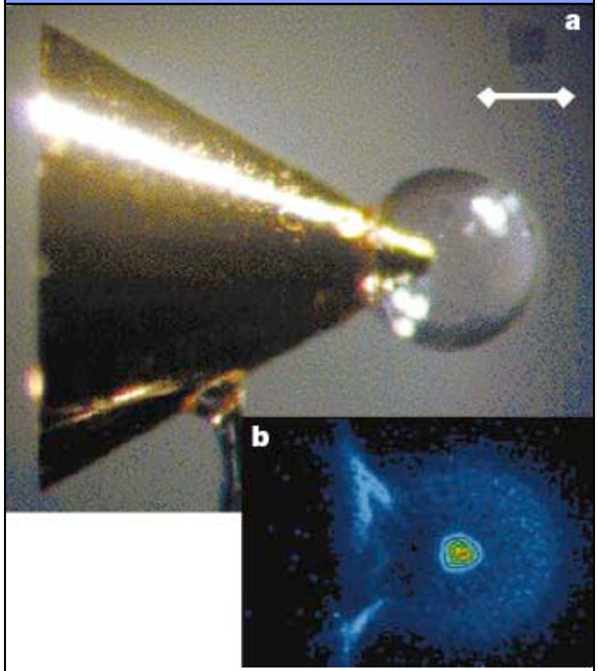
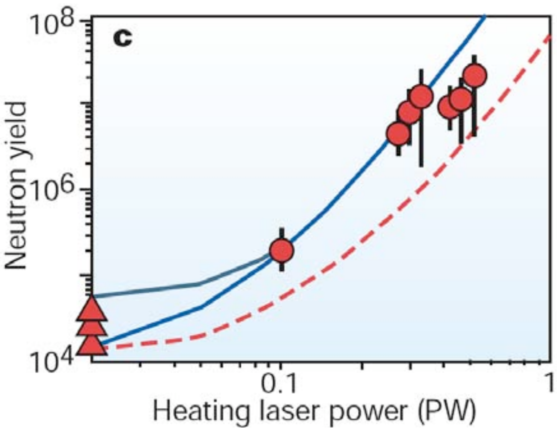
Online in FY09-11

x20 short-pulse energy
x200 long-pulse energy

A new generation of facilities are coming online capable of integrated tests of fast ignition physics



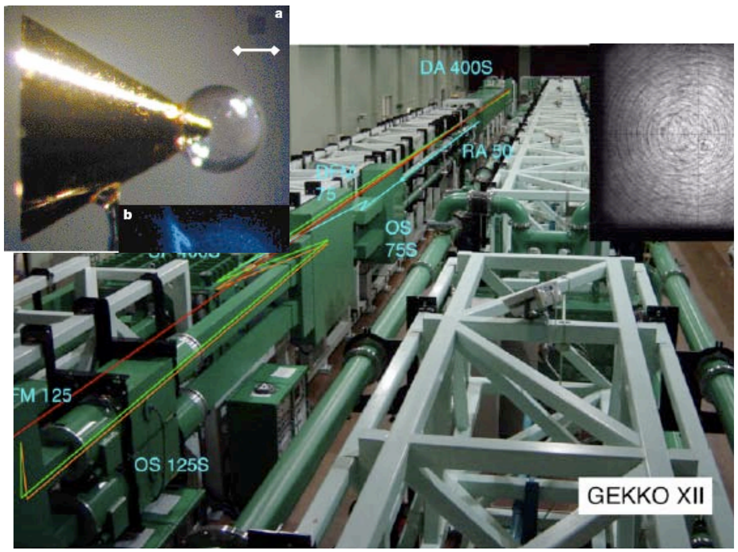
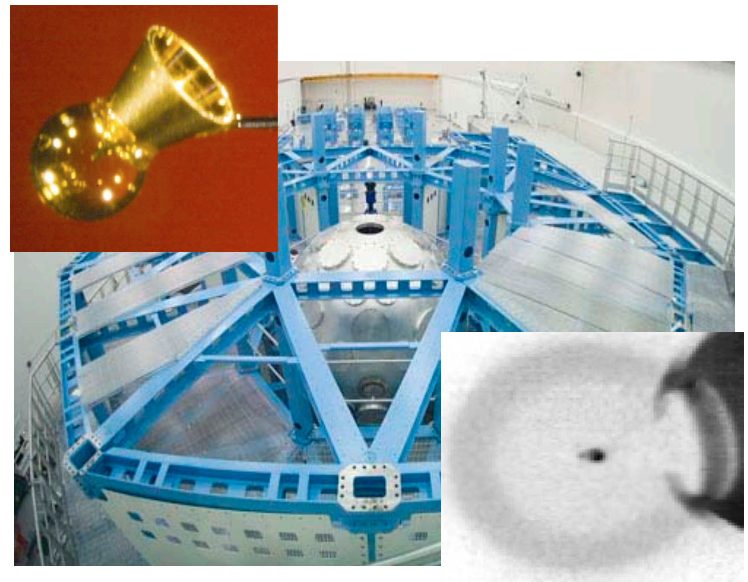
Gekko XII facility achieved the first demonstration of energy coupling to a compressed core at sub-scale

Gekko XII Laser Facility	CD shell + Au cone	Neutron yield
 ❑ 2.5 kJ nanosecond, 2ω compression ❑ 350 J picosecond ignitor pulse	 ❑ Cone-guided electron FI	 ❑ 1000x increase in neutron yield with ignitor pulse

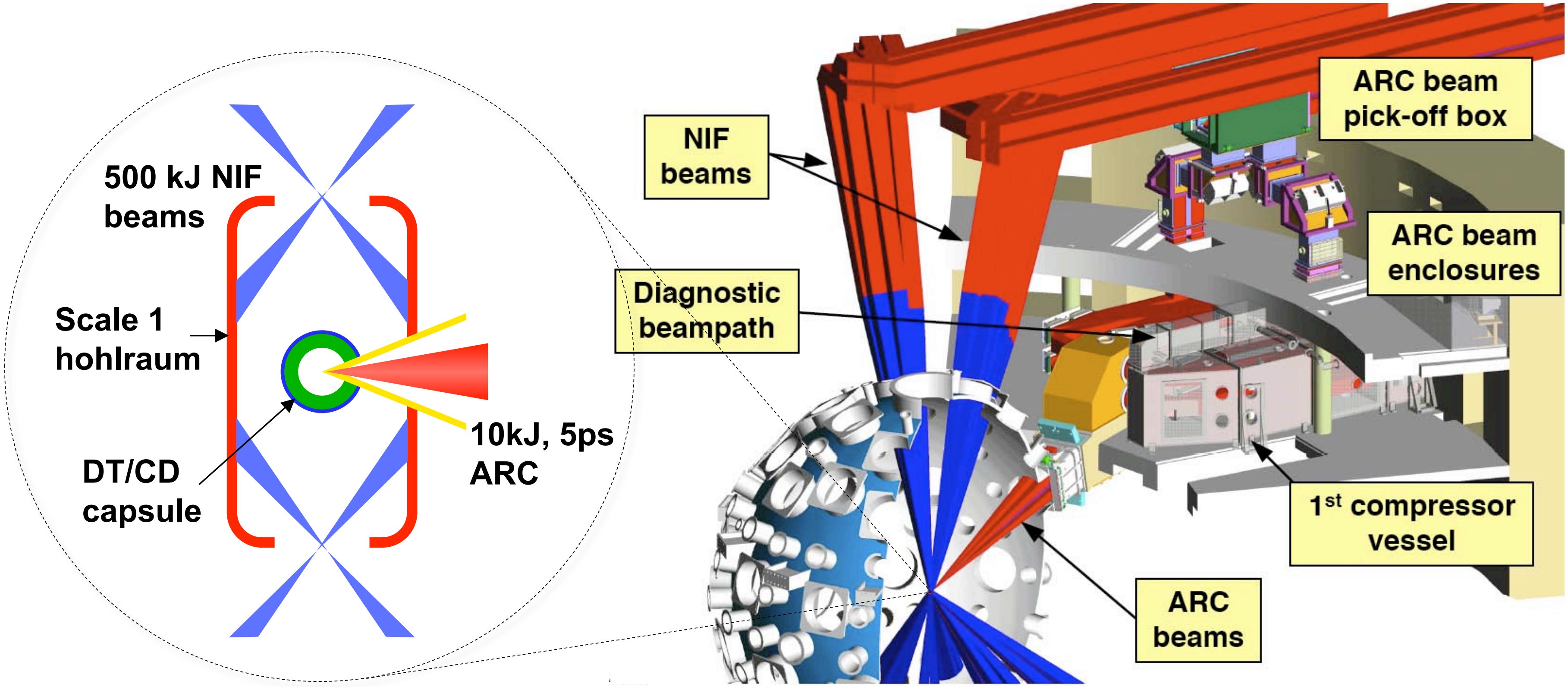
- Gekko XII experiment measure 20-30% coupling of laser energy to the core
- For ignition need to scale up by ~100x in energy

R. Kodama et al., Nature 418 (2002)

Two new facilities have come online in the last year and begun integrated FI experiments

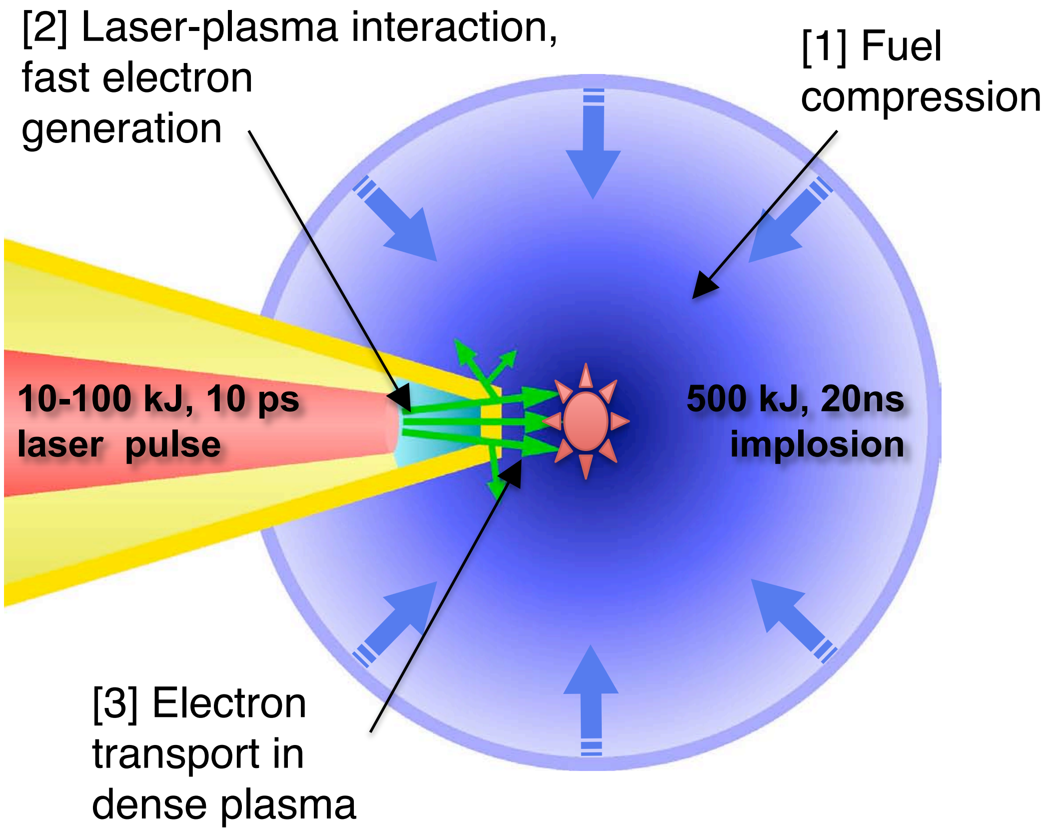
FIREX	OMEGA EP
	
10 kJ, 2ω compression, 10 kJ ignitor beam	30 kJ, 3ω compression, 2.6 kJ ignitor beam

NIF will enable integrated fast ignition experiments with the actual full-scale fuel assembly required for high gain



- We will measure & optimise *coupling efficiency* of an 10 kJ ignitor pulse to a full-scale fuel assembly ➔ **to determine laser, physics, and target requirements for high gain FI**

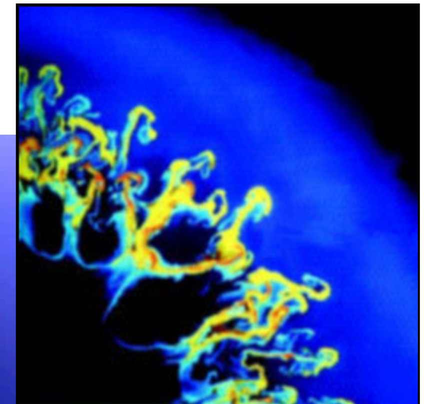
There are three principal design issues for electron cone-guided fast ignition

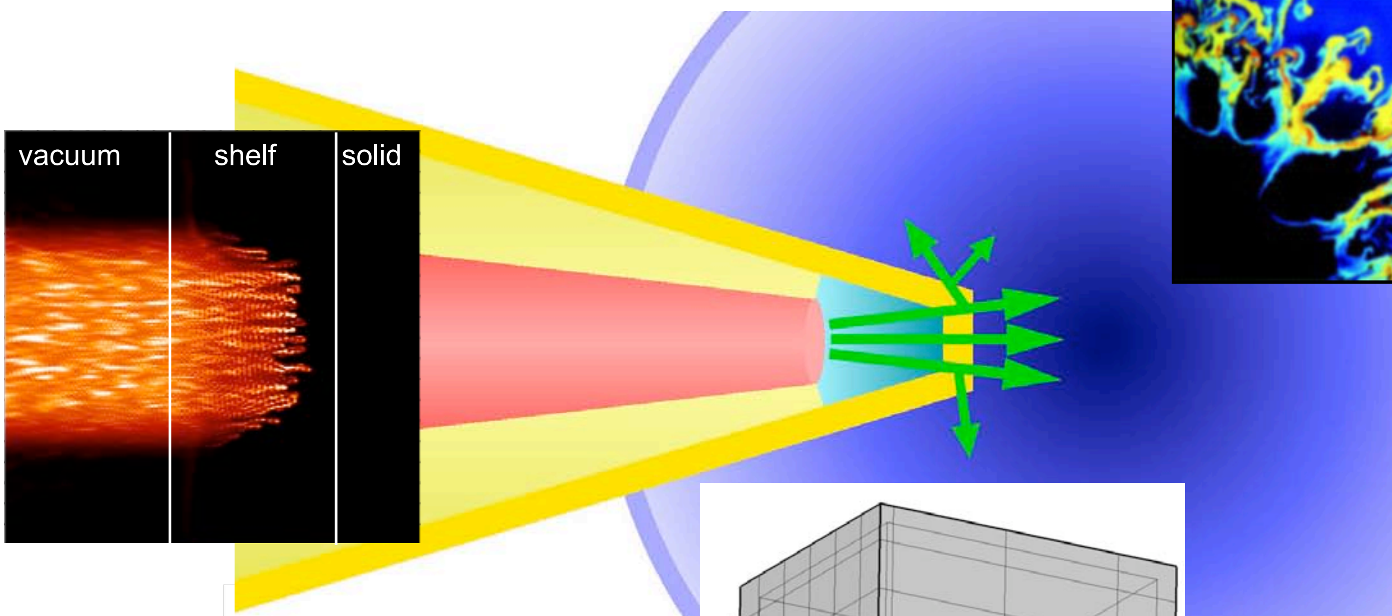


- Fast Ignition physics is extremely challenging as it encompasses ICF, relativistic laser interaction, particle beam transport in dense plasma – fundamental science of all intense laser interactions with high energy density plasma
- *No code capability exists that can model this physics self-consistently*

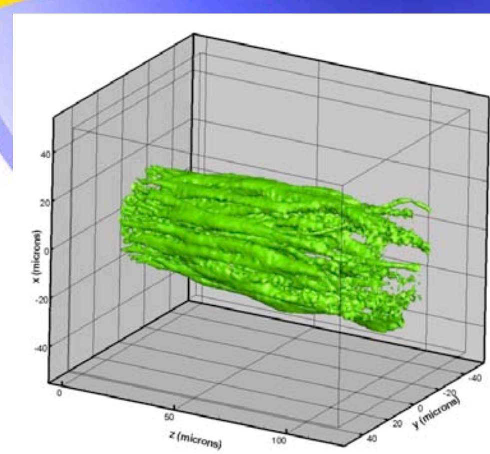
We are developing a new integrated code capability for simulating intense laser interaction with an HED plasma

3D rad-hydro code HYDRA (hydrodynamics, radiation, ionization kinetics, burn, etc.)



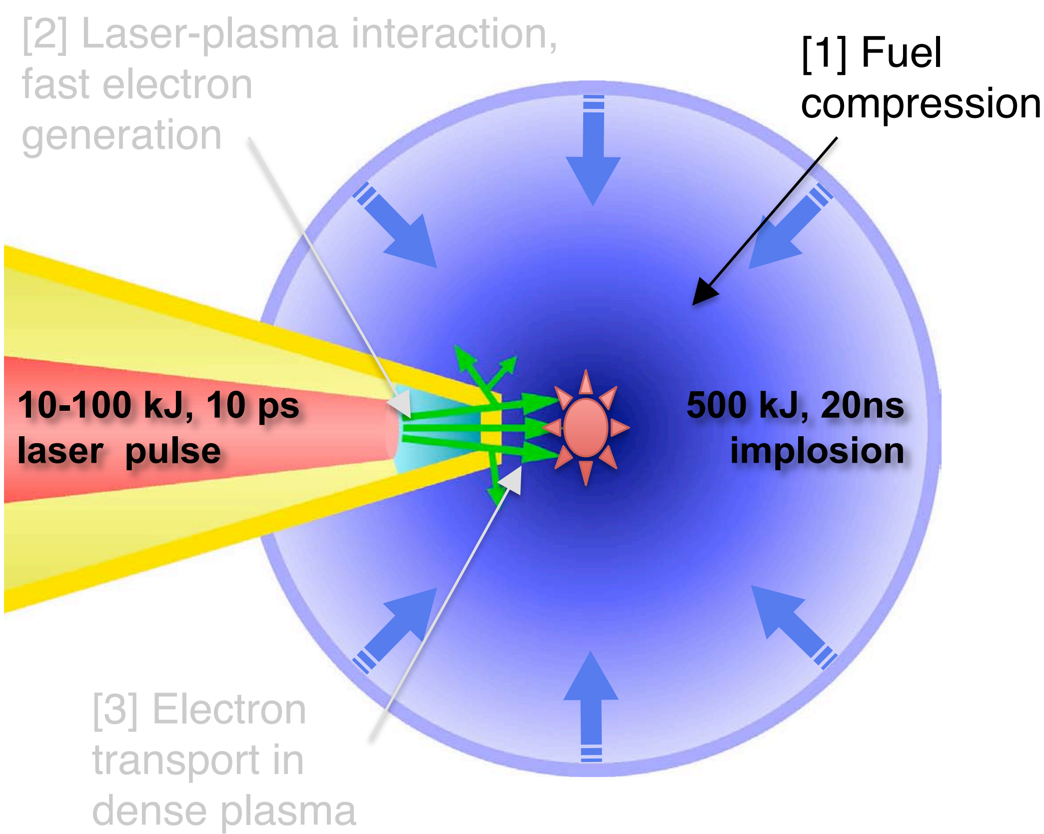


3D kinetic PIC code PSC (solves full Maxwell's equations for fields and kinetic particles, with v. high spatial, temporal resolution)

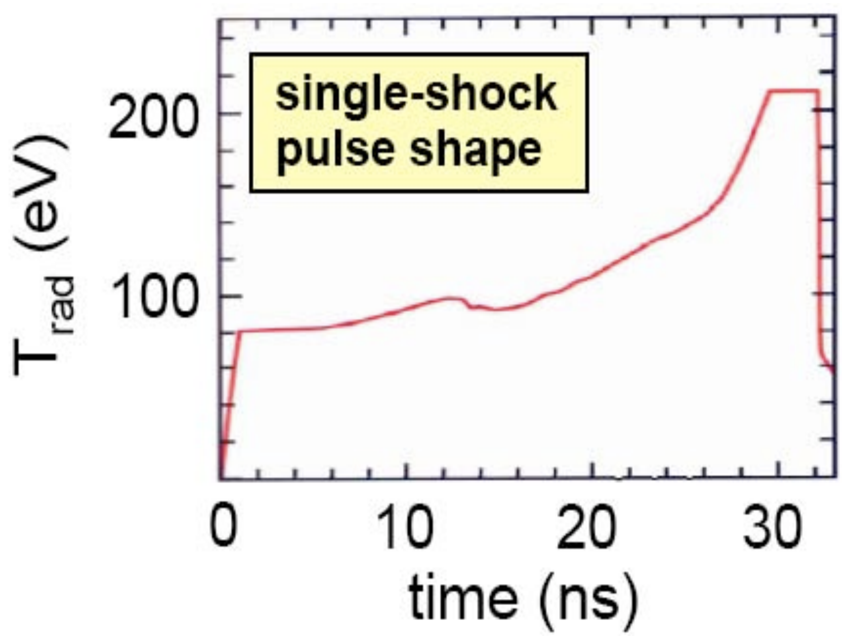


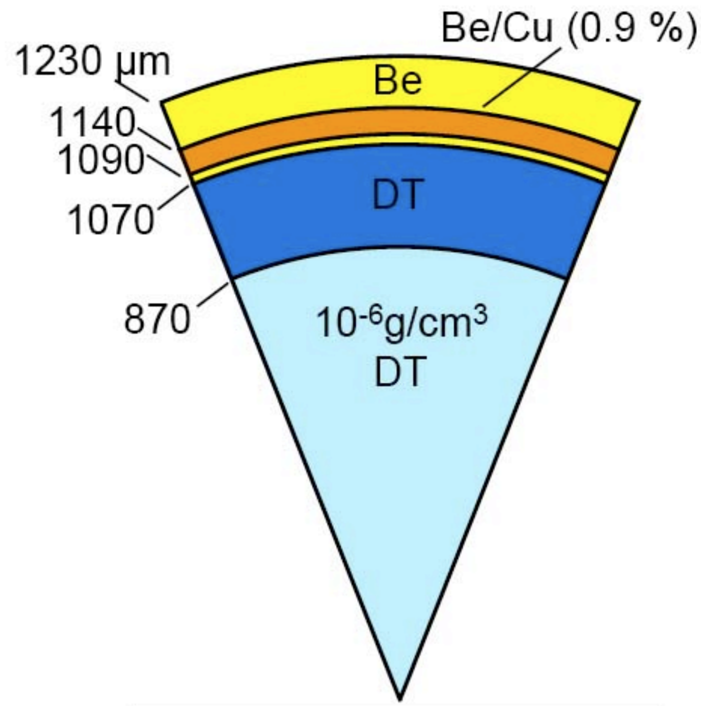
3D hybrid transport codes LSP & ZUMA (kinetic fast electrons with fluid background plasma)

There are three principal design issues for electron cone-guided fast ignition



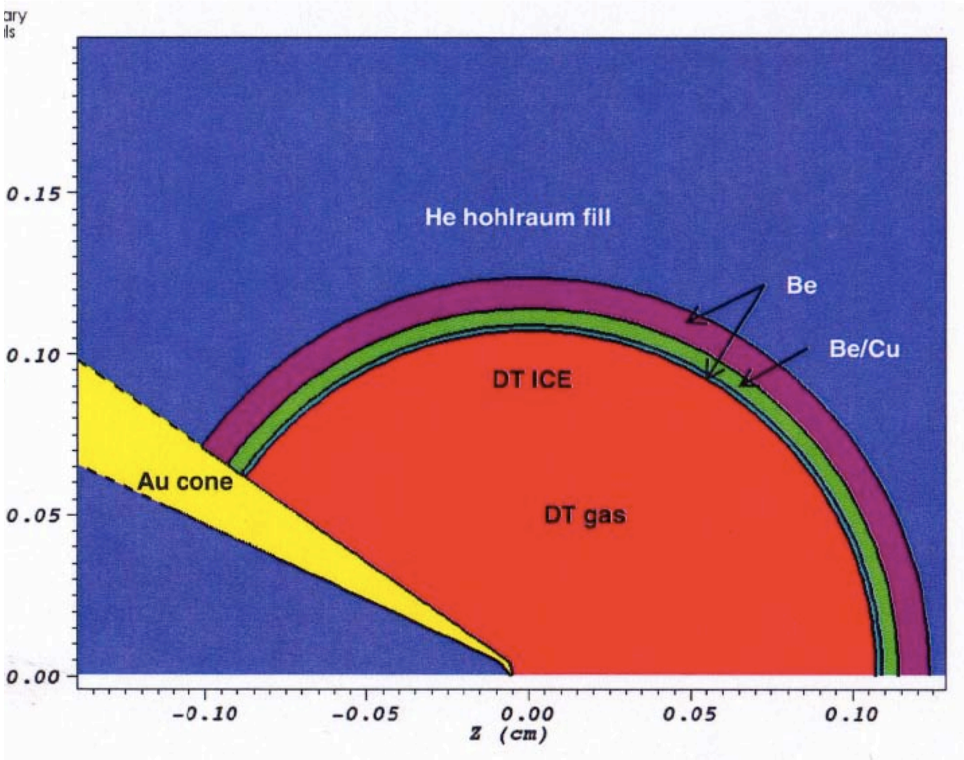
[1] Fuel compression: we have developed optimal 1D isochoric compression designs in DT and CD





$$m_{\text{fuel}} = 0.6 \text{ mg}$$
$$(\rho r)_{\text{fuel}} = 2.1 \text{ g/cm}^2$$

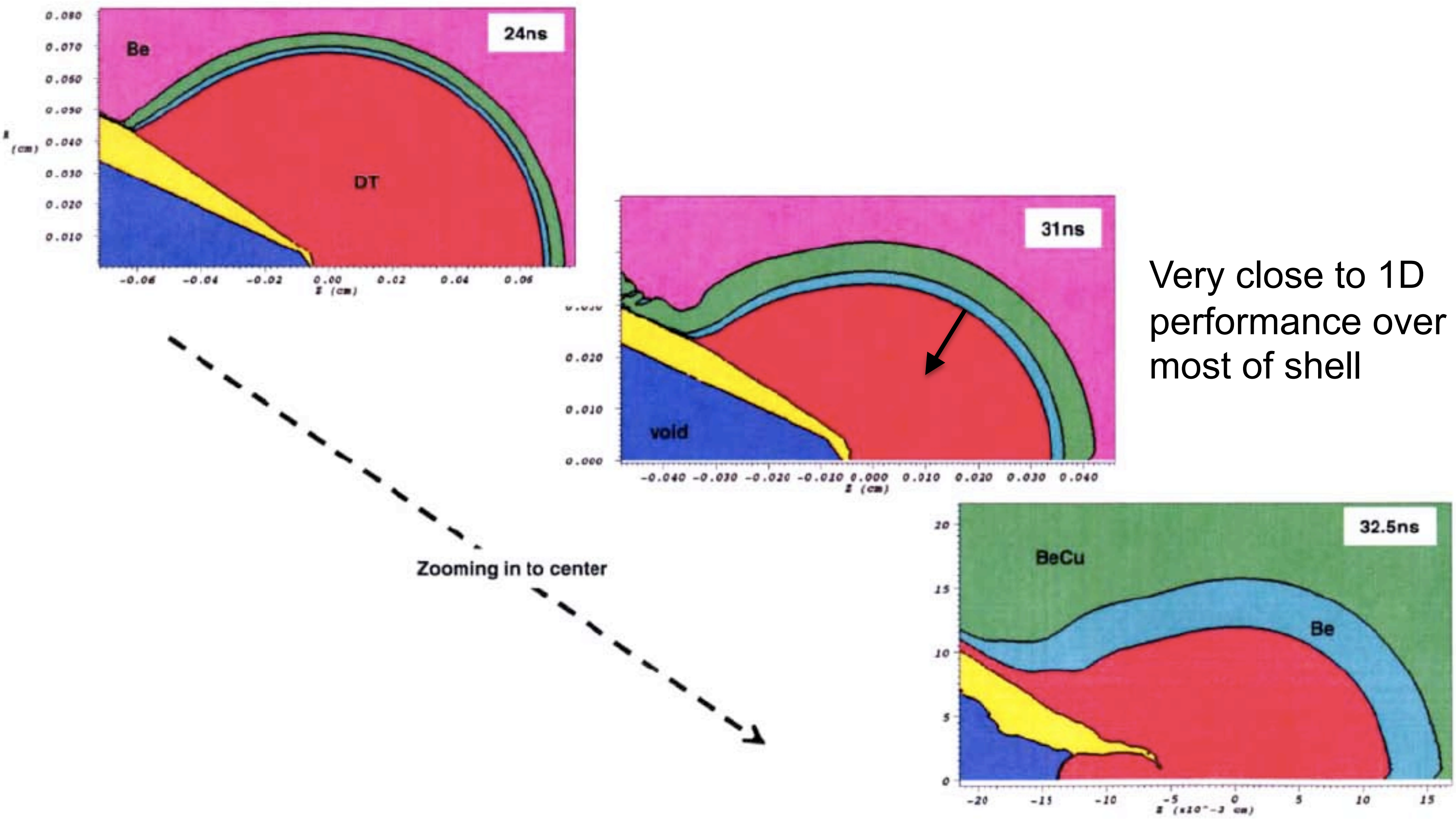
In 2D designs we must assemble the fuel around the cone tip – this is challenging at full-scale



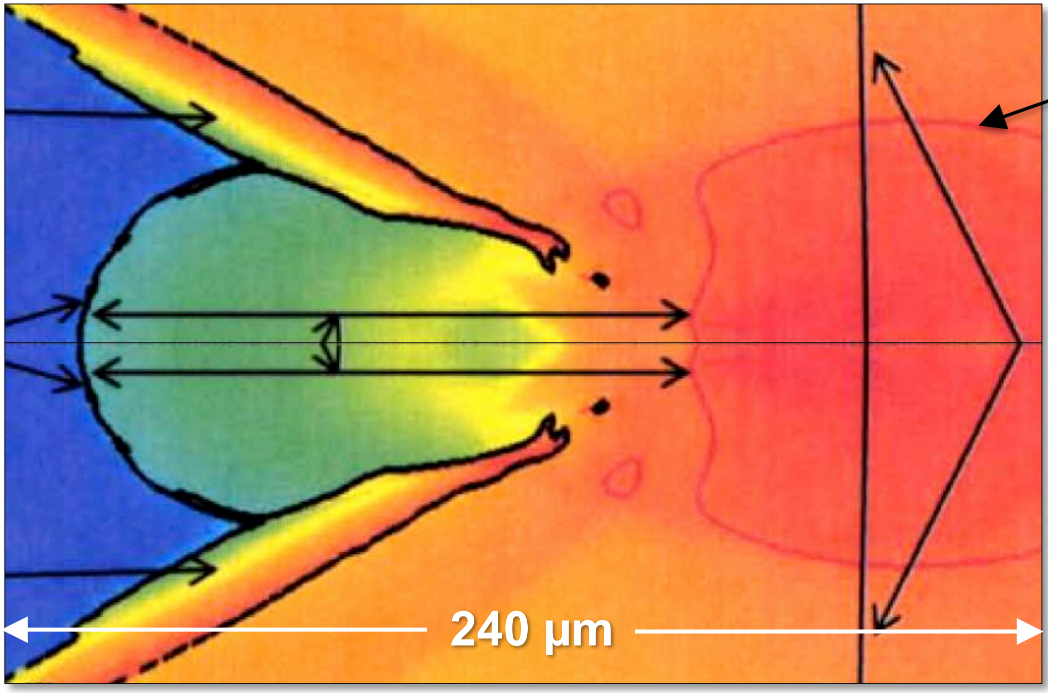
- Maintain 300g/cm^3 and 2g/cm^2
- Minimize ablation of cone wall and subsequent mixing (degrades yield)
- Maintain integrity of cone tip from extreme pressure on-axis at stagnation
- Minimise compressed core to cone tip distance (~100μm) to maximise fast electron coupling

- This has been a major challenge—multiple radiation-hydrodynamics codes have been used to resolve physics and simulation issues

Typical simulation result with calculated single-shock DT radiation drive

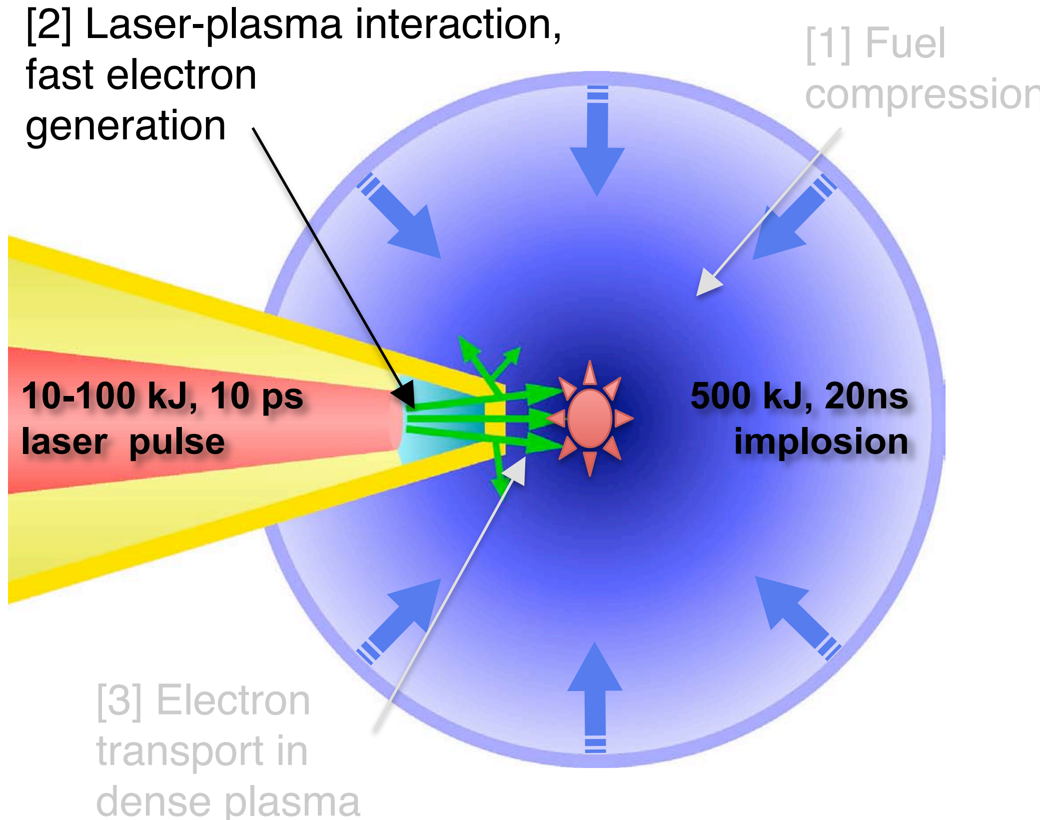


Rev 1 hydro implosion design achieves good peak density and ρR, but with slightly long transport distance



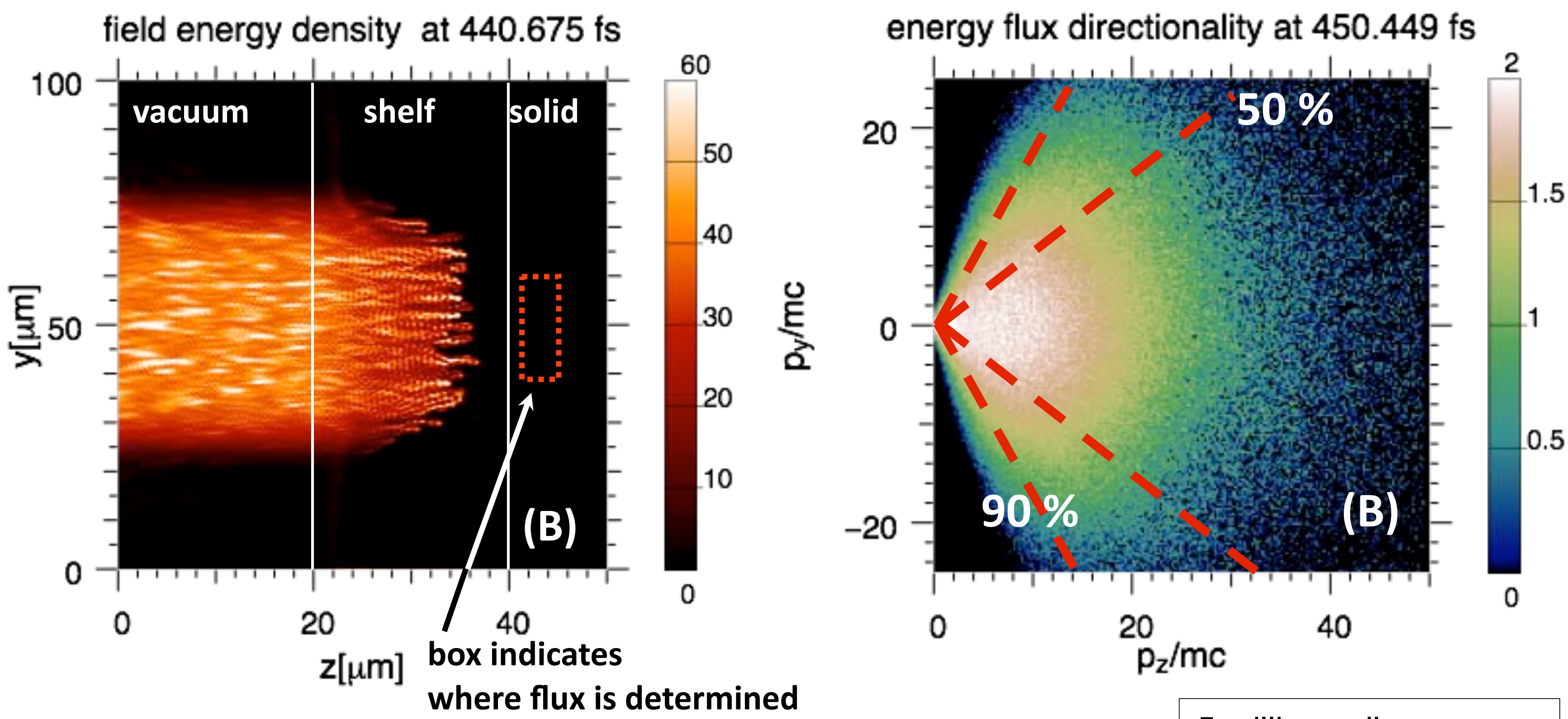
Parameter	Rev 1 Design
Peak density	380 g/cc
ρR	1.6 g/cm^2
Distance to critical surface	130 µm

There are three principal design issues for electron cone-guided fast ignition



[2] A Rev 1 electron source for NIF ARC is calculated with high resolution 2D PIC simulations

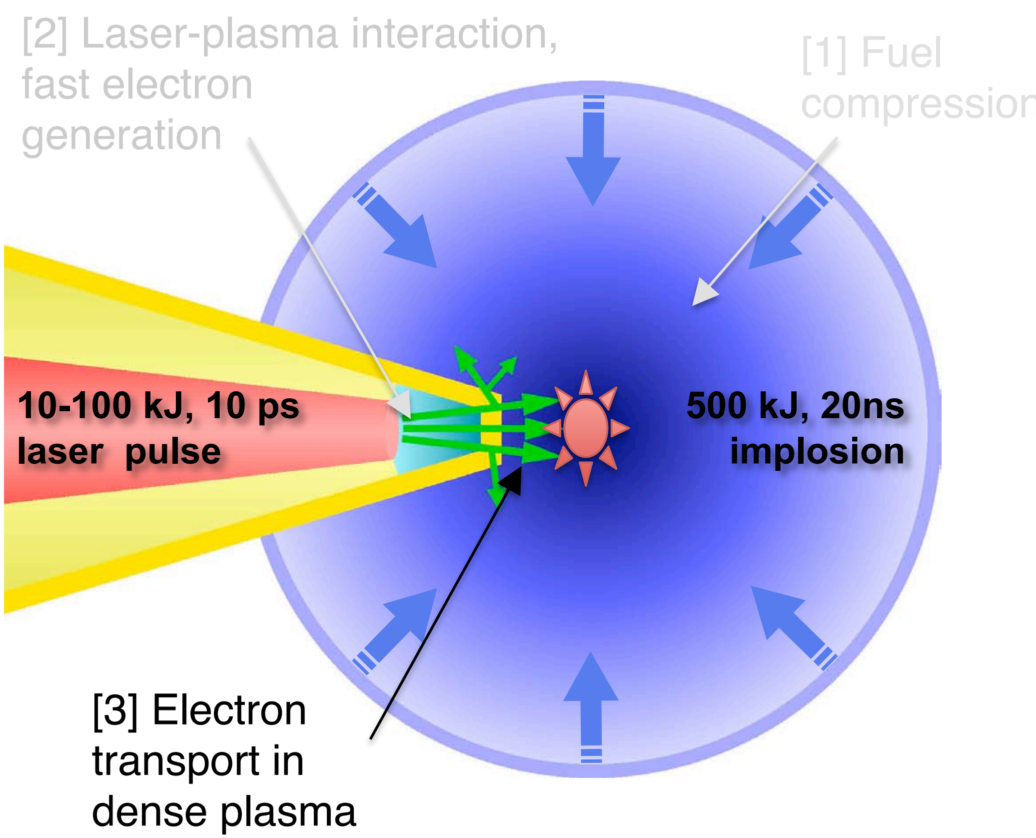
- High-res explicit PIC, planar geometry, reduced spatial and temporal scales
- Intensity equivalent to 4.3kJ, 5ps, 40μm diameter pulse



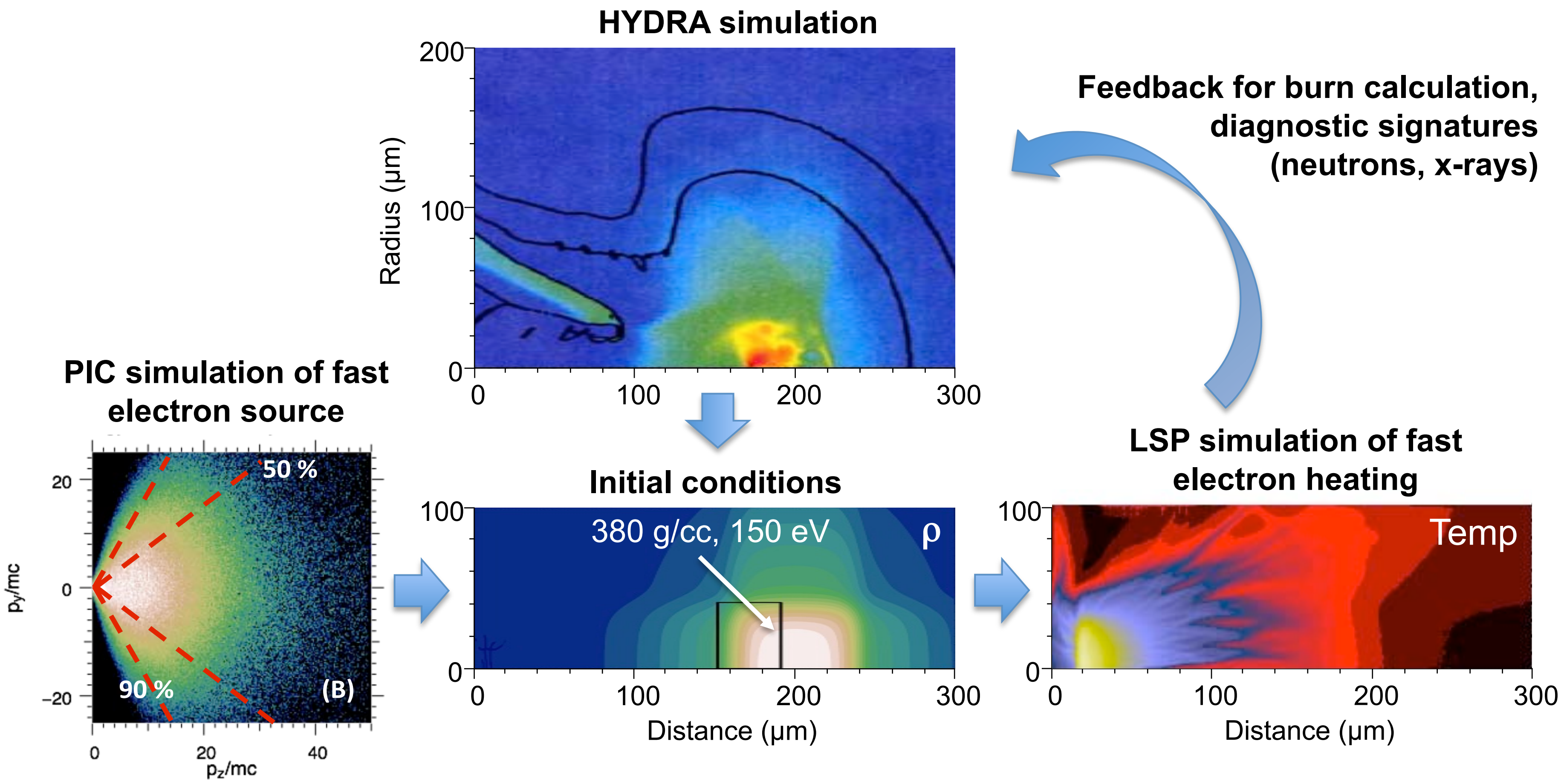
- Total conversion of light into electron energy flux is 60%
- 50% of electron flux is in 80 deg opening angle

5 million cells
1 billion particles
81 hours on 128 cpus

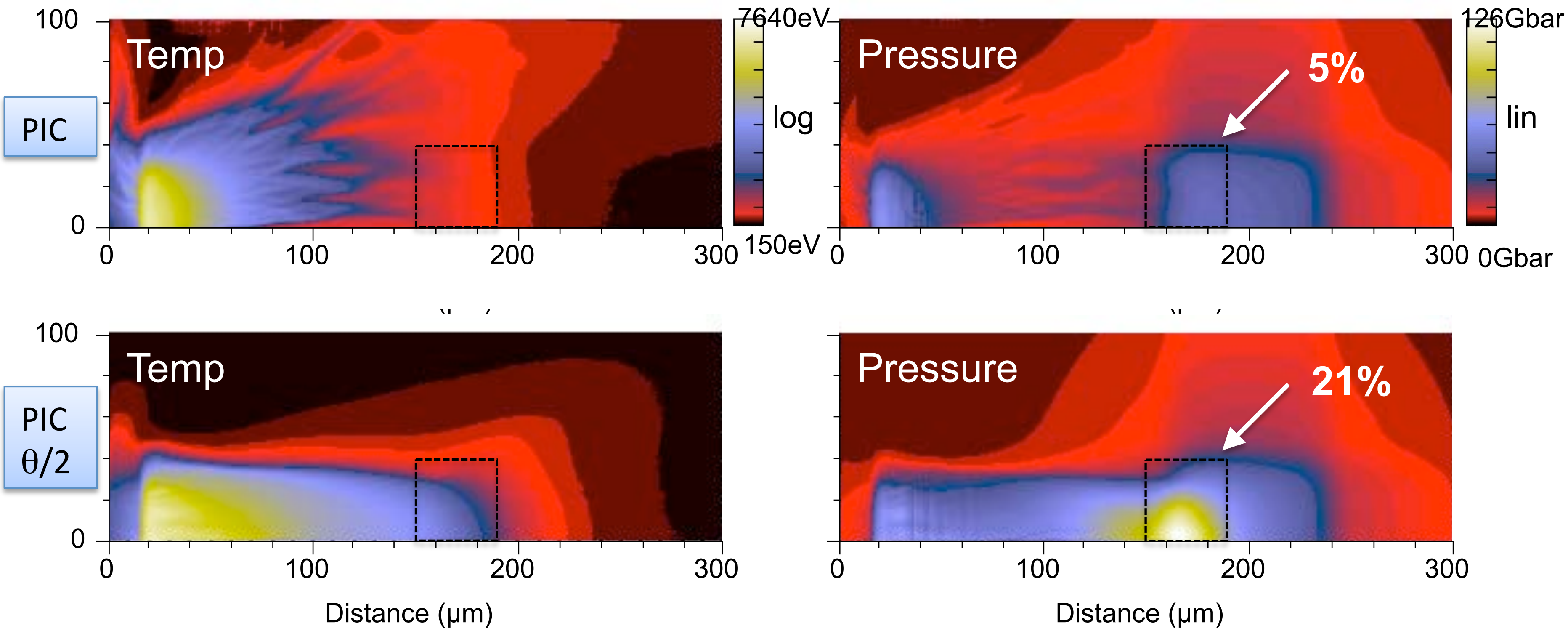
There are three principal design issues for electron cone-guided fast ignition



[3] Transport & Core Heating: Hybrid-PIC code LSP combines electron source and rad-hydro data

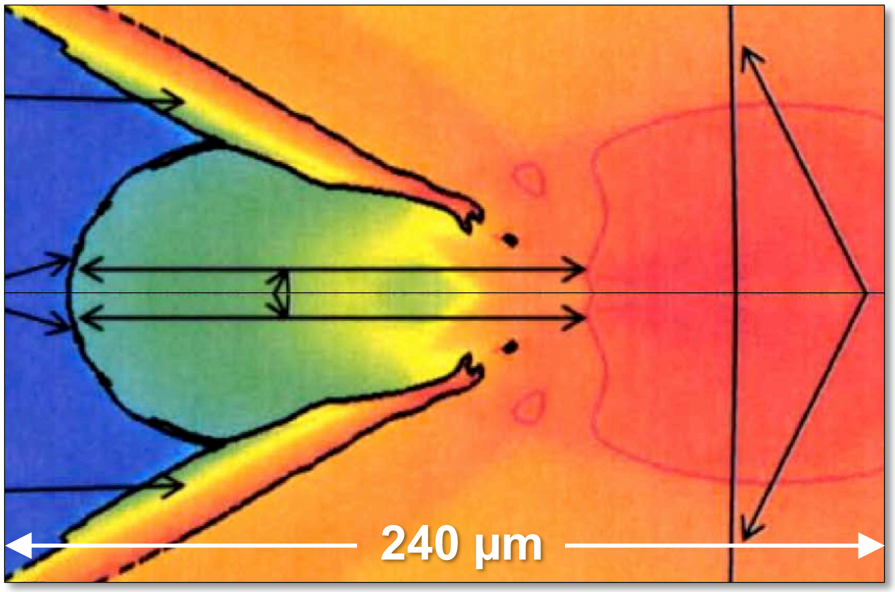


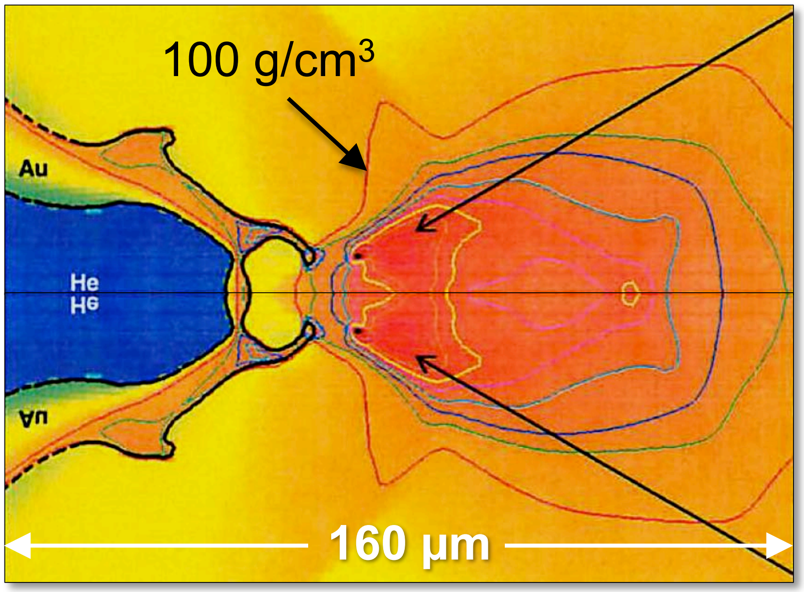
We have produced the first transport calculations using realistic hydro and PIC input calculations



- Coupling efficiency is lower than ideal - we need to better tailor electron source and/or reduce transport distance
- Transport simulations can rapidly explore parameter space for optimal fuel assembly and electron source profiles

Rev 2 design: Numerous improvements have led to large reduction in transport distance & intact cone tip

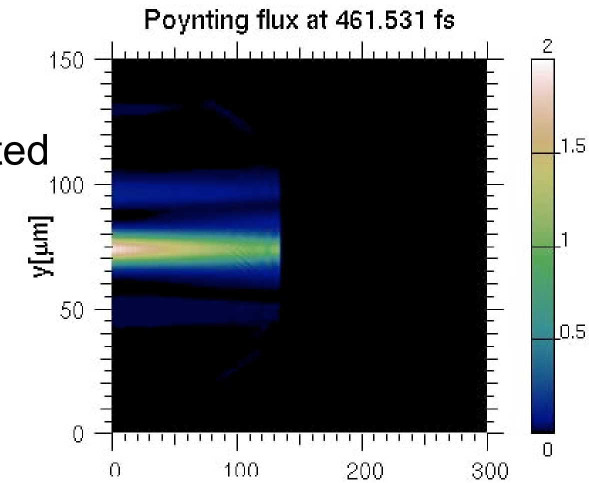


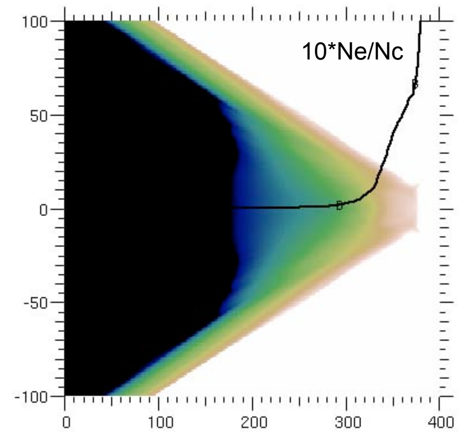


Parameter	Rev 1 Design	Rev 2 Design
Peak density	380 g/cc	360 g/cc
ρR	1.6 g/cm^2	1.36 g/cm^2
Cone tip	Destroyed	Intact
Distance to critical surface	130 µm	17 µm

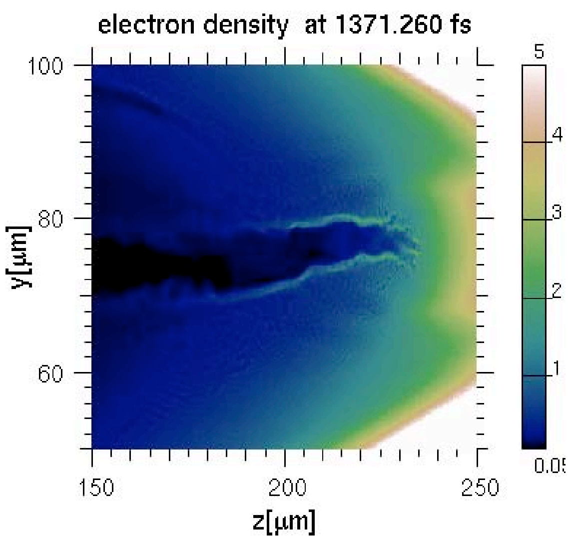
Rev 2 design: Electron source PIC at larger scale, cone geometry, realistic ARC focal intensity profiles

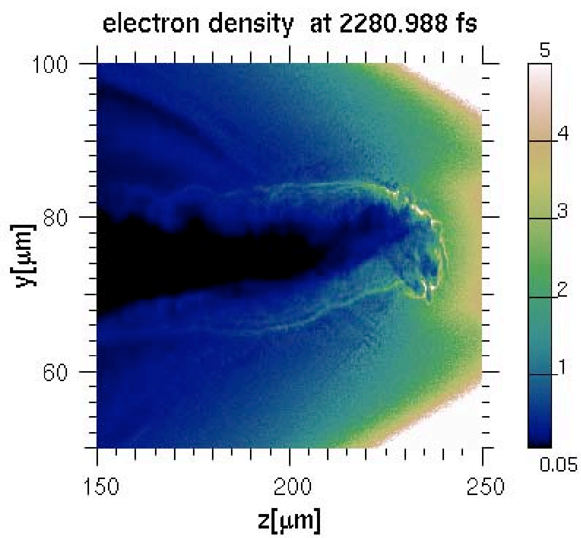
Reconstructed NIF ARC aberrated beam (PIC)

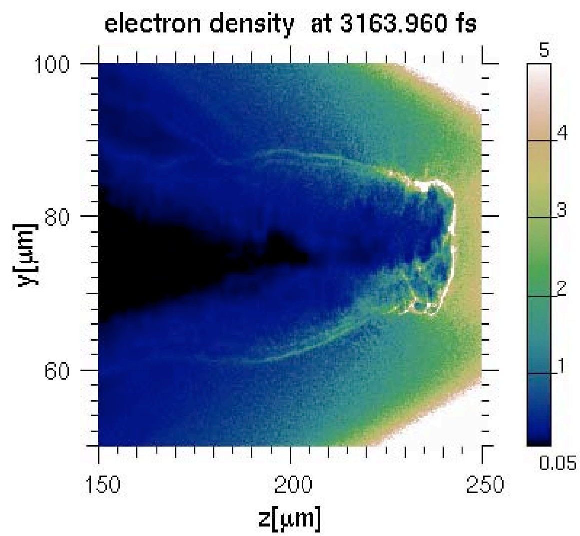




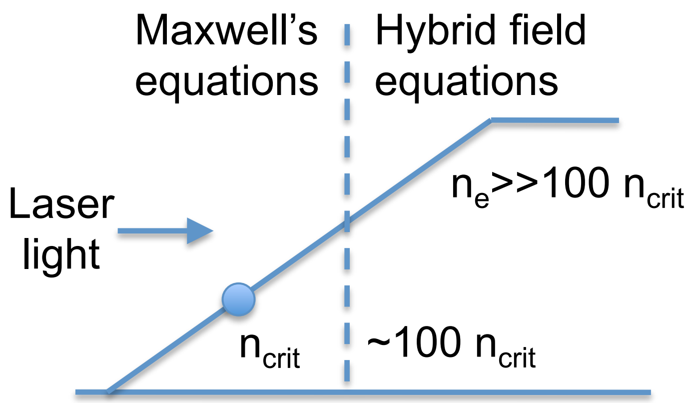
NIF ARC 250mJ pre-pulse (HYDRA)







Rev 2 design will use a new hybrid-PIC code that combines PIC with a hybrid particle solver at high ρ

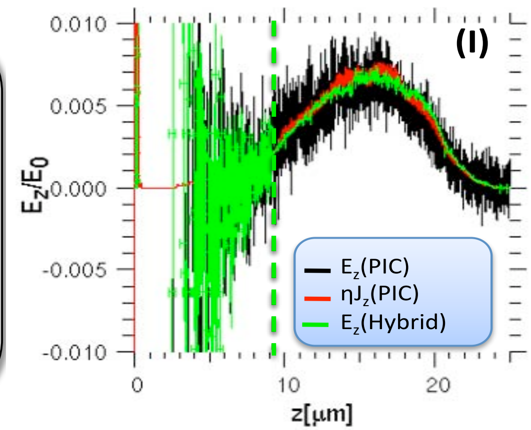


Hybrid Field Equations

$$\vec{J}_{cold,e} + \vec{J}_{ion} = \frac{c}{4\pi}\vec{\nabla}\times\vec{B} - \vec{J}_{fast,e}$$

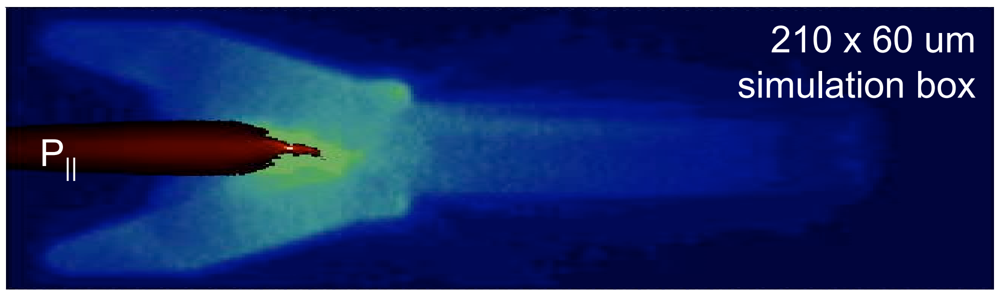
$$\vec{E} = \vec{\eta}\left(\vec{J}_{cold,e} + \vec{J}_{ion}\right) - (en_e)^{-1}\vec{\nabla}n_e T_e - (en_e c)^{-1}\vec{J}_{cold,e}\times\vec{B} + (en_e c)^{-1}\frac{\Delta\vec{P}^{e-efast}_{mom,coll}}{\Delta t}$$

$$\frac{\partial\vec{B}}{\partial t} = -c\vec{\nabla}\times\vec{E}$$

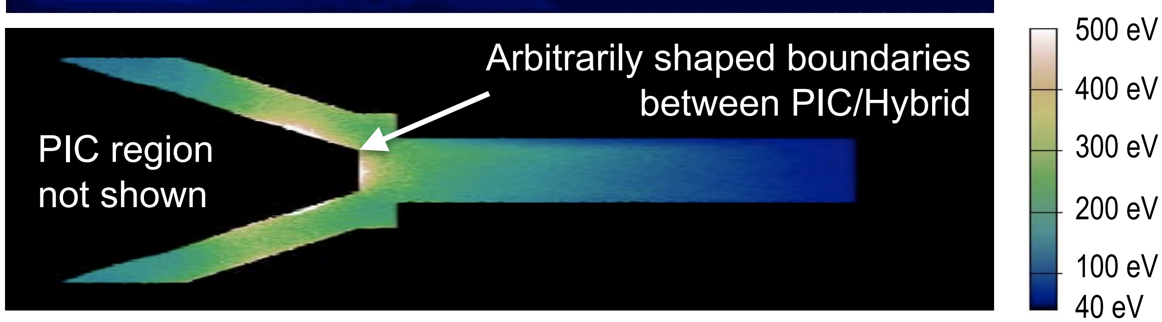


B.Cohen, A. Kemp, L. Divol (submitted JCP)

Energy density of elec>1MeV @ 500fs (and Poynting flux)

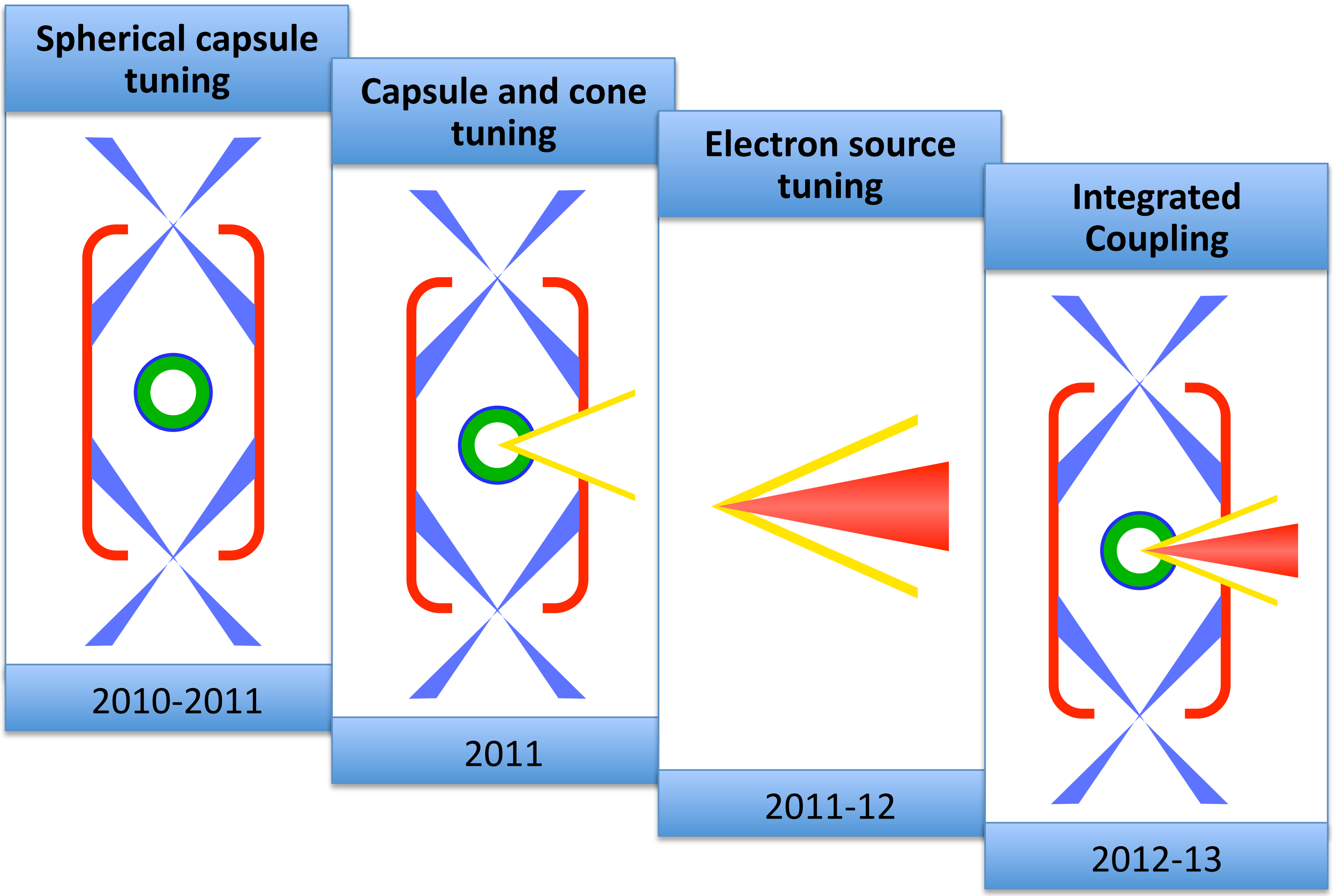


Te (eV) @ 500fs Cu Z_{eff} =4.6

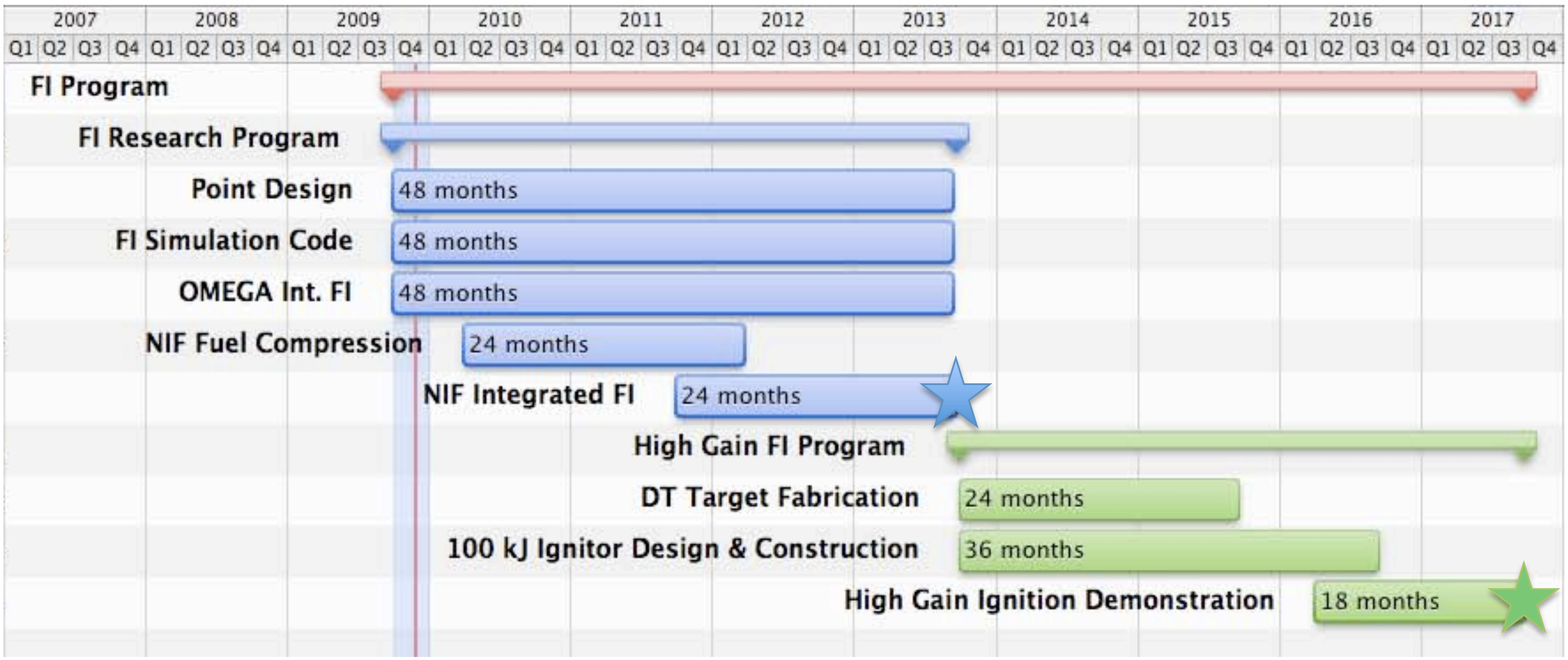


- The hybrid-PIC code enables us to model large, solid density targets with a realistic self-consistent electron distribution

Experimental campaign: FI can leverage the enormous capability for implosion tuning developed by NIC



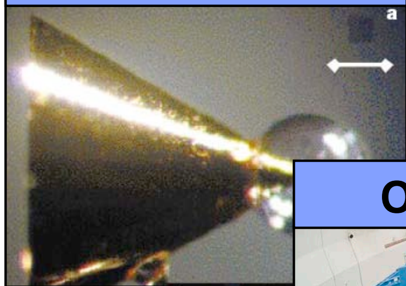
FI has two major goals: establishing feasibility/ requirements for high gain & demonstrating high gain



- (blue star) Establish the physics, target, and laser requirements for high gain FI—demonstrate compression, coupling efficiency, validated simulation capability, and high gain point design
- (green star) Implement a High Gain FI Demonstration Program (National FI Campaign)

Simulation tools & experiments over next few years will determine the architecture of a high gain facility

FIREX

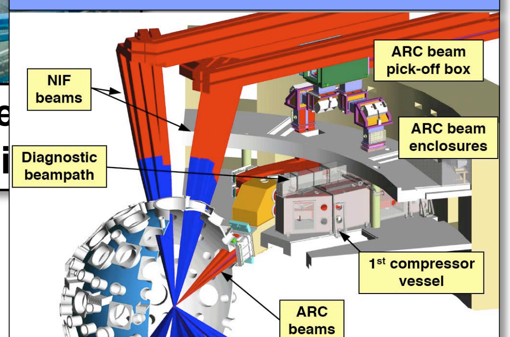


10 kJ compres
10 kJ ignit

OMEGA EP

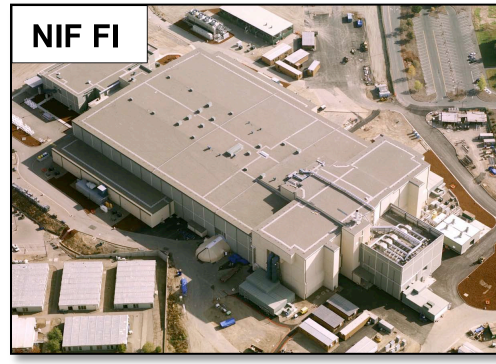
25 kJ compre
2.6 kJ igni

NIF

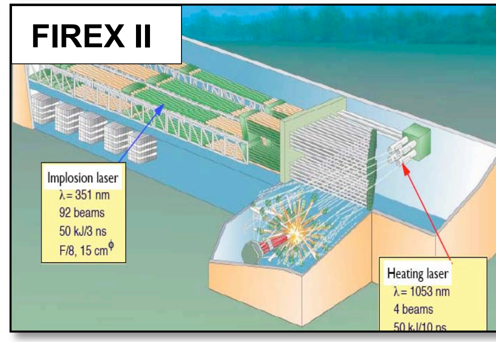


500kJ compression
10 kJ ignitor

NIF FI



FIREX II



HiPER