Fast Ignition Program

E. Michael Campbell

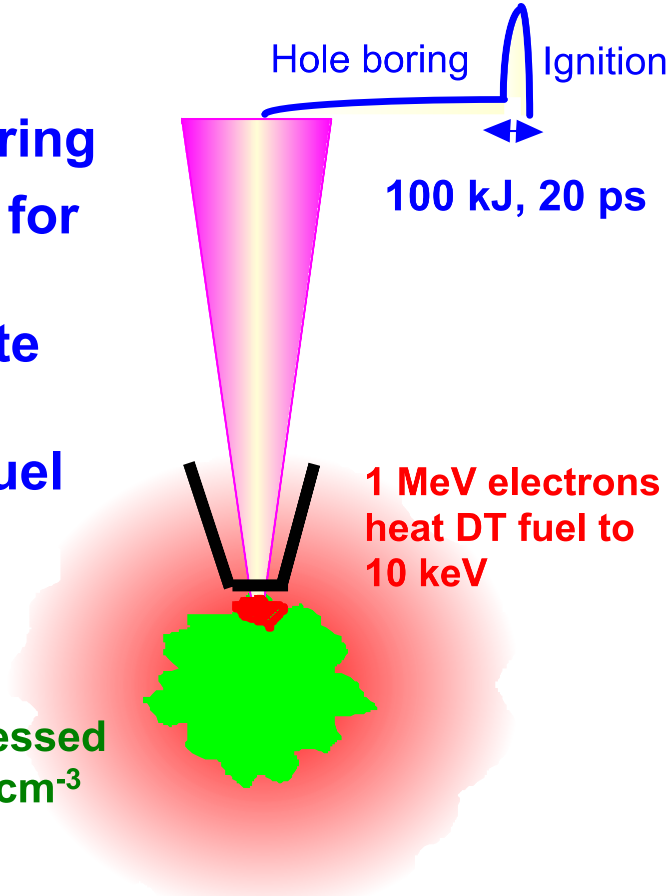
- Promise
- Status
- Challenges
- Implementation
- Plan

Presented at
FESAC Development Path Panel
General Atomics

January 14, 2003

The original FI concept uses laser generated MeV electrons to ignite DT fuel at about 300 $\mathrm{gcm^{-3}}$

Hole boring or cone for laser to penetrate close to dense fuel



Fast ignition

Ignition spot energy

$$E = 140\,(100/\rho)^{1.8}\ \mathrm{kJ}$$

e.g. ρ=300 g cm^{-3}, E=17 kJ

in <20 ps

to r=19 μm hot spot

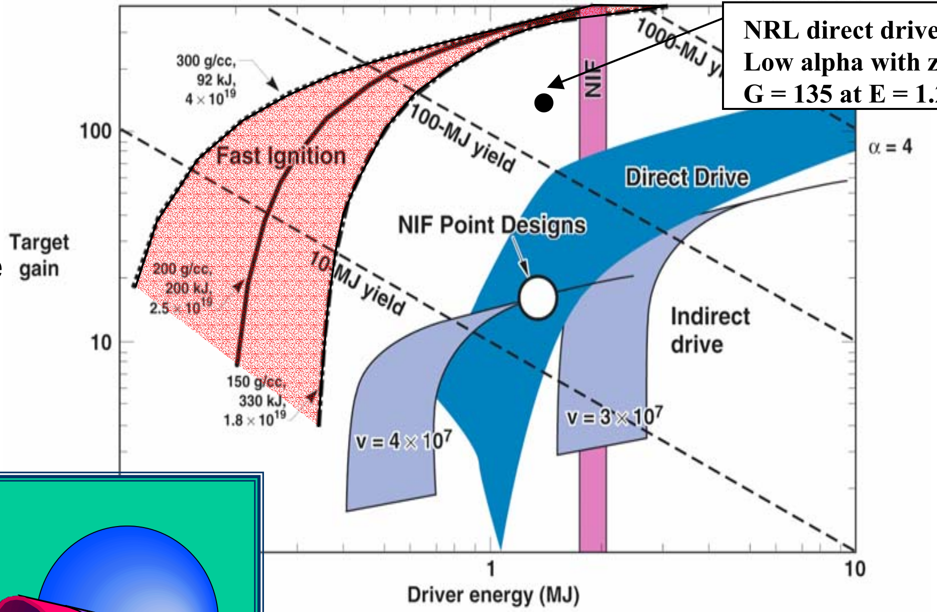
at 7×10^{19} Wcm^{-2}

Atzeni. Phys. Plas. 6 3316 (1999)

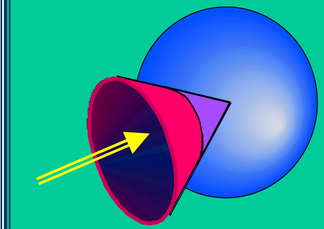
Tabak et al. Phys Plasmas 1,1626,(1994)

Fast Ignition concept leads to an attractive system

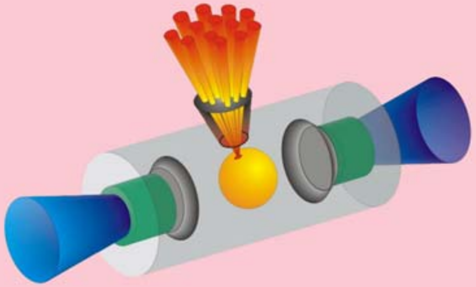
- Low threshold to reach ignition
  - ⇒ Use lower brightness drivers
- High gain for efficient power plant
- No central hot spot required -relaxes drive symmetry and target smoothness requirements- driver configuration and target fabrication advantages
- Compatible with any driver



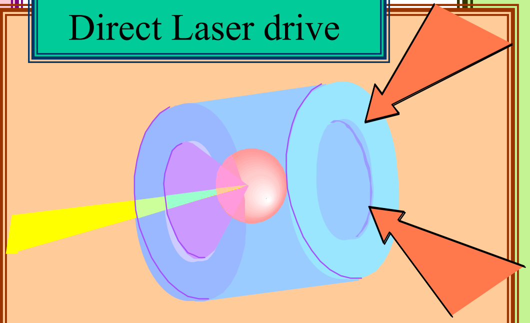
NRL direct drive design
Low alpha with zooming
G = 135 at E = 1.2 MJ



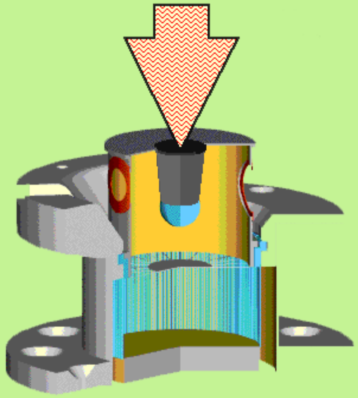
Direct Laser drive



Heavy Ion Beam Drive



Indirect Laser drive



Z-pinch Drive

Fast Ignition may allow longer wavelength laser implosion systems -The advantages are significant

- Efficiency
  - Typical energy efficiency for conversion of 1053 nm to 351 nm is 50% (NIF, Omega)

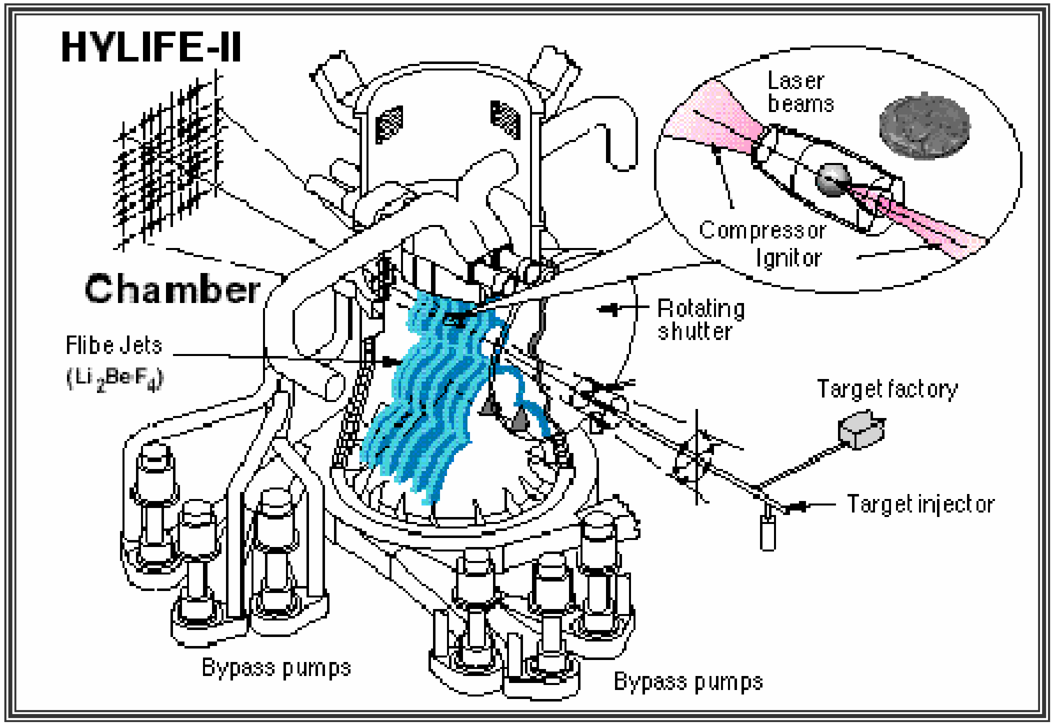
2x the pulsed power (or diodes!)

- Aperture
  - Damage threshold for 1053 nm is ~35 J/cm^2, 532 nm is 25 J/cm^2 and 351nm is ~12-15 J/cm^2

40%-70% reduction in aperture!

Allows flexible reactor development

- Relax construction constraints
  - Flexible drivers and driver locations
  - Possible self T-breeding
- Target injection
  - Not so temperature sensitive
  - Reentrant cone protects from hot gas



FI program leverages both NNSA and international capabilities

- Laser coupling and transport (LLNLLANL,LULI (France),RAL (UK),GEKKO(Japan)
  - $E_{laser} \sim 140\ (\rho/100)^{-1.8} \eta^{-1}$ kJ
- Compression (LLE,SNL,GEKKO,RAL)
  - $E_{comp} \sim 1.4 * 10^3\ \rho^{-4/3} (\rho R)^3 \eta^{-1}{}_{comp}$
- Integral experiments (GEKKO, RAL)

U.S. Fast Ignition research is linked to world-wide effort

- Requires facilities with powerful short-pulse (ps) lasers
- Substantial programs in England, France, Japan
  - Japanese researchers are staking their program on it
- United States program is important
  - Nova was first PW in ‘96
  - Proceeding with DoE high energy PW initiative
  - Next-step PW facility at SNL, NIF, Omega

Ecole Polytechnique
Palliseau, France

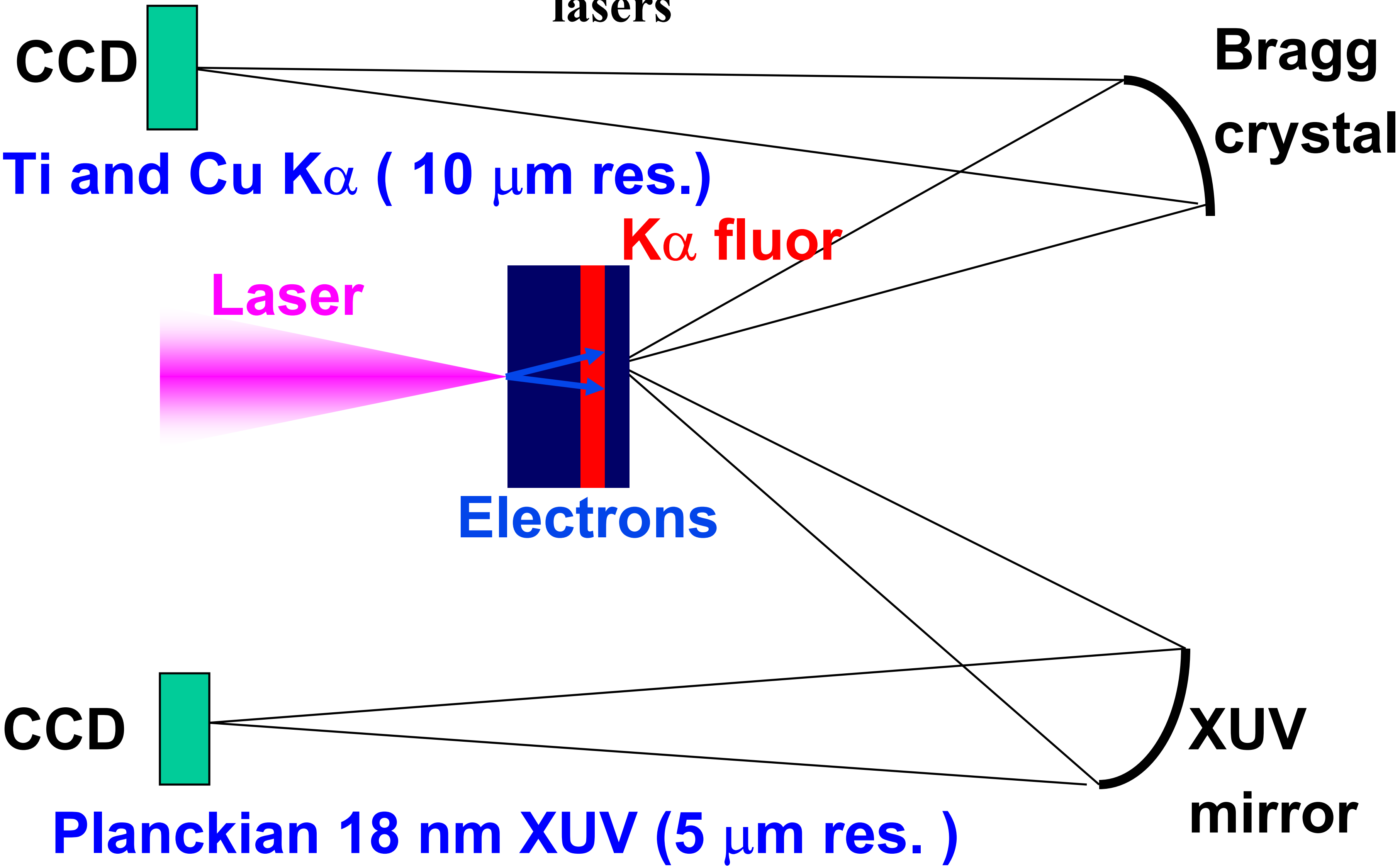
GSI & Technische Universitat
Darmstadt, Germany

Central Laser Facility
Rutherford Appleton Lab, UK

Institute for Laser Engineering
Univ. of Osaka, Japan

Max-Planck-Institut
Garching, Germany

Layered, planar targets have been utilized to study laser-plasma coupling and transport with 100 TW, 0.1 to 1 ps lasers

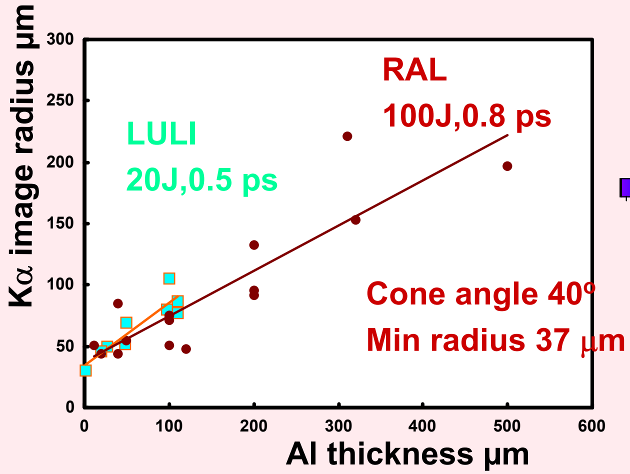


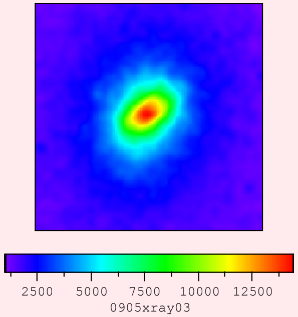
Ignition energy transport requires more understanding

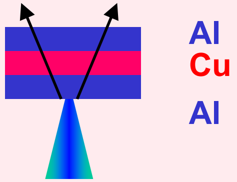
- Initial steps look good
  - Efficient electron production
  - Produce well defined beam
  - Can heat compact spot the size of K_α beam

- But beam and heated spot is much larger than the laser focal spot

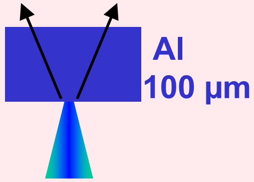
K_α imaging of electrons shows production of collimated beam

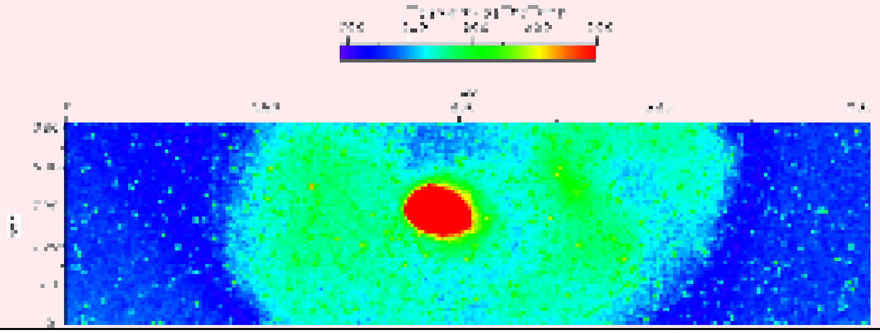




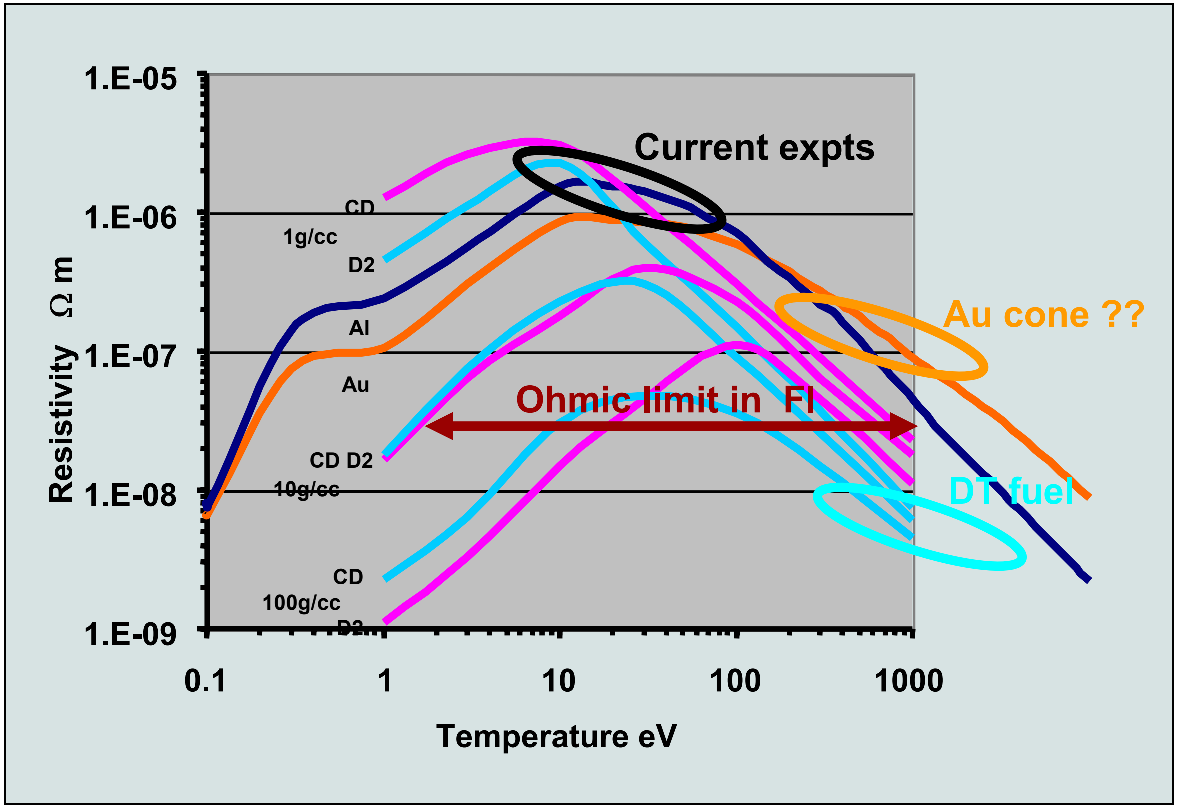


Thermal XUV shows 30 eV heating in 120 µm hot spot





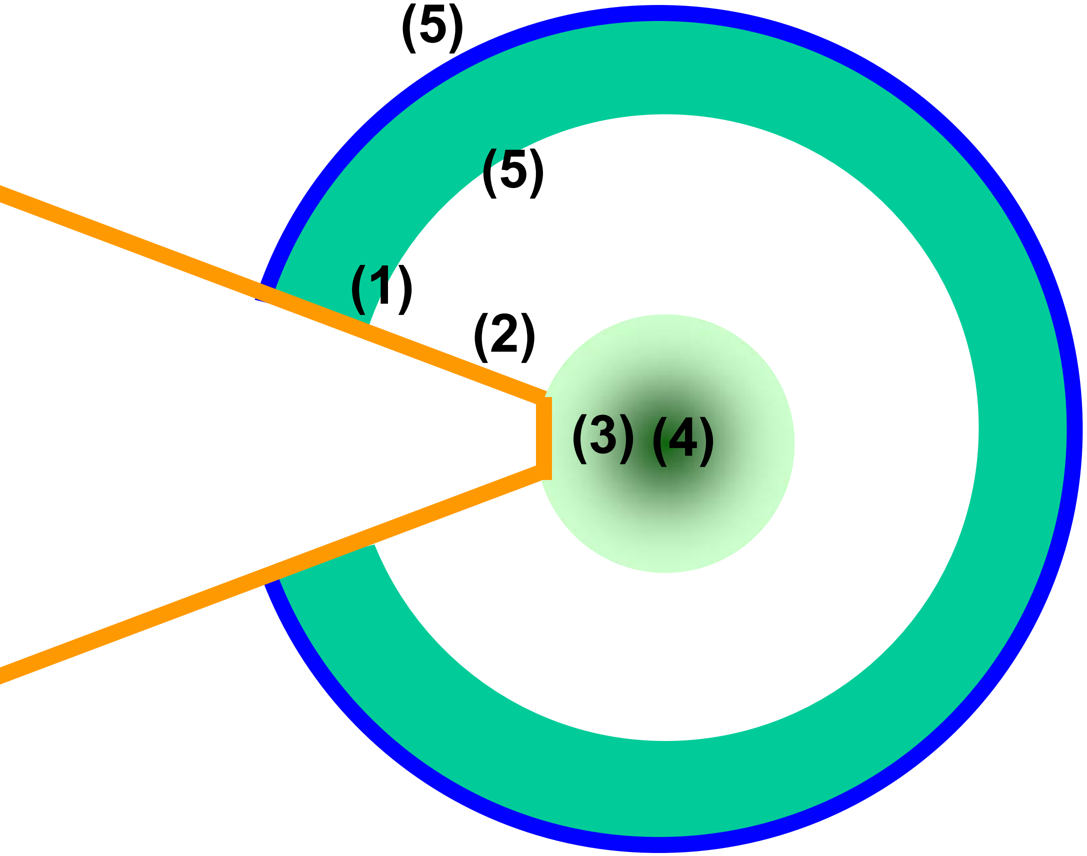
Resistivity dominates our current experiments but it will be negligible in full scale fast ignition



- Ohmic fields strongly affect electron transport in cold metals
- Facilities at Vulcan & Gekko allow testing in compressed plasmas

⇒ Currently developing new experimental geometries for such experiments

Fuel assembly targets with cones are a focus for FI reseach



Issues

(1) Shell /cone interface hydro entrainment of cone material

(2) Preheat of cone ahead of imploding shell

(3) Cone tip-dense core transport distance

(4) Avoidance of ‘hollow centre’ in compressed core

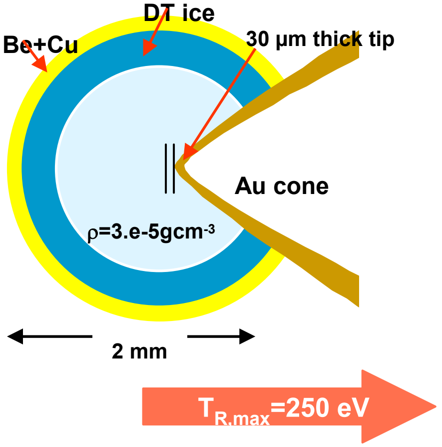
(5) Drive symmetry and surface smoothness requirements

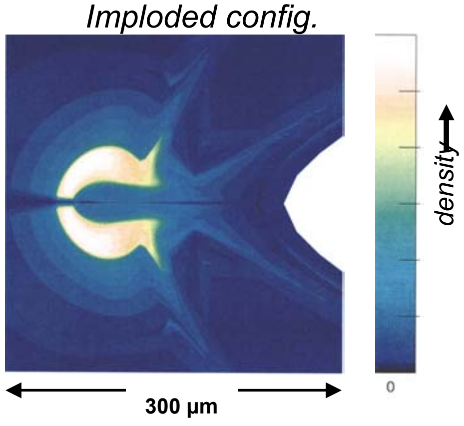
Validate fuel assembly concepts in ‘hydro- equivalent’ targets

Fuel assembly seems straightforward

LLNL designed NIF scale capsule (absorbs ~180kJ*) can be imploded to $\langle \rho R \rangle_{DT}$=2.18 g cm^{-2}.

*** expect 10% overall coupling efficiency, or better**

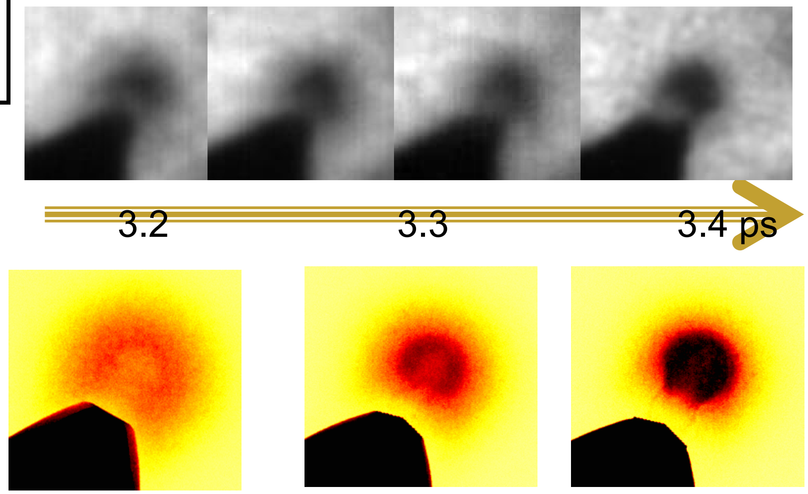




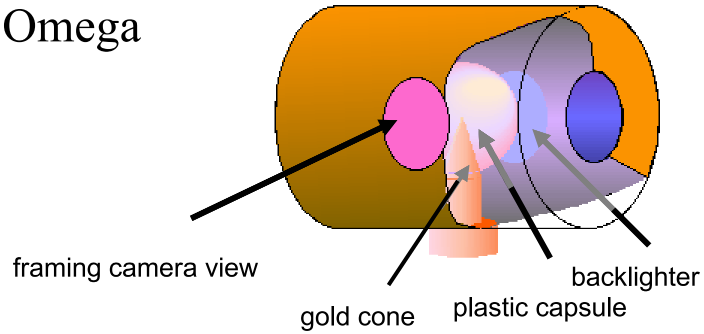
Blob has hollow core, is ~100 μm from cone.

- Basic target design works
  - Target compresses to ignitable mass in Lasnex
  - Initial expts show agreement with model
  - Other variations being tested at SNL and Omega

Omega expts match simulations

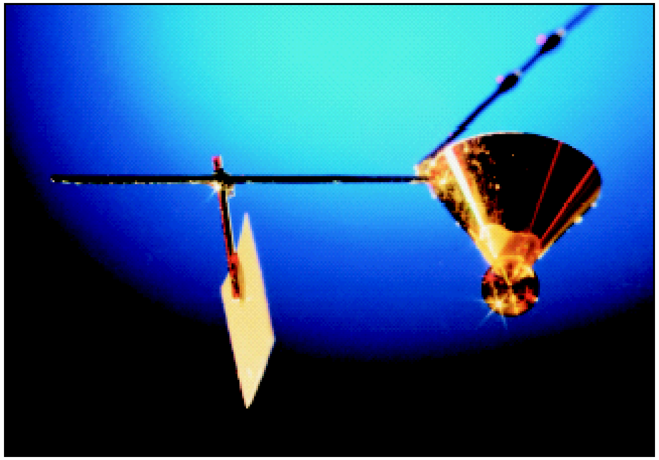


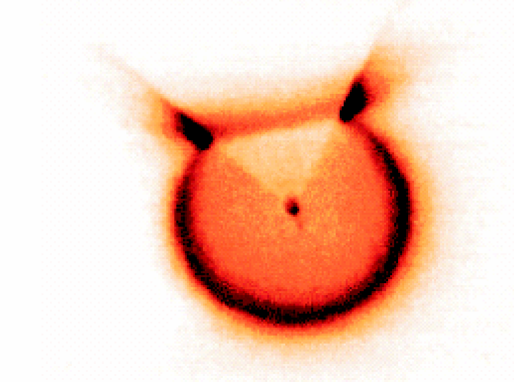
Expt at Omega



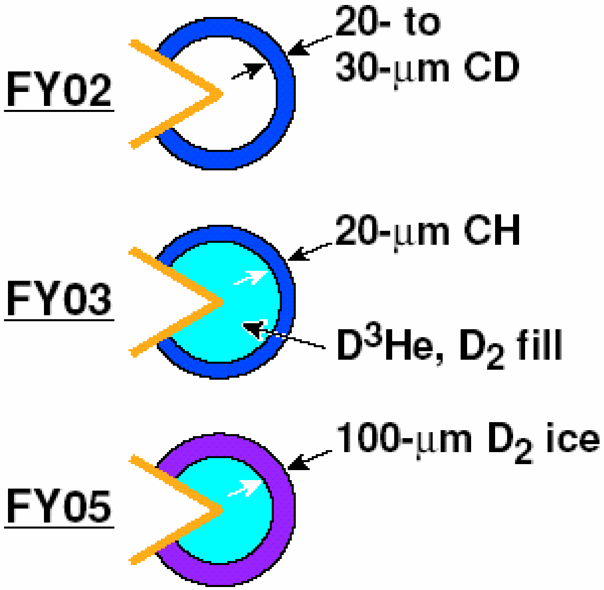
Fuel assembly experiments with cone-focused targets leverage the OMEGA direct-drive program

Direct-drive cone targets shot on OMEGA in FY02
(LLNL, GA)





Pinhole camera (H8)



FY02

20- to 30-μm CD

FY03

20-μm CH

D^3He, D_2 fill

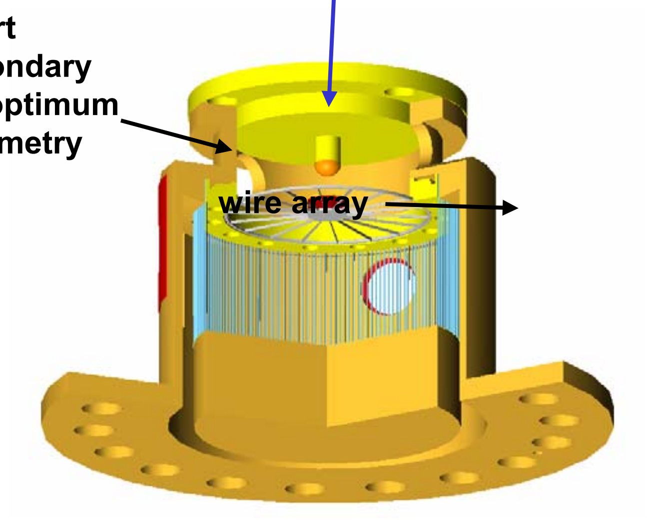
FY05

100-μm D_2 ice

The full suite of OMEGA diagnosics will be applied to these implosions.

A z-pinch driven fast-ignitor concept is being developed

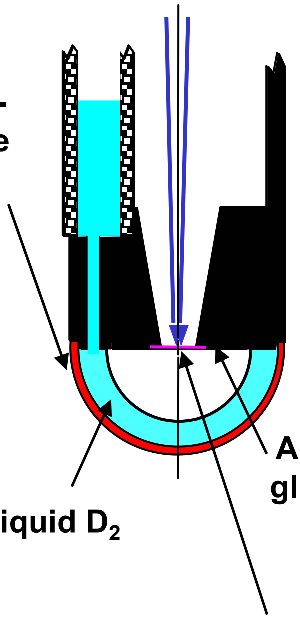
PW laser access to compressed fuel inside capsule support stalk



Short secondary for optimum symmetry

wire array

2-mm-diam hemi-spherical capsule on support stalk



Liquid D_2

Au-coated glide plane

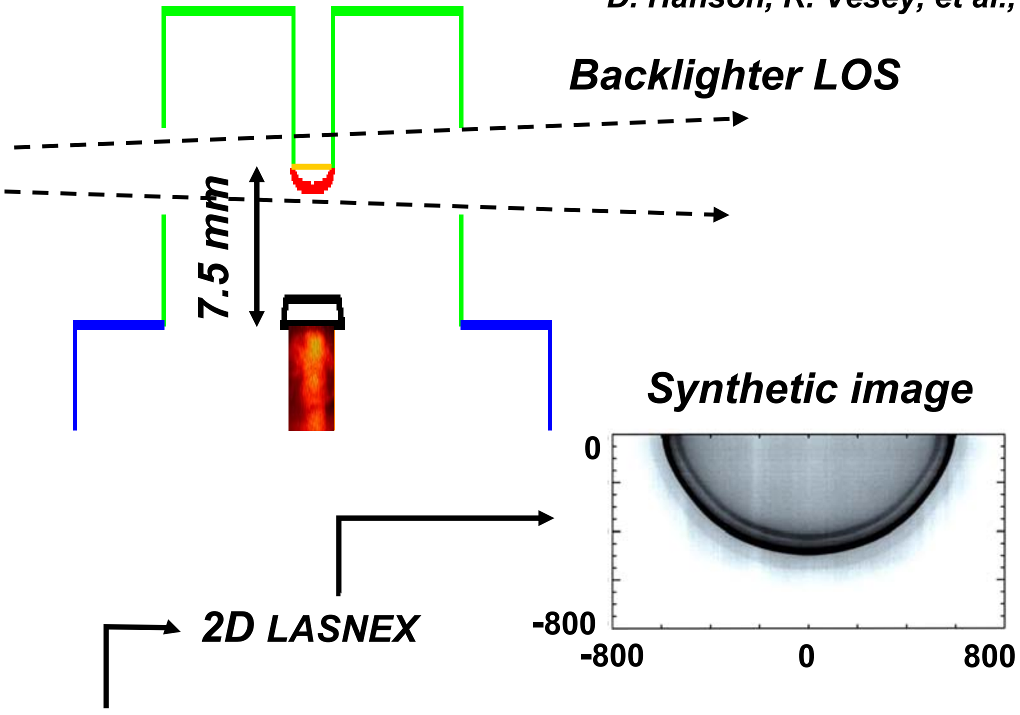
electron or ion conversion target

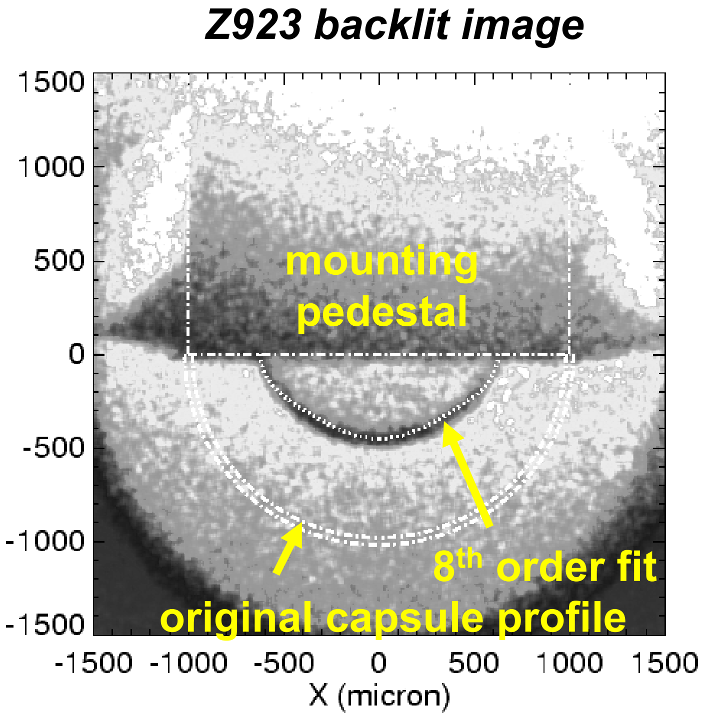
D. Hanson, R. Vesey, et al., 6th Fast Ignitor Workshop, 2002

- Z hohlraum designs should allow ρ = 90-100 g/cc, ρr = 0.4 g/cm^2
- Simulations for ZR with cryo-DT capsule give ρ = 160 g/cc, ρr = 0.65 g/cm^2

Fast ignition imploded fuel designs are being validated with experiments on Z

D. Hanson, R. Vesey, et al., 6th Fast Ignitor Workshop, 2002

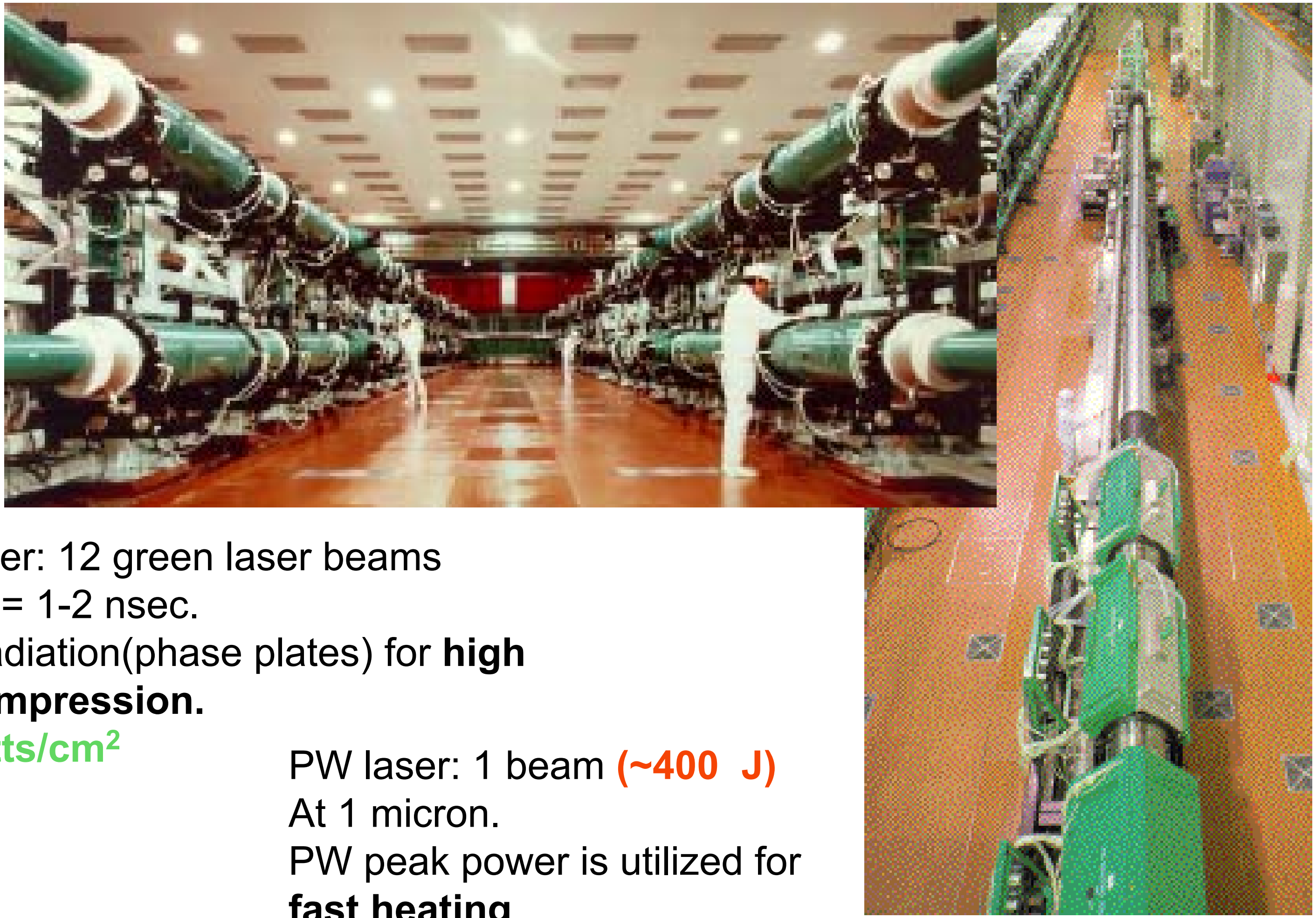




- Preliminary image analysis agrees qualitatively with 2D simulations
- 2D simulations give polar-averaged peak ρ = 60 g/cc, ρ r = 0.3 g/cm^2

The GEKO XII laser and PW Facility enable integral Fast Ignitor Experiments

ILE Osaka



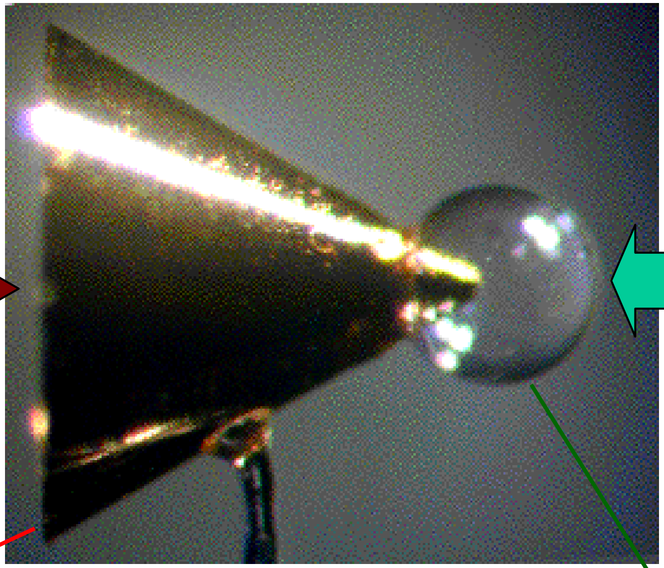
GEKKO laser: 12 green laser beams
E= 10 kJ, t = 1-2 nsec.
Uniform irradiation(phase plates) for **high density compression.**
I ~10^{14} watts/cm^2

PW laser: 1 beam **(~400 J)**
At 1 micron.
PW peak power is utilized for **fast heating**.
I~10^{19} watts/cm^2

Parameters for Integral Fast Ignition Experiments

ILE Osaka

The experiments was carried out with a Au-cone CD shell.
The CD shell was imploded with 9 beams of the GEKKO XII laser.



PW for heating
1 beam / 300 J
1.053 μm / 0.5ps

$I_L = 10^{19}$ W/cm^2

GXII for implosion
9 beams / 2.5 kJ/0.53 μm

1.2ns Flat Top w/ RPP

Au cone
30 ^{o} open angle (the picture: 60deg)
Thickness of the cone tip: 5μm
Distance of the cone top: 50μm from the center

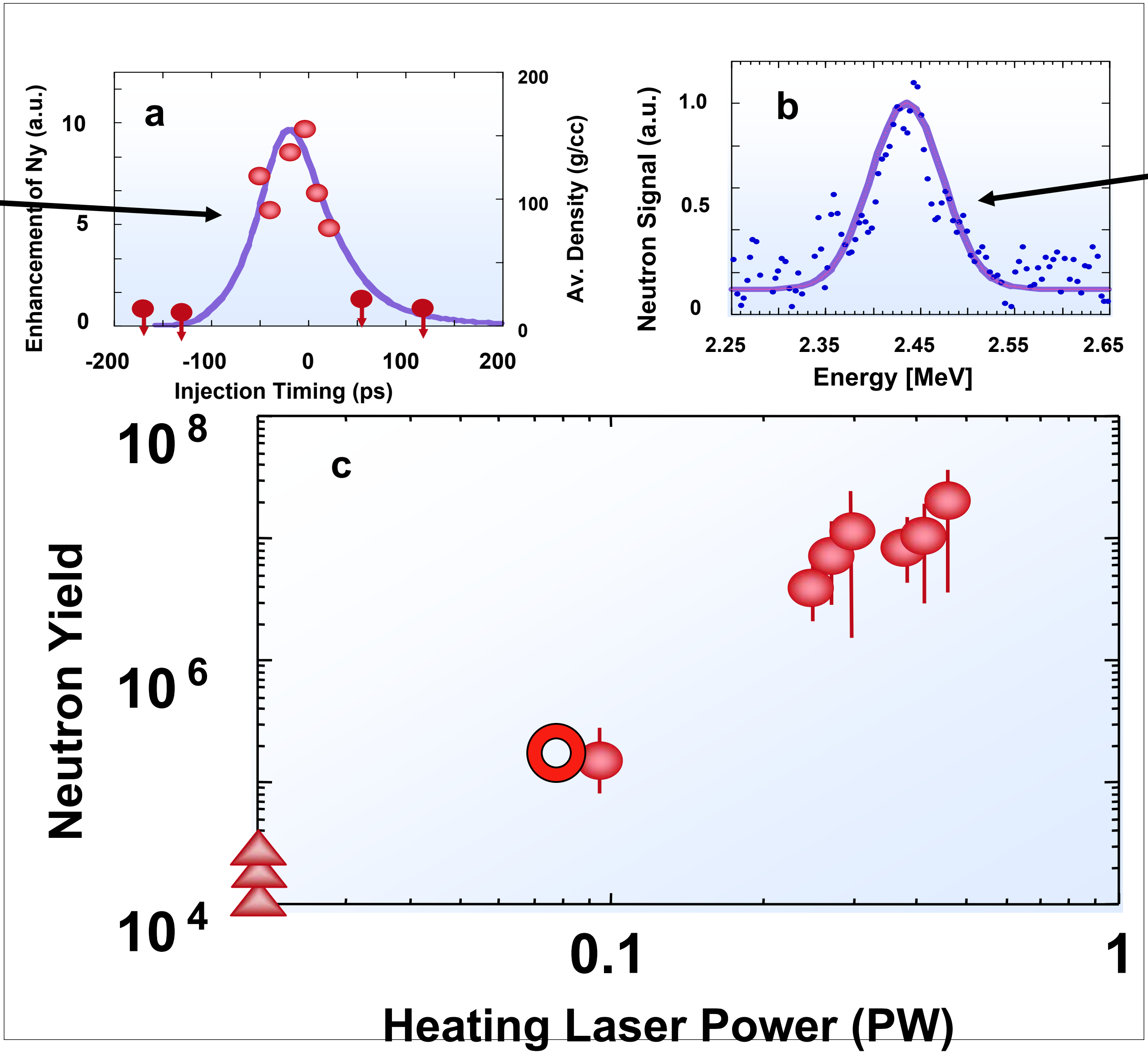
CD shell
500μmϕ/6-7μmt

Peta watt laser heating experimental results of cone guide target

ILE OSAKA

Required timing is 50ps

800keV

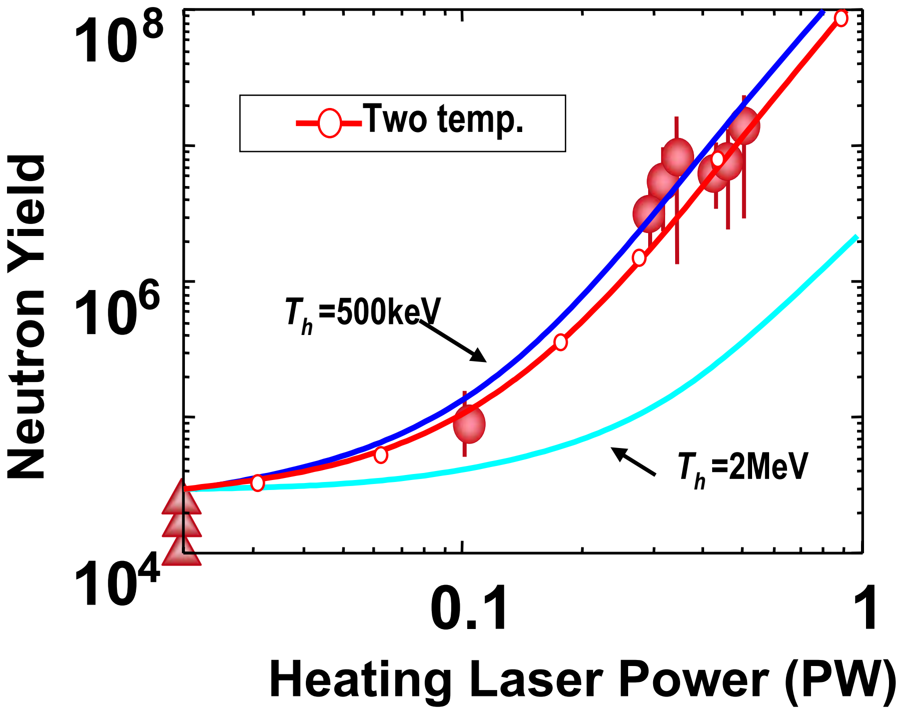


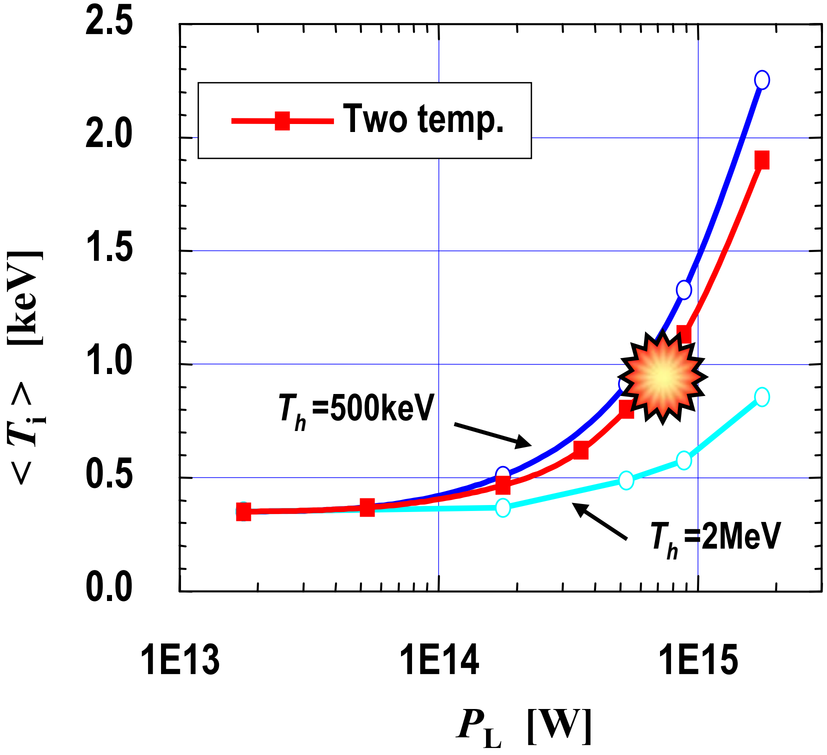
IF/OV1
T.Yamanaka

Integral FI experiments are well matched by Simulations

By assuming 30μmϕ beam spot and 40% energy coupling efficiency from laser to REB

Heating Laser power, $P_{\mathrm{Lh}} = I_{\mathrm{REB}} \times \pi r_{\mathrm{b}}^2 / \eta_{\mathrm{h}} = 1.77\mathrm{E}\text{-}5 \times I_{\mathrm{REB}}$

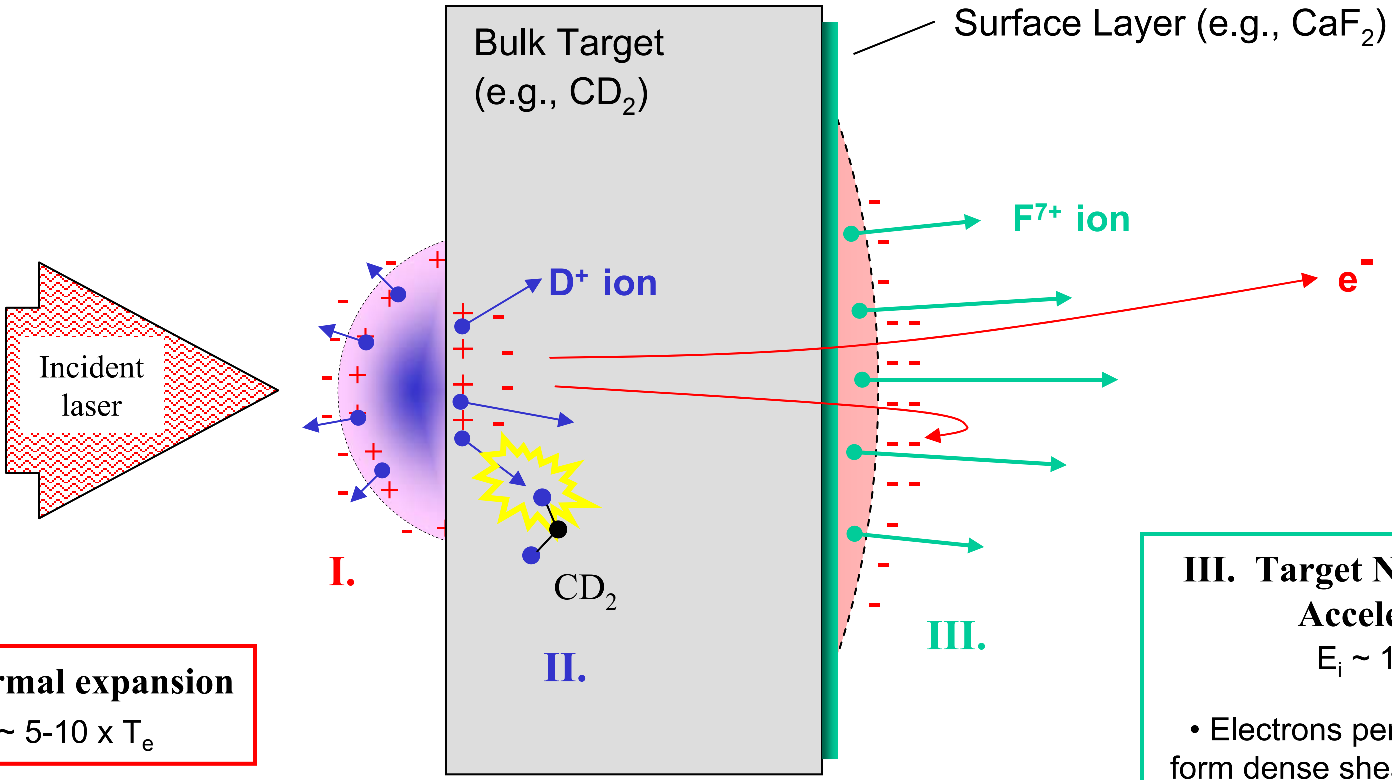




◎ Sub – MeV electrons play important roles in core heating.

◎

Protons and ions are accelerated in relativistic laser-solid interactions by three principal mechanisms



I. Thermal expansion

$T_i \sim 5\text{-}10 \times T_e$

II. Front-surface charge separation

Static limit: $T_i \sim T_e$

III. Target Normal Sheath Acceleration

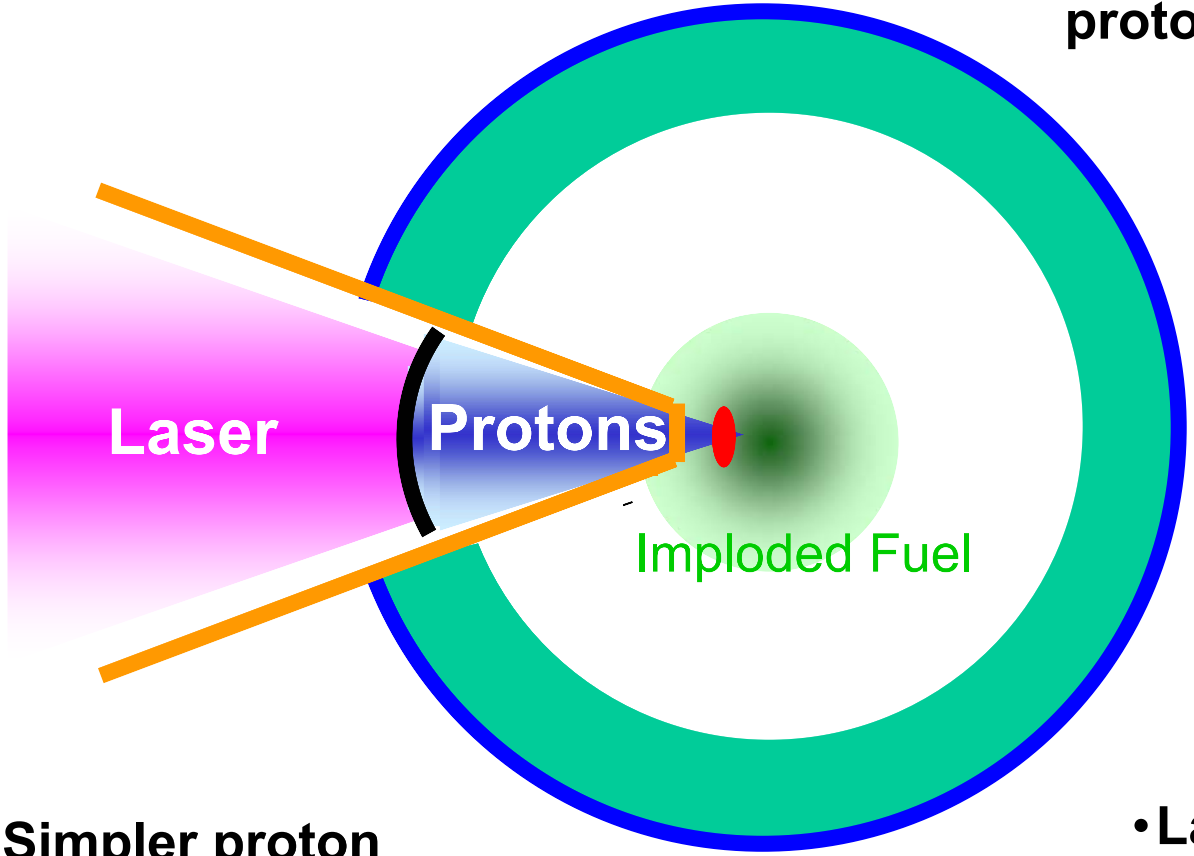
$E_i \sim 10 \times T_e$

- Electrons penetrate target & form dense sheath on rear, non-irradiated surface
- Strong electrostatic sheath field ionizes surface layer ($E_o \sim kT / e\lambda_d \sim$ MV/μm)
- Rapid (~ps) acceleration in expanding sheath produces very laminar ion beam

Proton ignition is a newer concept avoiding the complexity of electron energy transport

- Same driver and fuel assembly options

- Novel physics of Debye sheath proton acceleration



M. Roth *et.al.* Phys Rev. Lett 86,436 (2000).

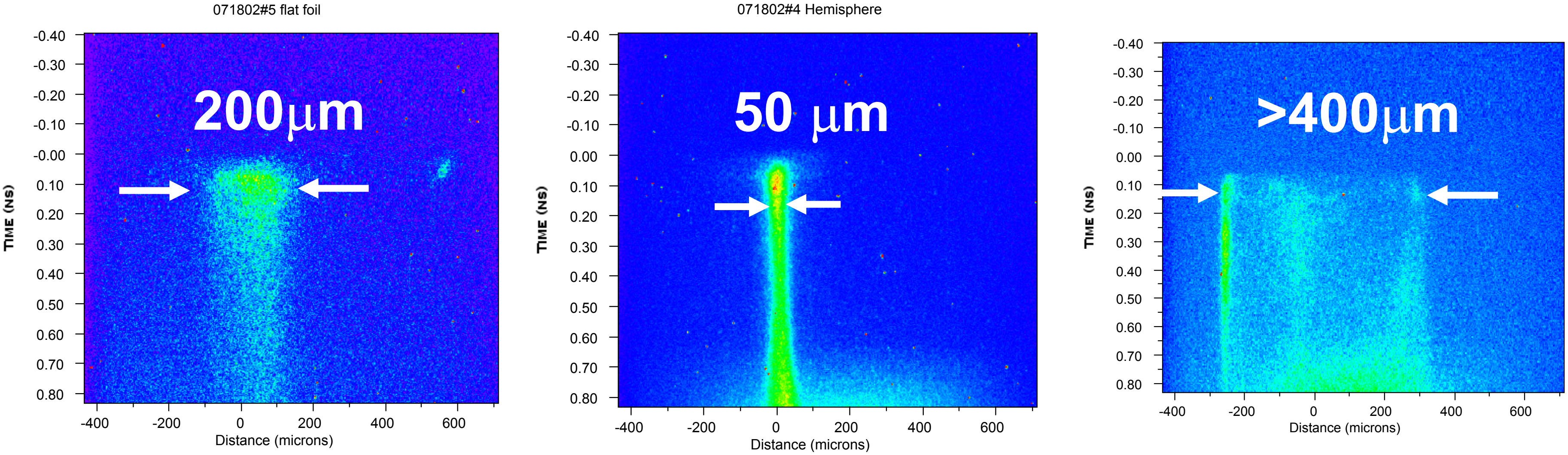
Ruhl et al. Plas. Phys. Rep. 27,363,(2001)

Temporal, et al. Phys Plasmas 9, 3102, 2002

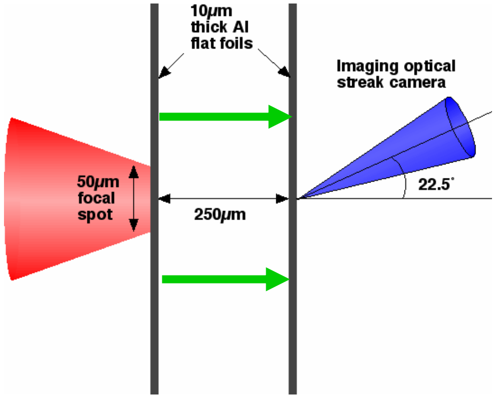
- Simpler proton energy transport by ballistic focussing

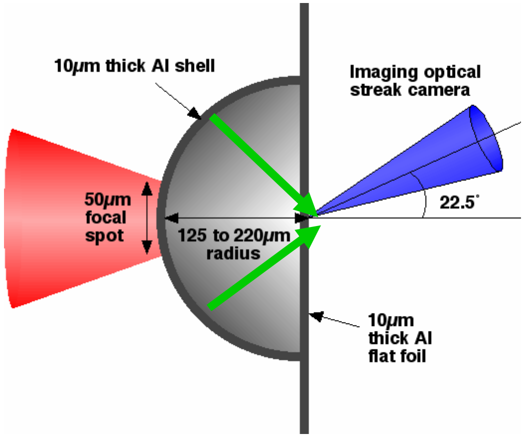
- Larger laser focal spot-easier to produce

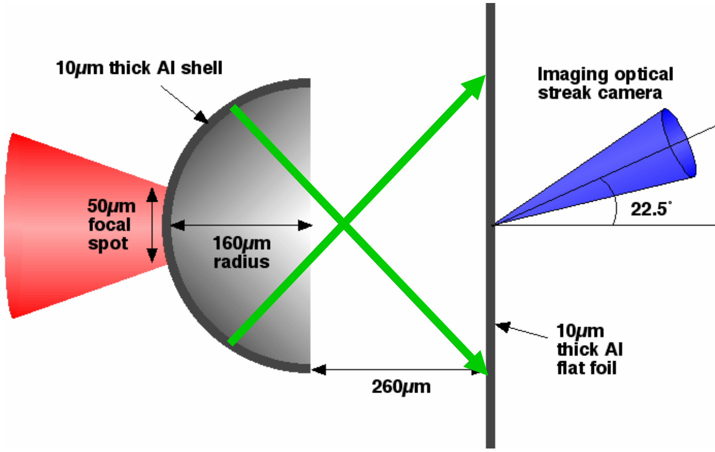
PW ION-Plasma coupling experiments have begun:100TW,100fs expt. at JanUSP shows proton focusing and enhanced isochoric heating of a 10 micron Al foil



Streak images of visible Planckian emission



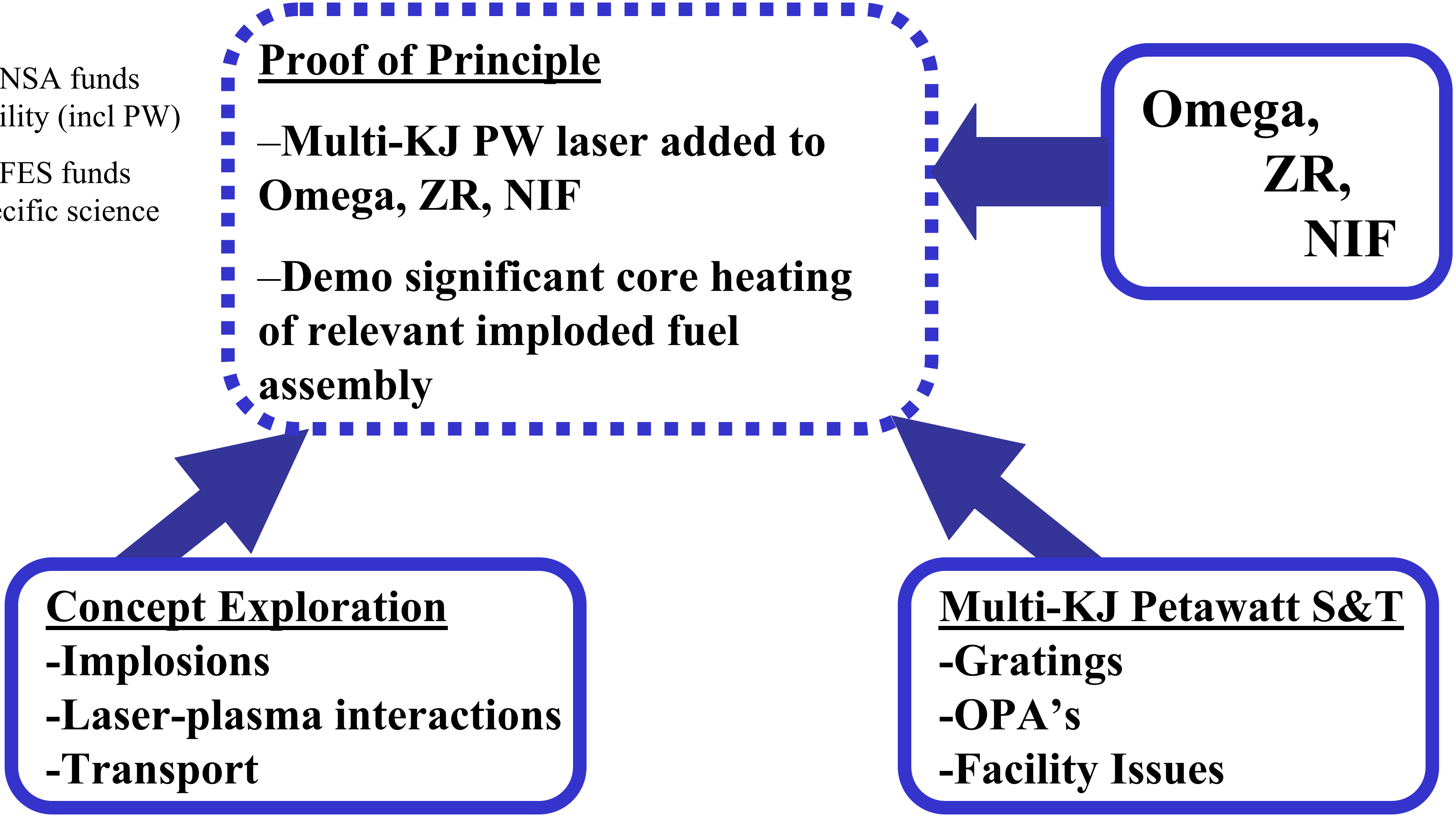




A credible US pathway for FI progression from Concept Exploration to Proof of Principle is emerging

–NNSA funds facility (incl PW)

–OFES funds specific science



Proof of Principle

–Multi-KJ PW laser added to Omega, ZR, NIF

–Demo significant core heating of relevant imploded fuel assembly

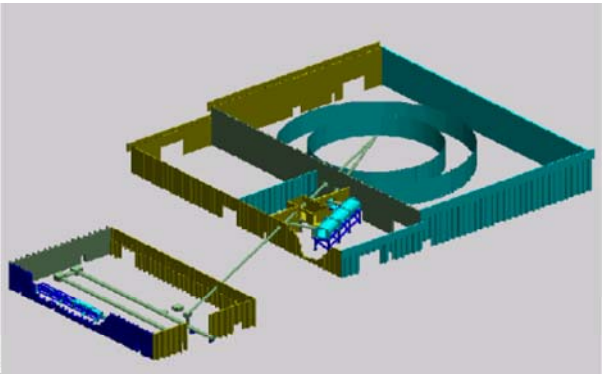
Omega,
ZR,
NIF

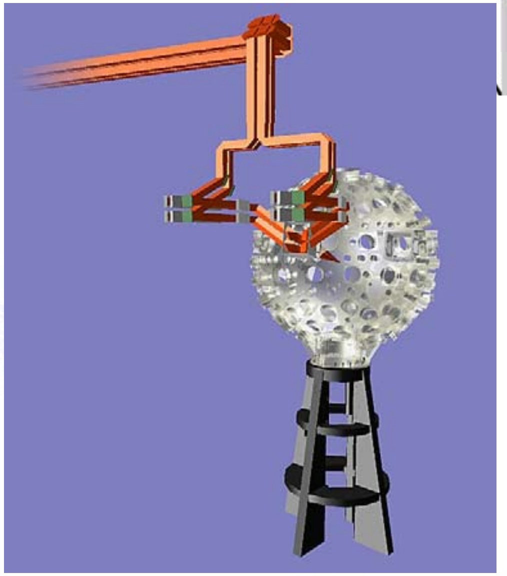
Concept Exploration
-Implosions
-Laser-plasma interactions
-Transport

Multi-KJ Petawatt S&T
-Gratings
-OPA's
-Facility Issues

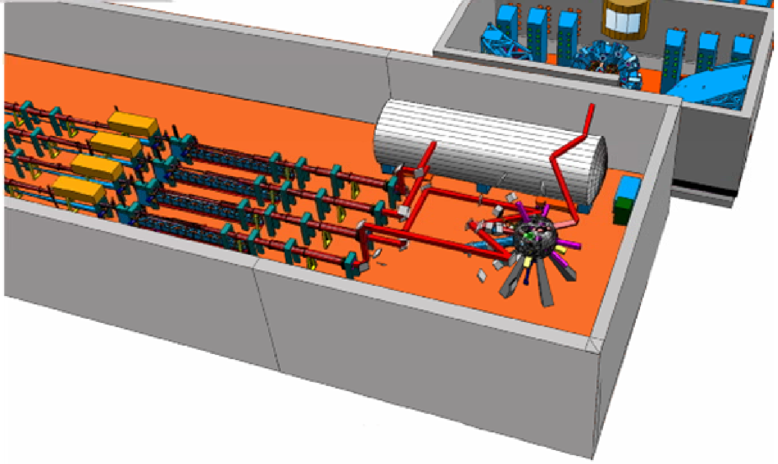
New DOE facilities proposed for FY06/07 would support a ‘proof of principle’ study of fast ignition

SNL Z Beamlet / Z





HEPW at NIF



Omega EP

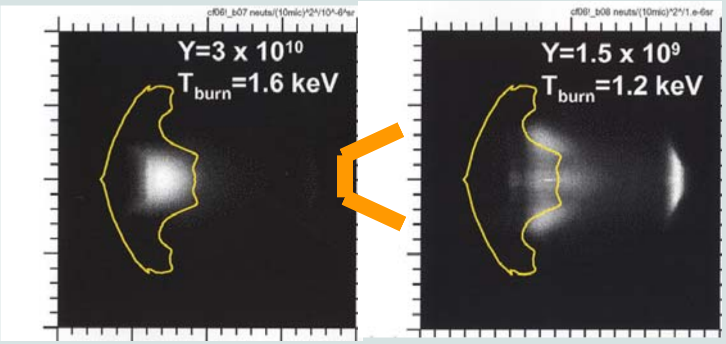
Integrated 2-20kJ short pulse experiments will better define ignition requirements

- Revisit key physics issues at FI relevant intensities with order of magnitude higher short pulse energy and pulse duration
- Conduct 2 to 20 kJ HEPW integrated experiments with FI relevant resistive and other effects at new DOE facilities
- Develop integrated model- hydro and burn, hybrid PIC electron transport, 3D PIC interaction physics, relativistic propagation - use new teraflop computers
- Cryo target fabrication and cryo -experiments
- Design full scale ignition expts

Significant hurdles specific to fast ignition

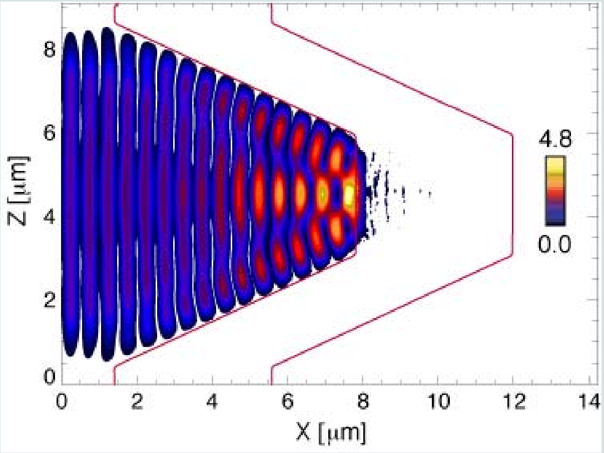
- ~10 kJ short pulse lasers for ignition energy
  - High damage threshold gratings
  - Good focus
- Cone design
  - Generate electrons efficiently
  - Minimize contamination of fuel
- Target design
  - Allow efficient transport & heating
- Pointing and timing

Nuclear burn sensitive to e-beam spread



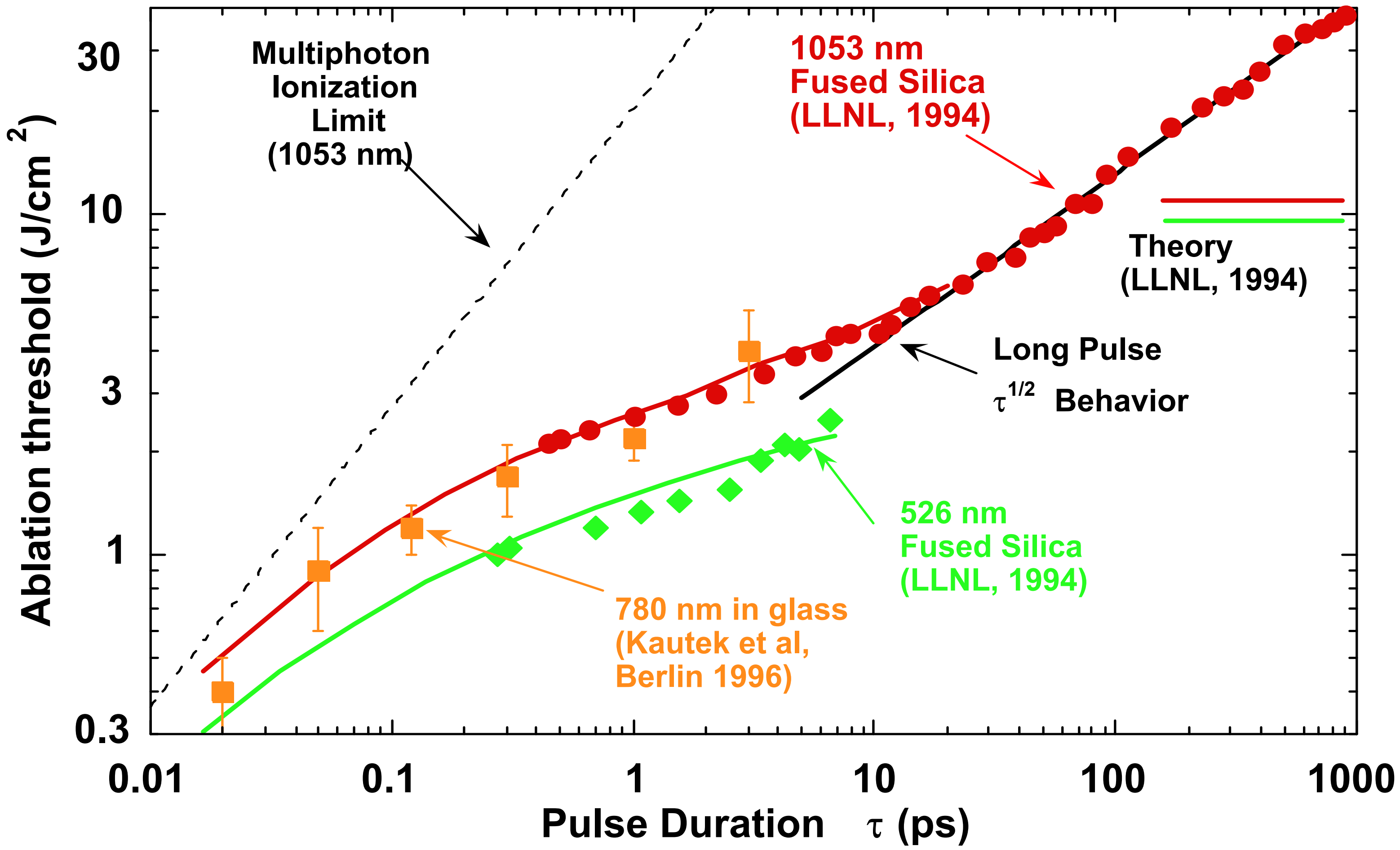
Simulated D-D neutron burn images

Laser μFocusing using a Conical Target

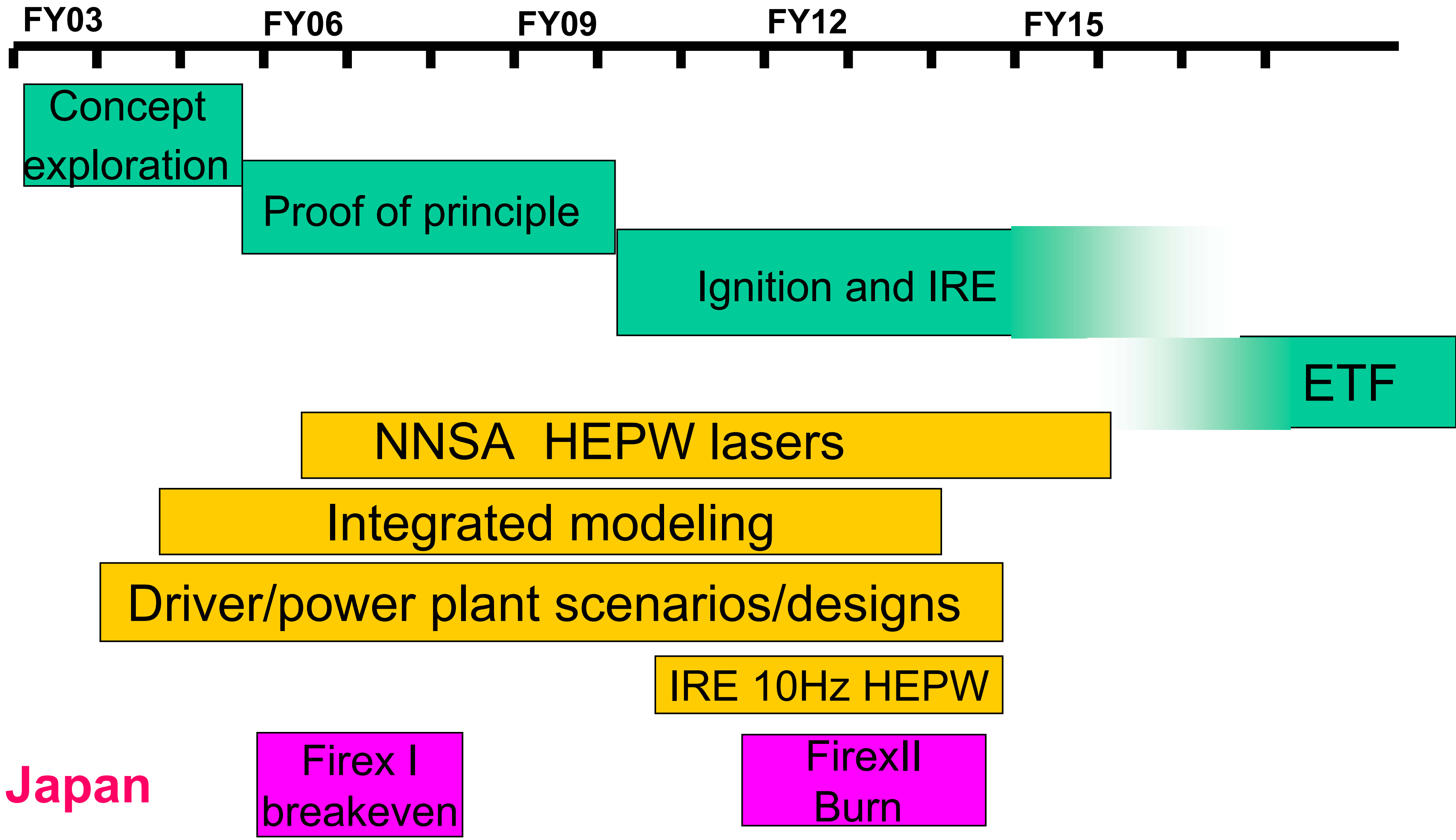


Contour plot of the square root of laser intensity

Efficient, Damage resistant dielectric gratings are required for FI



Proposed Roadmap for IFE by Fast Ignition



FY03

FY06

FY09

FY12

FY15

Concept exploration

Proof of principle

Ignition and IRE

ETF

NNSA HEPW lasers

Integrated modeling

Driver/power plant scenarios/designs

IRE 10Hz HEPW

Japan

Firex I breakeven

FirexII Burn

FI Reseach would require a n OFES-NNSA Partnership

- Concept exploration
  - OFES :$3-5M/year for modeling,experiments,targets
  - NNSA: $5-10M/year to develop laser technology (damage resistant gratings),design PW facilities
- Proof Of Principle
  - OFES:$ 5-10M/year for modeling,experiments,targets
  - NNSA: Add multikilojoule PW lasers to Ω, Z, NIF(estimate $30-50M per facility)
  -

NNSA has identified need for adding PW to existing facilities

- Radiography
  - High energy (hν >30 keV) xray backlighting
  - Proton Radiography (under development)
- Ultra-high energy densityphysics
  - -P >1Gbar
  - T_R~ 1 KeV
- Isochroic heating
  - Ions, high energy photons (under development)

Unused slides

-Concept Exploration-

Goal: Show sufficient physics agreement between modeling and experiment to propose PoP step

Activities:

- **Fuel assembly: experiments and hydro modeling**
- **Heating/Transport:**
  - **Experiments, with conductivity and scattering closer to compressed DT plasma**
  - **Modeling of cone, of experiments**
  - **Evaluate "ion ignition"**
- **Subscale modeling:**
  - **3D PIC (absorption, electron production)**
  - **Hybrid models benchmarked against experiments (electron transport)**

-Proof of Principle-

Goal: Show integrated understanding of the gain curve, and of components required for IFE reactor design to give confidence in attractive reactor design

Activities:

- **Integrated proof of principle experiments using the proposed NNSA HEPW facilities**
- **Integrated full scale models coupling hydro, optical properties, ignition and burn leading to an ignition target design**
- **Final Optics R&D**
- **Target Fabrication R&D**
- **Reactor Design Studies**
- **Demonstrate a full scale short pulse beamline**

-Demonstration-

Goal: Demonstration of high gain targets and full design of reactor including target factory and injection system

Activities:

- High gain ignition
- Integrated Research Experiment for final optics and target injection
- Reactor engineering design
- Cryo targets with path to mass production
- Pellet factory engineering design
- Driver demonstration

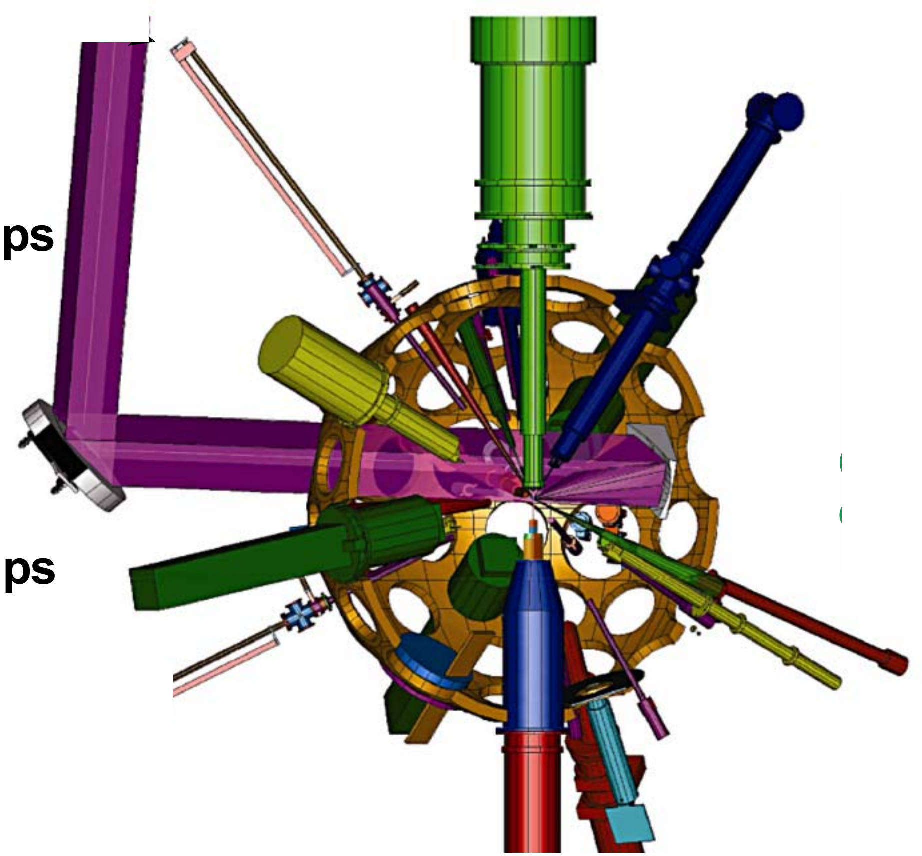
OMEGA EP is designed to perform integrated fast-ignition experiments with cryogenic implosions

Channeling beam:

- $I > 10^{18}$ W/cm^2
- E ~ 0.5 to 2.6 kJ in 100 ps
- $r_{focus} \sim 15\ \mu m$

Igniter beam:

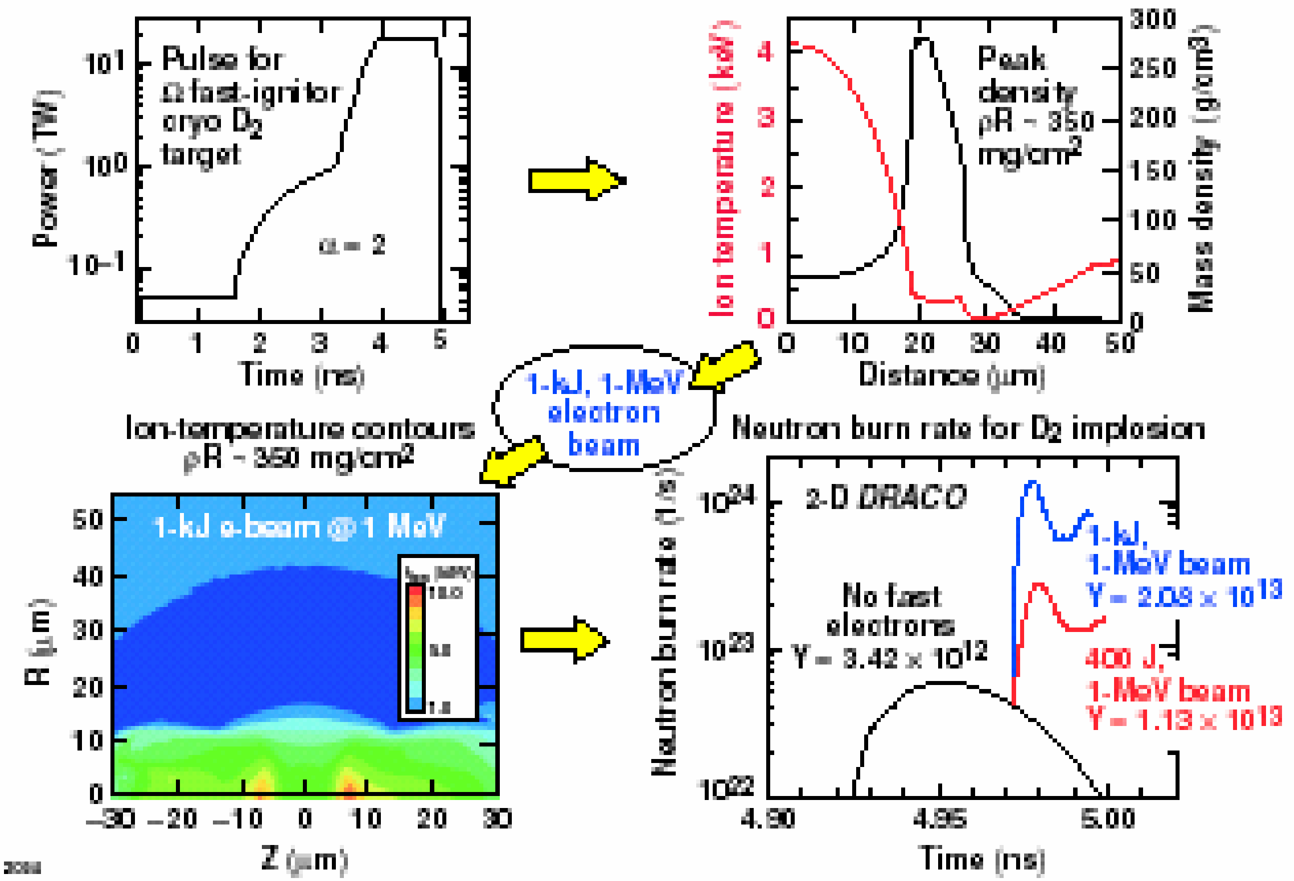
- $I > 10^{19}$ W/cm^2
- E ~ 0.5 to 2.6 kJ in <10 ps
- $r_{focus} < 10\ \mu m$



Fuel ρr up to 0.5 gcm^{-2} and ρ up to 500 gcm^{-3}

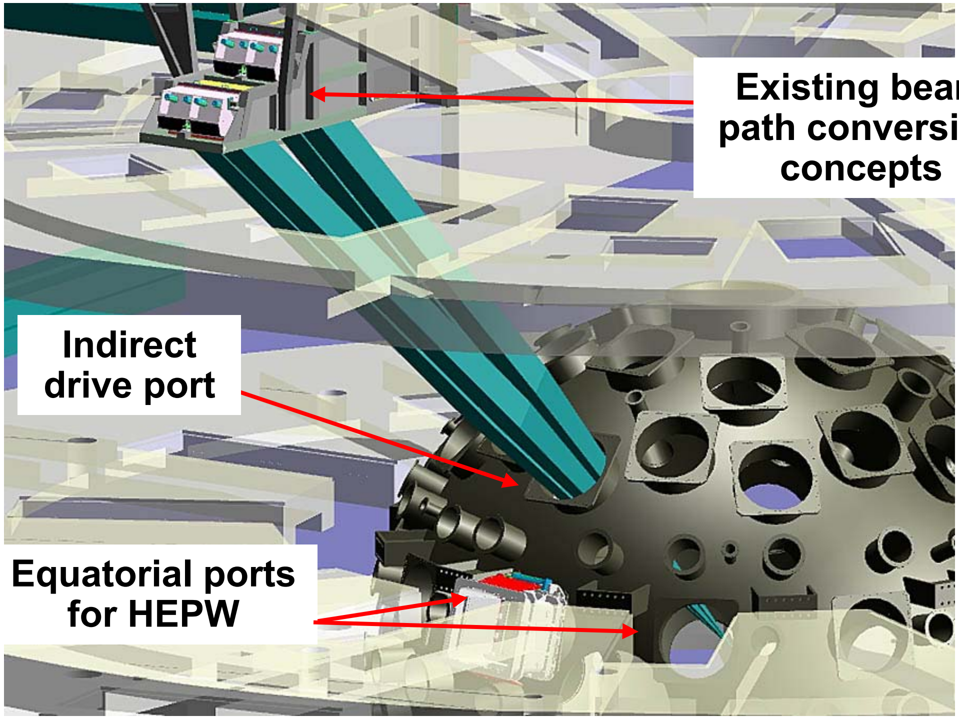
Direct-Drive Fast Ignition

Simulations show that a 1-kJ, 1-MeV electron beam raises the T_{ion} in the high-density fuel shell to ~10 keV



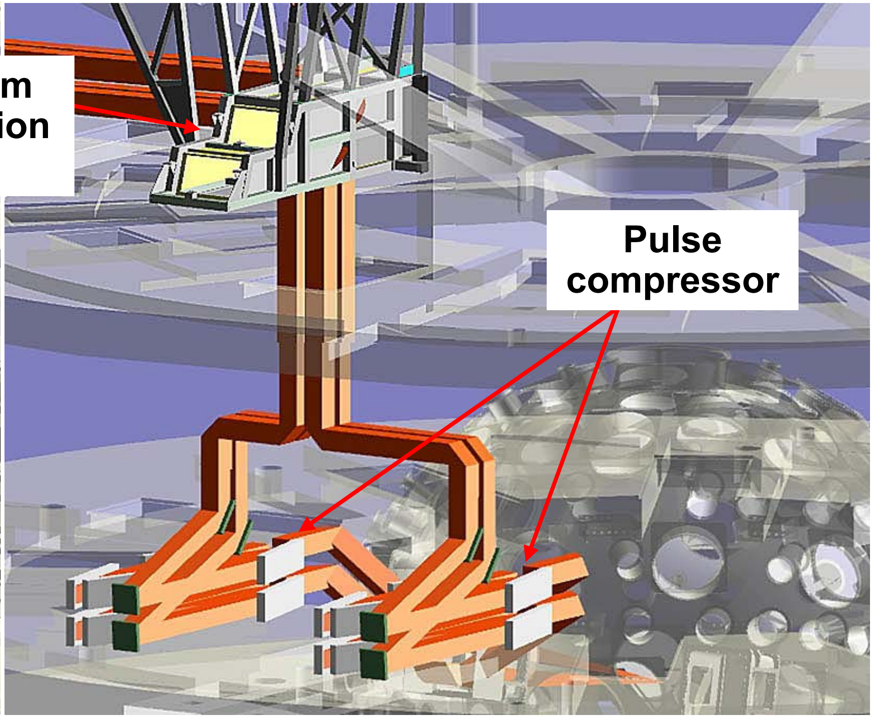
Planned modification of NIF will provide a quad of HEPW beams in suitable for FI expts

Indirect drive configuration



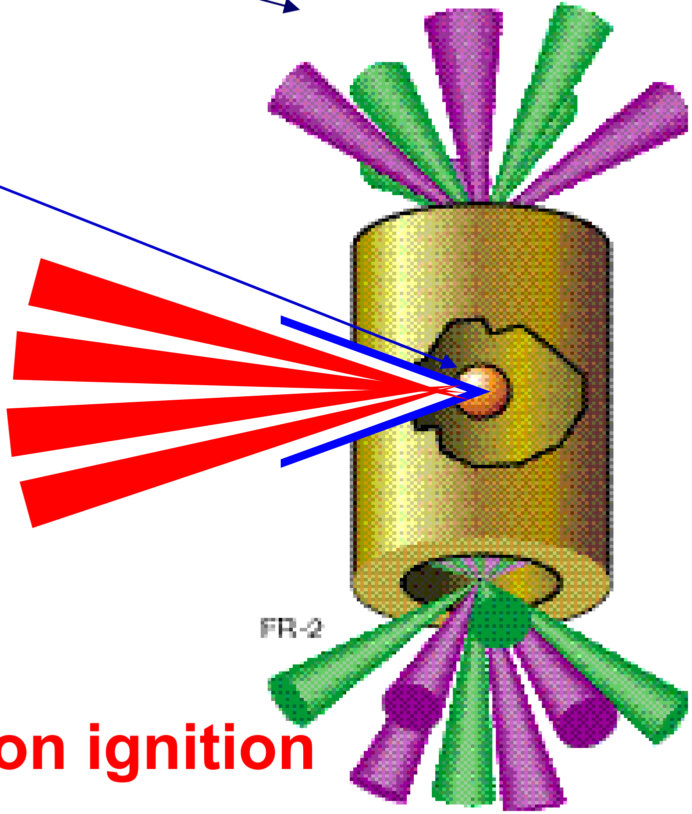
Original NIF

HEPW Configuration



HEPW adapted NIF

A ‘proof of principle ‘ FI experiment at NIF has been designed in detail using Lasnex modeling



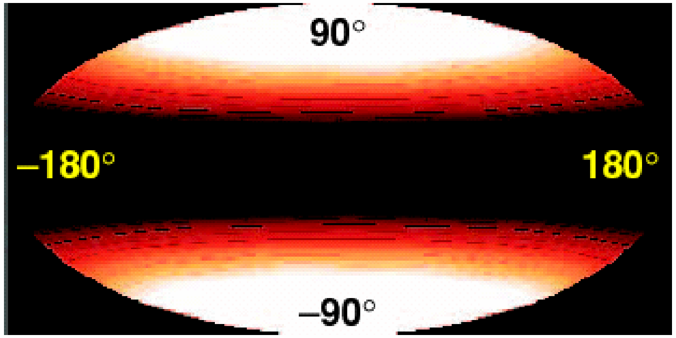
**250kJ Hohlraum drive with
8 fold 2 cone symmetry
(8 quads per LEH)**

**CD shell 740 μm radius
160 μm wall Imploded to
45 μm radius, 250 gcm^{-3}
ρr =1.o gcm^{-2}**

**4 HEPW ignitor beams
total of 20kJ, 20ps
driving electron or proton ignition**

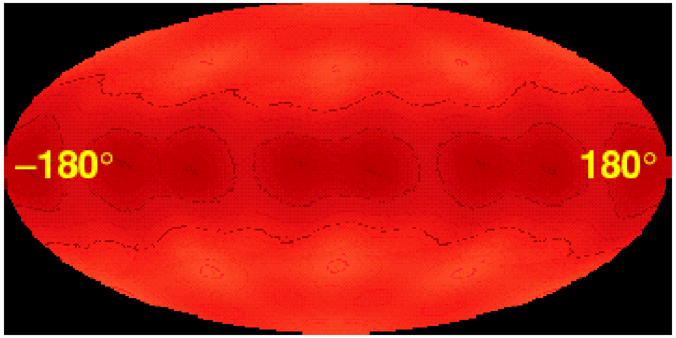
Direct-drive ignition and fast ignition may be possible on the NIF with the indirect-drive beam configuration

Aitoff projection of intensity on a capsule



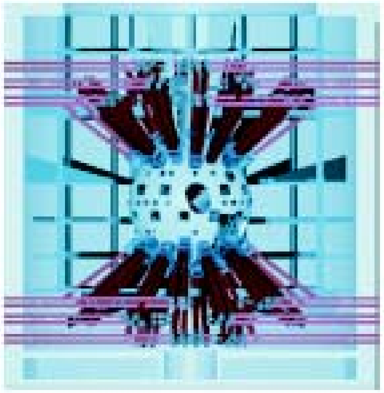
$\sigma_{rms} = 48\%$
peak-to-valley = 157%

NIF direct-drive distribution using 24 (×4) beams in indirect-drive illumination



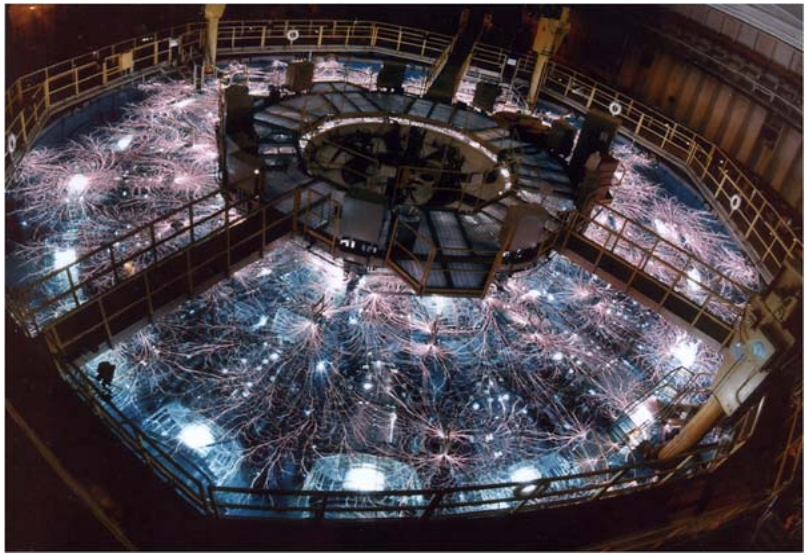
$\sigma_{rms} = 6\%$
peak-to-valley = 22%

NIF direct-drive intensity distribution with 24 (×4) beams repointed to a pattern similar to OMEGA 24



The penalty from asymmetric illumination may be mitigated by the clever use of phase plate design, beam pointing, pulse shaping, and ice layer/capsule shimming.

Pulsed power-a new testbed for xray driven fuel assembly FI studies



- Rapid Progress in Z pinch physics has provided ~2MJ and ~200TW of xrays for fuel assembly
- The Beamlet laser from LLNL has been successfully coupled to Z
- Modifications are underway
  - Increase xray energy to >**3 MJ**
  - **CPA** modification to beamlet
    - > 1kJ in 1-5 psec