IFE Summary

Kunioki Mima

GPI,Japan, and IFN, UPM, Spain

Out -line

1) IFE Concept and Papers of 2010 IAEA-FEC
2) Central isobaric ignition
   NIF, LMJ, OMEGA
3) Two step ignition
   Fast ignition, shock wave ignition,
   Impact fusion, and others
   FIREX/LFEX, OMEGA-EP, HIF
4) Beyond NIF and IFE Technology
   HiPER, LIFE, LIFT, HIF:
   Laser, Chamber, Target, Interface

13th IAEA-FEC 2010, Daejeon, Korea, Oct.16,2010

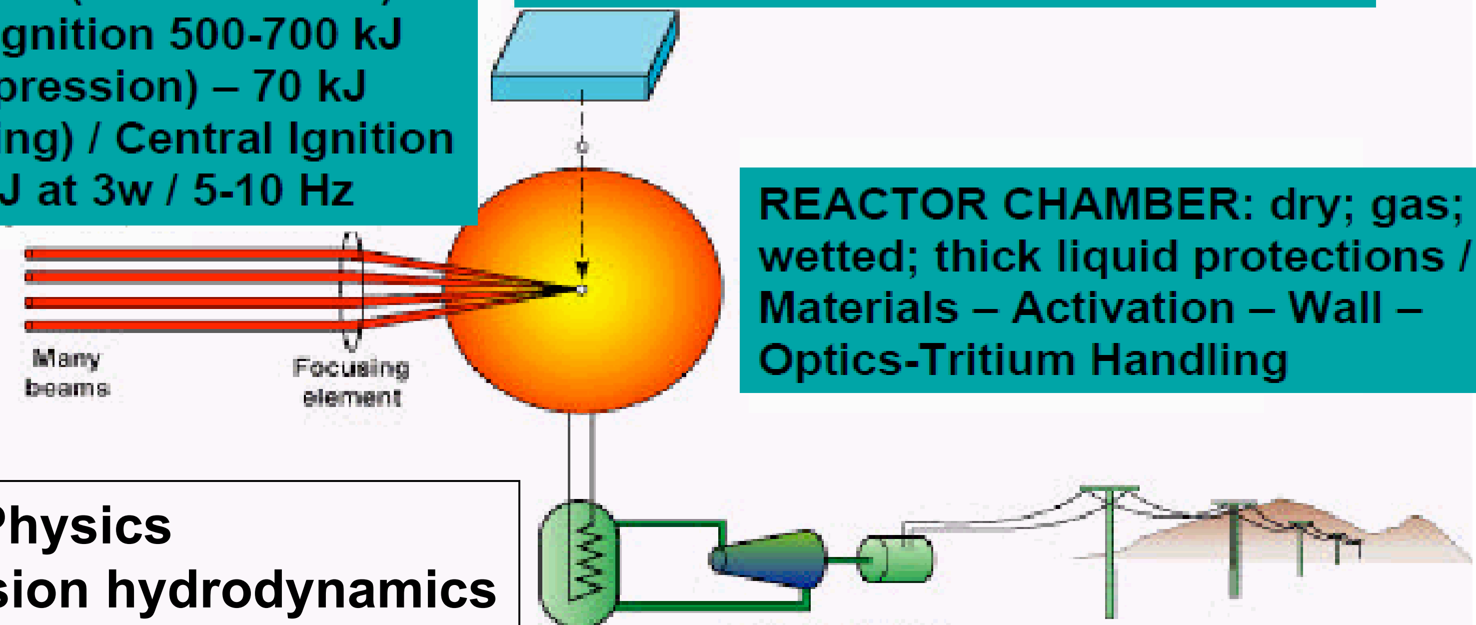
Inertial Fusion Energy Science

Power Plant System based on INERTIAL FUSION

DRIVER (LASER or Ions)
Fast Ignition 500-700 kJ (compression) – 70 kJ (heating) / Central Ignition 4-5 MJ at 3w / 5-10 Hz

Target Fabrication – Injection and Tracking / 5-10 Hz

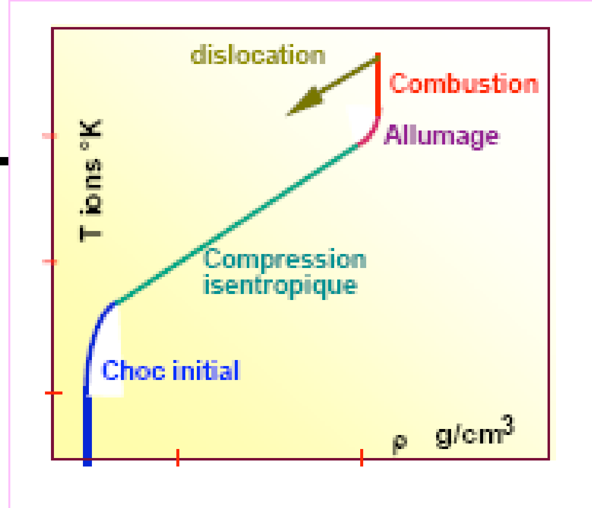
REACTOR CHAMBER: dry; gas; wetted; thick liquid protections / Materials – Activation – Wall – Optics-Tritium Handling



SYSTEMS for ENERGY EXTRACTION / Primary-Secondary Circuits-Turbine-Electric Generator

Target Physics
- **Implosion hydrodynamics**
- **Ablation physics: LPI**
- **Hohlraum physics**
- **Heating physics: RLPI, REB transport, Ion acc.**

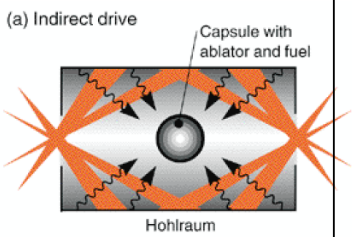
IFE Schemes



Inertial fusion consists of four main stages
1) Quasi-isentropic shell compression
2) Heating of a small portion of fuel
3) Fuel ignition at the moment of stagnation
4) combustion of the cold fuel in the shell

Conventional schemes single shaped pulse

- **Indirect drive**
- **Direct drive**

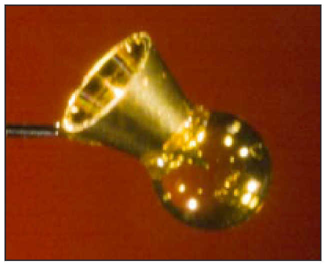


IFE/1-1
D.Meyerhofer
P6-5,P6-10Desai
P6-16Hora,
P6-17Kouhi

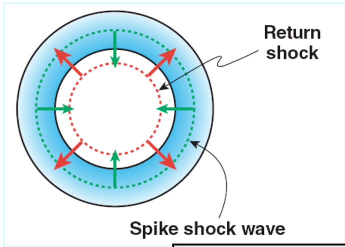
OV/2-1 J.Lindl (NIF)
OV/5-1 S. Jacquemot(LMJ)
IFE/1-3 E.Moses(NIF)
P6-8Li,P6-11Kim,p6-15Lei

Alternative schemes separate ignition pulse

- **Fast ignition cone**
- **Shock ignition**
- **Impact Ignition**



OV/4-1 H.Aechi, IFE/1-2 Shiraga
P6-1 Johzaki, P6-2 Sephens,
P6-3Hegelich,P6-6Logan,P6-9
P6-12Nagatomo, P6-14Nakao,



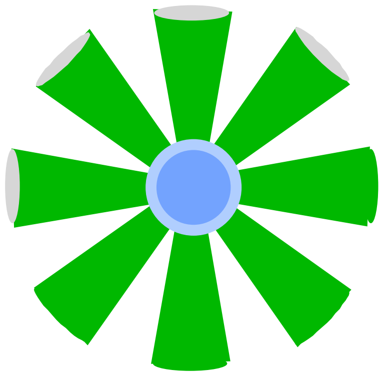
IFE/1-1
D.Meyerhofer
P6-6,P6-7
P6-13Perkins

P6-4 Murakami

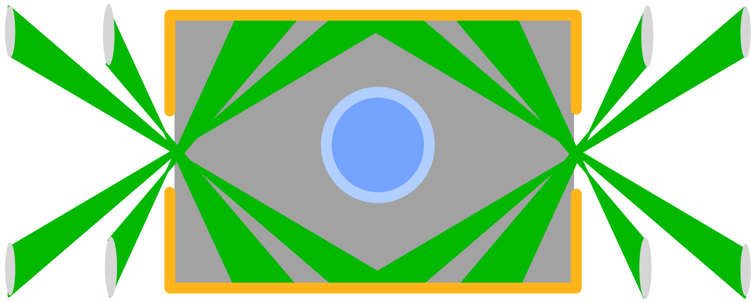
P6-7 Weave

After V.Tikhonchuku

Central ignition(two options): direct and indirect drive



direct drive with lasers

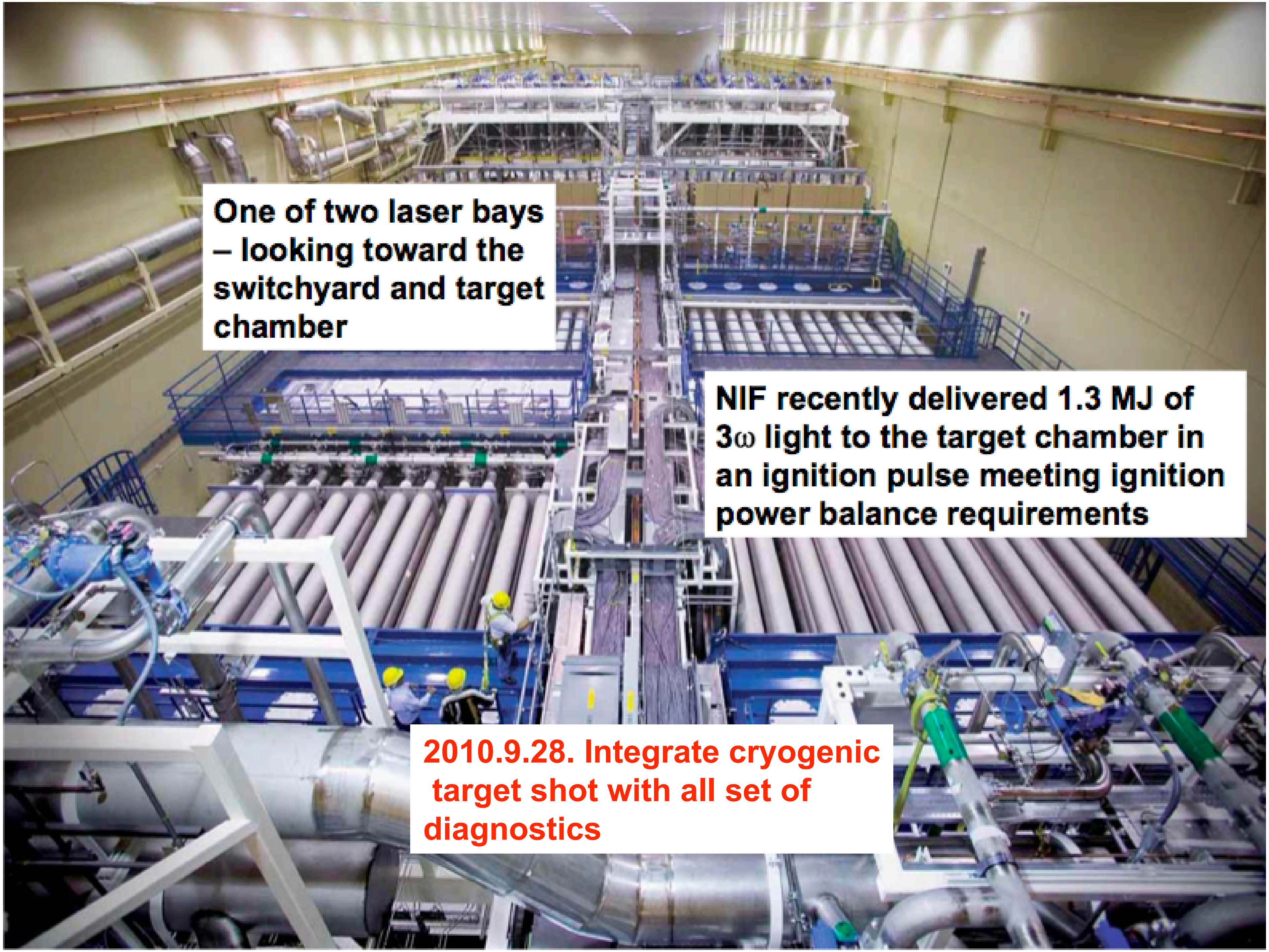


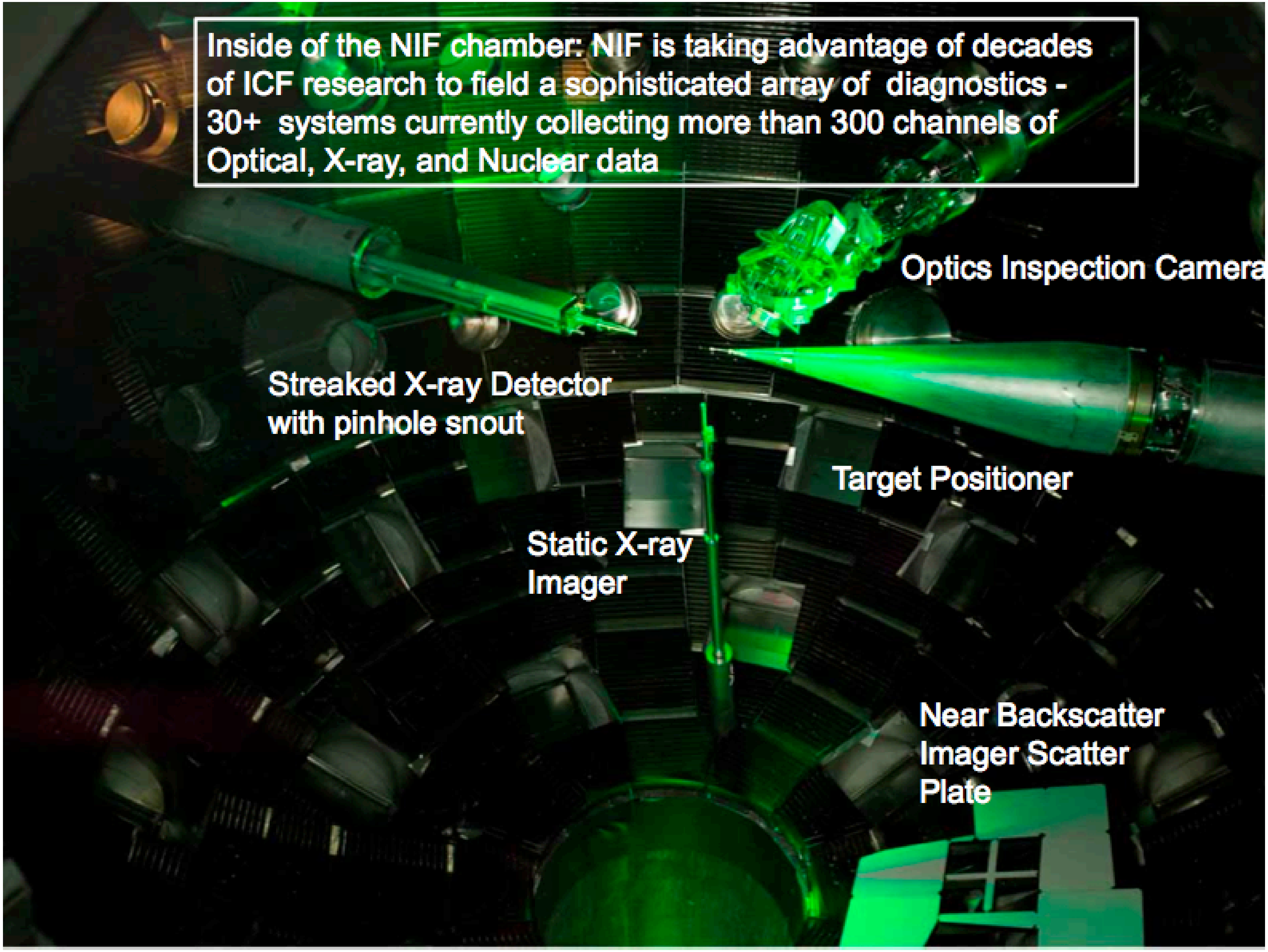
indirect drive by X-rays

Better efficiency but:
- smaller ablation pressure
- parametric instabilities
- danger of preheat,
- hydrodynamic instabilities
- less symmetric implosion
- more beams are needed

Less efficient but:
- higher pressure
- more stable and
- more symmetric implosion
- less beams are needed

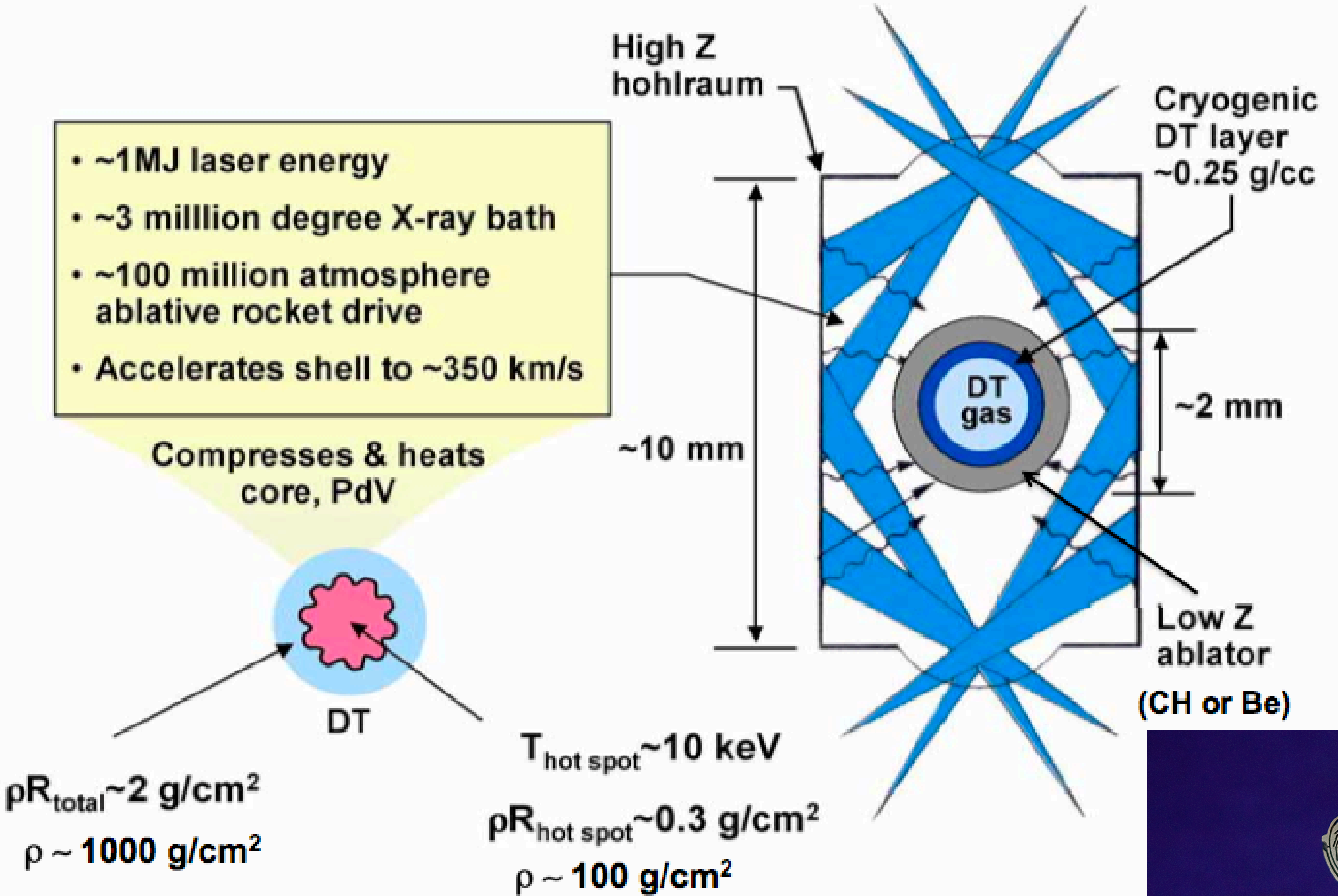
NIF (USA) and LMJ (France)

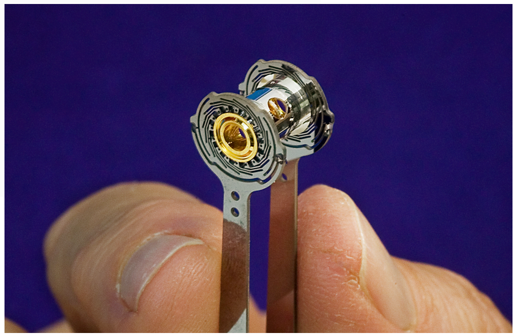

One of two laser bays – looking toward the switchyard and target chamber
NIF recently delivered 1.3 MJ of 3ω light to the target chamber in an ignition pulse meeting ignition power balance requirements
2010.9.28. Integrate cryogenic target shot with all set of diagnostics


Inside of the NIF chamber: NIF is taking advantage of decades of ICF research to field a sophisticated array of diagnostics - 30+ systems currently collecting more than 300 channels of Optical, X-ray, and Nuclear data
Optics Inspection Camera
Streaked X-ray Detector with pinhole snout
Target Positioner
Static X-ray Imager
Near Backscatter Imager Scatter Plate

On NIF we use a hohlraum driven implosion to generate the ρR & T needed for ignition

OV/2-1 Lindl



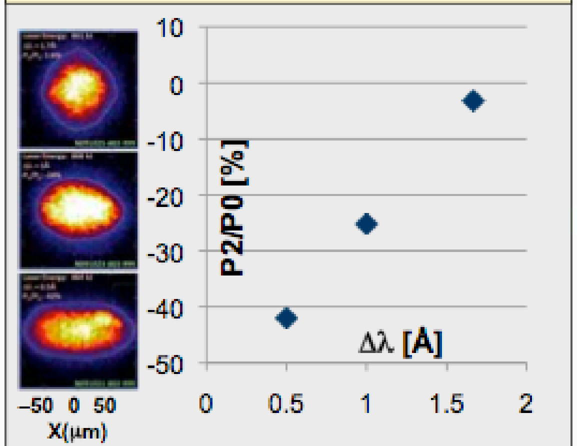


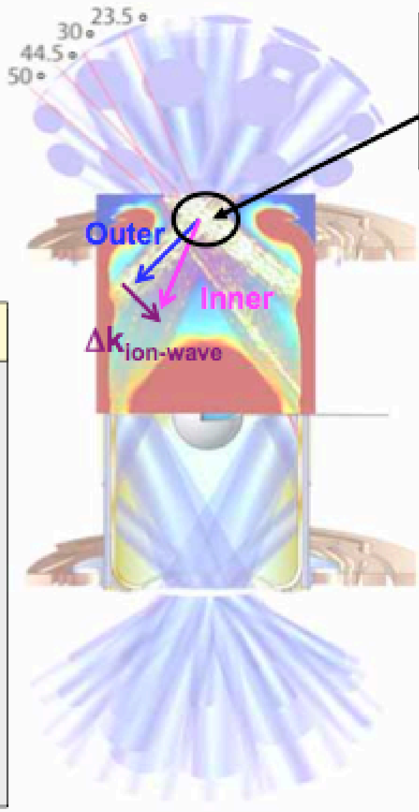
Symmetry: requires a controlled energy balance between the inner and outer beams

We use a plasma-optical-switch, & transfer energy from outer to inner beams by increasing $\Delta\lambda = \lambda_{inners} - \lambda_{outers}$

2009/9
Plastic target
with DHH_e^3 gas

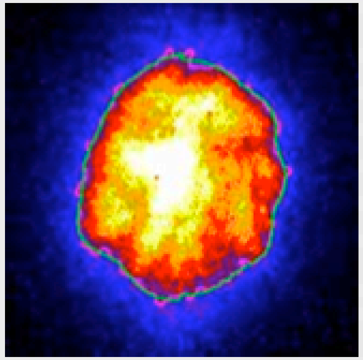
NIC '09 9 keV Capsule emission





The beams transfer energy to one another via Brillouin scattering from ion waves

Symmetry: Must be round enough at high convergence to get dense & ignite



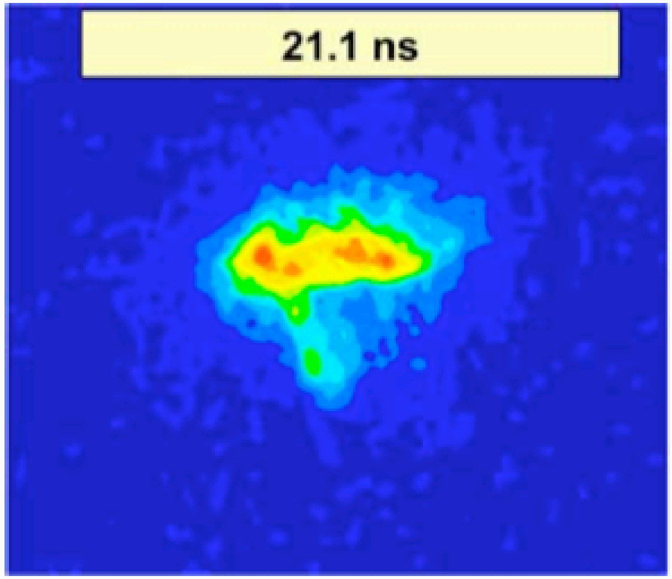
S. Glenzer et al., *Science* 327, 1228 (2010)

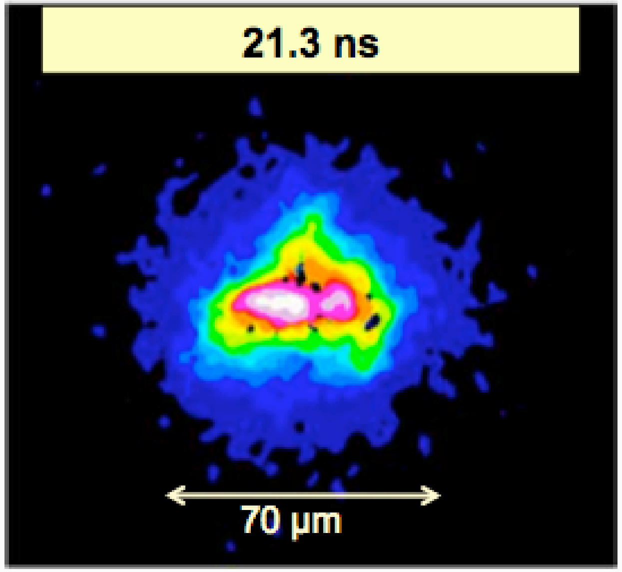
N. Meezan et. al. PoP 17, 056304 (2010

P. Michel et. al. PoP 17, 056305 (2010)

The GXD obtained high quality images which indicate we need to further improve capsule surface features from dust and other assembly artifacts

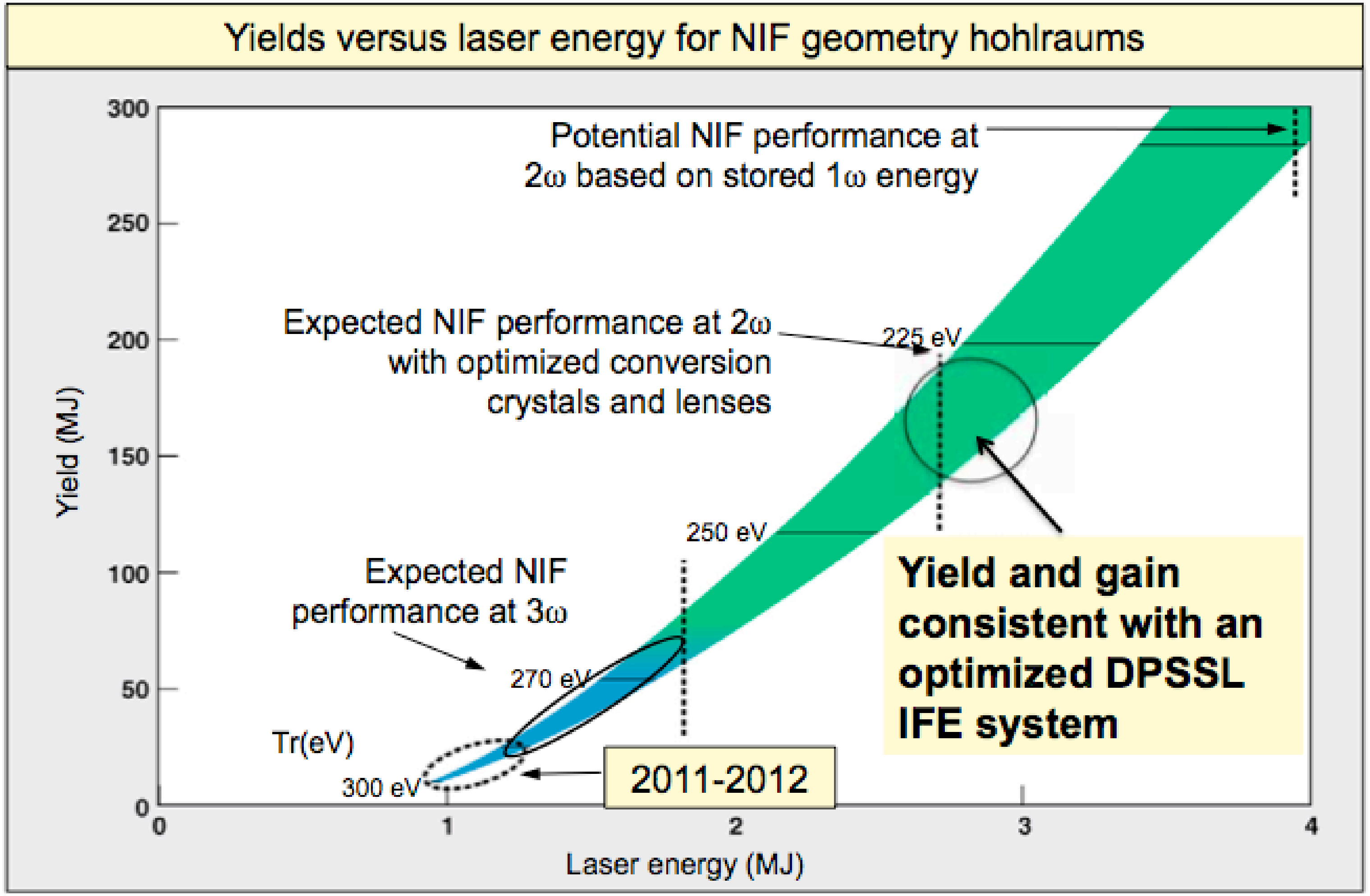
A sequence of frames from GXD shows a jet of material passing through and cooling the hot spot as the implosion reaches peak emission





In the coming year, we will adjust symmetry, implosion velocity, shock timing, and mix to optimize the fuel assembly in THD targets in preparation for 50/50 DT experiments

Ignition experiments in 2011–2012 lay the ground work for target performance which meets IFE requirements



Current status of the LMJ facility

up to 240 beams in 60 quads, up to 2 MJ/600TW

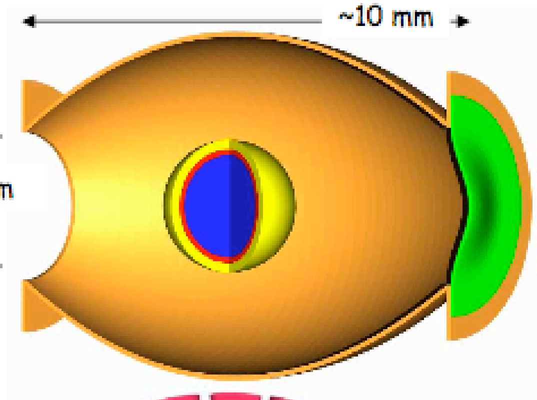
building commissioned, 2(/4) laser bays completed, target chamber being equipped
cryo. target assembly under characterization & insertion systems validated

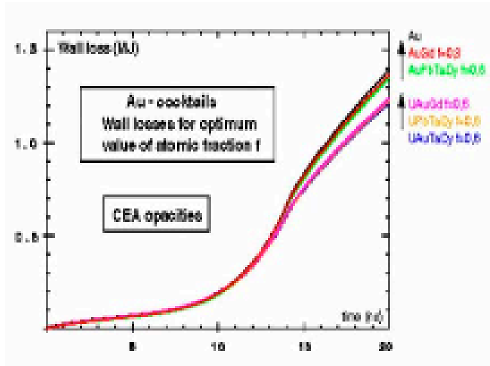
1st experiments end of 2014

Improved target design provides flexibility

* cocktail hohlraum (75%U-25%Au) to improve the hohlraum energetics

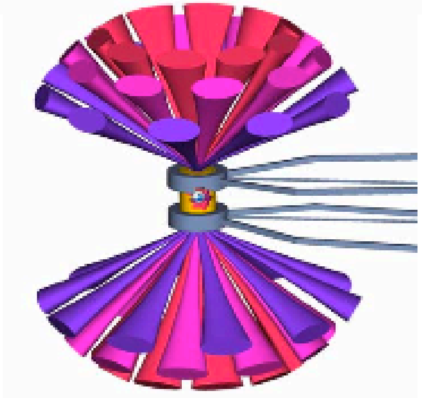
* rugby-shaped hohlraum
  for a significant x-ray drive enhancement

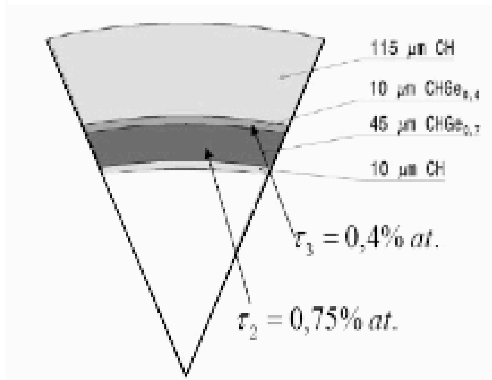




* gradually doped ablator
  to reduce hydro. risks & control rad. preheating

* 160 laser beams in 2 cones

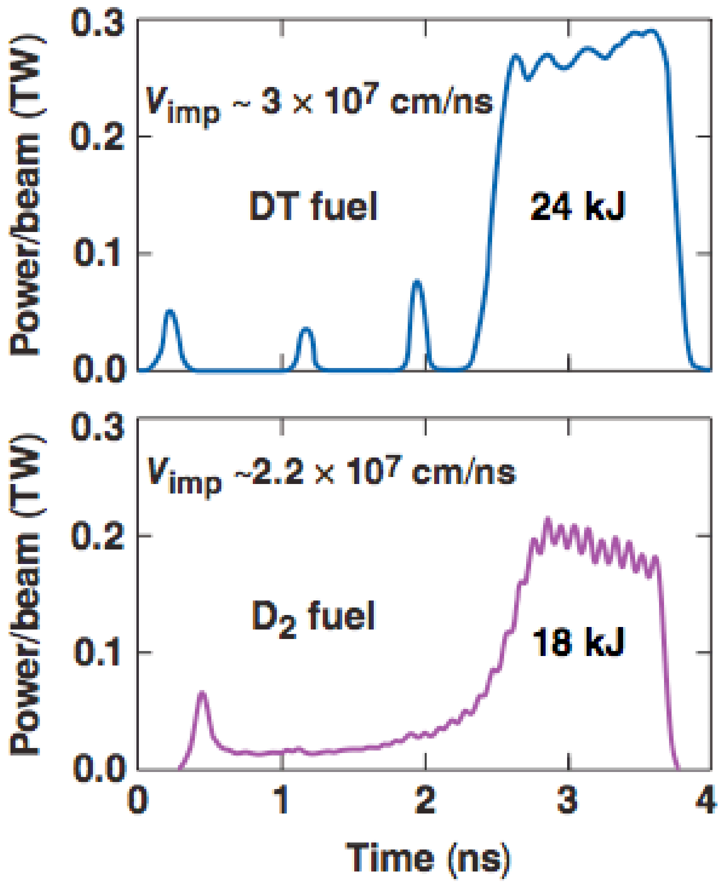


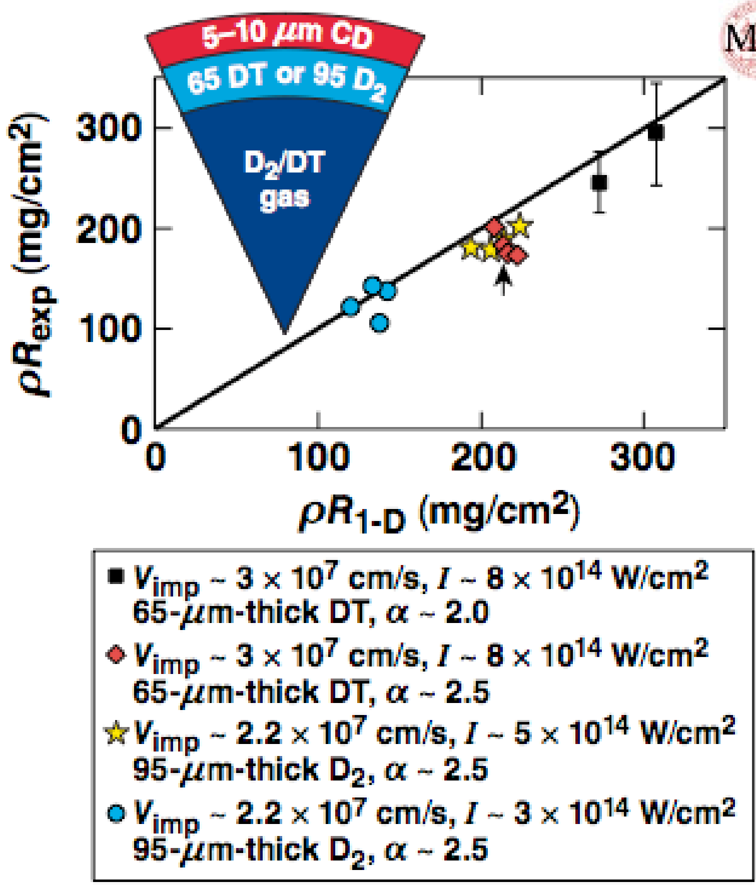


↳ 1.2 MJ - 330TW

LLE, Rochester Cryogenic Implosion Experiment Results

Areal densities of up to 300 mg/cm^2 have been measured in cryogenic target implosions on OMEGA*





1-D areal densities have been achieved for drive intensities from <3 × 10^{14} up to 8 × 10^{14} W/cm^2.

E18406e

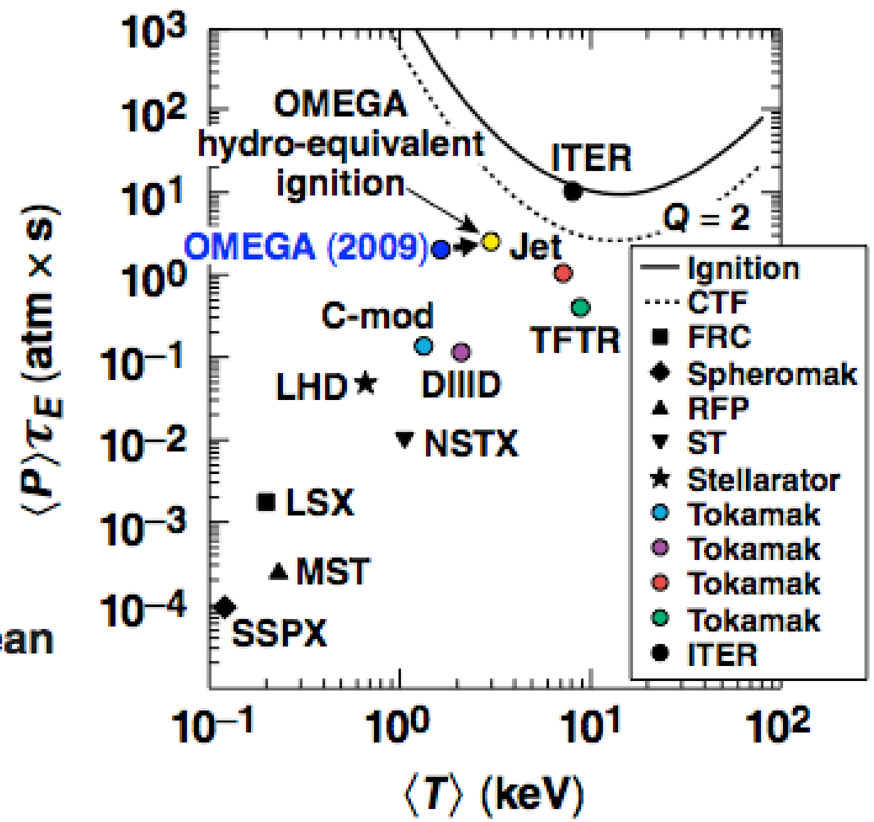
*V. N. Goncharov *et al.*, Phys. Rev. Lett. 104, 165001 (2010).

OMEGA Cryogenic Implosion Plasma is comparable to JET

OMEGA cryogenic implosions have achieved $P\tau$ ~ 1.7 atm-s

UR LLE

- On OMEGA, ignition-equivalent performance requires
  - χ ~ 0.04, $\langle T \rangle$ ~ 3.4 keV
  - $P\tau$ ~ 2.6 atm-s
- Cryogenic implosions to date
  - ρR = 0.3 g/cm^2, $\langle T \rangle$ = 2 keV
  - YOC = 10% give
  - χ ~ 0.03, $P\tau$ ~ 1.7 atm-s
- For comparison, the Joint European Tokamak has produced
  - χ ~ 0.14, $P\tau$ ~ 1 atm-s

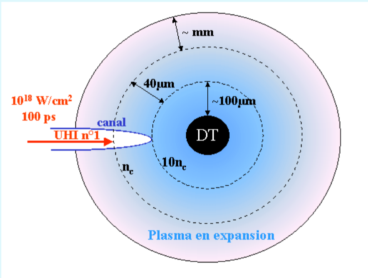


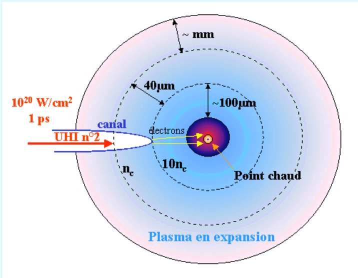
E18675c

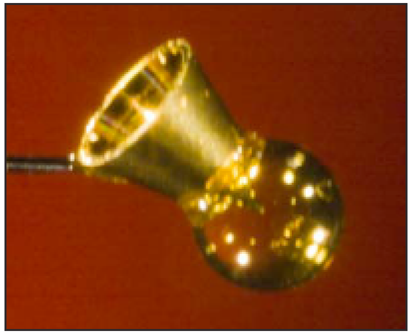
Alternative schemes for the inertial fusion energy

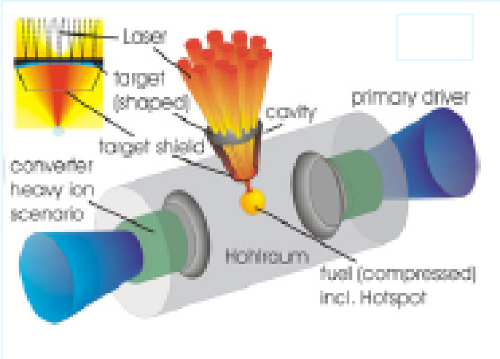
Fast ignition consists of two steps: low entropy compression and high power ignition

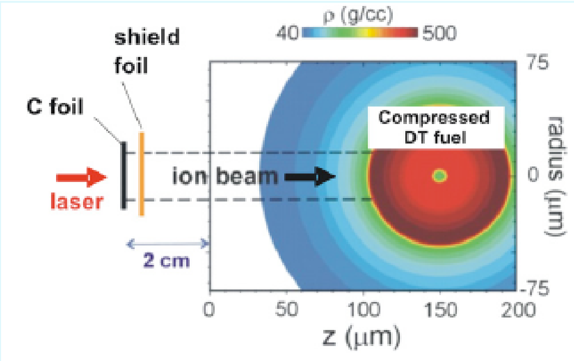
- fast electron injection through the laser-formed channel — **Tabak et al. Phys. Plasma 1994**
- fast electron injection through the gold cone — **OV H.Azechi, IFE/1-1 D.Meyehofer**
  IFE/1-2 Shiraga,P6-1 Johzaki, P6-2 Sephens,P6-3Hegelich,P6-6Logan,P6-9P6-12Nagatomo, P6-14Nakao
- ion injection from the external source — **p6 M.Hegelich, P6-6 G.Logan**
- central hot spot heating with a shock — **IFE/1-1 D.Meyerhofer p6-7 J. weave**
- Impact ignition — **p6 M.Murakami, p6-7**

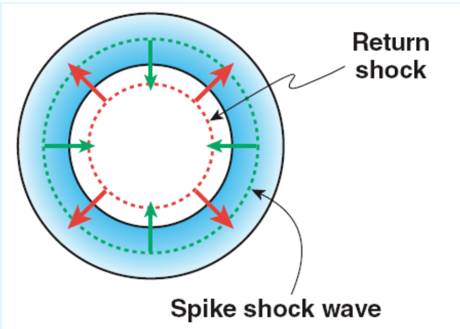






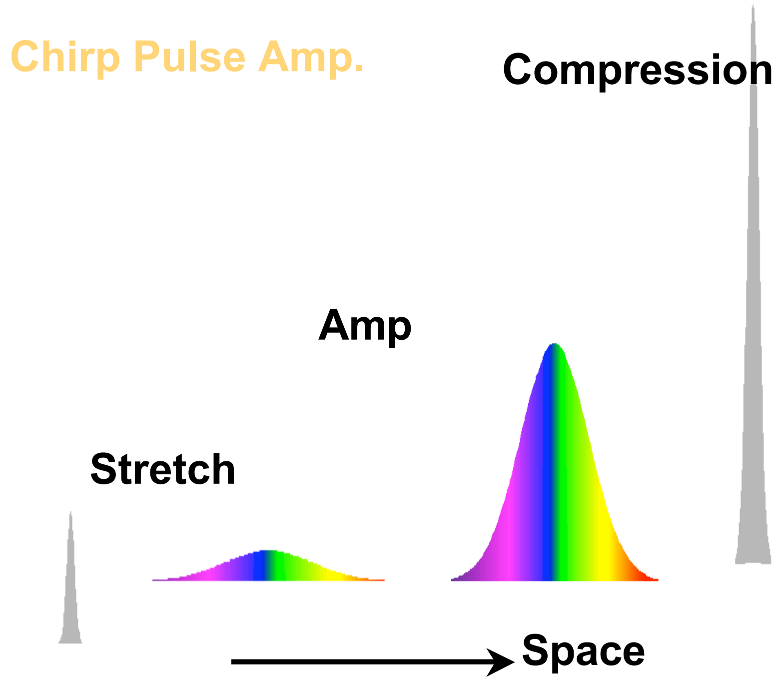


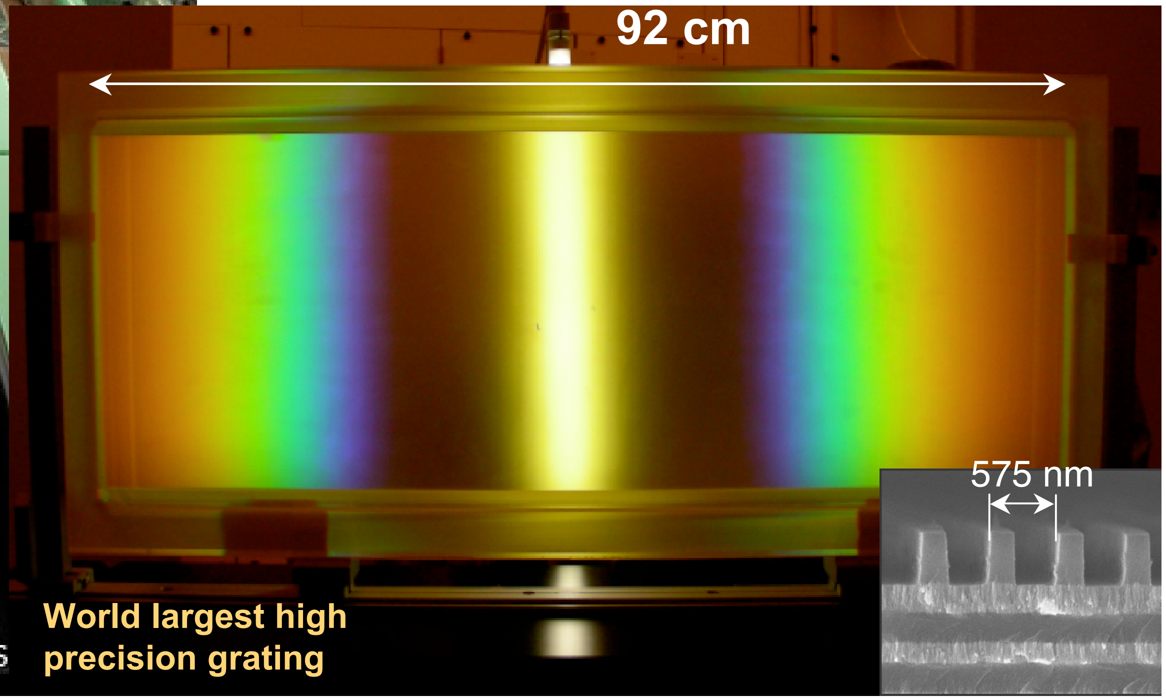




Short and intense laser pulses, high laser power are required for all schemes

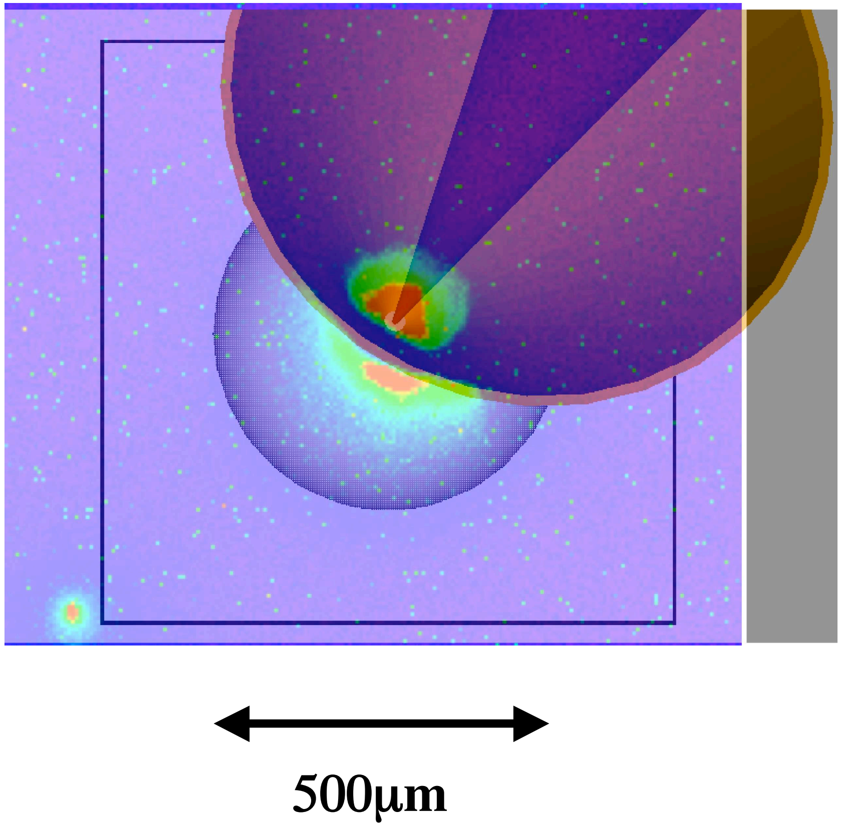

LFEX:
World Largest Short Pulse Laser
Photograph by Joe Nis


Chirp Pulse Amp.
Compression
Amp
Stretch
Space

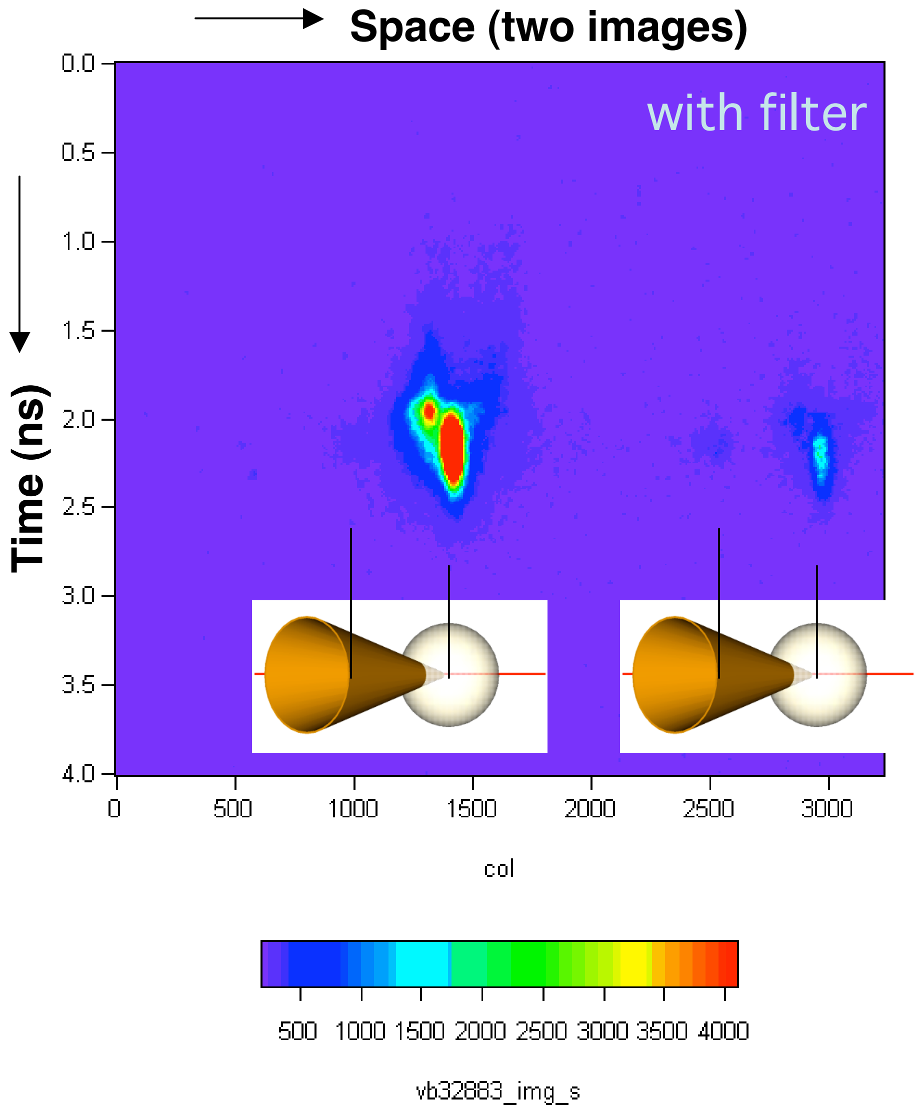

92 cm
575 nm
World largest high
precision grating

4. Results and issues

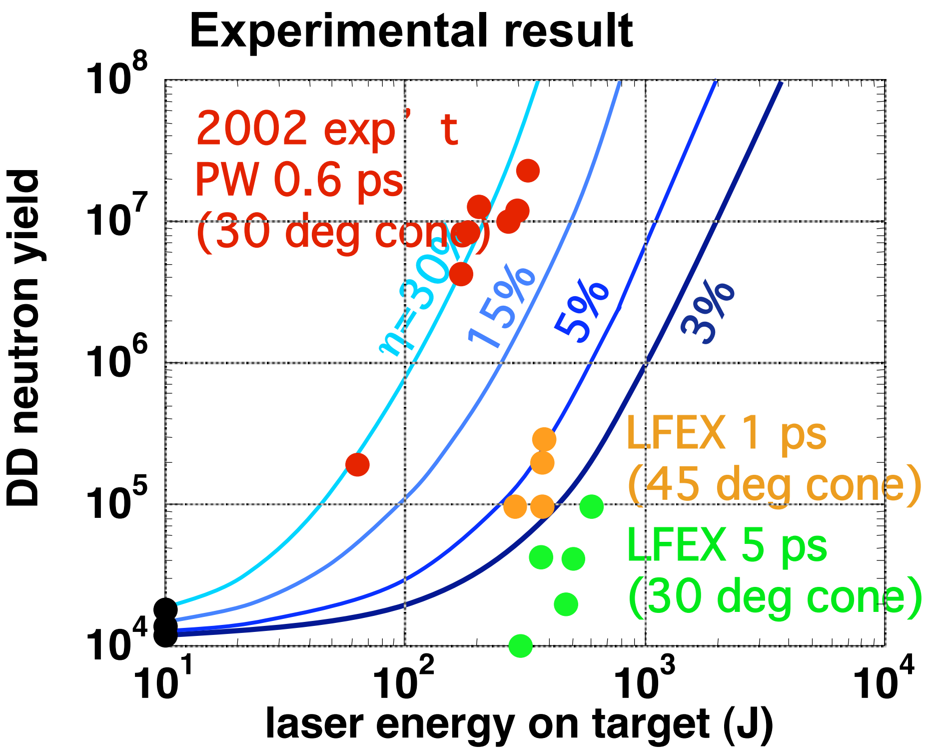
X-ray pinhole camera observing from the cone side (time integrated)

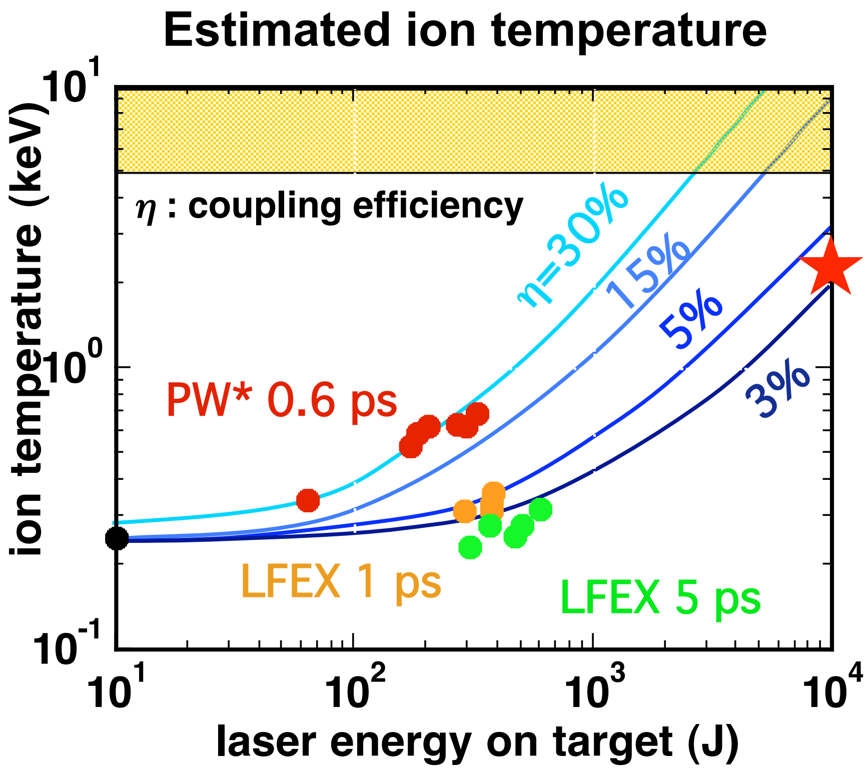


X-ray streak camera (time resolved)



Neutron yield enhanced by up to 30-times

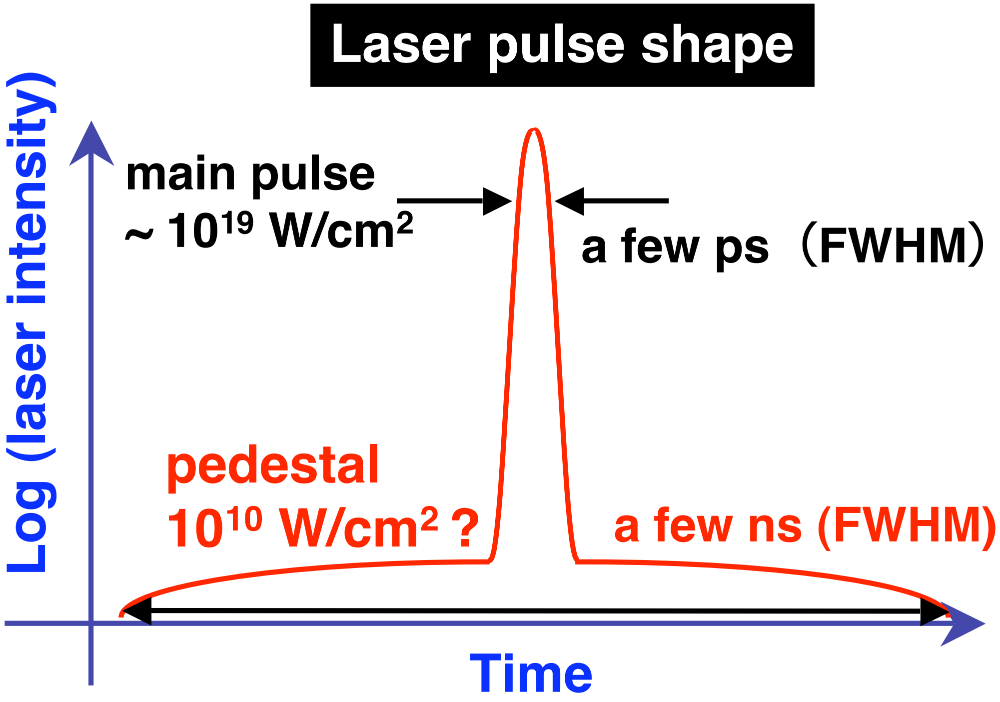




However, coupling efficiency from LFEX laser to the compressed fuel was estimated to be 3-5 %, much lower than expected.

→ IFE/P6-01 Johzaki
IFE/P6-12 Nagatomo

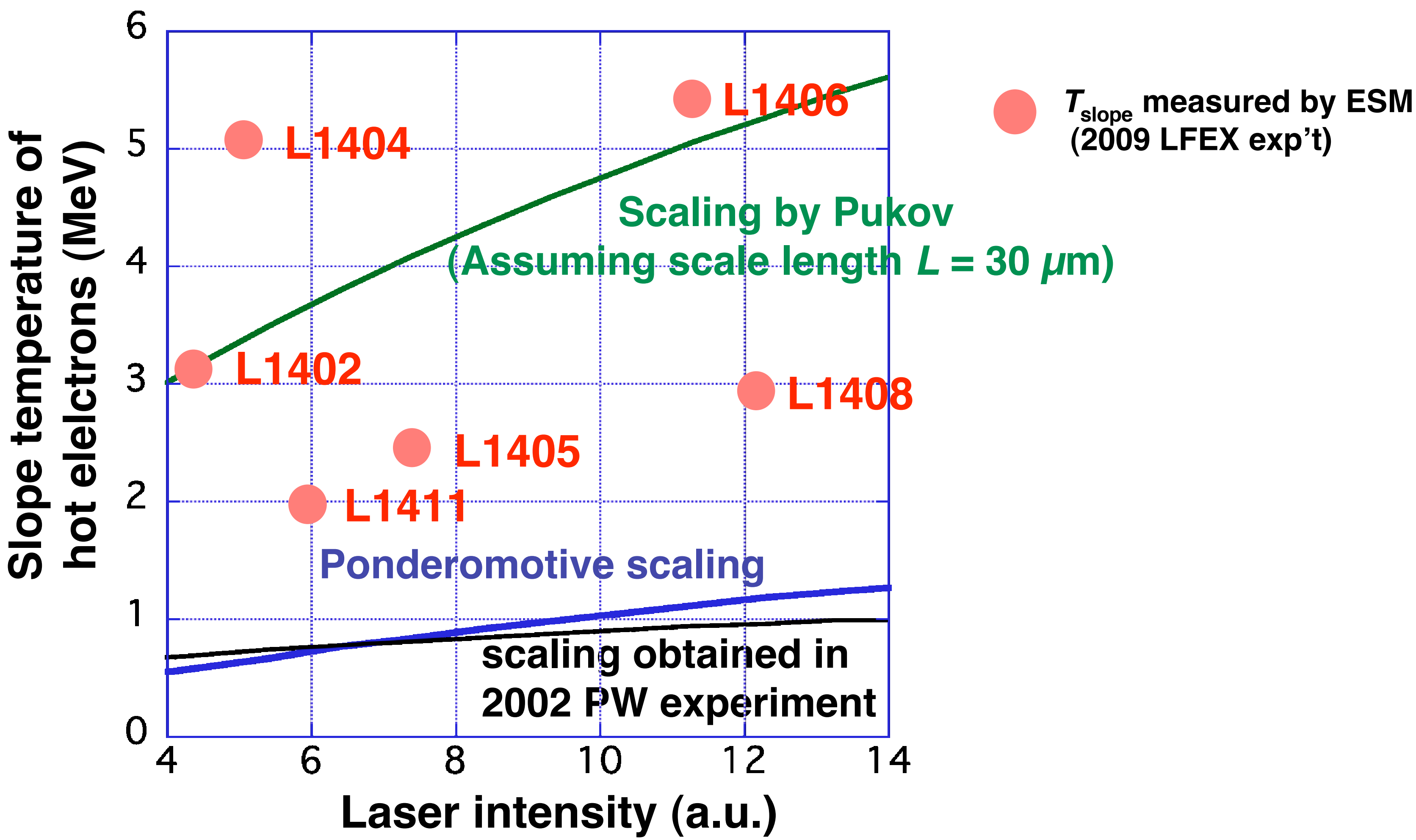
Electron acceleration in a preformed plasma may enhance too-hot electron generation



pedestal >10^{10} W/cm^2

_ pre-plasma formed in cone
_ electrons accelerated in long-scalelength plasma
_ too-hot electrons generated
_ coupling efficiency reduced

Slope temperature of hot electrons was relatively high compared with that obtained in the 2002 experiment.



Result indicates existence of pre-formed long-scalelength plasma.

FI integrated experiment in 2010 is on going

Contrast in LFEX pulse is being substantially improved by introducing

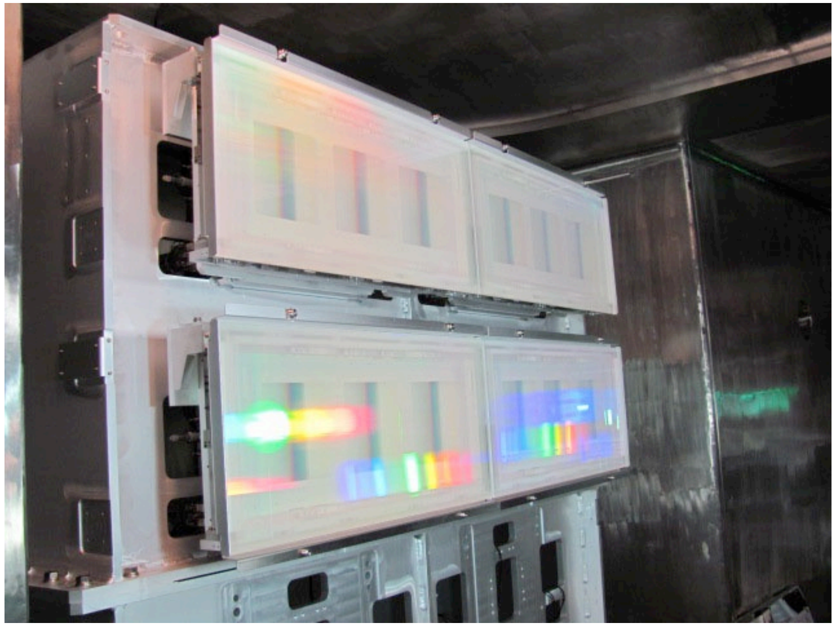
・saturable absorber, and

・AOPF (amplified optical parametric fluorescence) quencher

for a few ns range, and

・reduced spectral ripples

for ps range.



The 2nd beam has been activated.

・1 kJ in 1 beam (2009)

→ *2 kJ in 2 beams (2010)*

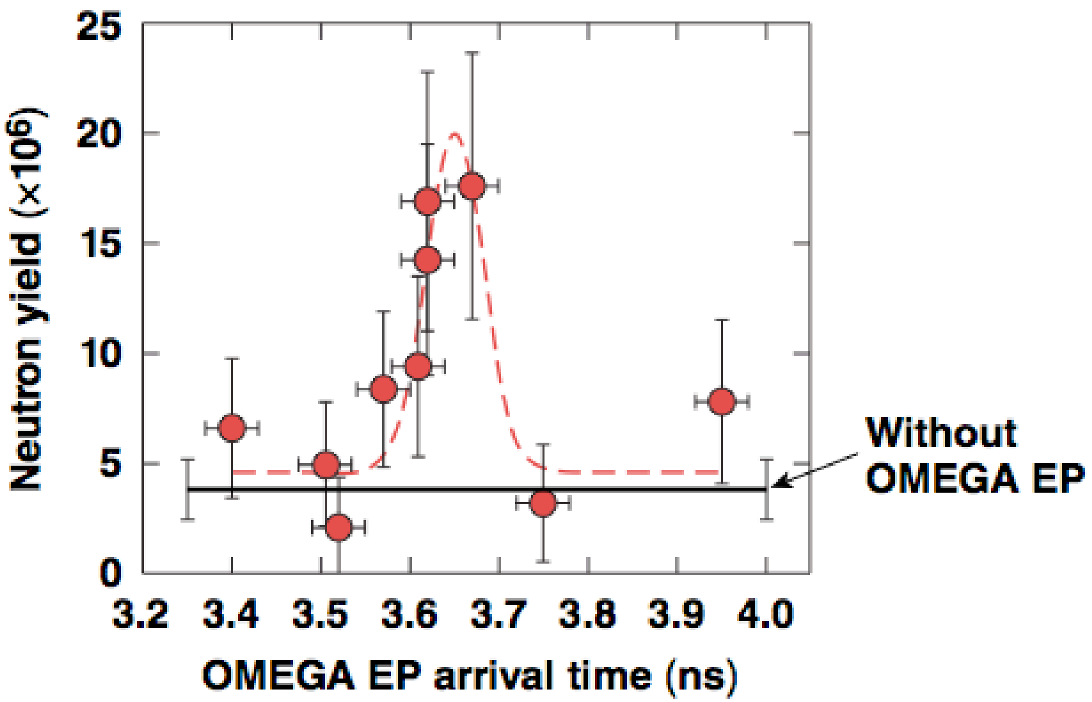
・Beam profile improved toward

10kJ/4beam operaion.

2-keV heating is expected in 2010.

Electron driven fast ignition feasibility study at LLE, Rochester

The neutron yield increased by a factor of 4 with an appropriately timed OMEGA EP beam



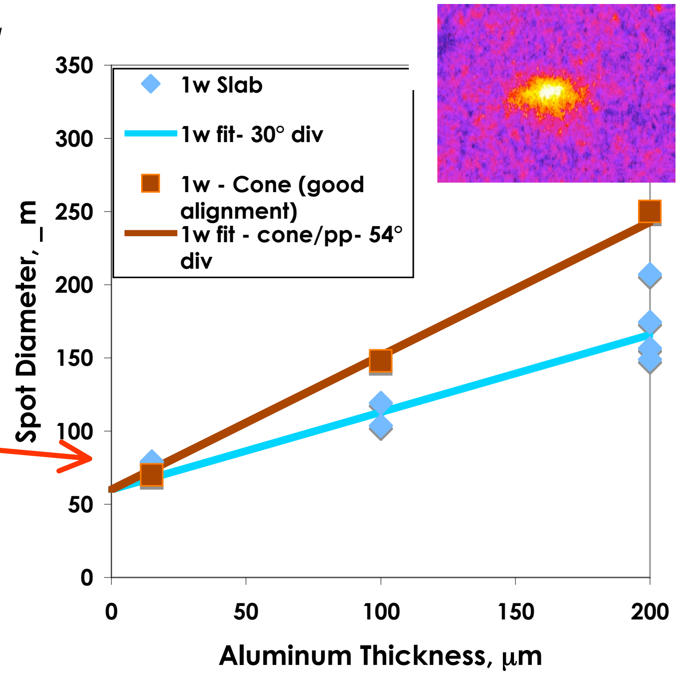
$1.4 \pm 0.5 \times 10^7$ additional neutrons were produced with the short-pulse laser.

E19320 **Need reduction of pre-pulse and pre-plasma**

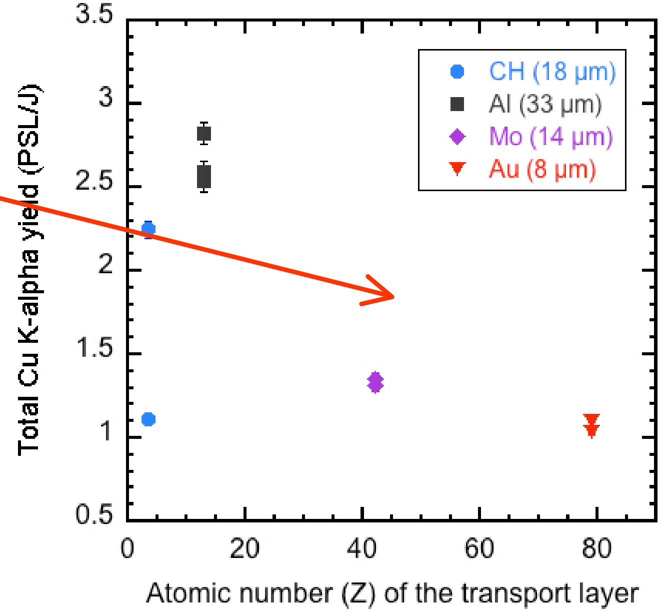
Shows hot electron divergence in resistive material

R.Stephens: IFE/p6-02

- **Divergence lower than previous in Al targets**
  - **Low scatter from careful target and pulse characterization**
  - **~30° from flat**
  - **~50° from inside cone tip**
  - **Unaffected by ~10 mJ prepulse**



- **Hi-Z layers substantially impede transport**
  - **Transport reduced 2x for added Au (8 µm) or Mo (14 µm) layer**



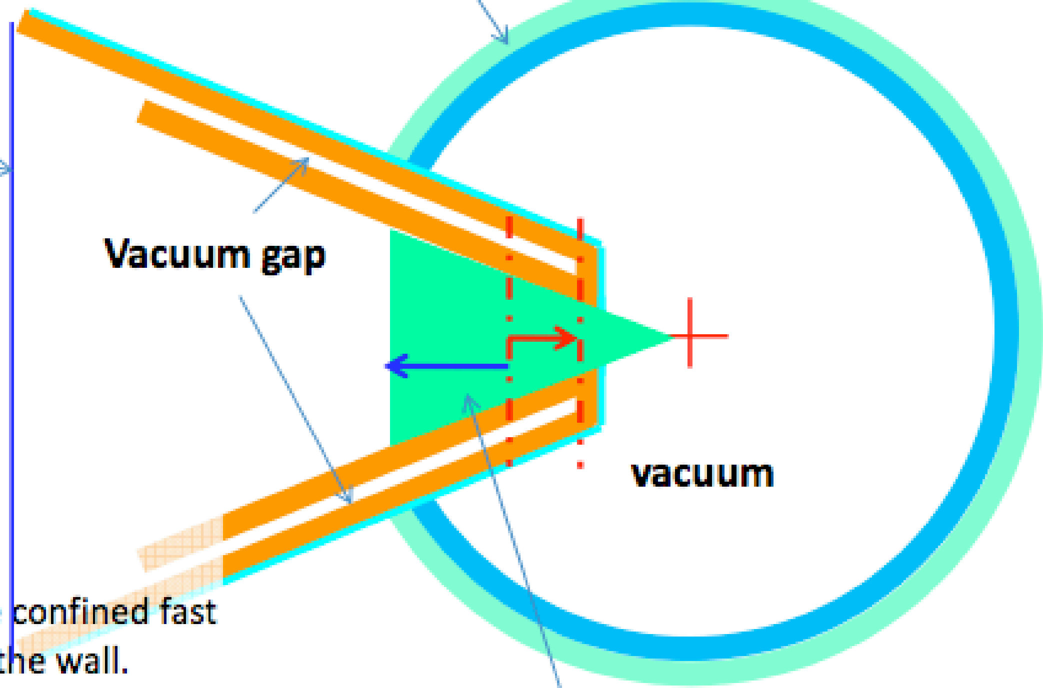
A new fast ignition target design for FIREX-I

IFE/P6-1 T. Johzaki, etal

Thin foil
[DLC or CH
(0.03~0.1um)
+ Al (30nm)]
pre-pulse absorber

CH coating
Tamping Au ablation

Br doped shell
double ablation stabilization of RT instability



Extended Au Double Cone with shorter inner wall

Fast electron confinement & guiding to the core

1. Shorter inner wall prevents the confined fast electrons from escaping along the wall.
2. **Extended vacuum gap guided the fast electron close to the core.**
3. **We can make interaction surface larger by pulling the tip surface away from the core, which lowers the heating laser intensity & softens fast electron spectrum.**

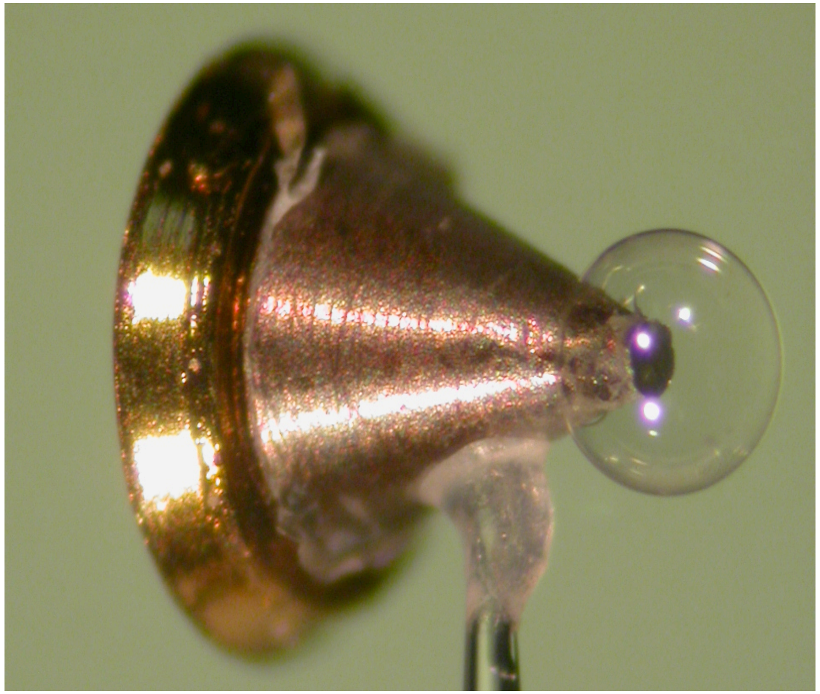
Low-Z "TONGARI" (pointed) tip

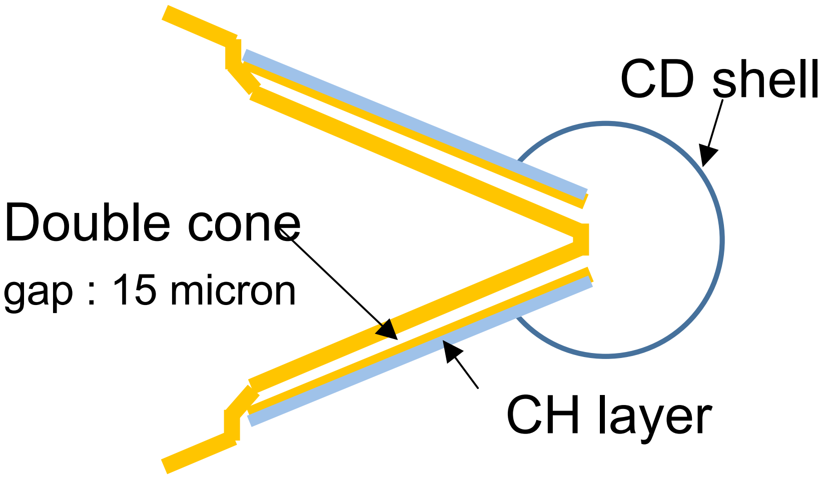
Low-Z ...... lowering the collisional effects during long distance propagation

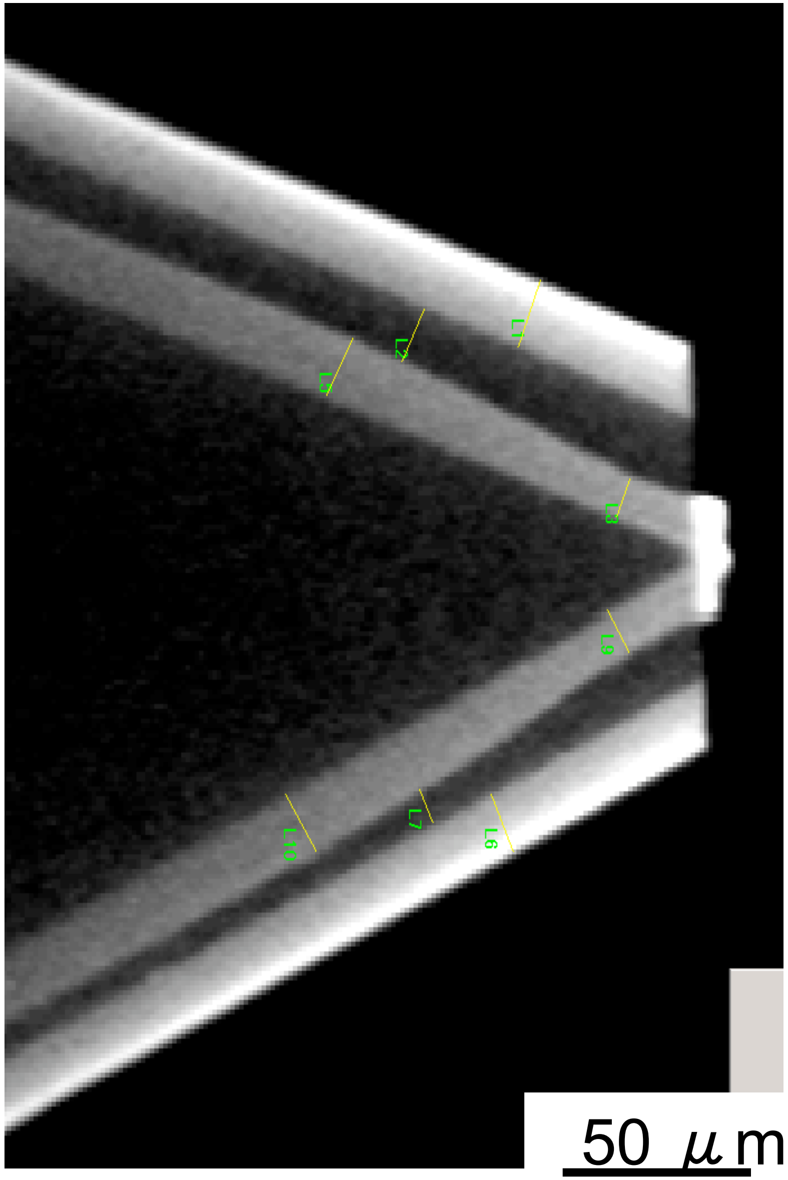
TONGRI... keeping the tip for a long time by letting plasma jet slip on the TONGARI surface

1st prototype of double-cone target were prepared for preliminary laser shot on FIREX

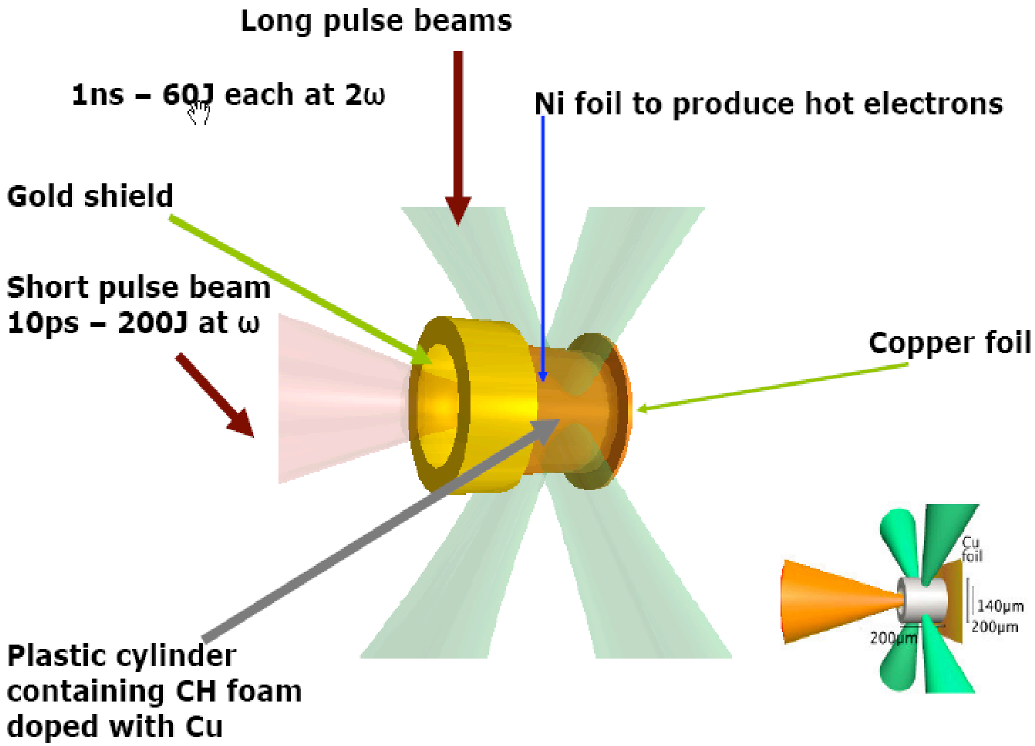
(IFE/P6-27 Honmma, Norimatsu)

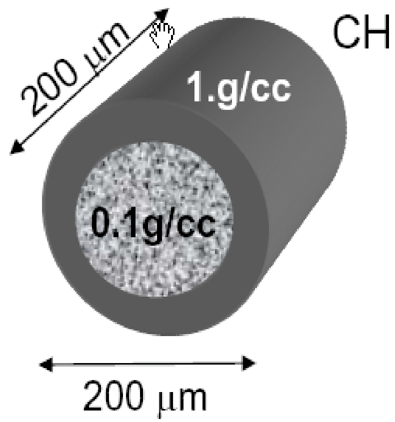


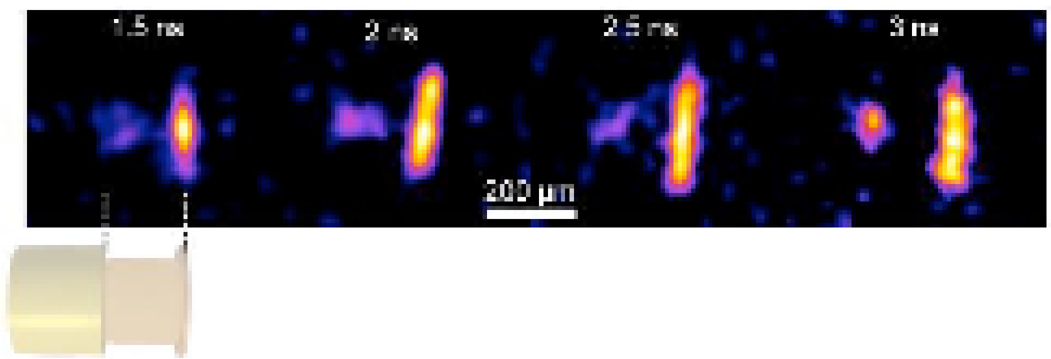




Hot electron transport in hot dense plasmas: HiPER WP10(D.Batani)
D.Batani, Y.Rhee, etal IFE/P6-09

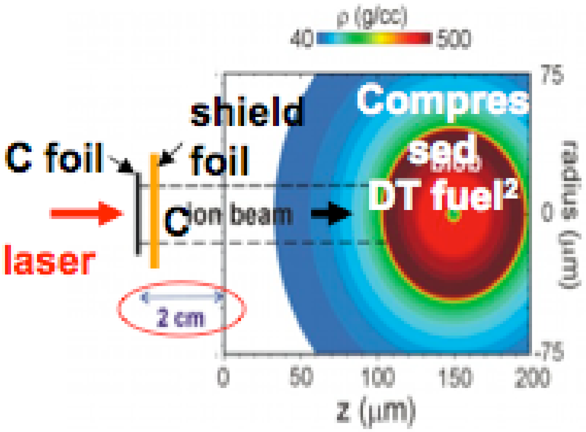




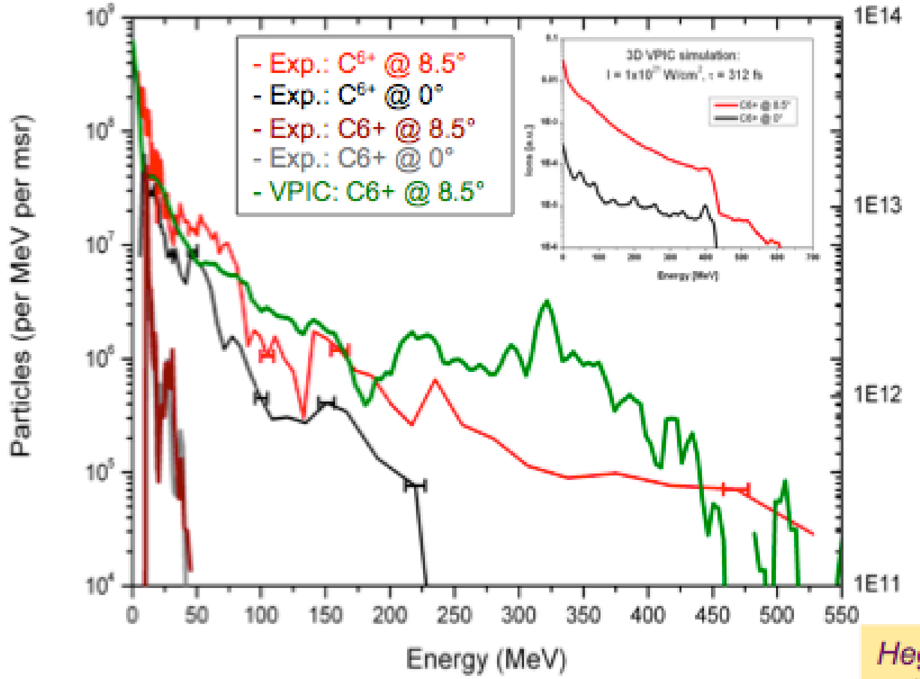


Fast Ignition with H.E. Ion

LANL: B.M.H. Hegelich : P6-03



Beam Ion	Energy (MeV)	Number of Ions	Laser Irrad. (W/cm^2)
Protons	7 – 19	10^{16}	~ 10^{20}
C^{6+}	400-480	10^{14}	~ 10^{21}

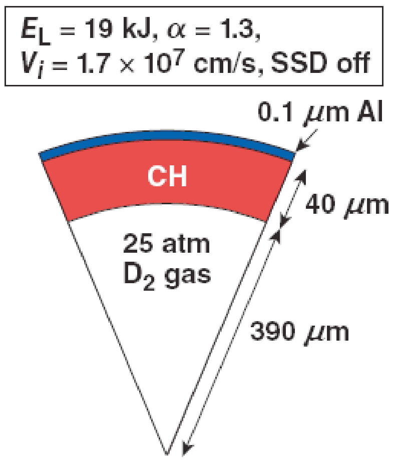


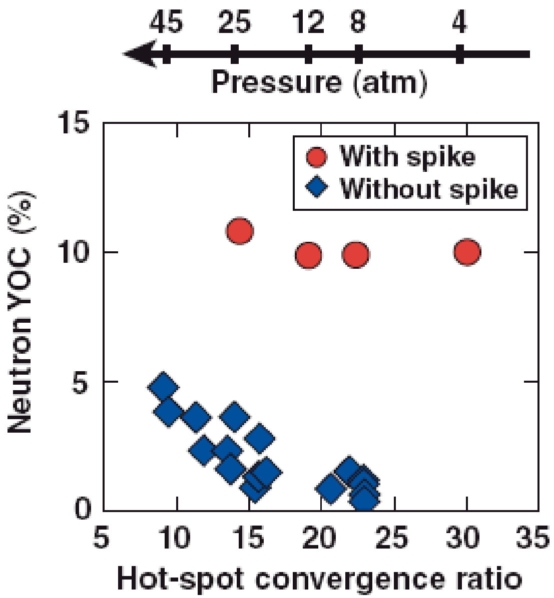
- Simulations agree with measured C spectra (energy, number, angular distribution)
- $V_{ion}/v_{proton} > 0.5$ (1.02 for best shot)
- Spectra retain mono-energetic remnants from adiabatic phase

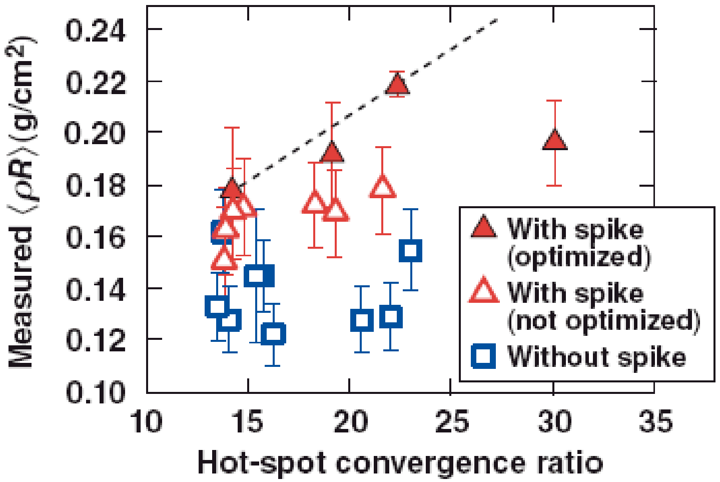
Hegelich, et al., Nature Physics (2010) submitted

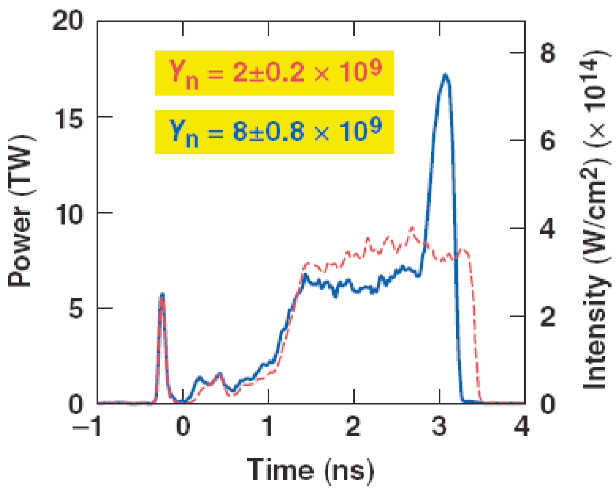
Shock ignition experiments on Omega facility
IFE/1-1 D.M.   LLE, Univ. Rochester

Shock ignition experiments on Omega: 4_ neutron yield, better convergence







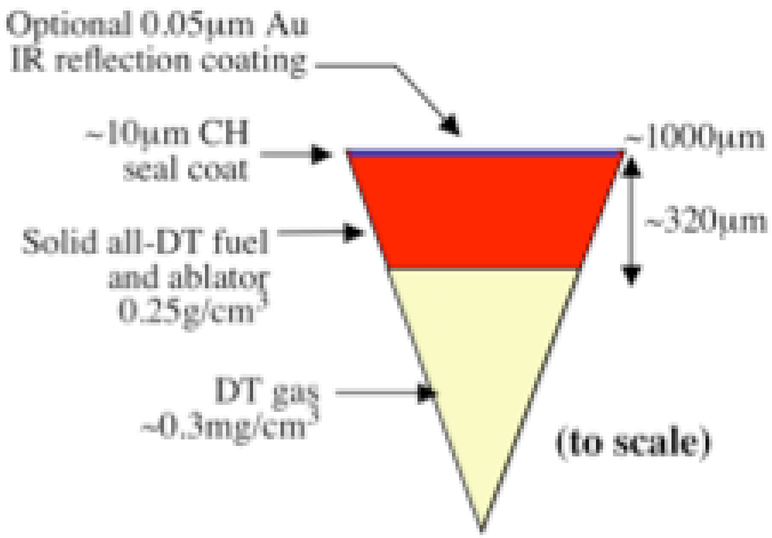


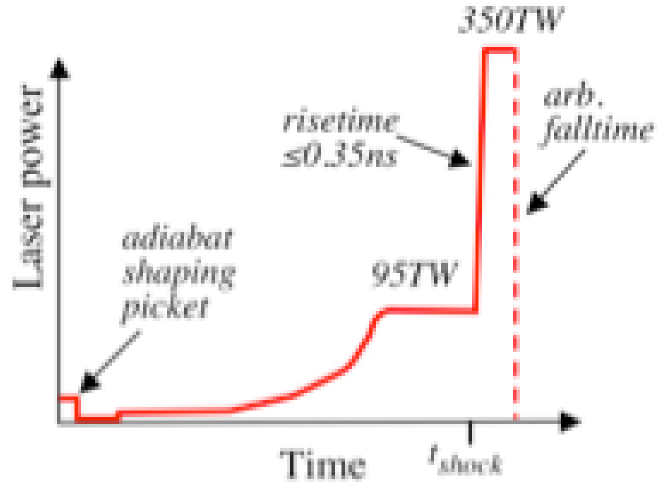
Shock-assisted implosions show increased fuel areal densities and much better symmetry

Hot electron generation and transport remain the main issue

Shock Ignition Target for NIF

TFE/p6-17 Perkins





• Yield , gain	33.4MJ , 60.4
• Drive energy: main + shock	0.253+0.5 = 0.553MJ
• Peak powers: main, shock	95TW, 350TW
• Ignition window at $Yield_{50\%}$	400ps
• Marginal shock energy, power	0.14MJ, 260TW (for Y≥30MJ)
• IFAR(66%)	15.3
• V_{max}: main only, main+shock	2.54e7, 2.98e7 cm/s
• CR: r_0/r_{HS} (conv defn), r_{gas}/r_{HS}	34.4, 23.4

After L.J.Perkin, R.Betti, etal, PRL,103, 045004 (2009)

Heavy ion fusion can use a variety of driver, focusing, chamber, and target options (IFE/P6-6 G.Logan)

Accelerator
- Induction Linac
- RF Linac
- RF Linac + Storage Ring/ Synchrotron
- Induction Recirculator
- Dielectric Wall Accelerator

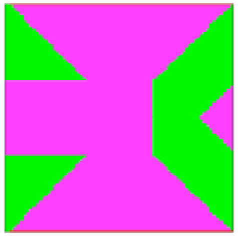
Focusing
- Ballistic, Neutralized
- Ballistic, Vacuum
- Self Pinch, 2-stage

Chamber
- Thick-Liquid-Protected Wall
- Thin-Liquid-Protected Wall
- Solid Dry Wall + Gas Fill
- Granular-Solid Flow Wall

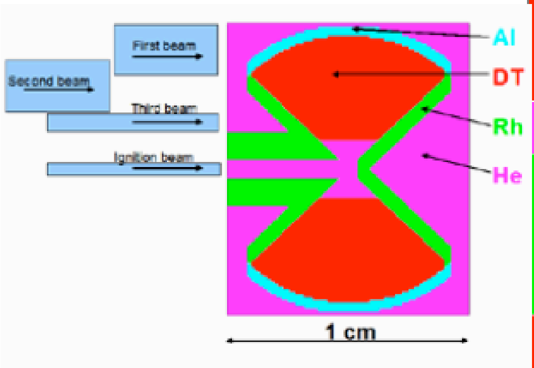
Target
- Indirect Drive, Central Hot Spot Ignition
- Indirect Drive, Fast ignition
- Direct Drive, Central Hot Spot Ignition
- Polar Direct Drive + Shock Ignition
- Hydro Drive +Fast or Shock Ignition

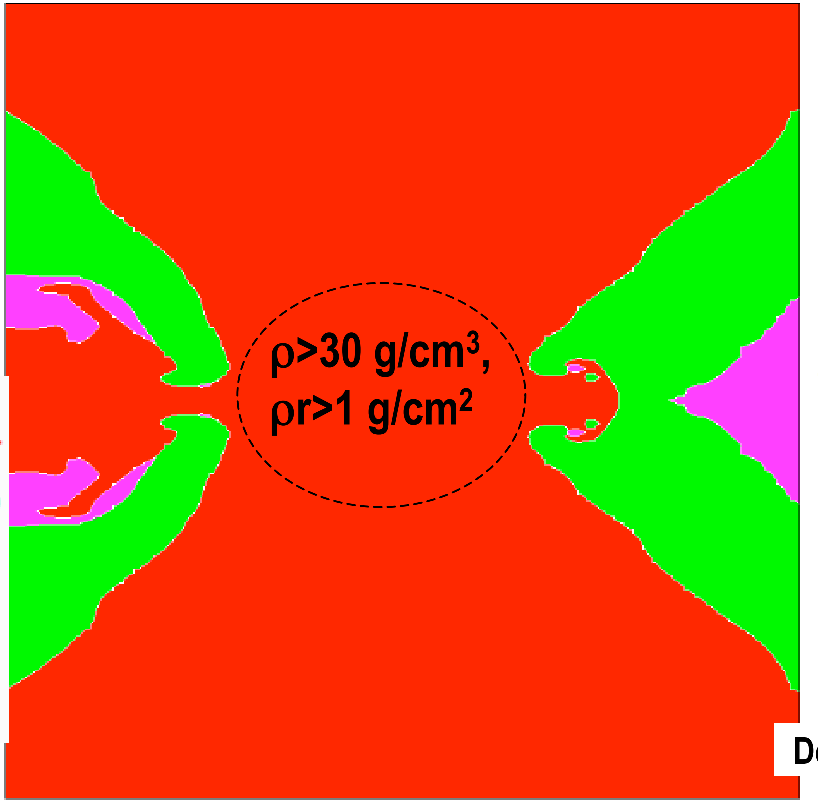
HIF R&D effort mostly on the blue- type options in this chart. Induction or RF linac drivers with ~ 100 beams can apply to any target option.

Material distribution at initial time and just before injection of the ignition beam, showing very small mix effects.



1X





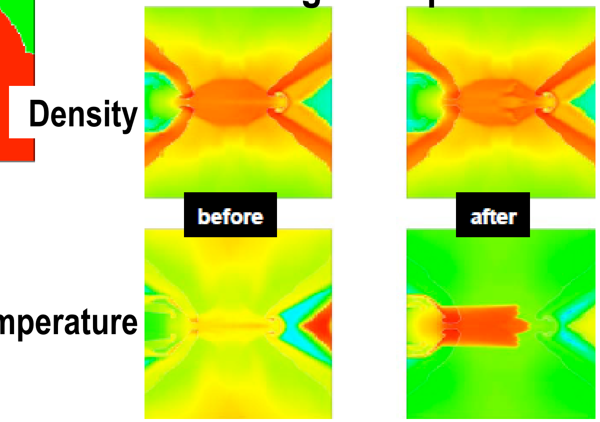
3X

DT

Case

Void

Density and temperature before and after the ignition pulse



Near term plans include sub-ns pulses for the third ring of beams, seeking ρ_{DT}>100g/cm3, & hollow ignition beam for shock heating.

Reactor Technology “beyond NIF&LMJ”

Chamber

IFE/1-5 M. Pelrado (Spain) ,and P6-22 Juárez, R:
Chamber dynamics, Neutronics, Materials, Safety for HiPER Facilty
P6-23 Alvarez, J.(Spain): The Role of the Spatial and Temporal Radiation Deposition in Inertial Fusion Chambers
P6-24 Cuesta-Lopez, S.(Spain): Modeling Advanced Materials for Nuclear Fusion Technology
P6-25 Gonzalez-Arrabal, R.(Spain): Study of diffusion and retention of light species (H and He) in pure W and W-based materials
p6-21T.Norimatsu(Japan): Chamber dynamics

IFE Driver

[Laser]
OV/5-1 S.Jacquemot(France): HiPER DPSSL
IFE/1-4 C.Barty(USA): LIFE DPSSL
P6-7 J.Weave(USA): KrF
P6-18 H.J.Kong(Korea): DPSSL
[HIF]
p6-6 G.Logan: HIB for FI and Shock Ig.

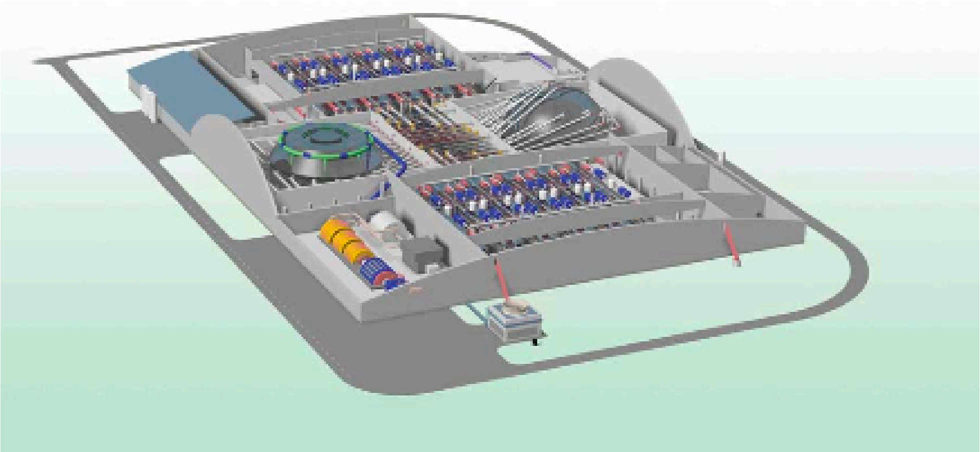
Target

OV/5-1 S.Jacquemot(France)
p6-19 M.kalal (Czech): Target injection/trucking
p6-26 A.V.Hamza (USA): NIF targe fabricaion
p6-27H.Homma (Japan) : Target Fabricaion

The HiPER project

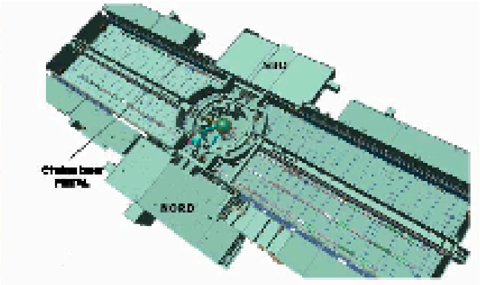
to demonstrate high repetition rate operation and solve power-production bottlenecks

26 Eu partners



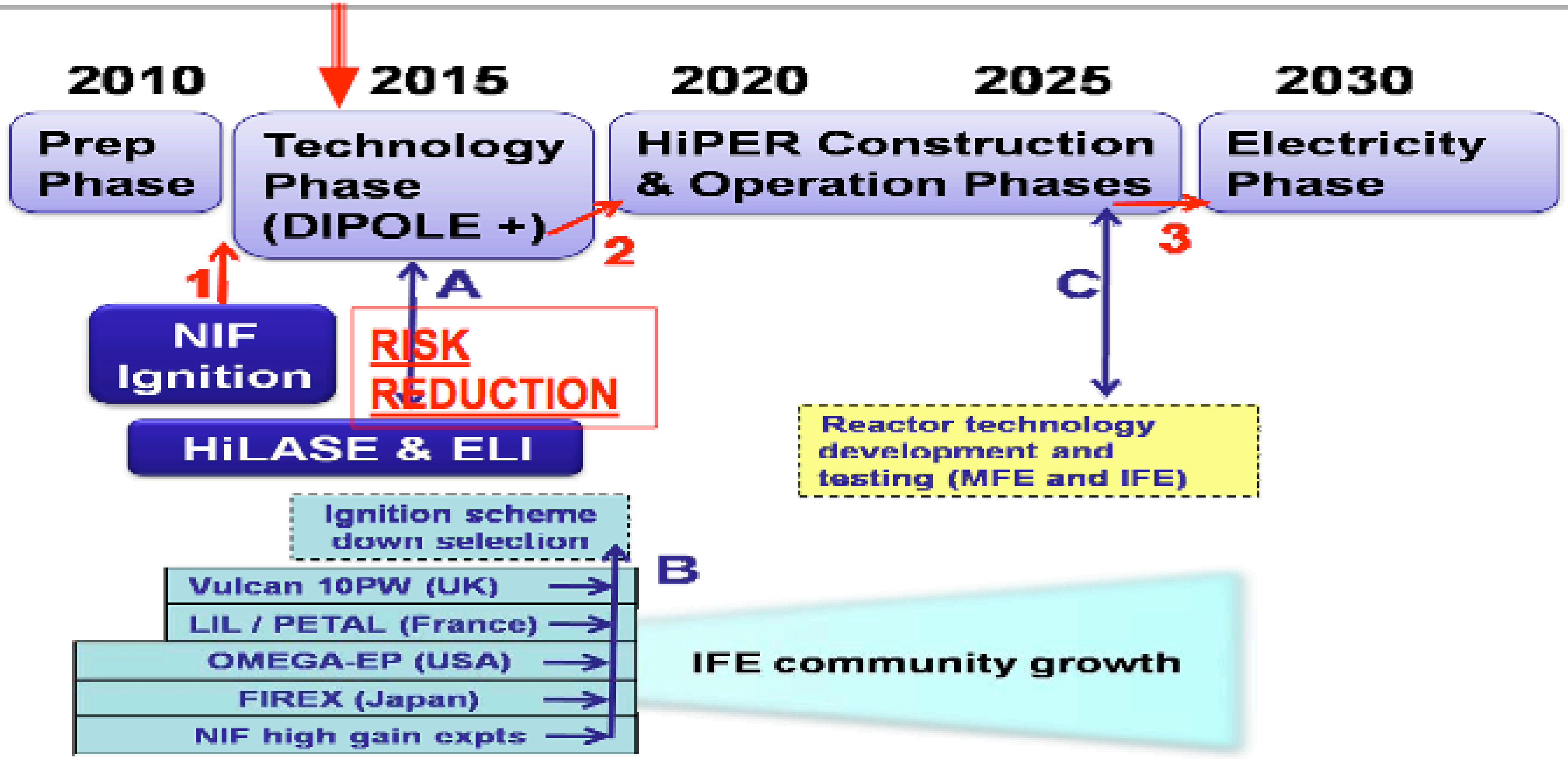
in a single facility step

PETAL on LMJ:
a forerunner to address physics issues

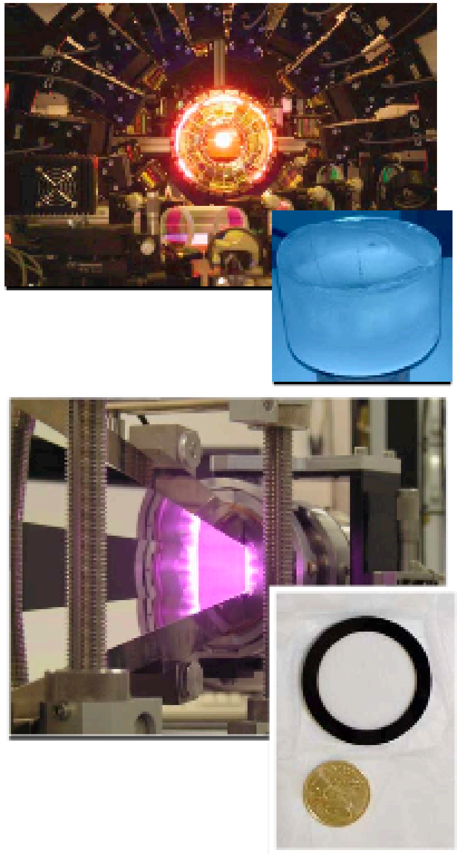


Independent Experiments to demonstrate REPETITIVE OPERATION to be *INTEGRATED* in the HiPER Construction

CHAMBER TECHNOLOGY: understanding physics and propose DESIGNS for ENGINEERING FACILITY (HIPER 4A / BURST Mode) and next step of POWER PLANT (HIPER 4B)



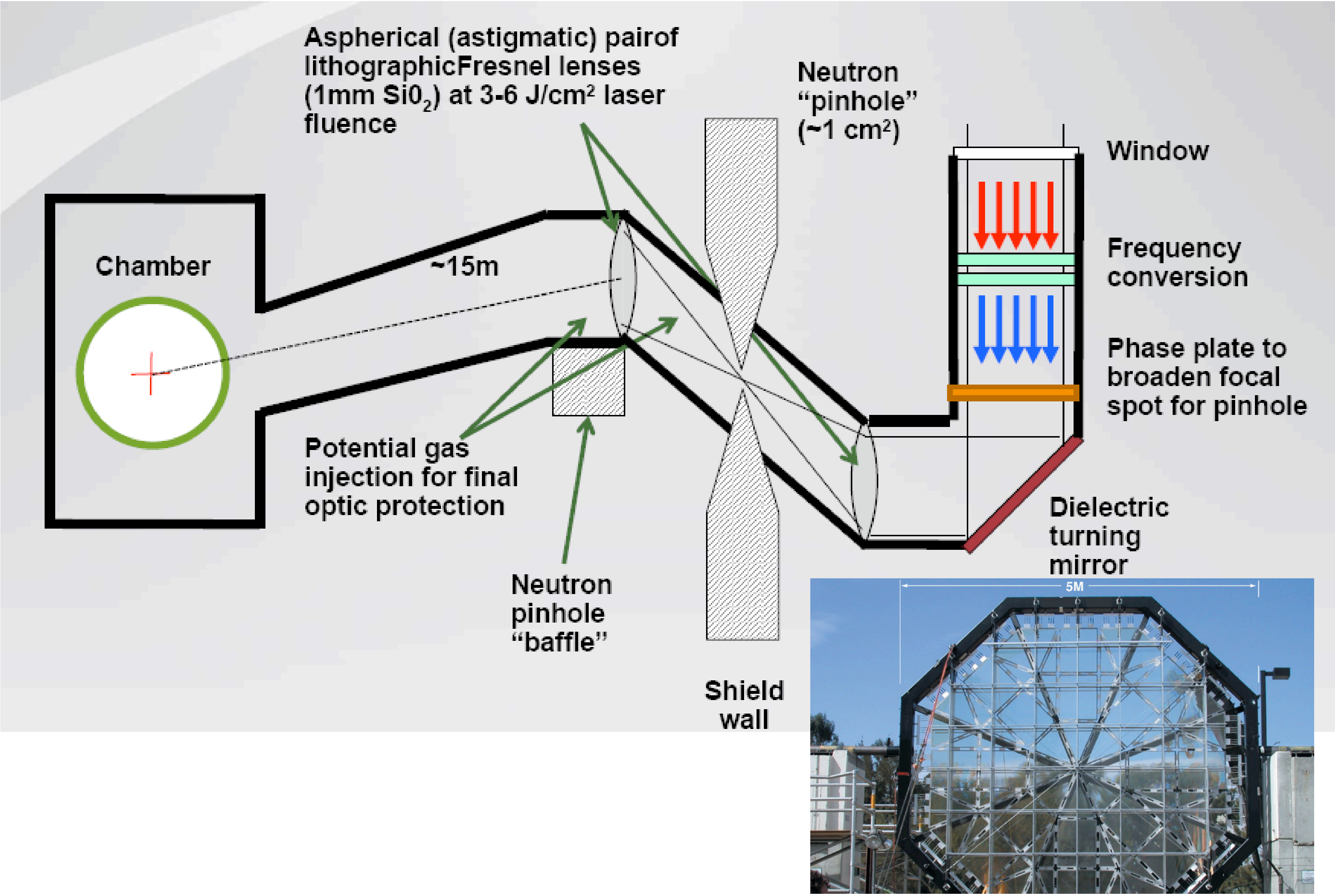
The European DPSSL program



DPSSL Programs	Goal Achievement	Gain medium	Amplifier architecture
Germany POLARIS	150 J @ 0.1Hz 12 J @ 0.003 Hz	Yb: CaF_2 crystals	RT° and cryo gas cooled multi-slab
France LUCIA	100 J @ 10Hz 7 J @ 2 Hz	Yb:YAG crystals & ceramics	RT° and cryo gas cooled active mirror
UK DiPOLE	1kJ @ 10 Hz none	Yb:YAG ceramics & glass	cryo gas cooled multi-slab
Czech Republic hilase	100 J @ 10Hz & 6J @ 100Hz none	tbd	tbd

Protection of optic elements

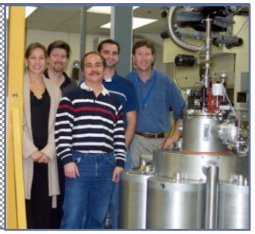
HiPER/ France



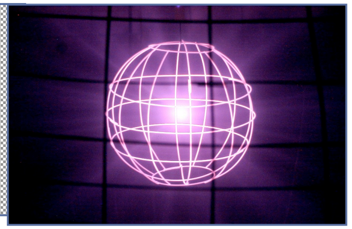
Reactor first wall: cyclic thermal stresses

- Damage to armor from ions and cyclic thermal stress remains one of the most critical issues
- The chamber is large so the wall remains below the melting point of W
- A coordinated R&D program was undertaken to study long-term damage

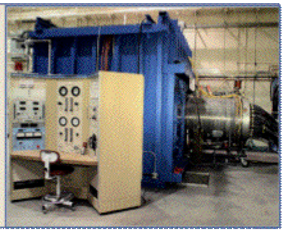
X-rays:
XAPPER – LLNL



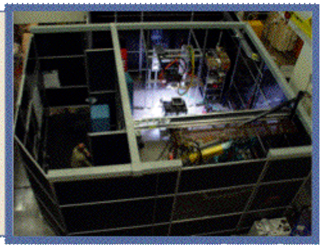
Helium:
IEC – Wisconsin
He beam – UNC



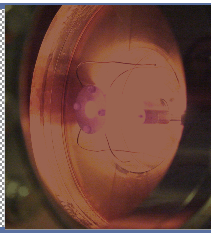
Ions:
RHEPP – SNLA



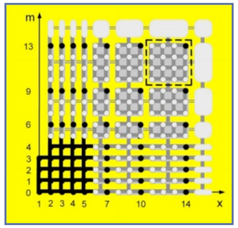
Cyclic heating:
IR lamp, e-beam:
ORNL

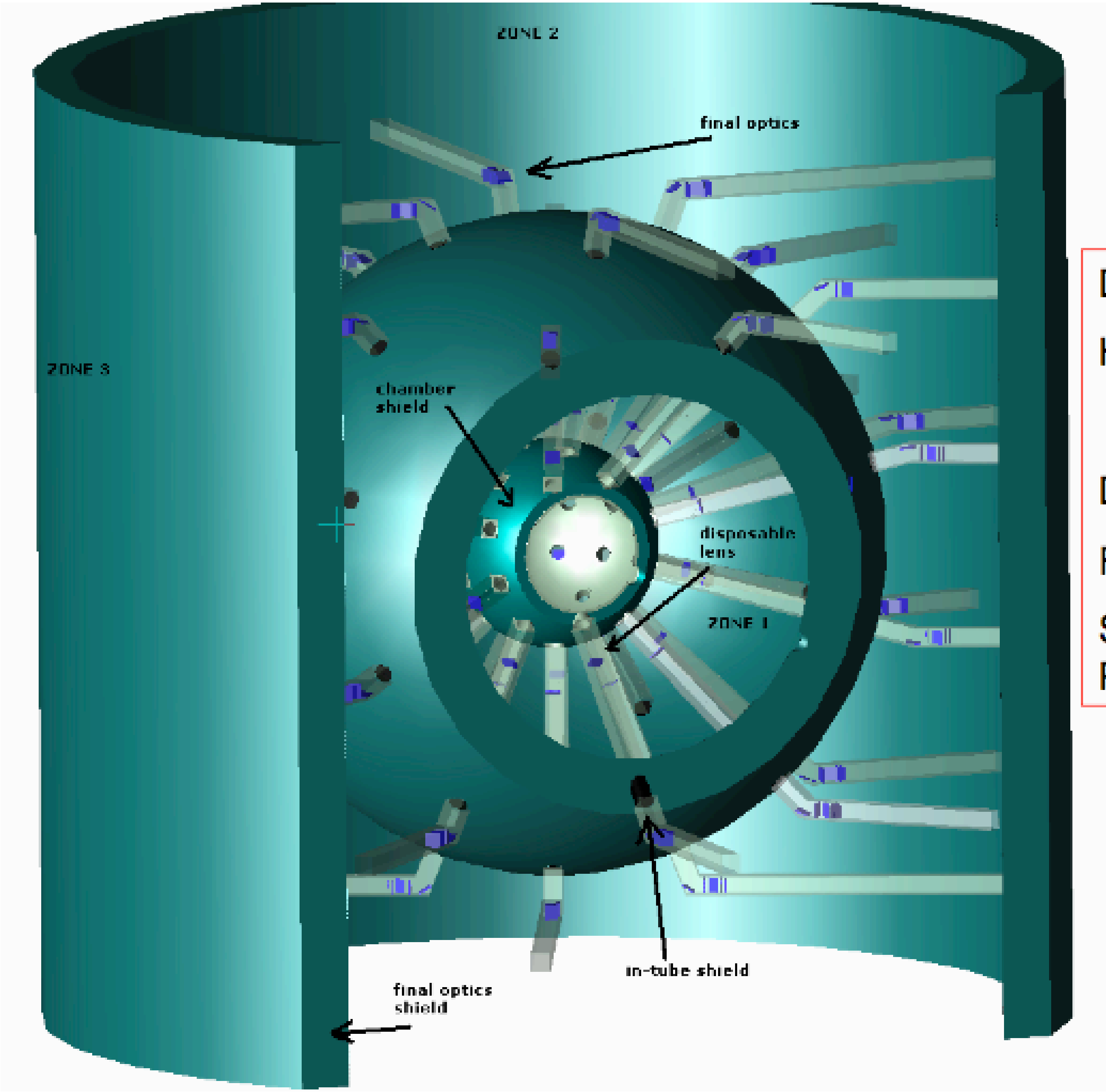


Cyclic heating:
Lasers – UCSD



Modeling:
UCLA, Wisconsin,
Berkeley, ORNL





IFE/1-5 M.Perlado
And related posters

DESIGN OF

HIPER 4A

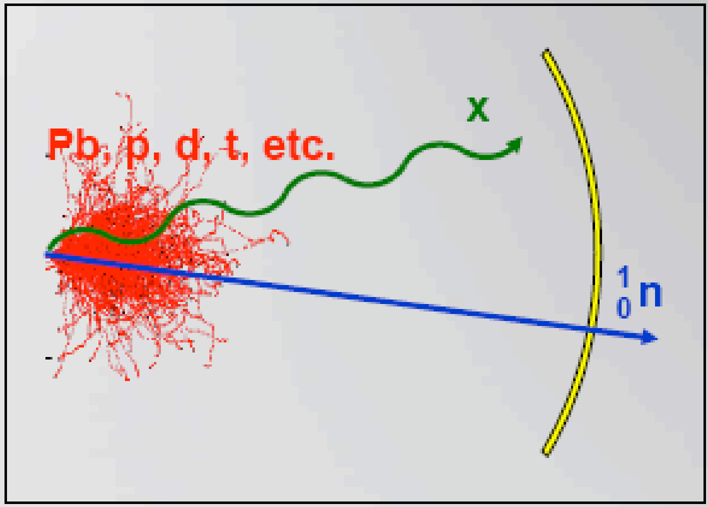
Dimensioning

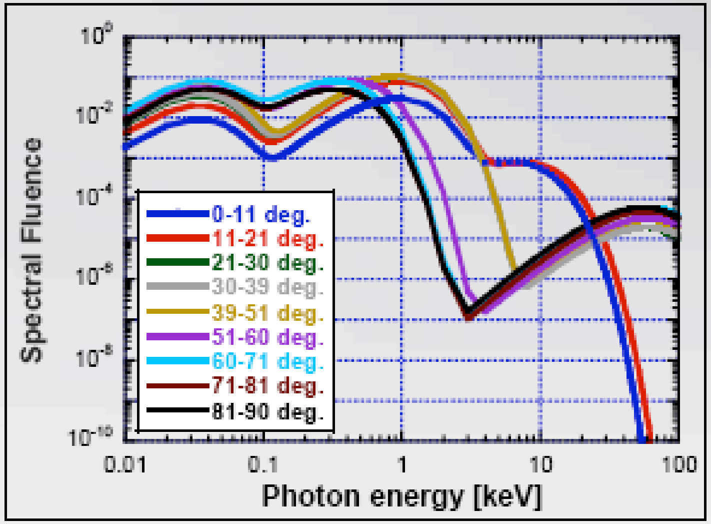
First Wall analysis

Safety and Radio-Protection

First wall protection: chamber gas fill

Parameter	Value
Target yield	200 MJ
Repetition rate	15 Hz
Fusion power	3000 MW
Chamber radius	5 m
X-rays	12%
Ions	10%



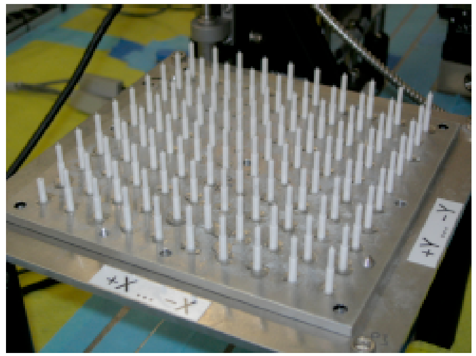


Chamber fill gas can attenuate x-rays and ions to protect the first wall

Target technology development

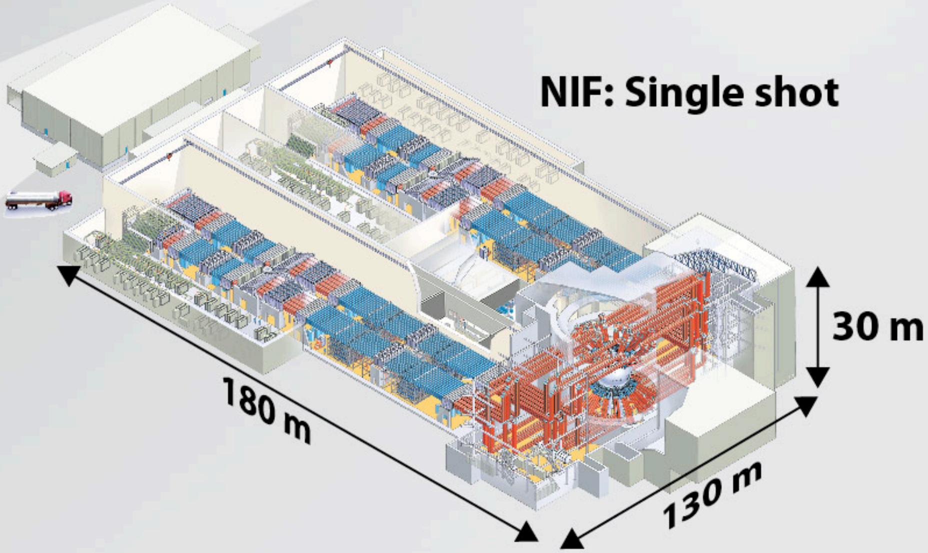
- Optimisation of fuel pellet manufacture and high repetition integration is one of the key areas of study for HiPER
- Cost is an important, but manageable factor

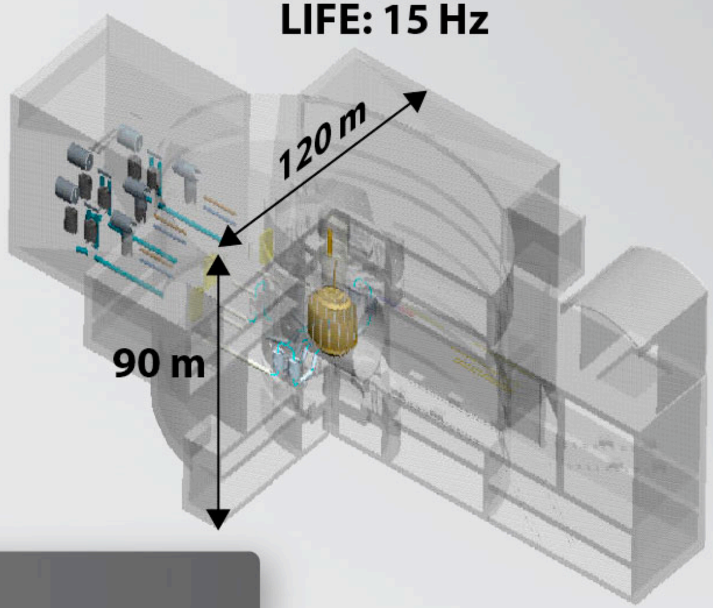
	LIFE	Lego ®	Mil Spec Bullet	Aluminum Cans
Number/year	3–6 x 10^8	1.8 x 10^9	9 x 10^9	
Dimensional tolerance	± 50 μm	± 10 μm	± 40 μm	
Cost	$0.20–0.30	$0.06	$0.21	$0.012



Bullets are an interesting comparison; they are multi-component, multi materials, that tolerate high acceleration and high velocity

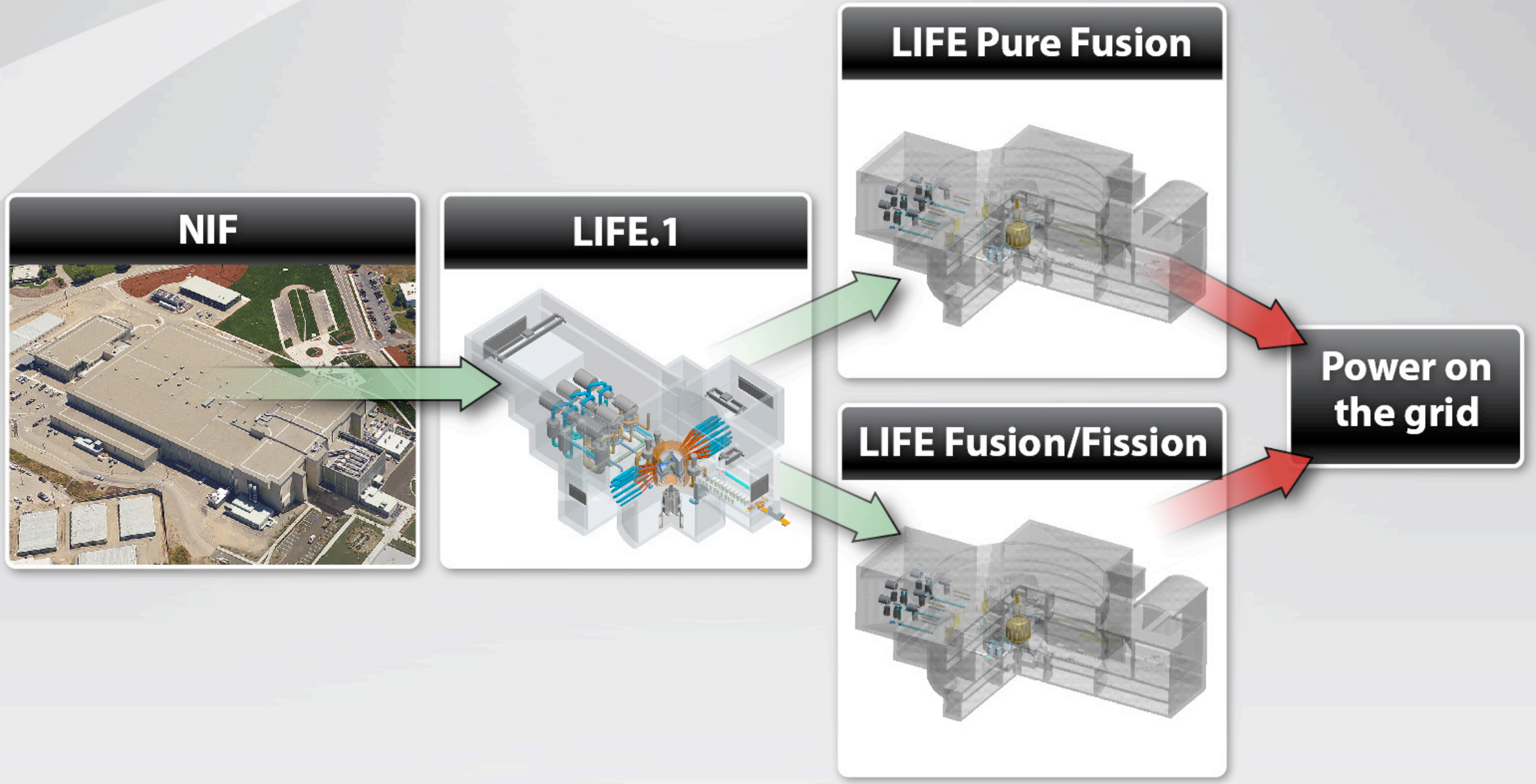
A LIFE plant would have a similar footprint to NIF while generating 1 GWe





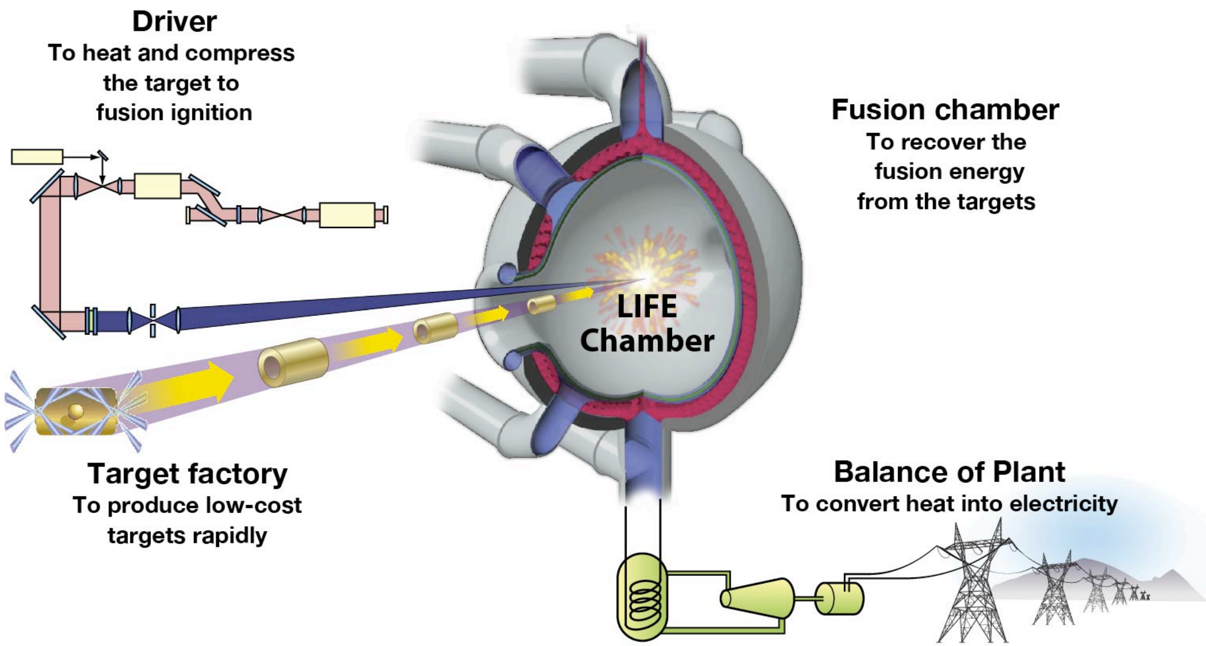
Similar:
- Physical size
- Laser energy
- Target performance
- Concept of operations (LRUs, ...)

LIFE strategy enables multiple missions, based on a common intermediate demonstration plant



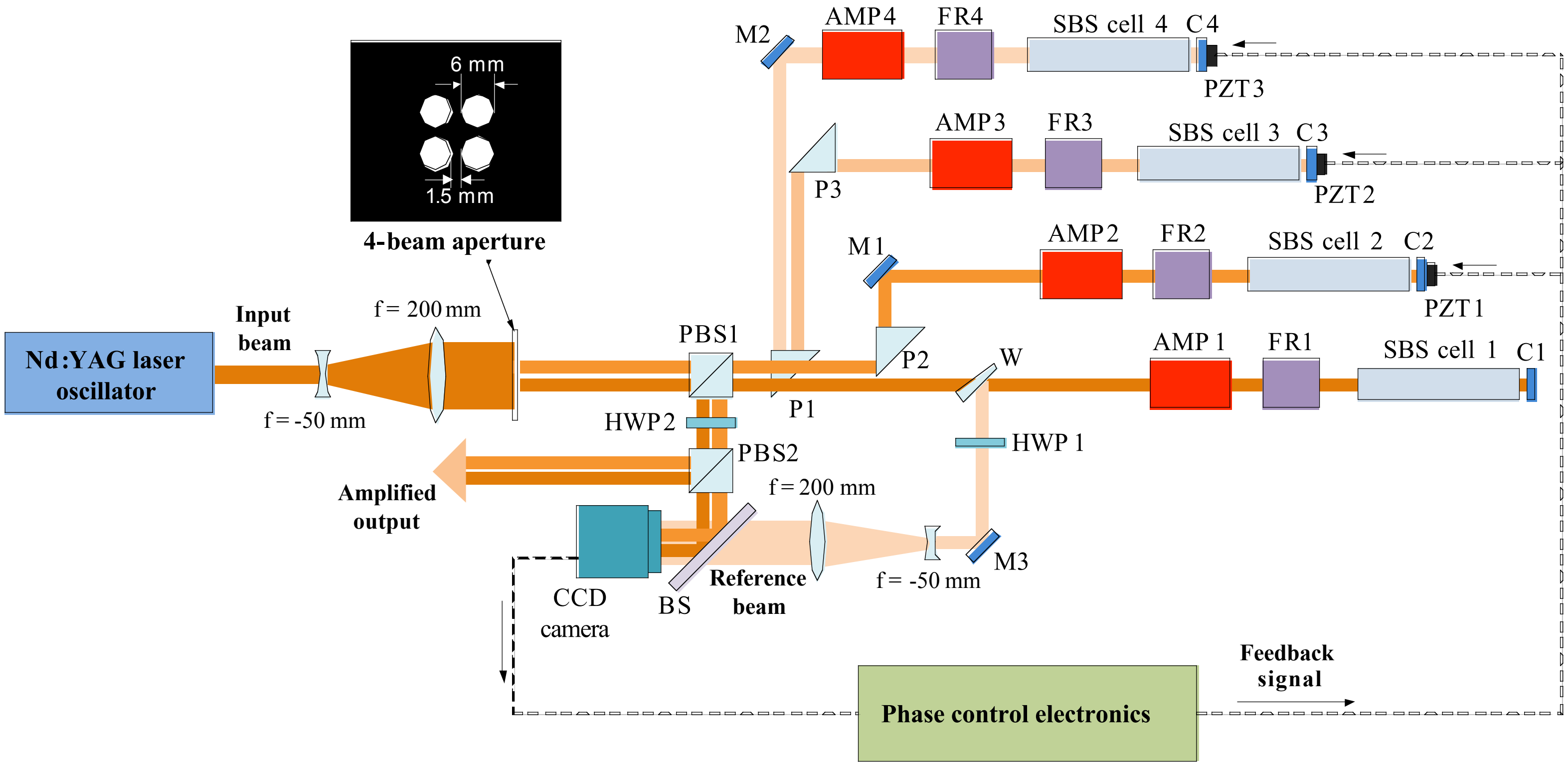
Fusion energy “soon enough to make a difference”

- Commercially attractive
- Use of existing grid
- Passively safe
- Low price volatility
- Public acceptability
- Sustainable
- Carbon-free operation
- Non geo-political
- Timely delivery



- No enrichment
- No reprocessing
- No high level waste storage

Experimental setup for the wavefront dividing 4-beam combination

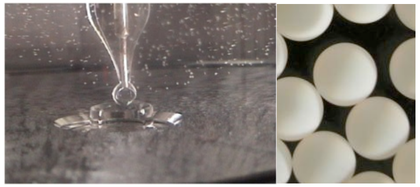


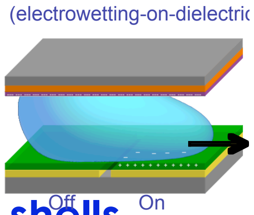
PB1&PBS2, polarizing beam splitters; HWP1&HWP2, half wave plate; P1, P2&P3, 45 degree prisms; BS, beam splitter; W, wedged window; FR1, FR2, FR3&FR4, Faraday rotators; C1, C2, C3&C4, concave mirrors; PZT1, PZT2&PZT3, piezoelectric translators.

J. S. Shin, S. Park, H. J. Kong, and J. W. Yoon, Applied Physics Letters. 96.131116, 2010.

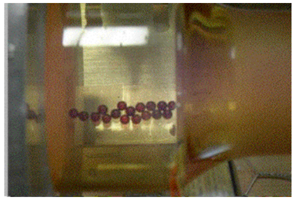
IFT is the leading developer of IFE target supply processes and target related systems

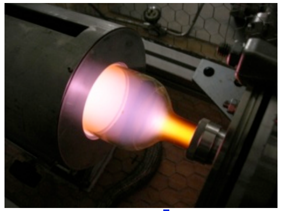
Direct drive process steps have experimental demo programs…





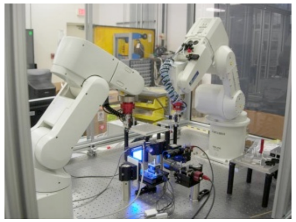
Making foam or CH shells





Coat shells with plasma polymer and metallic layers

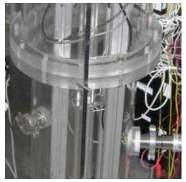
Permeation fill targets & layer in a cryogenic fluidized bed



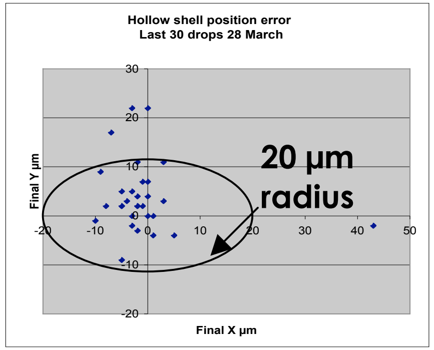
Robotic assembly

Inject targets (gas-gun or electromagnetic)

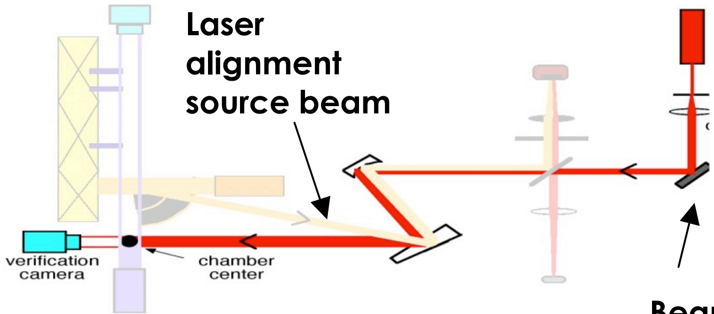
Target loading and charging



±3 kV steering electrodes



Electrically steer targets - FTF or other applications

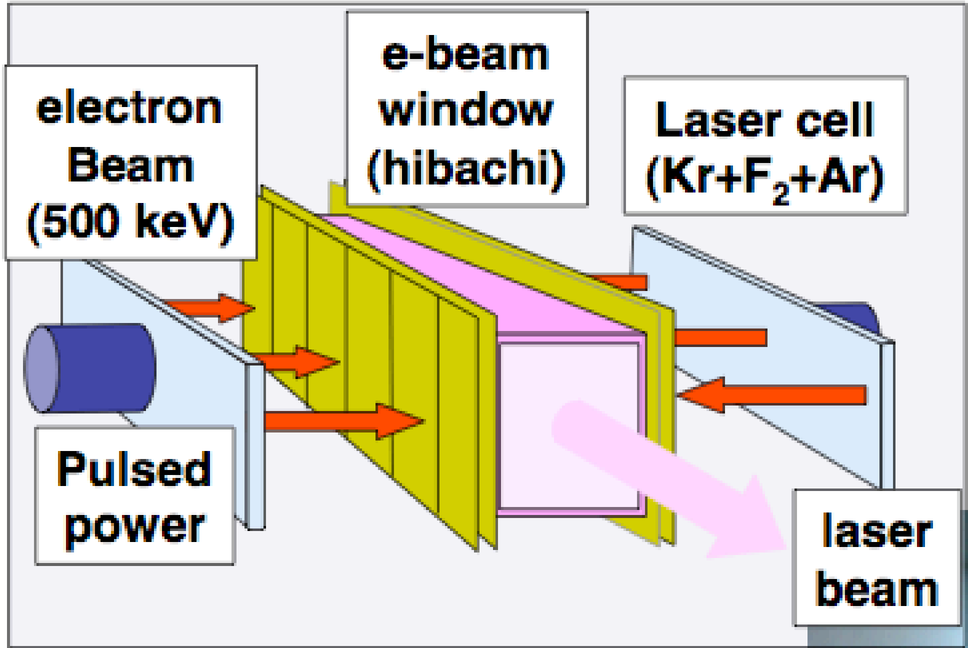


Beam Steering

Hit-on-fly demo for target tracking

P6-19 Kalal : proposing optical trucking with SBS phase conjugation mirror.

Large Krypton Fluoride (KrF) lasers are gas lasers, pumped with electron beams



NRL
Electra Laser Facility
300 - 700 J @ 140 nsec
2.5 to 5 Hz

KrF lasers and direct drive targets meet four fundamental essentials for fusion energy

Simplicity

- Direct Drive Physics simpler
- Direct drive targets easier to fabricate

Performance

- KrF lasers have unique advantages that should get high gain (> 150) for energy
- Predict KrF has efficiency needed for energy

Cost (laser size)

High gains lead to smaller lasers
- Gains 300, 2 MJ laser
- Gains 150, 500 kJ to 1 MJ

Robustness

- Gas laser (easy to cool, hard to break)
- Mostly Industrial Pulsed Power technology

Concluding Remarks

- NIF started the cryogenic implosion integrate experiment in 2010.9
- As for direct drive, LLE, Rochester demonstrated the ignition scale area density: $0.3g/cm^2$ with D_2 cryogenic targets.
- Integrated fast ignition experiments started at ILE, Osaka. Understandings became higher. The most critical issue is pre-plasma and electron divergence.
- Shock ignition became the 3rd ignition scheme. Expected to be tested by NIF.
- IFE fusion technology R&D started world wide.
- In particular, the comprehensive R&D are progressing in HiPER (EU) and LIFE(US).
- In 1~2 years, the IFE research will start new era.