Fast Ignition Program Overview

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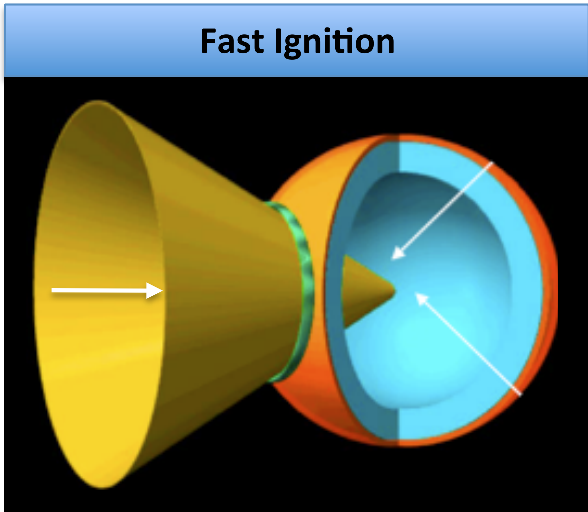
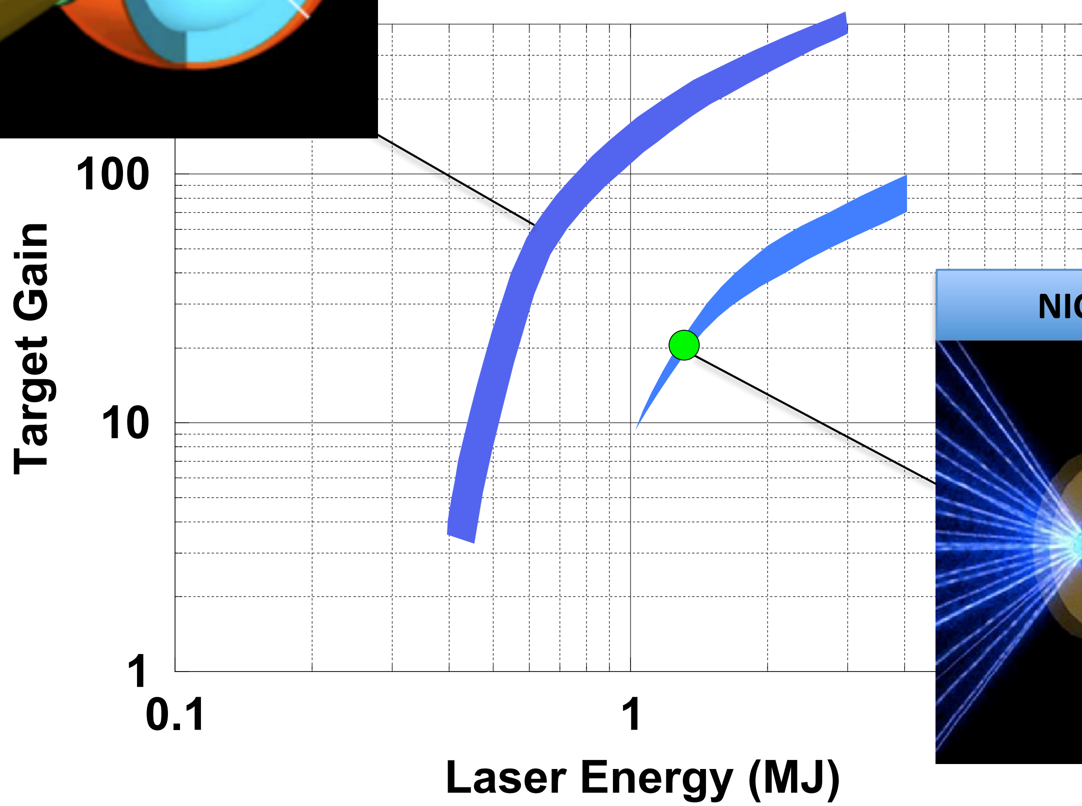
LLNL-PRES-463260

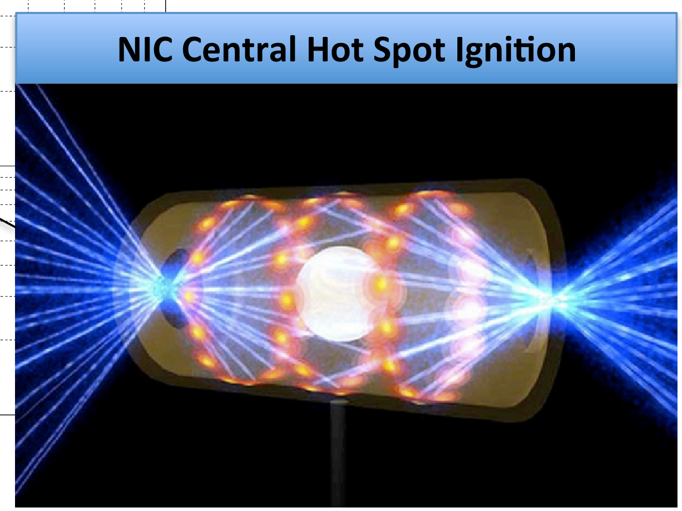
Fast Ignition is an alternate approach to conventional ICF for achieving high gain target fusion



- In CHS a high velocity isobaric implosion creates a high ρ, low T shell surrounding a high T, low ρ igniting hotspot
- In FI a low velocity isochoric implosion assembles fuel to high ρ, and a separate short-pulse heats a small region to ignition temperature

Lower velocity
➔ Higher fuel mass
➔ Higher gain

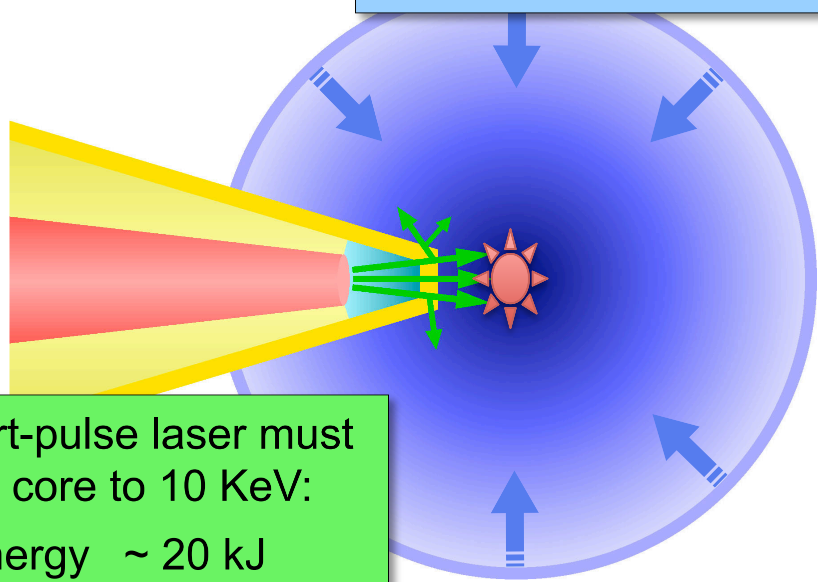




Ignition requires using an ultraintense laser-generated electron beam to heat a small fuel region to >10 keV

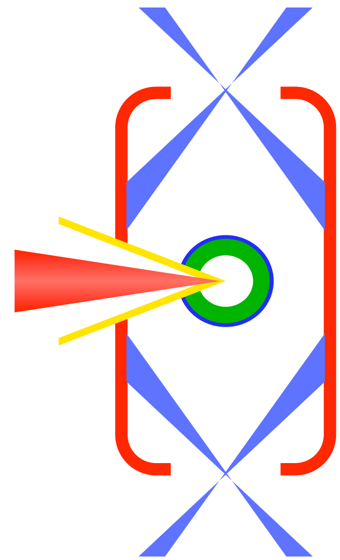
- Long pulse laser must compress fuel to:

  $\rho \sim 300\ g/cm^3$
  $\rho R \sim 2\ g/cm^2$



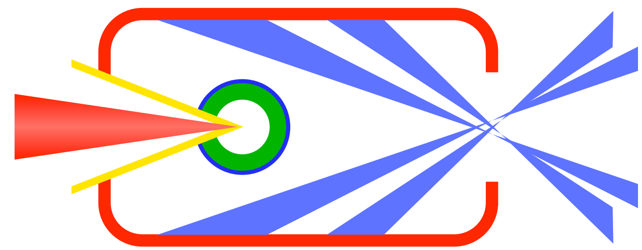
- Short-pulse laser must heat core to 10 KeV:

  Energy ~ 20 kJ
  Δz ~ 40 µm
  τ ~ 20 ps



NIF compatible geometry

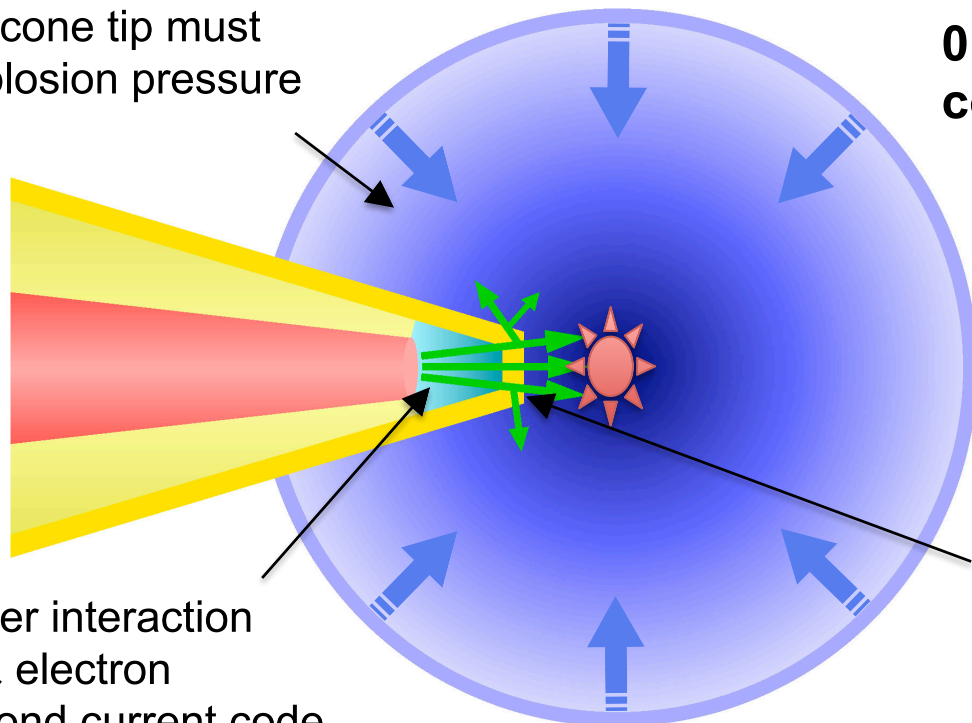
Low-angle incidence IFE option



- Significantly reduced symmetry requirements (non-spherical implosion) means more flexible irradiation geometries attractive for IFE

S. Atzeni, POP 8, 3316 (1999)

There are three principal scientific & design challenges for electron cone-guided fast ignition



- FI physics is extremely challenging—it encompasses ICF, relativistic laser interaction, particle beam transport in dense plasma—the fundamental science of all intense laser interactions with high energy density plasma

FI has attracted a large active research community with several joint University-National Laboratory programs

US FI Programs

Electron FI

FSC

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

OFES

ACFI

GENERAL ATOMICS

UR LLE

UCSD

THE OHIO STATE UNIVERSITY DEPARTMENT OF PHYSICS

UNIVERSITY OF ALBERTA EDMONTON, ALBERTA, CANADA

Los Alamos NATIONAL LABORATORY EST. 1943

Ion/Proton FI

Intl. FI Programs

HiPER

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

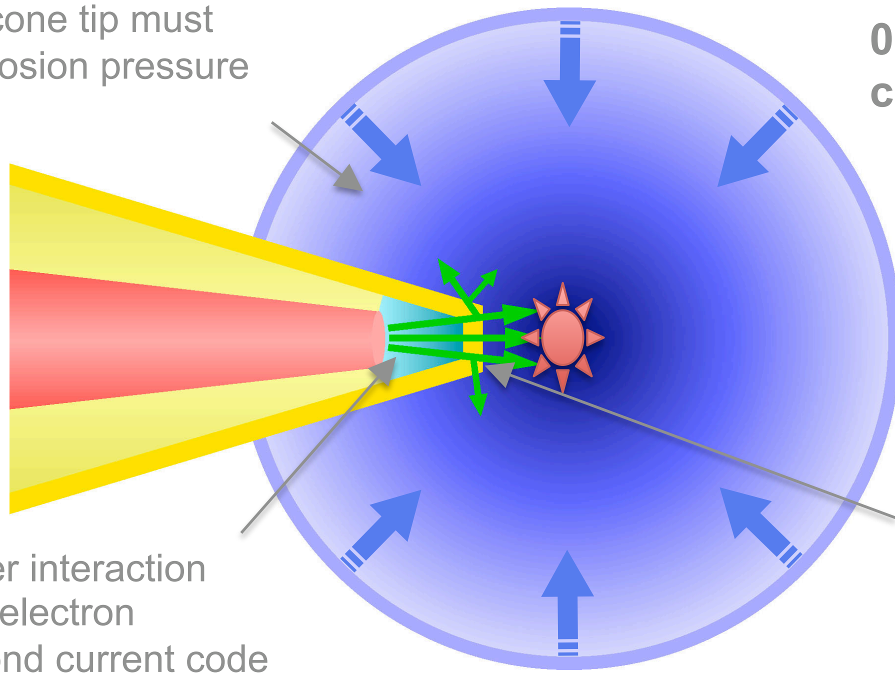
ILE, Osaka University

There are three principal scientific & design challenges for electron cone-guided fast ignition

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

0.5-1.0 MJ, 20ns compression drive

100-200 kJ, 20 ps ignitor pulse



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

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

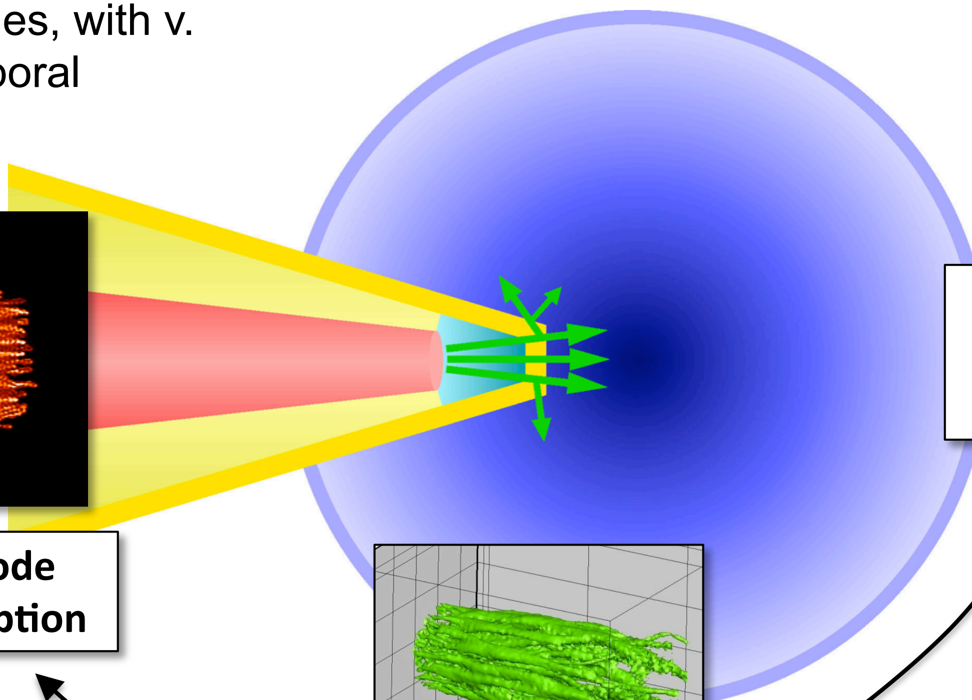
- ***No code capability exists that can model this physics self-consistently***

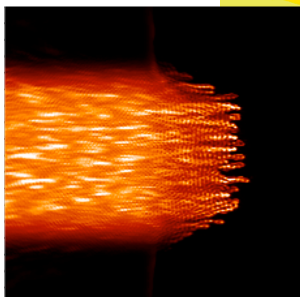
I. Predictive Simulation Capability

II. Experimental Validation

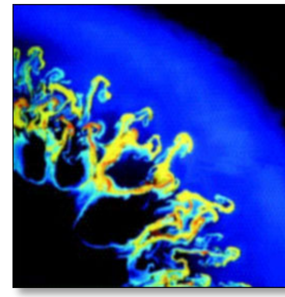
We embarked on a program to build a predictive simulation capability for FI and short-pulse HED physics

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





PSC PIC code
laser absorption



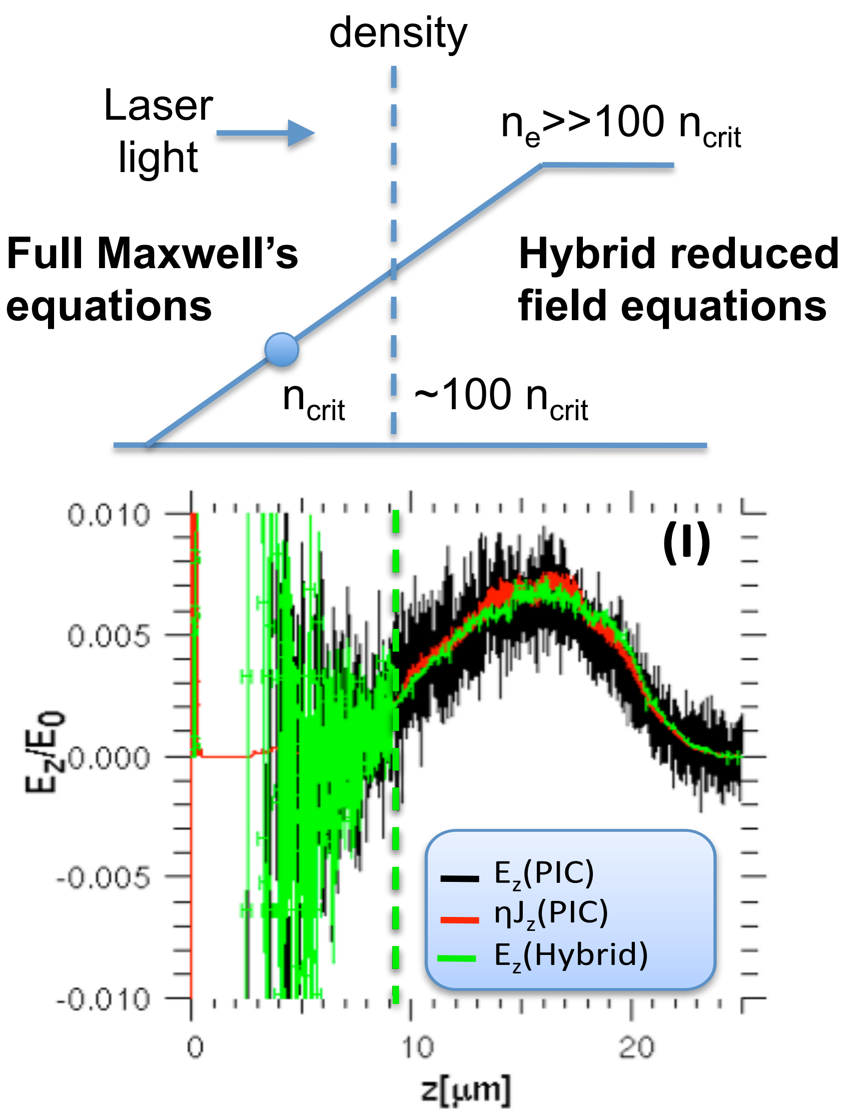
LASNEX, HYDRA
rad-hydro codes
implosion & burn

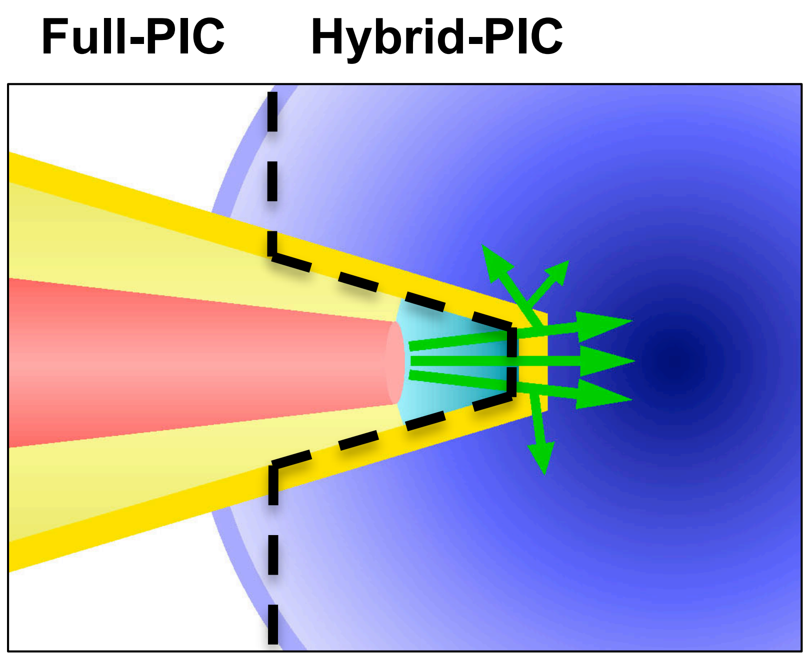
2D/3D rad-hydro (hydrodynamics, radiation transport, ionization kinetics, burn, etc.)
–leverages NNSA code development

ZUMA hybrid code
electron transport

3D hybrid transport (kinetic fast electrons with fluid background plasma)

A new Hybrid-PIC scheme enables self-consistent modeling of FI laser interaction with high density plasma



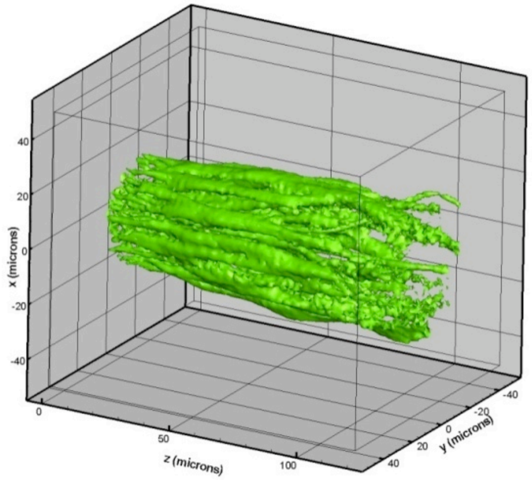


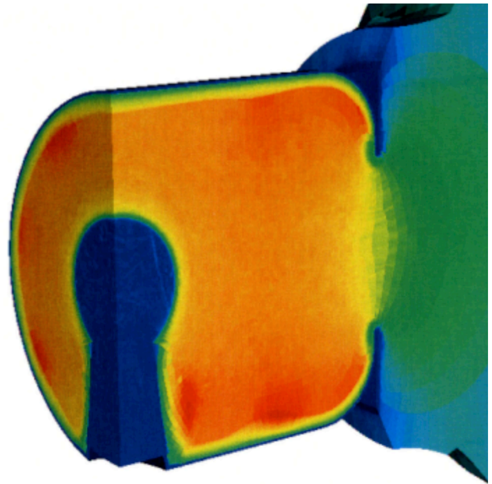
- Hybrid treatment in dense region allows reduced spatial & temporal resolution
- **1000x** speed enhancement demonstrated in 2-D simulations

B.I. Cohen et al., J. Comp. Phys. **229**, 4591 (2010); A.J. Kemp et al., Phys. Plas. **17**, 056702 (2010)

For self-consistent transport and burn calculations we have linked a hybrid-PIC code with the ICF code, HYDRA

ZUMA:
3-D hybrid-PIC relativistic electron transport code





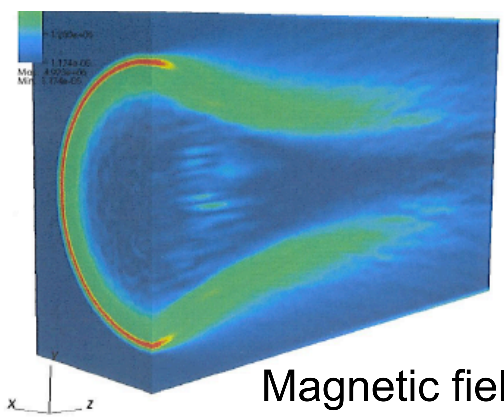
HYDRA:
3-D multiphysics radiation-hydrodynamics ICF code

Two codes run in parallel: dissimilar domains, meshes, and timesteops

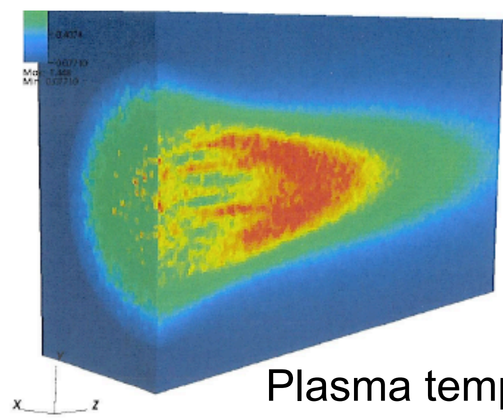
Overlink
Maps data between meshes

Energy, momentum deposition rates and magnetic fields exchanged

Test case:
3-D relativistic electron beam injected into 50 g/cc DT plasma



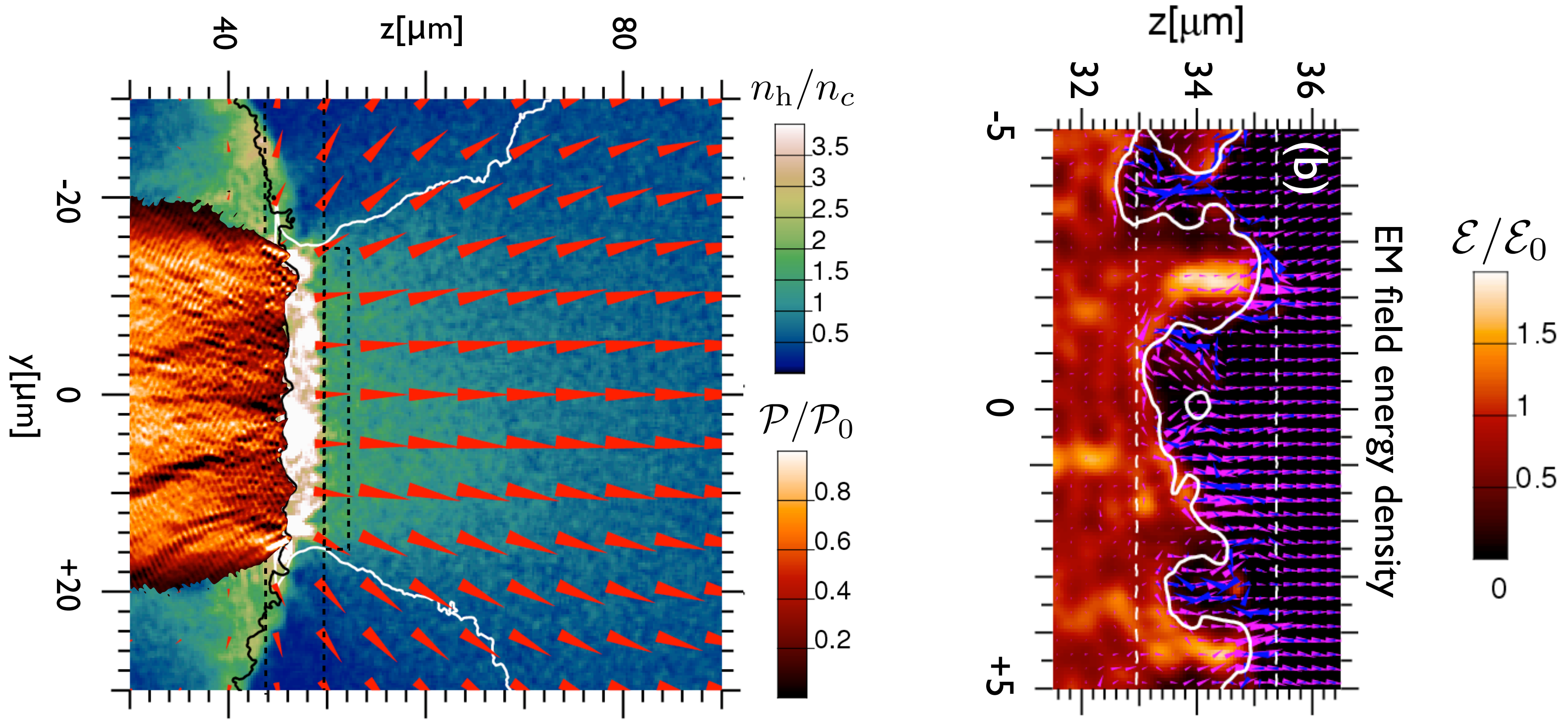
Magnetic field



Plasma temperature

We have performed the first simulations of an FI ignitor laser pulse at full spatial scale

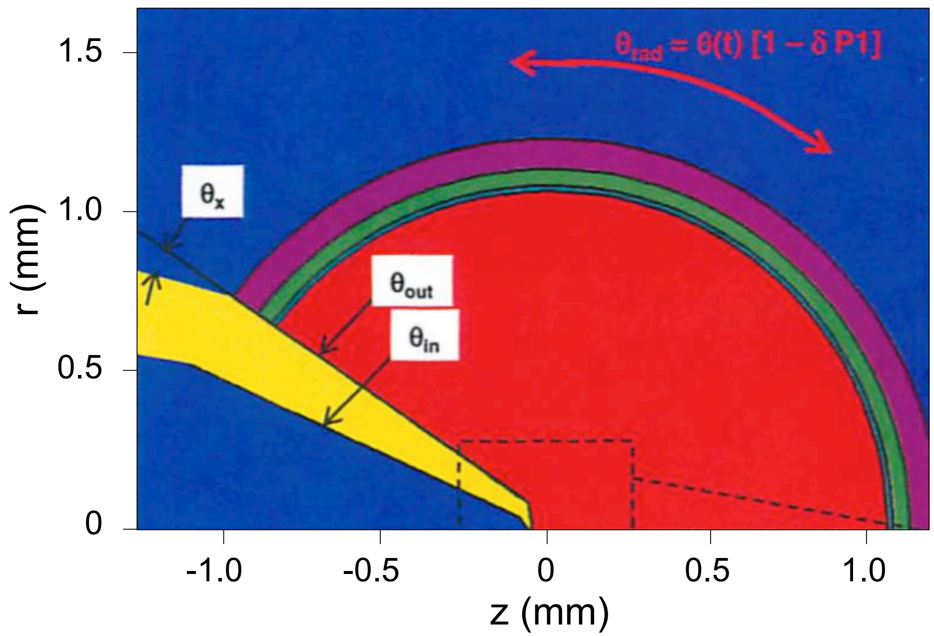
- 200kcpu-h @2048 cpus on ATLAS
- Simulate 40 µm diameter laser pulse for 2 ps duration
- I=1.4x10^{20} W/cm^2, 120x160 µm box, 50 cells/µm, 32e+32i ppc



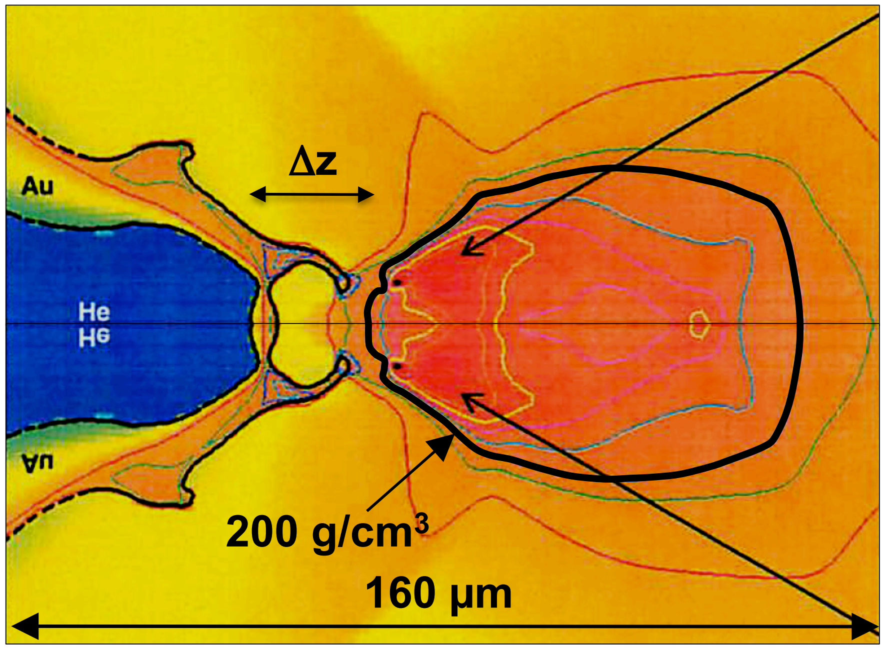
- These simulations provide the first realistic electron source distributions for subsequent transport calculations
- We observe high coupling efficiency but divergent beam due to µm-scale laser self-focusing

In 2D radiation-hydrodynamic implosion designs we can keep cone tip intact and obtain small tip-core distance

Optimization parameters



Optimal fuel assembly

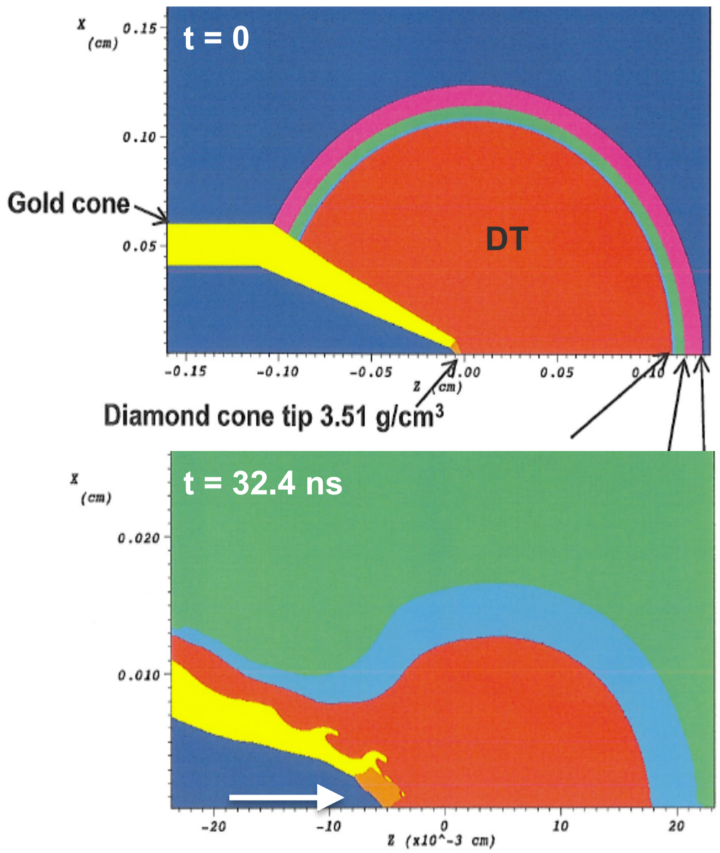


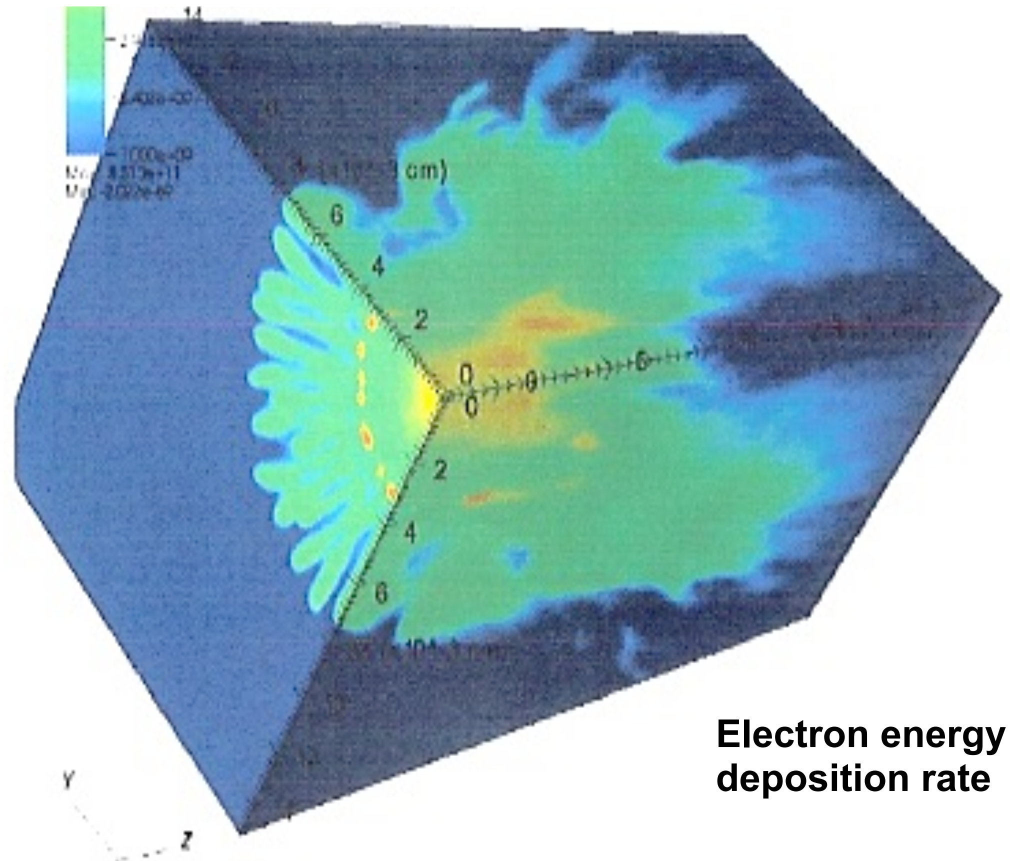
- We use a single shock radiation drive optimized for isochoric fuel assembly
- Optimize design to obtain max ρR prior to shock breakout at cone tip

- Peak ρ ~ 360 g/cc
- Peak ρR ~ 1.36 g/cm^2
- Cone-to-core Δz < 50 µm
- Target ignites with ~17 MJ yield

We have recently begun performing fully integrated 2D/3D capsule implosion, core heating and burn simulations

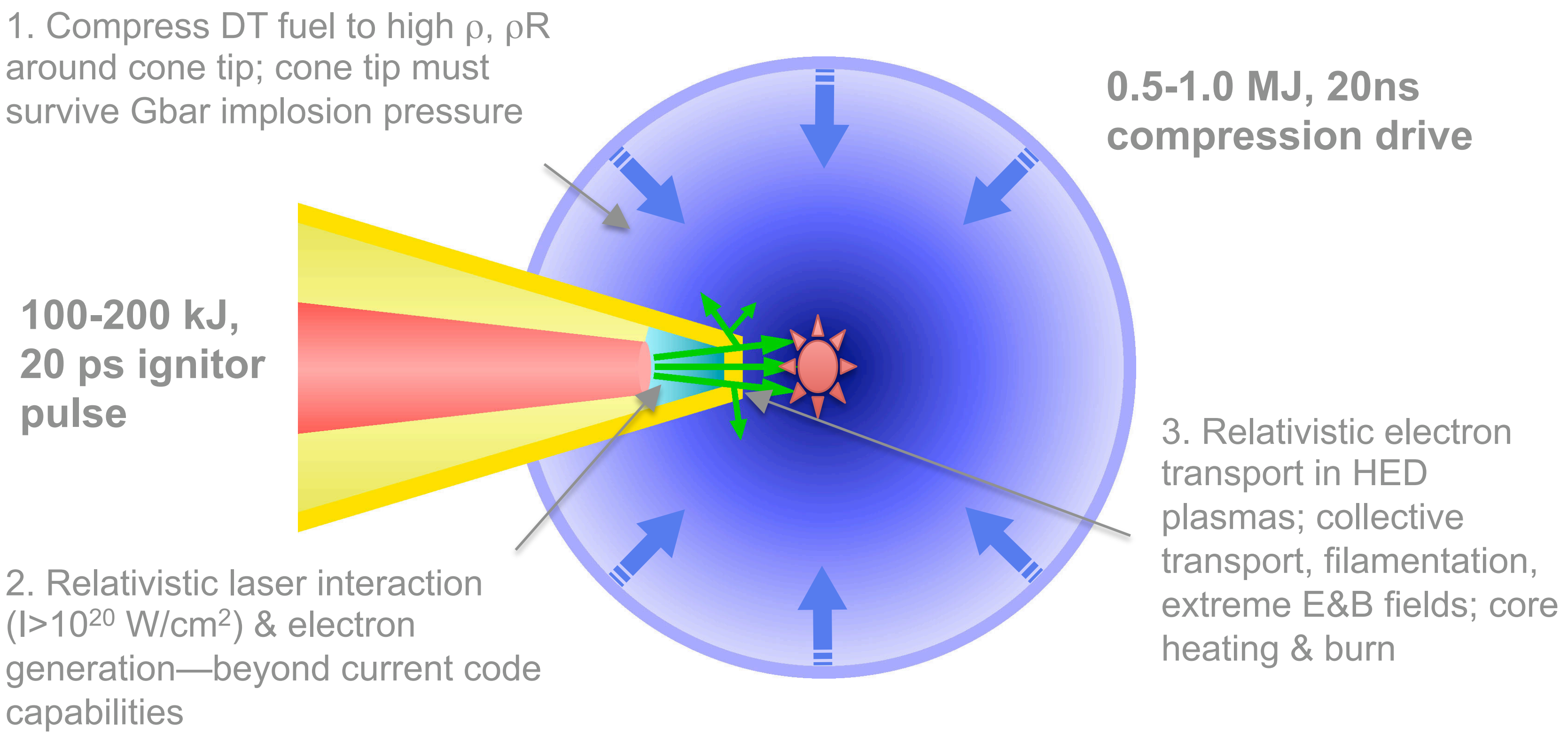
- 3D simulation initialized with axisymmetric profiles at beginning of electron pulse
- 47.7 million zones in HYDRA mesh with 100 million IMC photons run on 1024 processors
- 36 millions zones in Zuma mesh – 1 μm resolution on each mesh





- We are now developing a self-consistent FI Point Design with a goal of gain>100 with 1 MJ total laser drive

There are three principal scientific & design challenges for electron cone-guided fast ignition

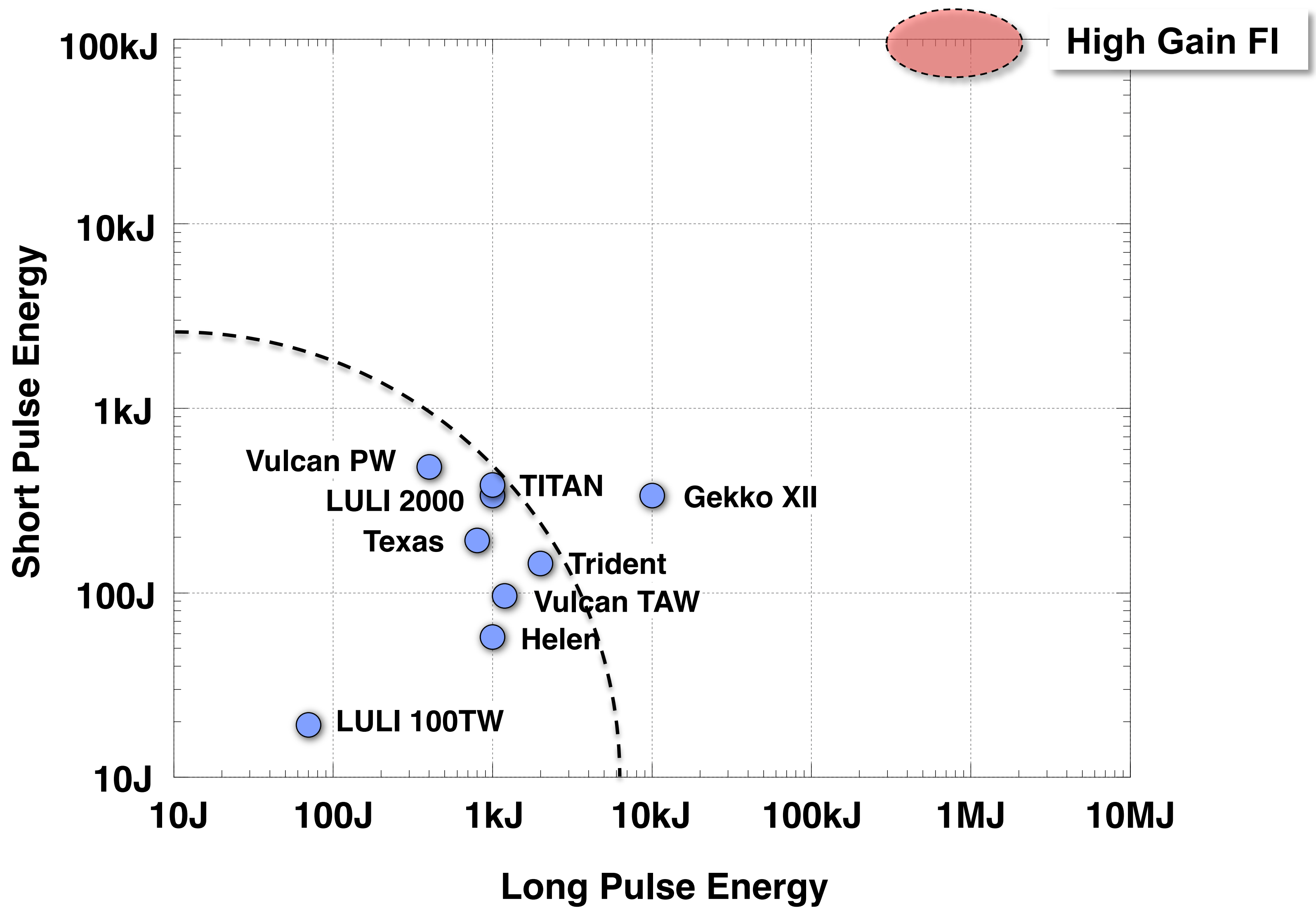


- ***No code capability exists that can model this physics self-consistently***

I. **Predictive Simulation Capability**

II. **Experimental Validation**

A new generation of facilities have come online capable of integrated tests of fast ignition physics



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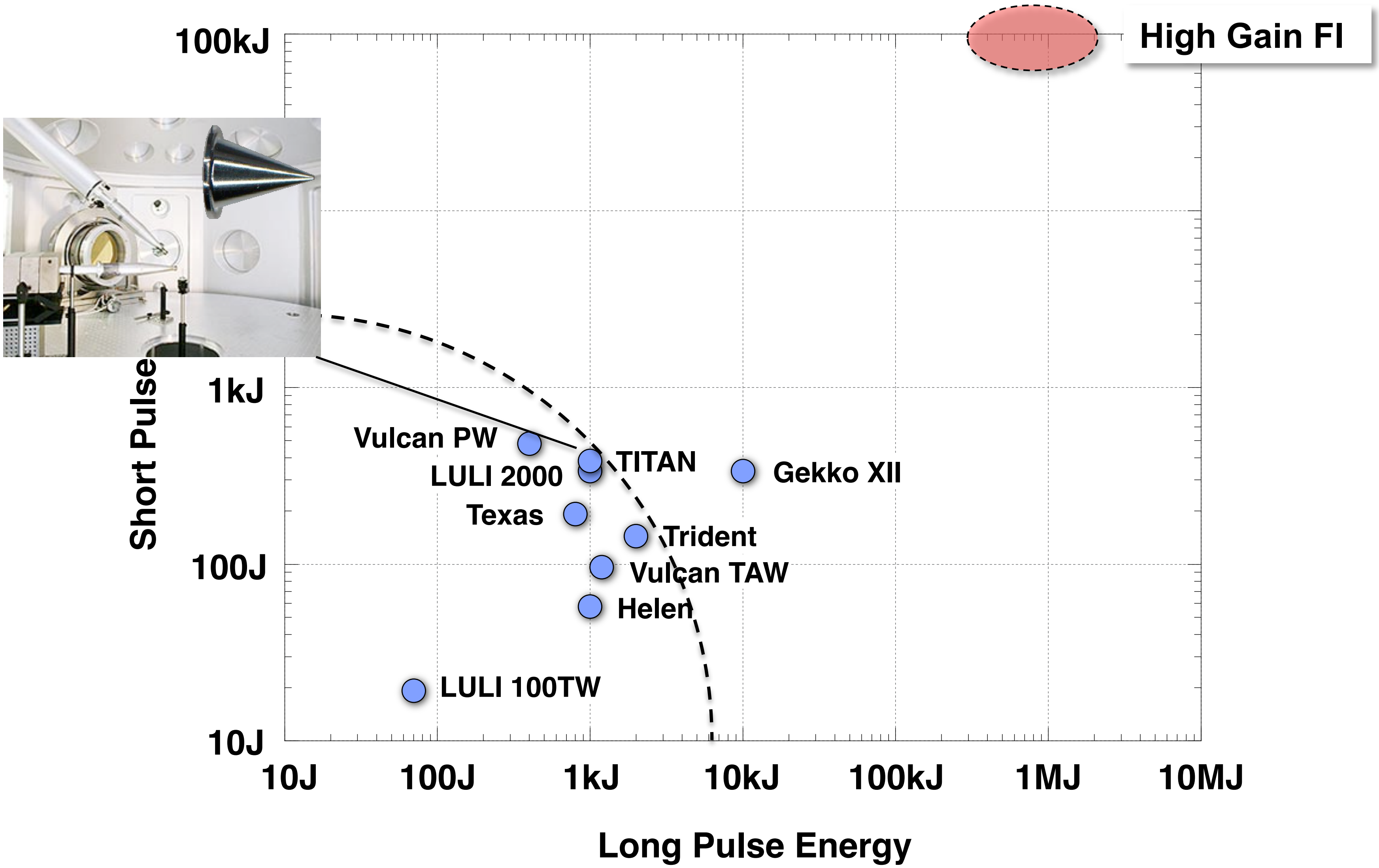

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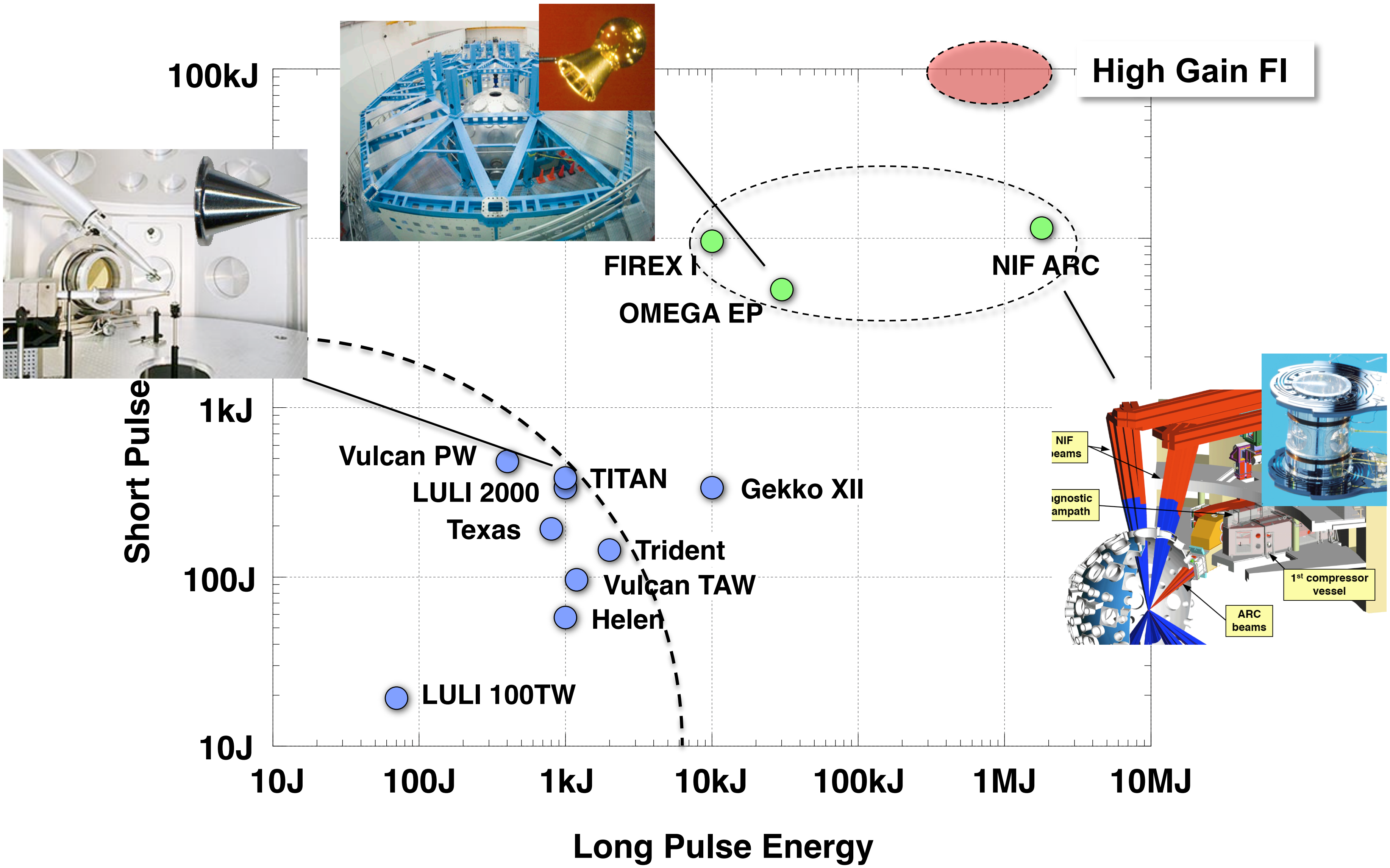
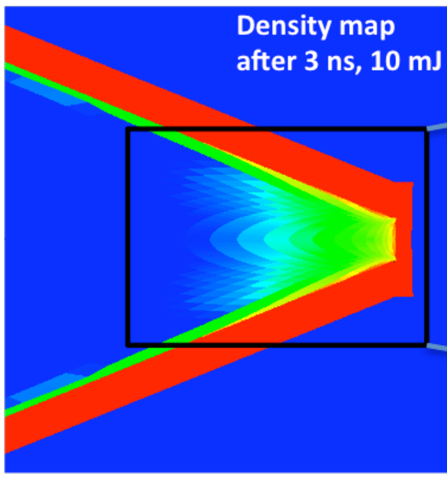
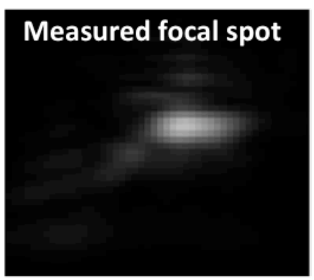


TITAN: New benchmark quality experiments are combining with massively parallel full-scale PIC simulations

HYDRA rad-hydro simulation
10^{13}W.cm^{-2}, 3 ns, 2 mm x 2mm

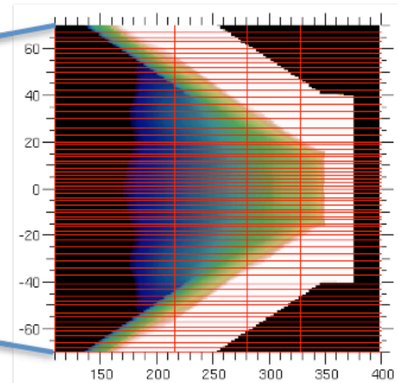


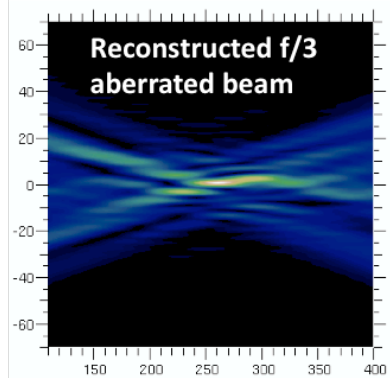


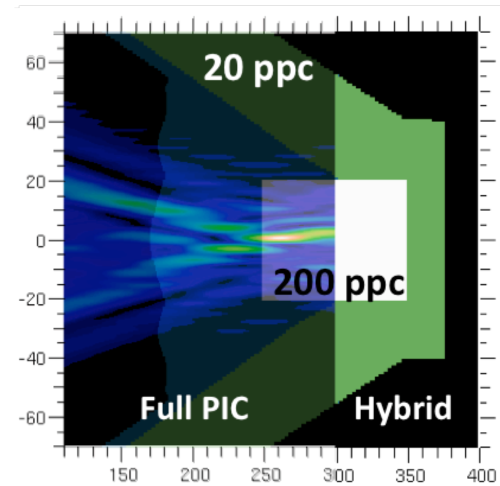
Input parameters are measured laser prepulse and actual target metrology

Massively parallel PIC/Hybrid simulation
10^{20}W.cm^{-2}, 2 ps, 200 x 200μm

Load balancing on MPP cluster

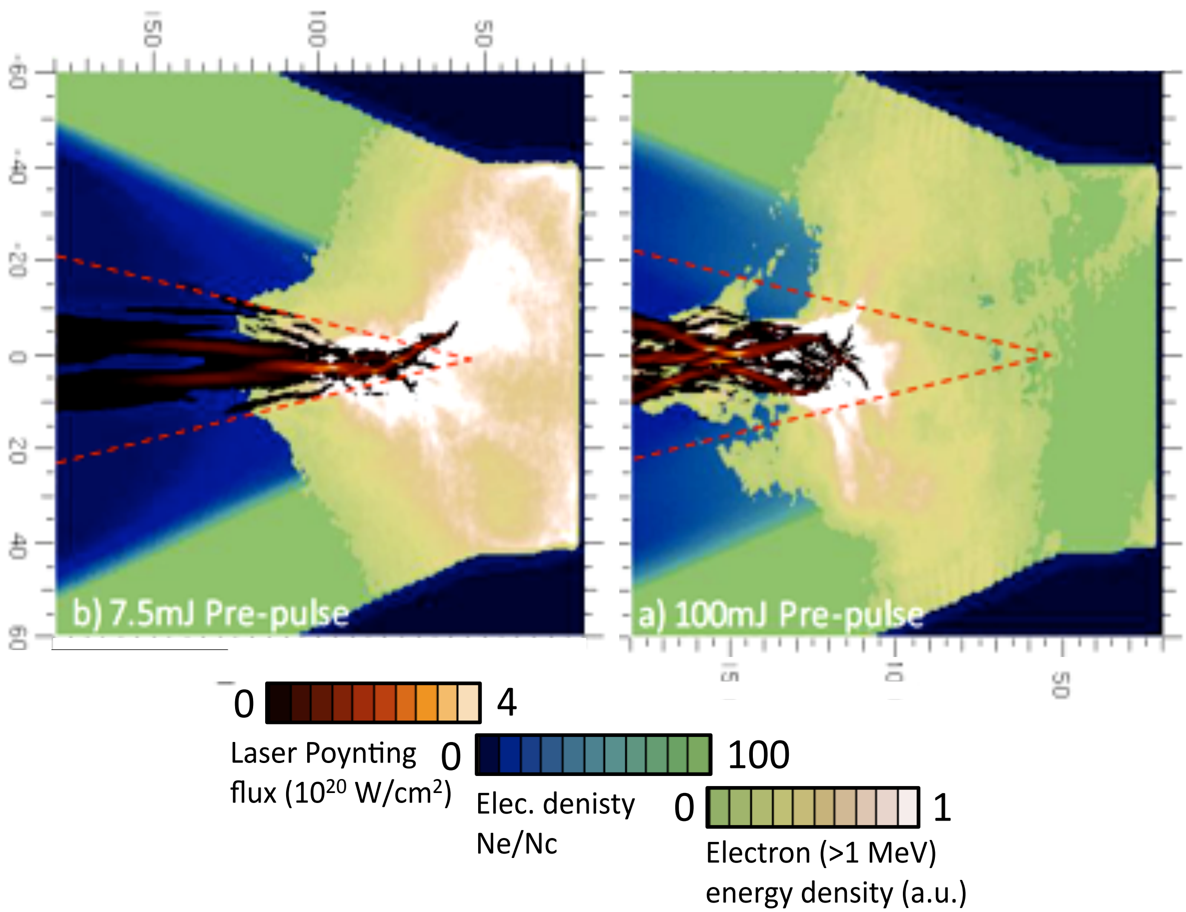


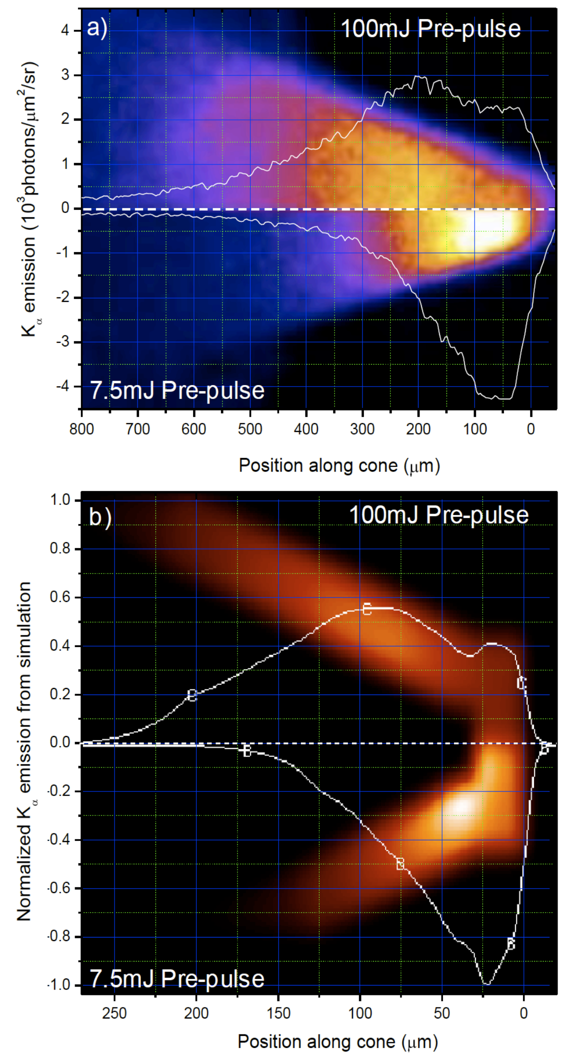




Multi-scale multi-physics massively parallel simulation with realistic input parameters

TITAN: New benchmark quality experiments are combining with massively parallel full-scale PIC simulations

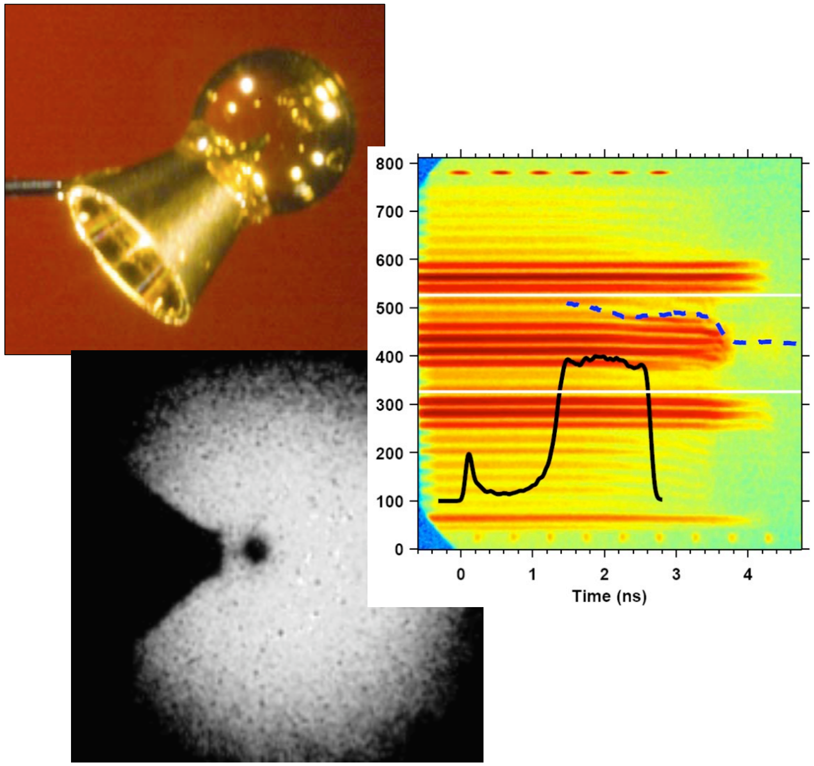


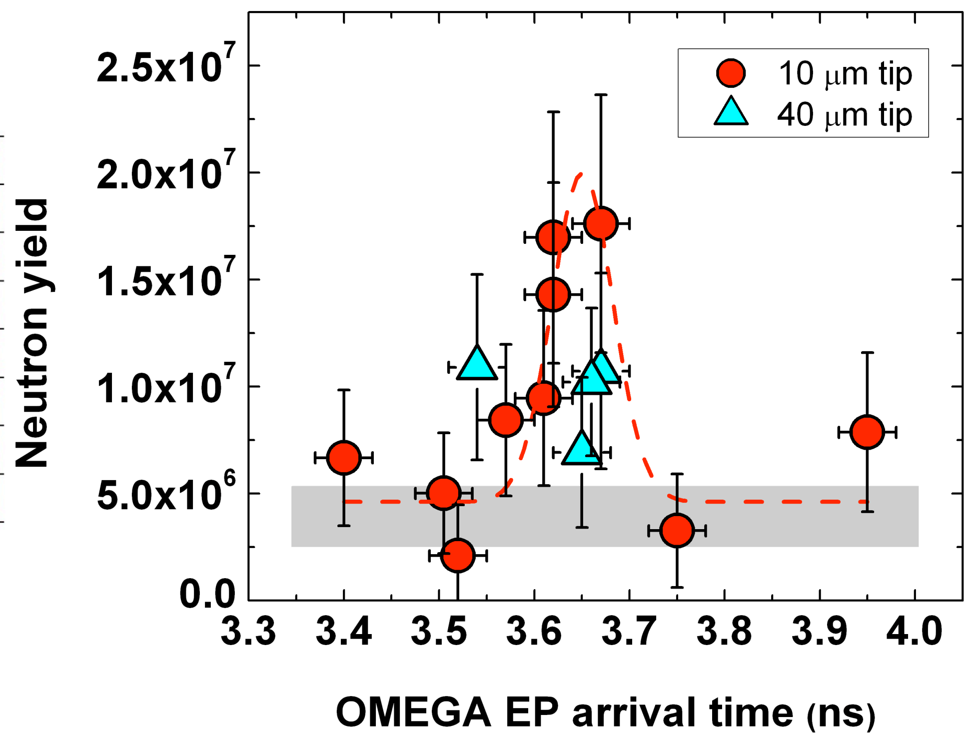


- Predictive simulation capability is emerging for relativistic laser interaction with HED plasma

A. G. MacPhee et al., PRL. **104,** 055002 (2010)

OMEGA EP: A robust experimental platform has been established for studying integrated FI physics

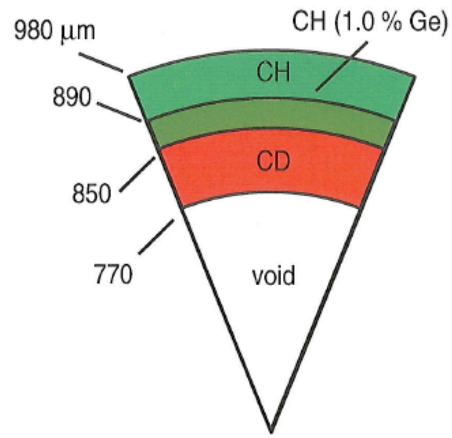




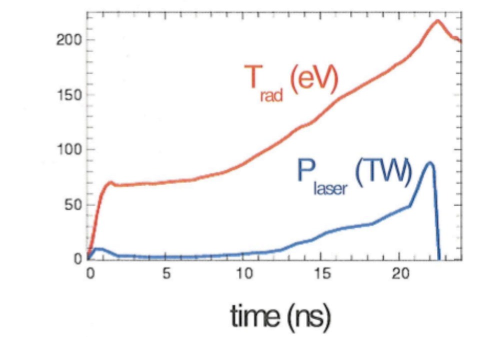
- First confirmation of fast electron core heating since original Osaka experiments
- High laser and diagnostic performance of OMEGA EP makes it an ideal facility for studying FI physics, and validating integrated simulation codes

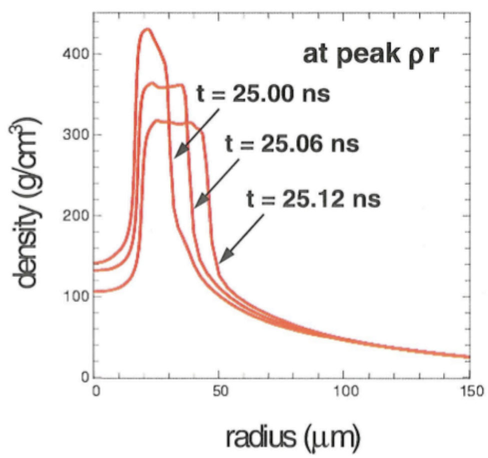
NIF: First campaigns are planned to study full-scale compression of a cone-in-shell FI target

FI hydro-equivalent warm capsule

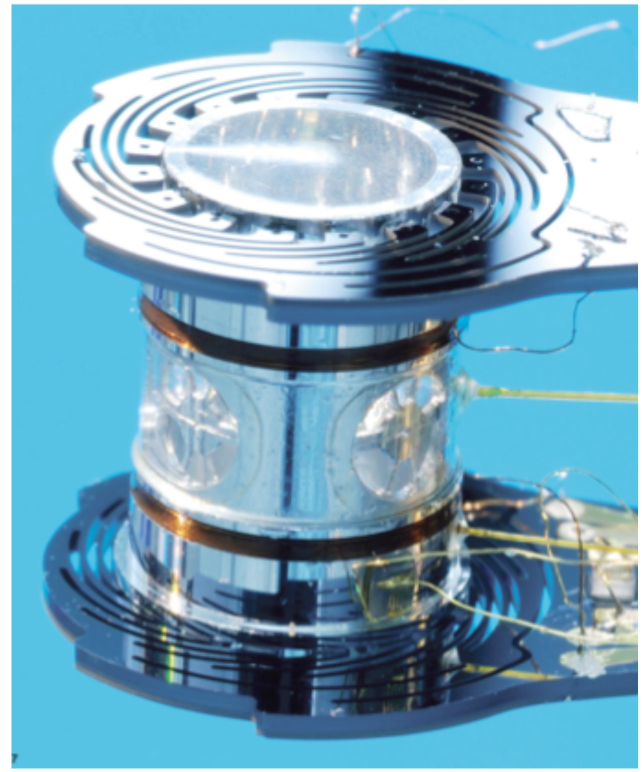


fuel mass (mg)	0.74
implosion vel. (mm/ns)	0.106
peak density (g/cm³)	431
peak fuel ρ r (g/cm²)	1.70
laser energy (kJ)	440



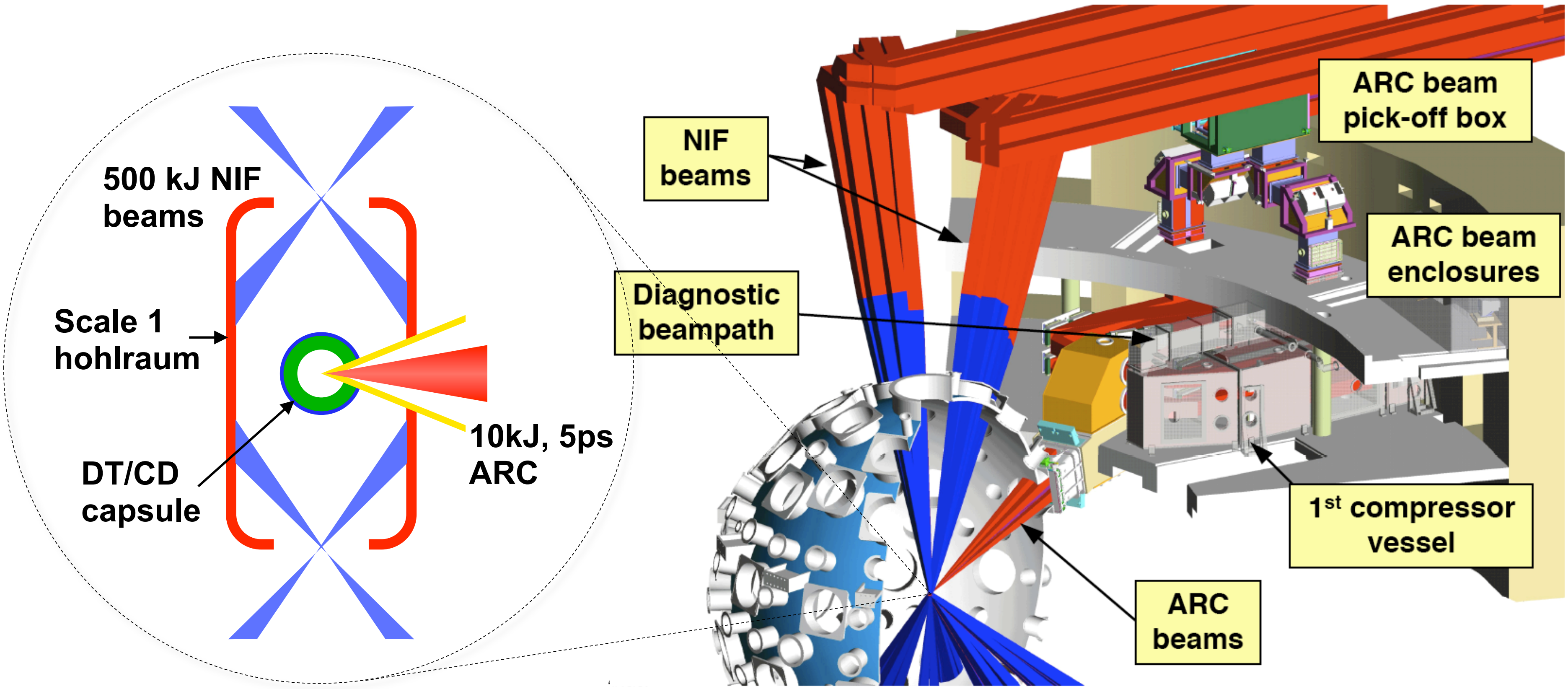


Standard NIC hohlraum



- A series of experiments on NIF over the next 2-3 years can validate all key physics of FI compression at full hydrodynamic scale
- Experimental techniques, tuning methodologies, diagnostics developed by the NIC directly apply to FI

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



- At 10 kJ, 5 ps ARC can be used to demonstrate efficient fast electron heating of a full scale hydro assembly, and thus, provide a high degree of confidence in a final high gain fast ignition point design

We aim to demonstrate FI feasibility within the next 4-5 years through predictive simulation & experiment

- The last two years have seen tremendous progress in the development of large-scale predictive simulation capability for FI—we are close to fully integrated simulations

- We are applying these tools to develop and refine a fully self-consistent FI Point Design

- We now have the laser facilities required to experimentally validate all key physics of FI—relativistic laser interaction, full-scale fuel compression, and core-heating. The national and international research communities in FI are working toward this in a highly co-ordinated way