Inertial Confinement Fusion and the Nobel Prize 2018 - can they help each other?

Isochoric heating of compressed matter and the progress of proton fast ignition

Markus Roth

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Sebastian Le Pape, LLNL

Content

- Inertial Confinement Fusion
- Improvement by reducing the laser plasma instabilities
- Approaching the burning plasma regime
- Fast ignition

SUPA

University of Strathclyde Glasgow

Lawrence Livermore National Laboratory

There are at least three ways to achieve nuclear fusion

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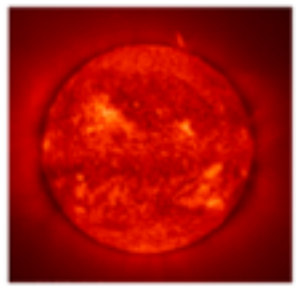
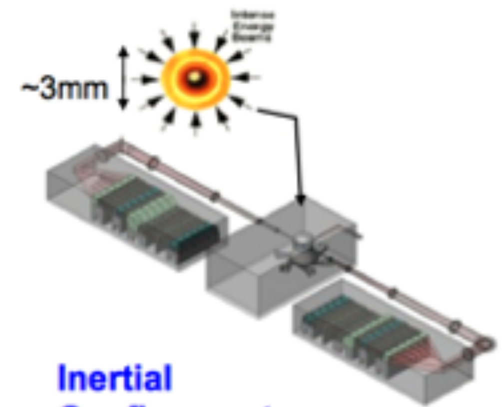


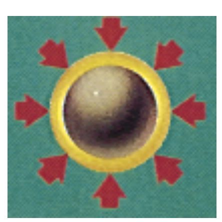
Gravitational Confinement

Magnetic Confinement

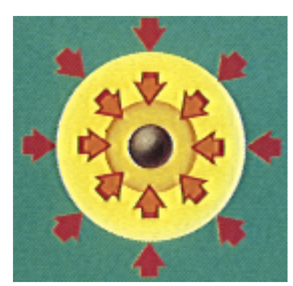


Inertial Confinement
by Laser Implosion

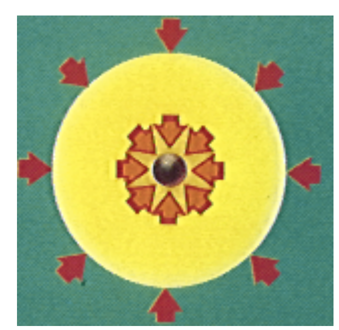
Density	10^4 x solid	solid / 10^8	10^3 x solid
Temperature	1 keV	10 keV	10 keV
Confinement time	10^5 years	seconds	10's ps



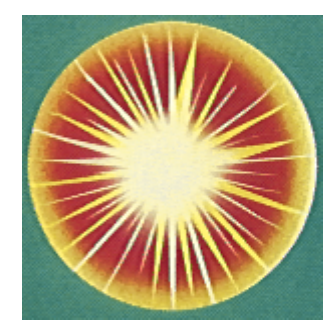
Surface heating by intense heating with intense radiation



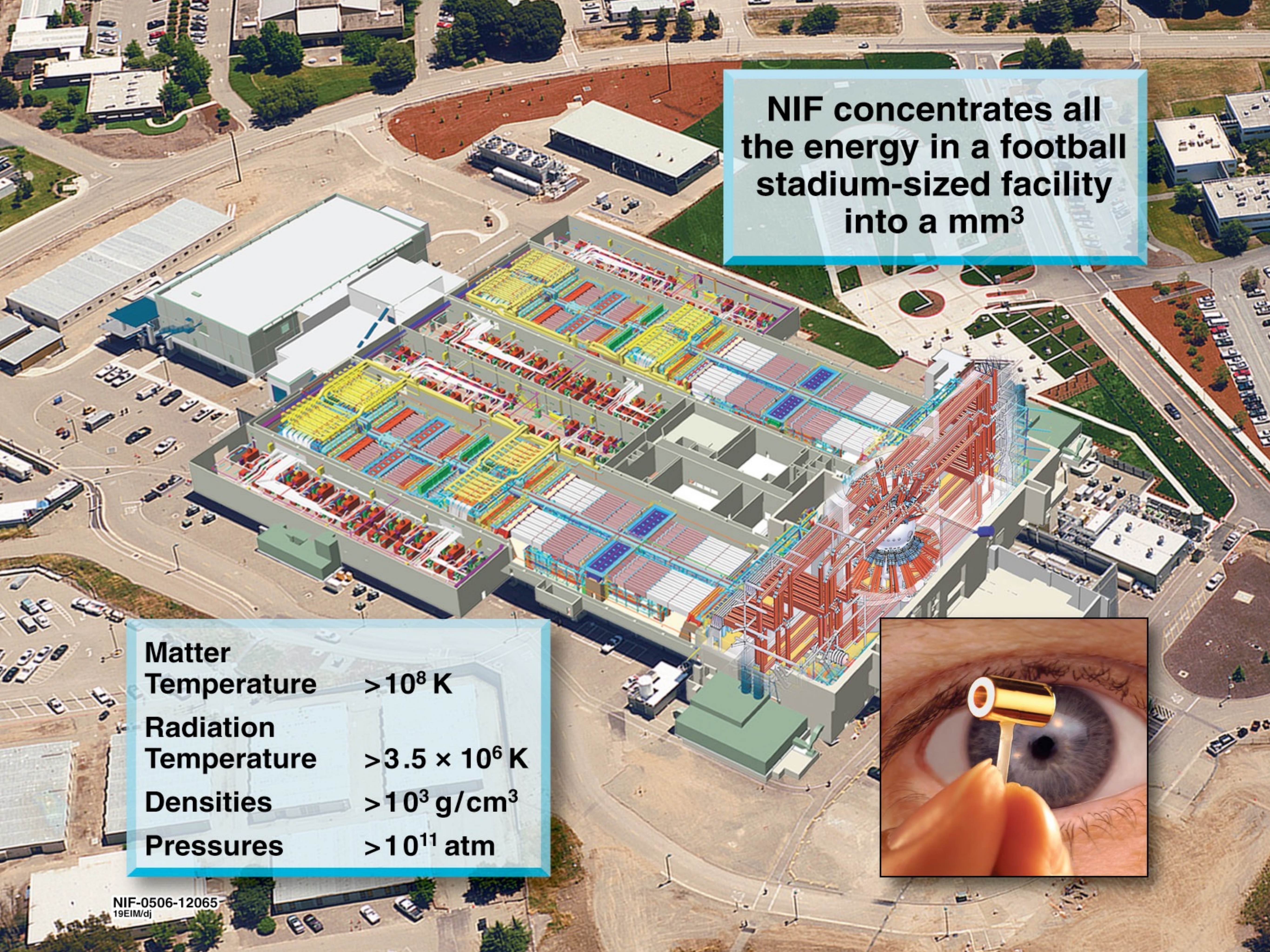
Compression
Rocket principle



Central ignition



Burn


NIF concentrates all the energy in a football stadium-sized facility into a mm³
Matter Temperature >10⁸ K
Radiation Temperature >3.5 × 10⁶ K
Densities >10³ g/cm³
Pressures >10¹¹ atm
NIF-0506-12065
19EIM/dj

192 laser beams deliver energy and power to a 1 cm hohlraum surrounding a 1 mm radius fusion capsule

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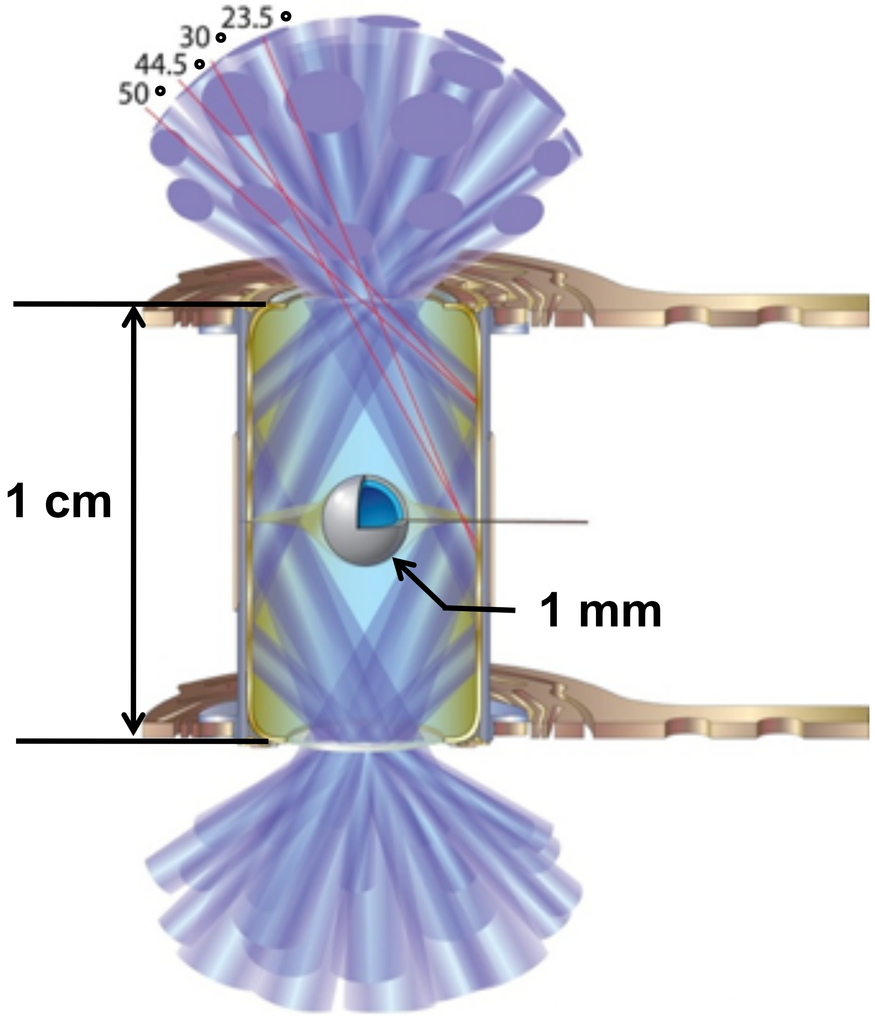
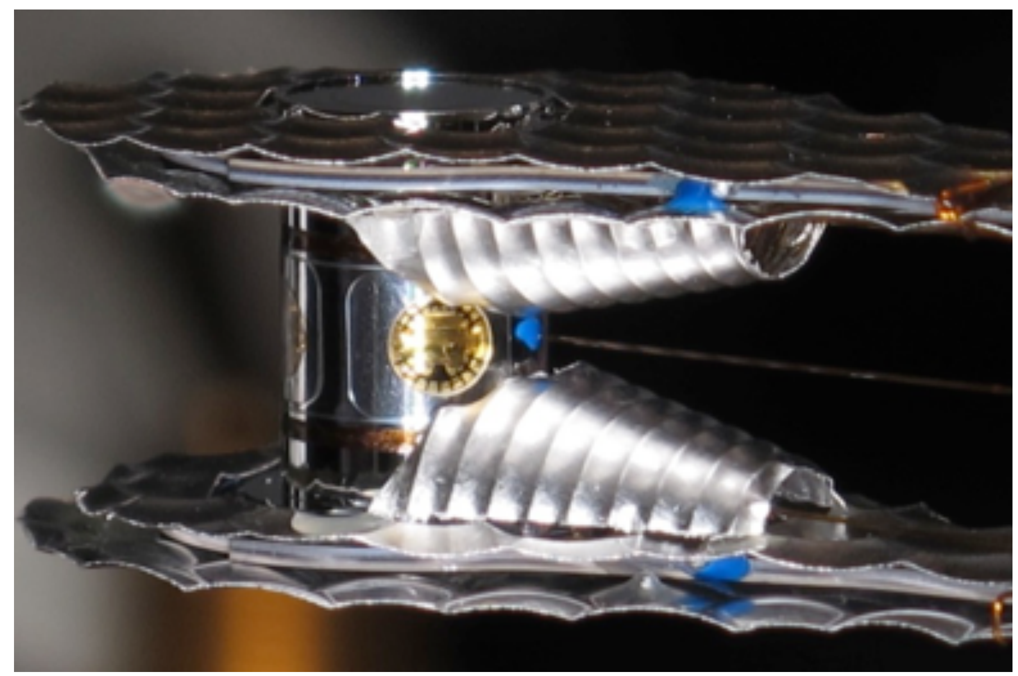
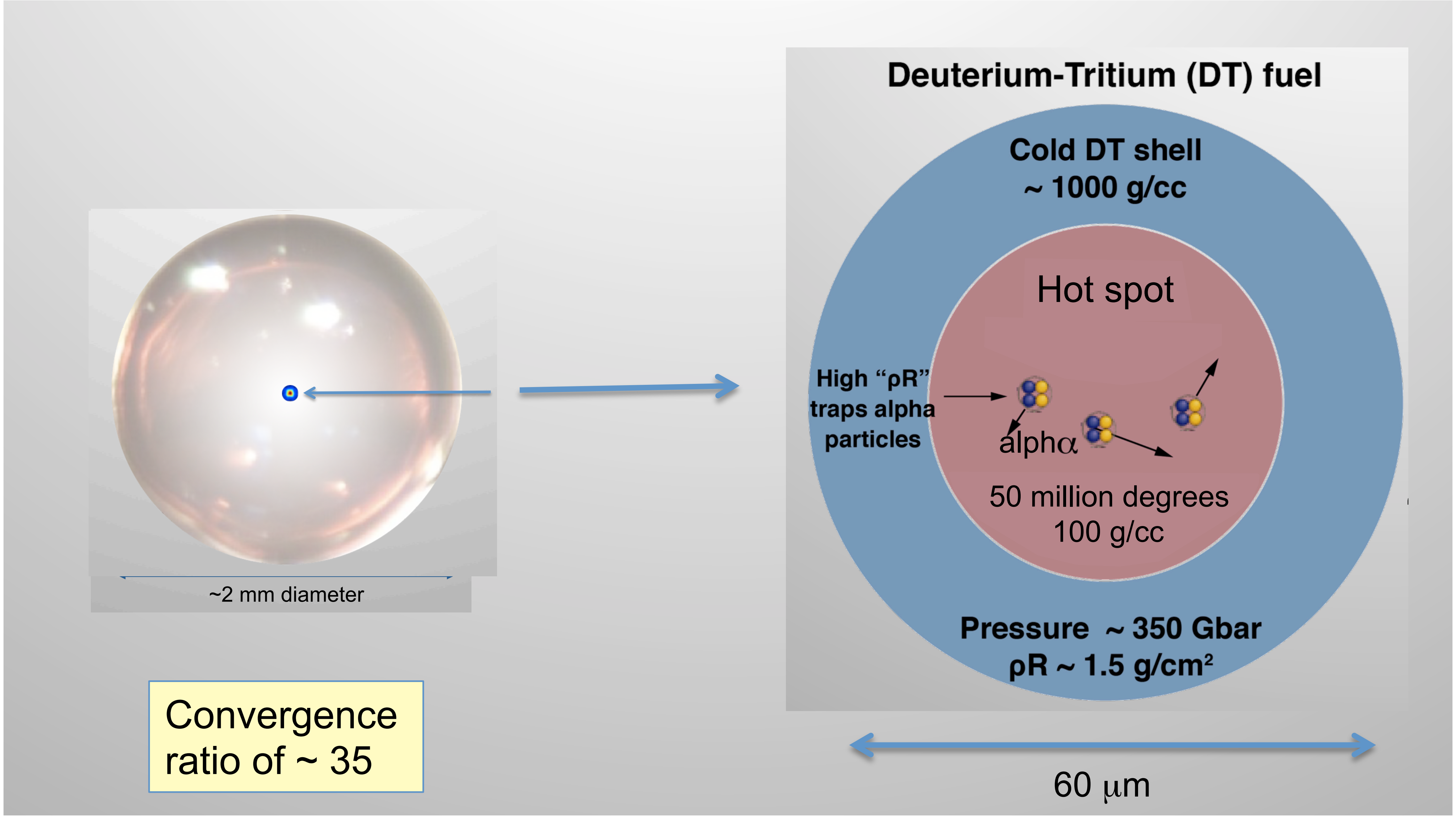




Ignition is a grand challenge



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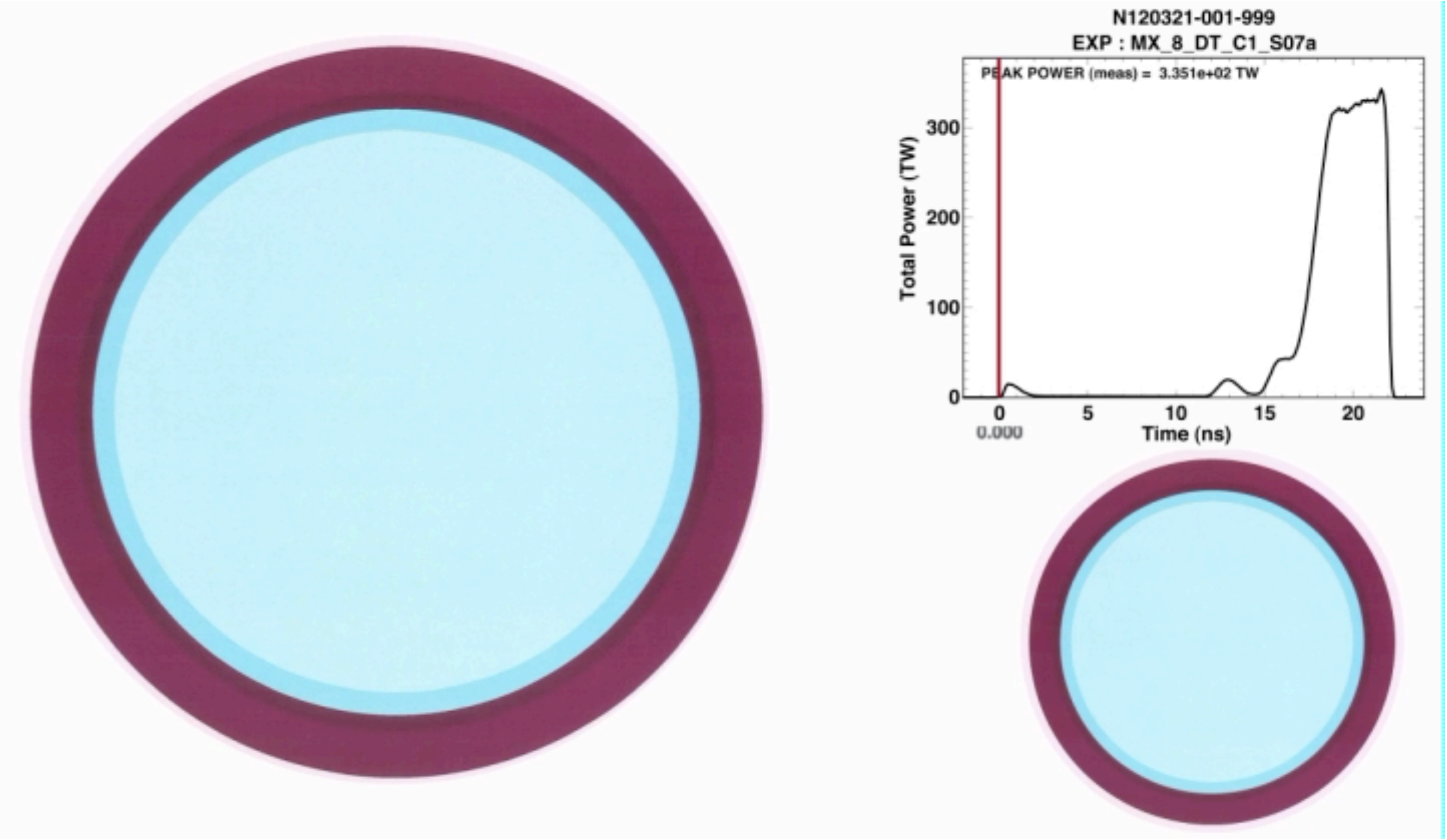
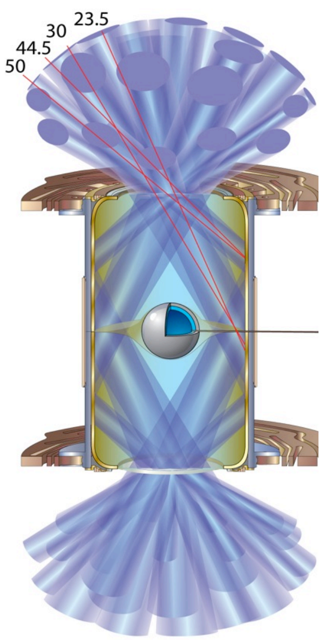
The principal challenge with compressing a capsule by 40x convergence is controlling hydro-instabilities



The better performance allows for larger Hohlraum for higher fusion yield

Hydrodynamic or *Euler* scaling



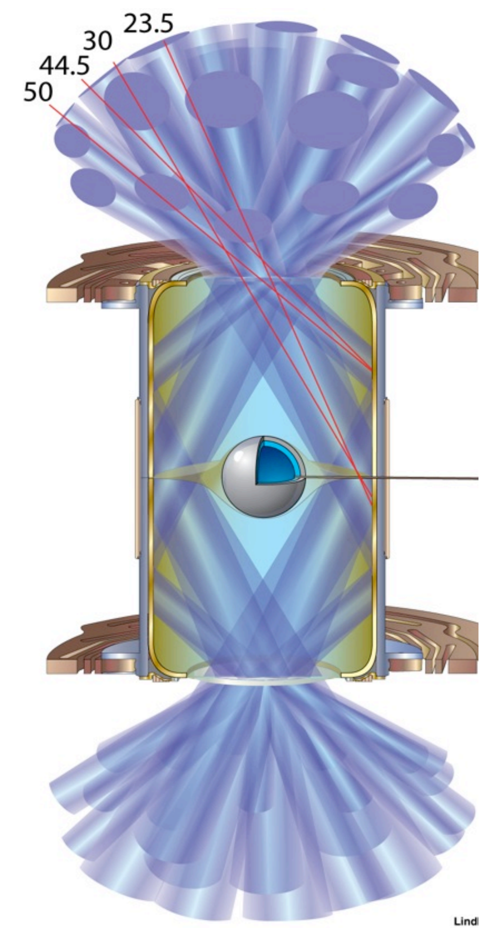
$L \sim S.L$

$t \sim S.t$

ρ, P, T ~ const.

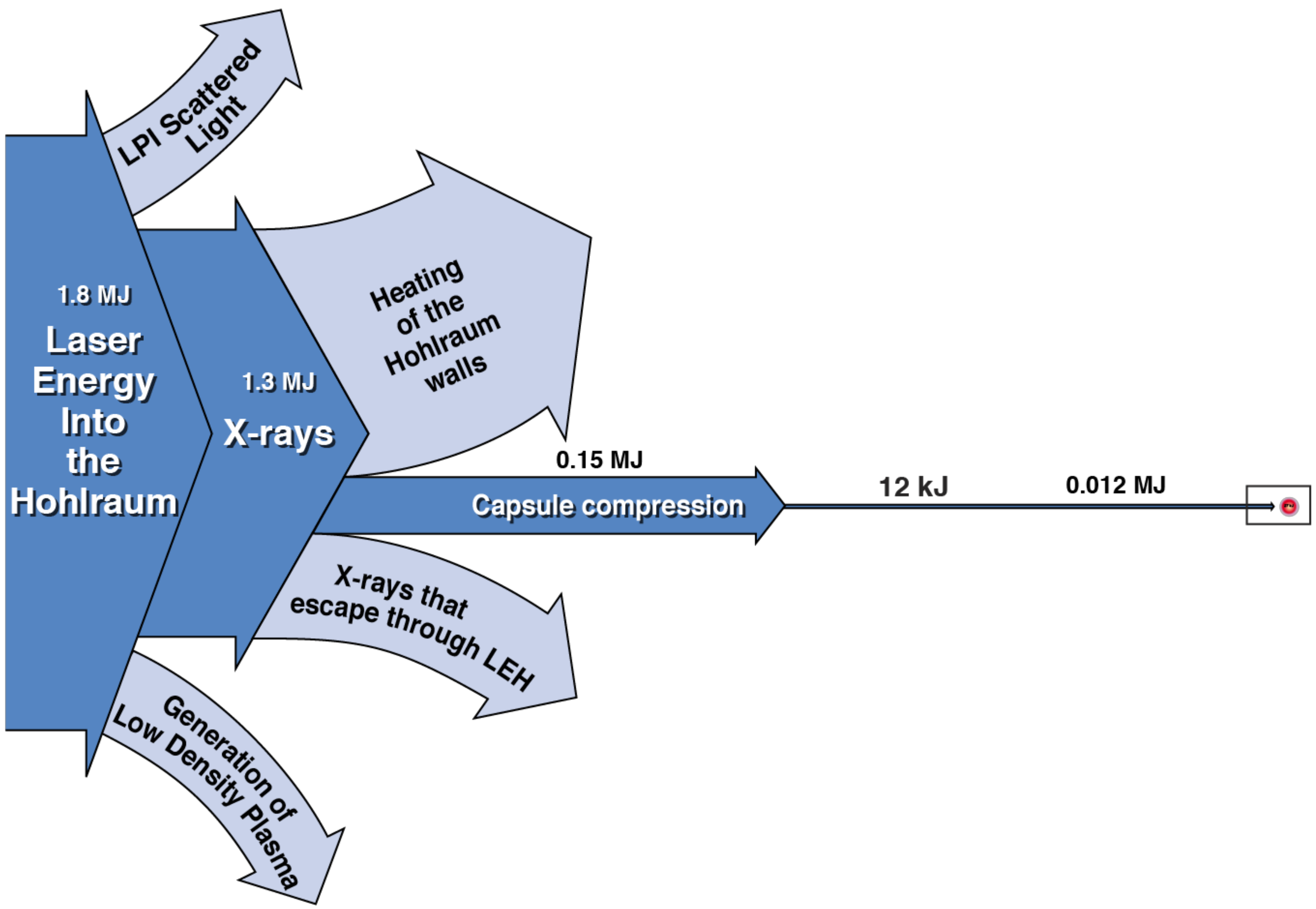
$E_L \sim S^3.E_L$

$P_L \sim S^2.P_L$



$Y \sim \rho^2 T^4 V \tau \sim S^{4.4}$

Where does the energy go?



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Advanced Approaches to Ignition

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- Optimised isobaric ignition (e.g. using 2ω)
- Double shell (non-cryo solution?)
- Electron Fast Ignition (with or without cone)
- Proton Fast Ignition
- KE foil Ignition
- Shock Ignition, …

WHY?
- Smaller infrastructure; higher gain;
- Improved tolerances to laser/target non-idealities
- Broader scientific applications
- Potential for zero (or reduced) Tritium use

<u>For each, assess:</u>
- Pros / cons
- Facility (laser, targetry, delivery, reactor, waste)
- Level of confidence
- Compatibility between options (since confidence<1)
- Required R&D plan

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Ignition scale facilities

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NIF

LMJ

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Advanced Ignition R&D Platforms

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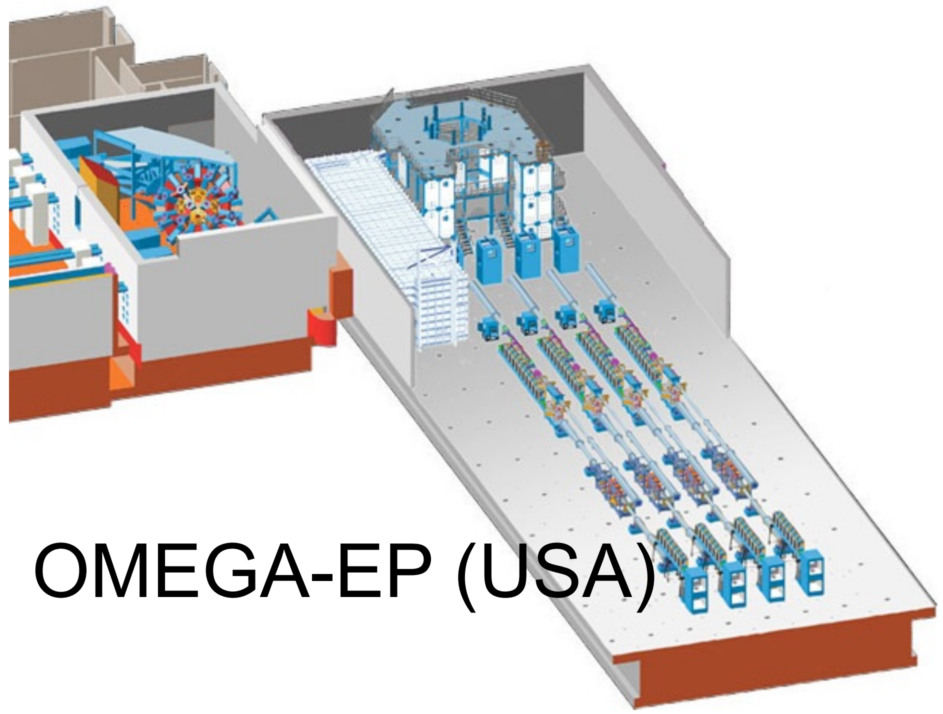
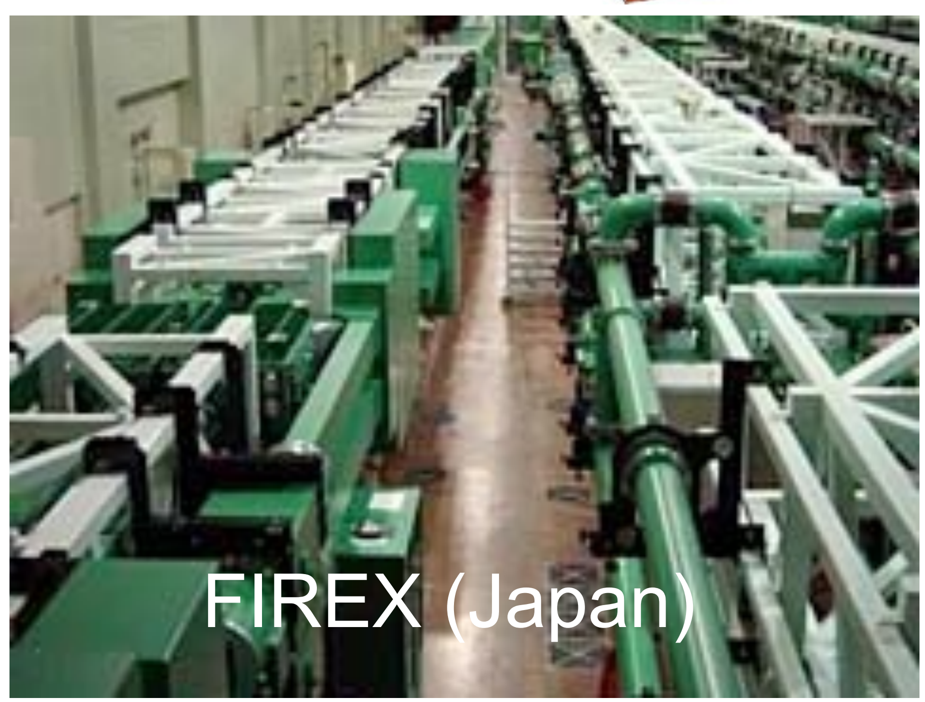
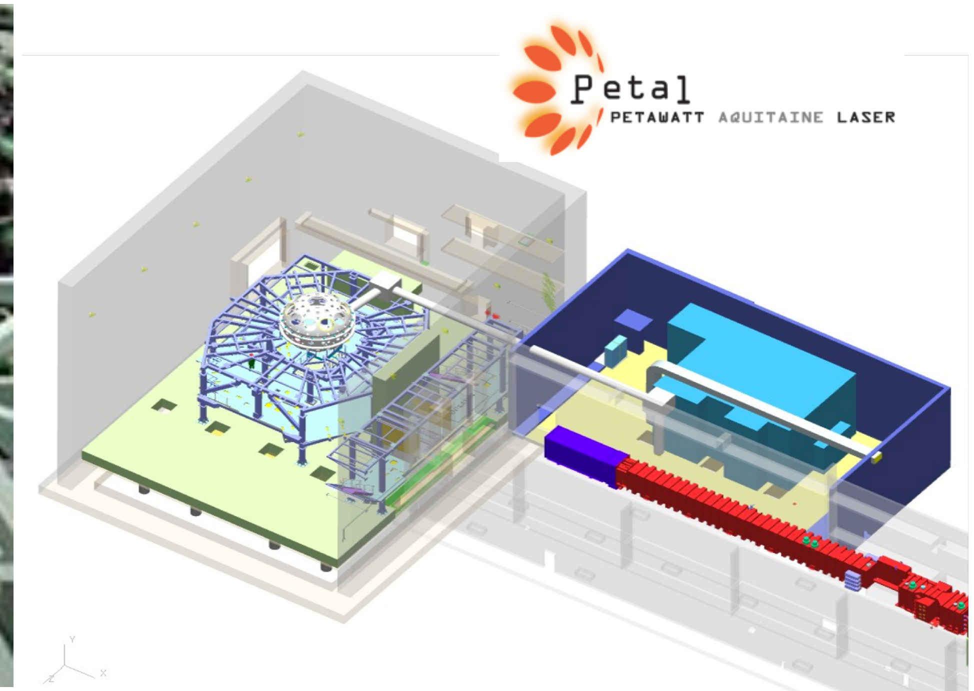


Laserlab
Europe





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Fast Ignition

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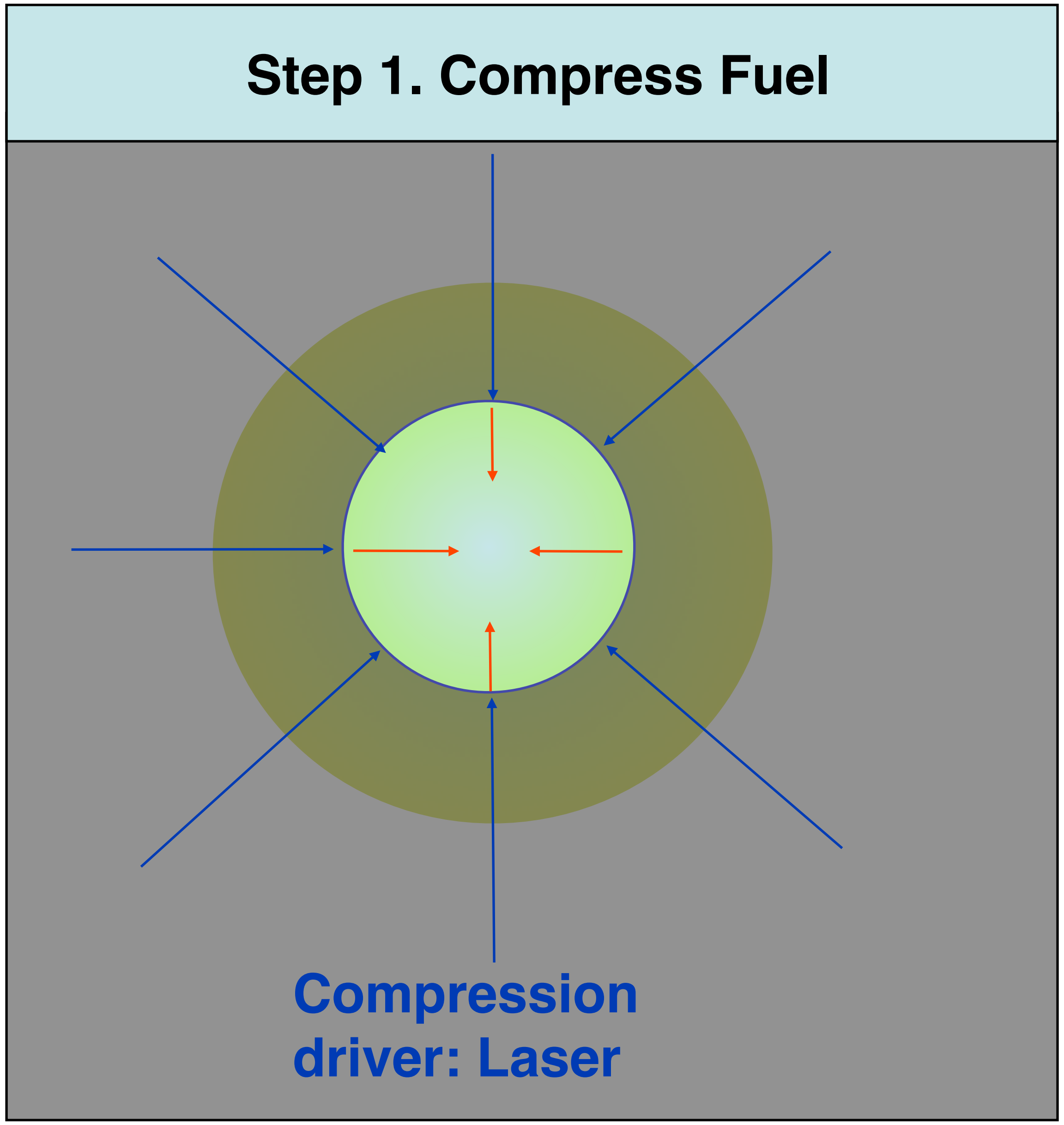
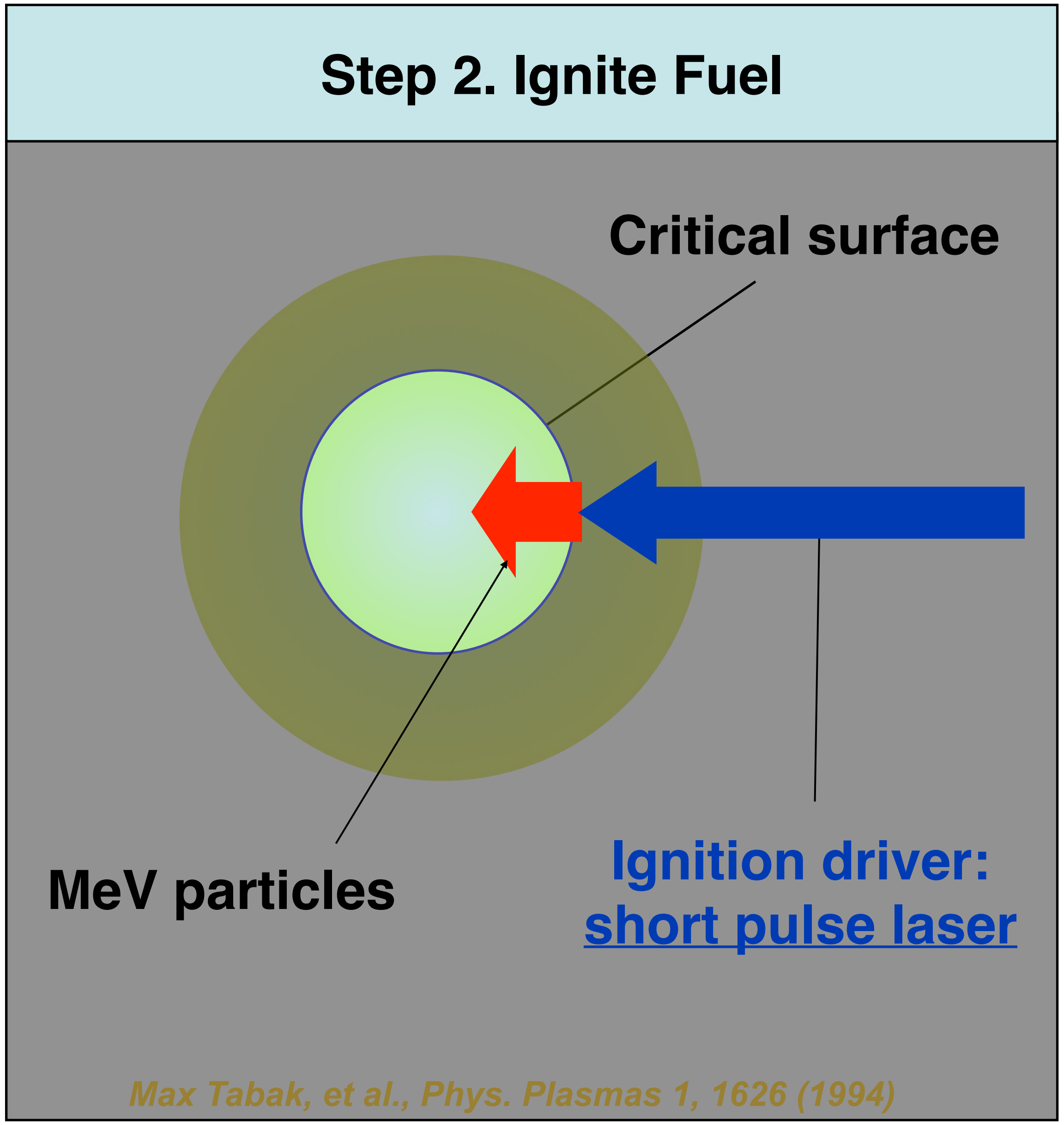


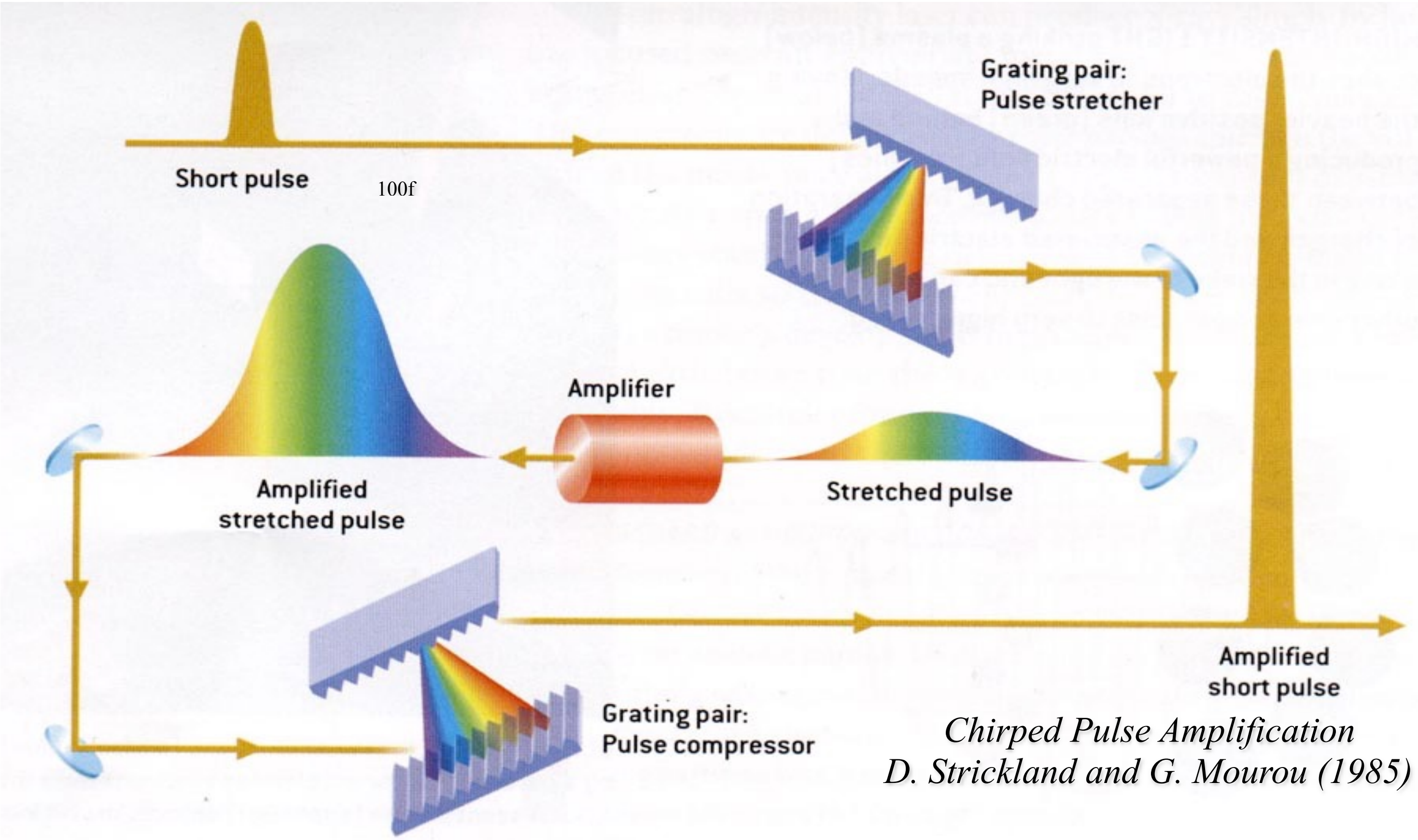


Fast Ignition separates the functions of compression & ignition of the fuel; less compression is required (more fuel can be assembled) and symmetry relaxed.

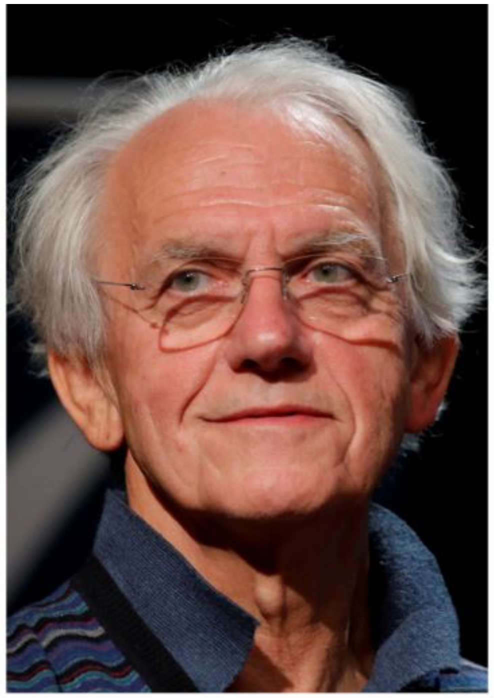
Think – Hot-Spot ignition = Diesel Engine, Fast-Ignition = Gas Engine (spark-plug)

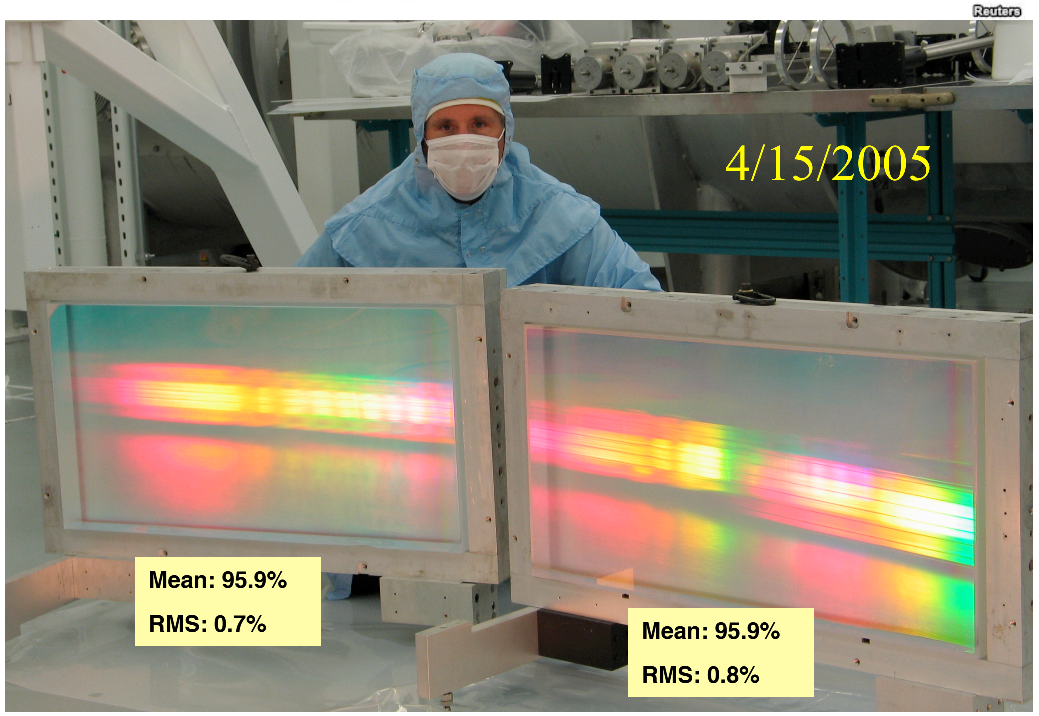
CPA (Chirped Pulse Amplification)

can generate high energy pulses up to 10^{15} W



Chirped Pulse Amplification
D. Strickland and G. Mourou (1985)





Volume 55, number 6 OPTICS COMMUNICATIONS 15 October 1985

COMPRESSION OF AMPLIFIED CHIRPED OPTICAL PULSES

Donna STRICKLAND and Gerard MOUROU
Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, NY 14623-1299, USA

Received 5 July 1985

We have demonstrated the amplification and subsequent recompression of optical chirped pulses. A system which produces 1.06 μm laser pulses with pulse widths of 2 ps and energies at the millijoule level is presented.

The onset of self-focusing of intense light pulses limits the amplification of ultra-short laser pulses. A similar problem arises in radar because of the need for short, yet energetic pulses, without having circuits capable of handling the required peak powers. The solution for radar transmission is to stretch the pulse by passing it through a positively dispersive delay line before amplifying and transmitting the pulse. The echo is compressed to its original pulse shape by a negatively dispersive delay line [1].

We wish to report here a system which transposes the technique employed in radar to the optical regime, and that in principle should be capable of producing short ($\lesssim$1 ps) pulses with energies at the Joule level. A long pulse is deliberately produced by stretching a

sion system is shown in fig. 1. A CW mode-locked, Nd : YAG laser (Spectra-Physics Series 3000) is used to produce 150 ps pulses at an 82 MHz repetition rate. Five watts of average power are coupled into 1.4 km of single-mode non-polarization-preserving optical fiber. The fiber (Corning Experimental SMF/DS™) has a core diameter of 9 μm. The average power at the output of the fiber is 2.3 W. The pulses have a rectangular pulseshape with a pulse width of approximately 300 ps, as can be seen from the autocorrelation trace in fig. 2. The bandwidth of the pulses is 50 Å. The stretched pulses are injected into a pulsed, Nd : glass, regenerative amplifier, by reflection from an AR coated window. An AR coated window is used to protect the fiber end from being damaged by the

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An initial fast ignition experiment can be done at NIF

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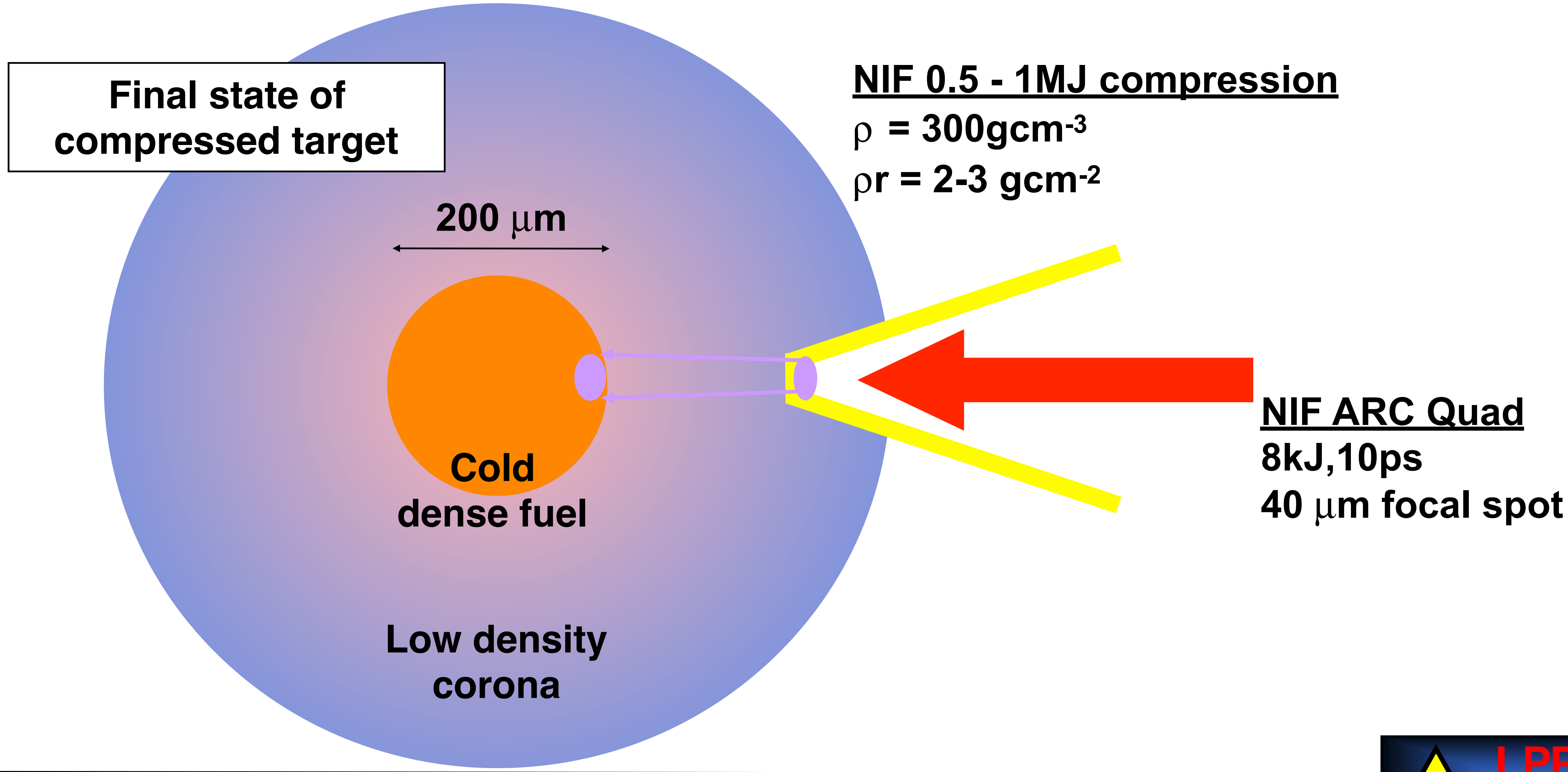
- Measure the coupling efficiency at full hydro scale
- Determine the minimum short-pulse laser energy for high gain and high yield on NIF and define high yield/high gain FI applications on NIF



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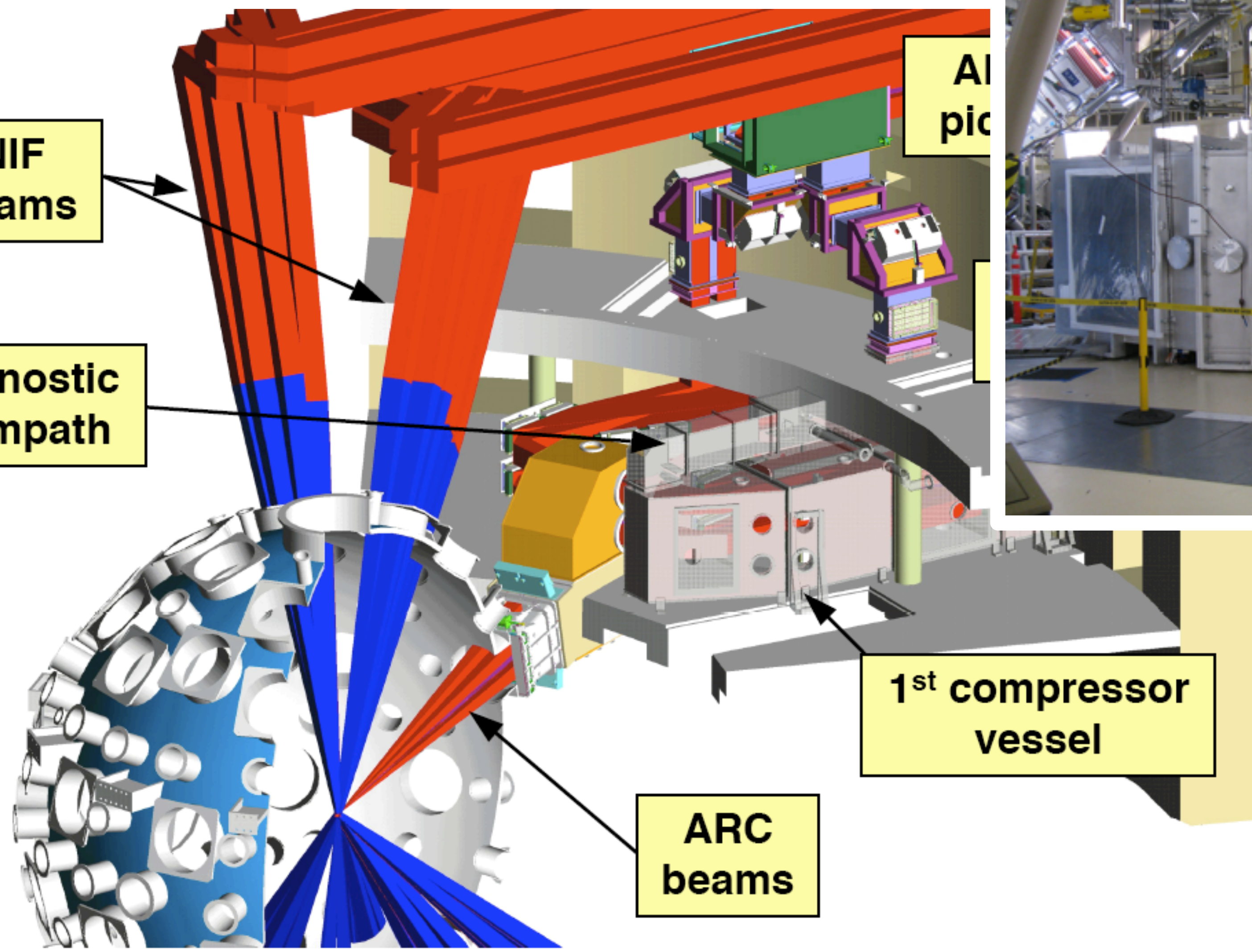
One quad of NIF beams is being converted for high-energy short-pulse operation at 7.6 kJ, 5 ps



Compressor installed in target area

- First of two ARC compressor vessels are installed in NIF, providing two short-pulse NIF beamlines at 3.8 kJ, 5 ps — operational in 2011
- NIF+ARC provides an opportunity for integrated FI experiments testing fast electron heating of a high-gain compressed fuel assembly in indirect-drive or polar direct-drive geometry

Largest-scale proton fast ignition experiment to date

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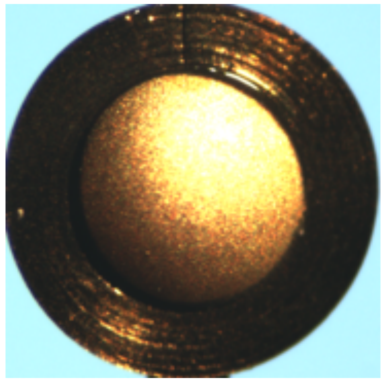
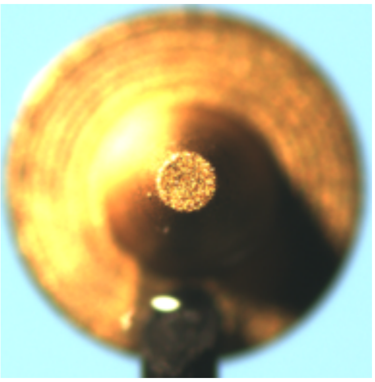
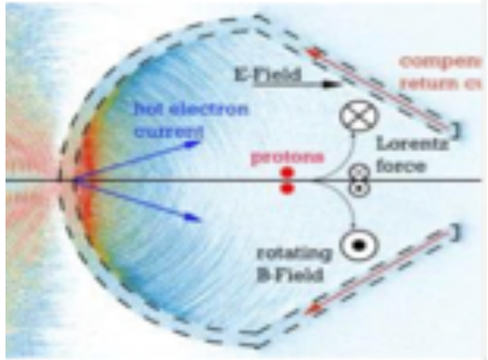
1. Investigate proton focusing and spectral changes. Which target configuration is best suited?



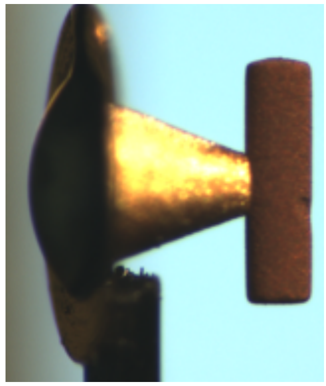


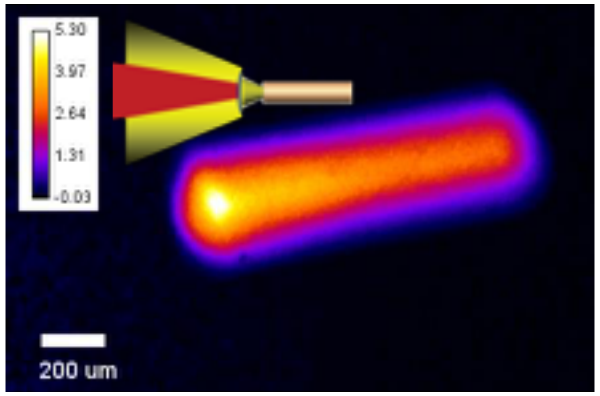
2. Diagnose the electric field surrounding the hemi-cone targets (|**E**|, d, τ)



T. Bartal *et al.*, Nature Physics **8**, 139–142 (2012)

3. Measure proton energy deposition and heating in matter





Imaging data from LFEX

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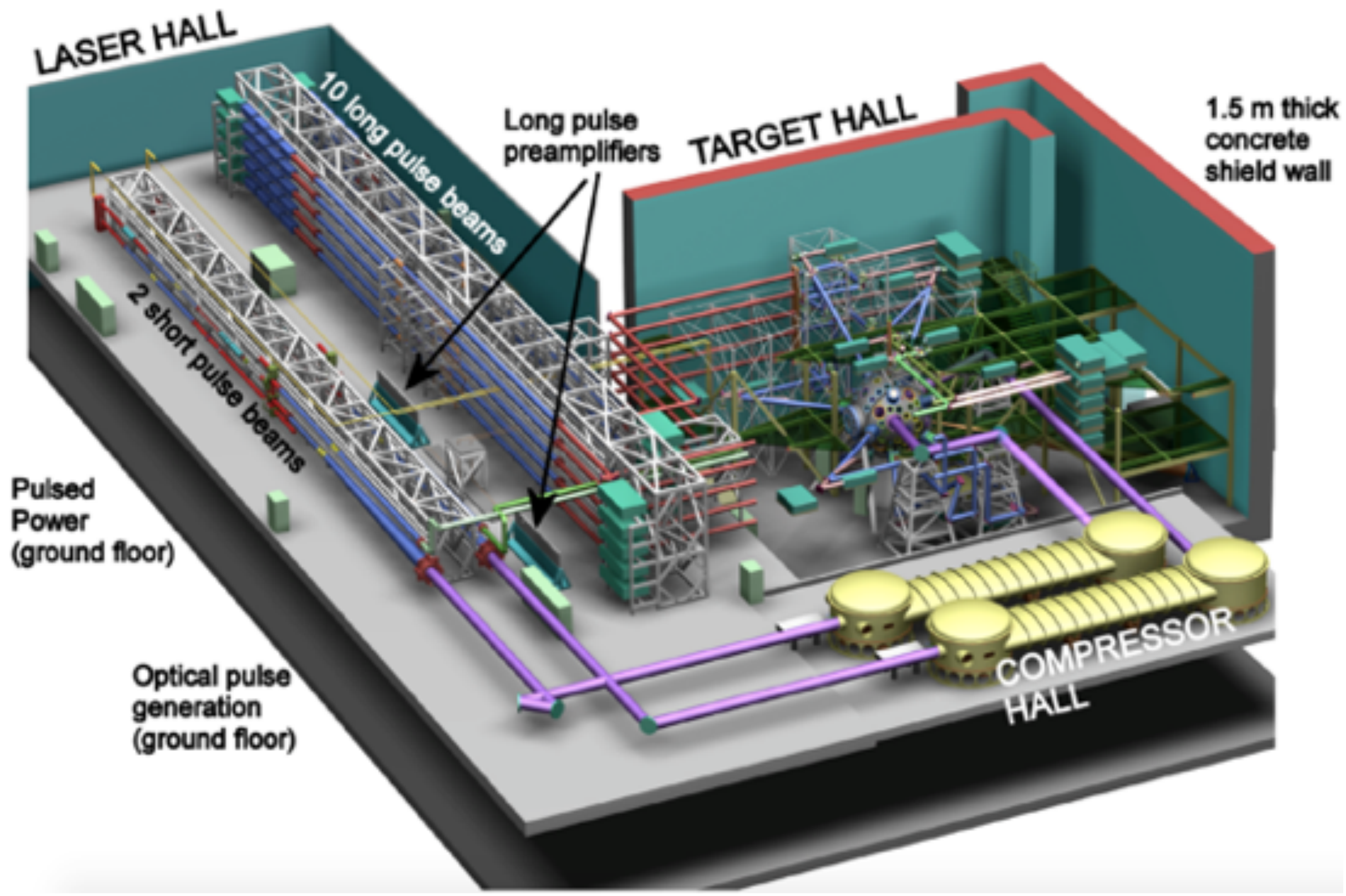
ORION Laser (UK)

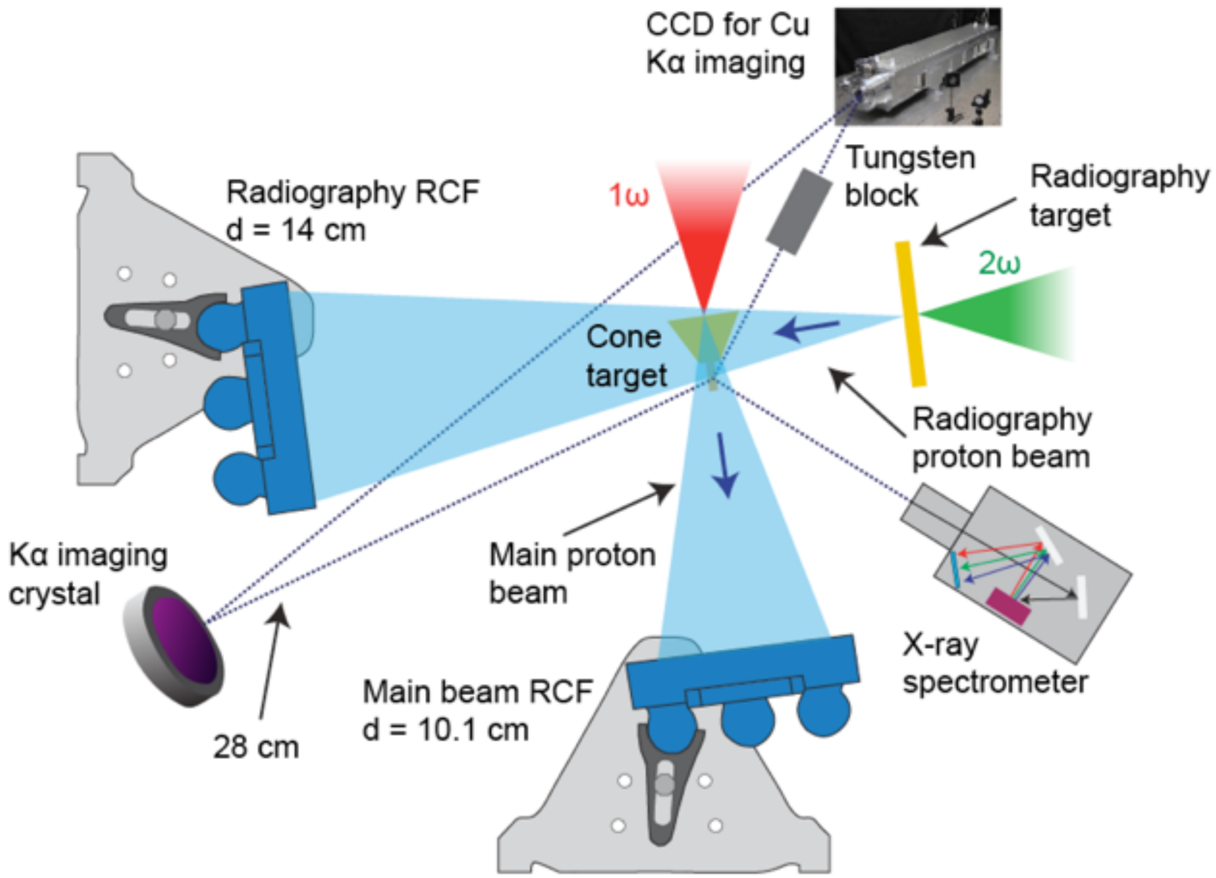
- Two short pulse beams and long pulse beams

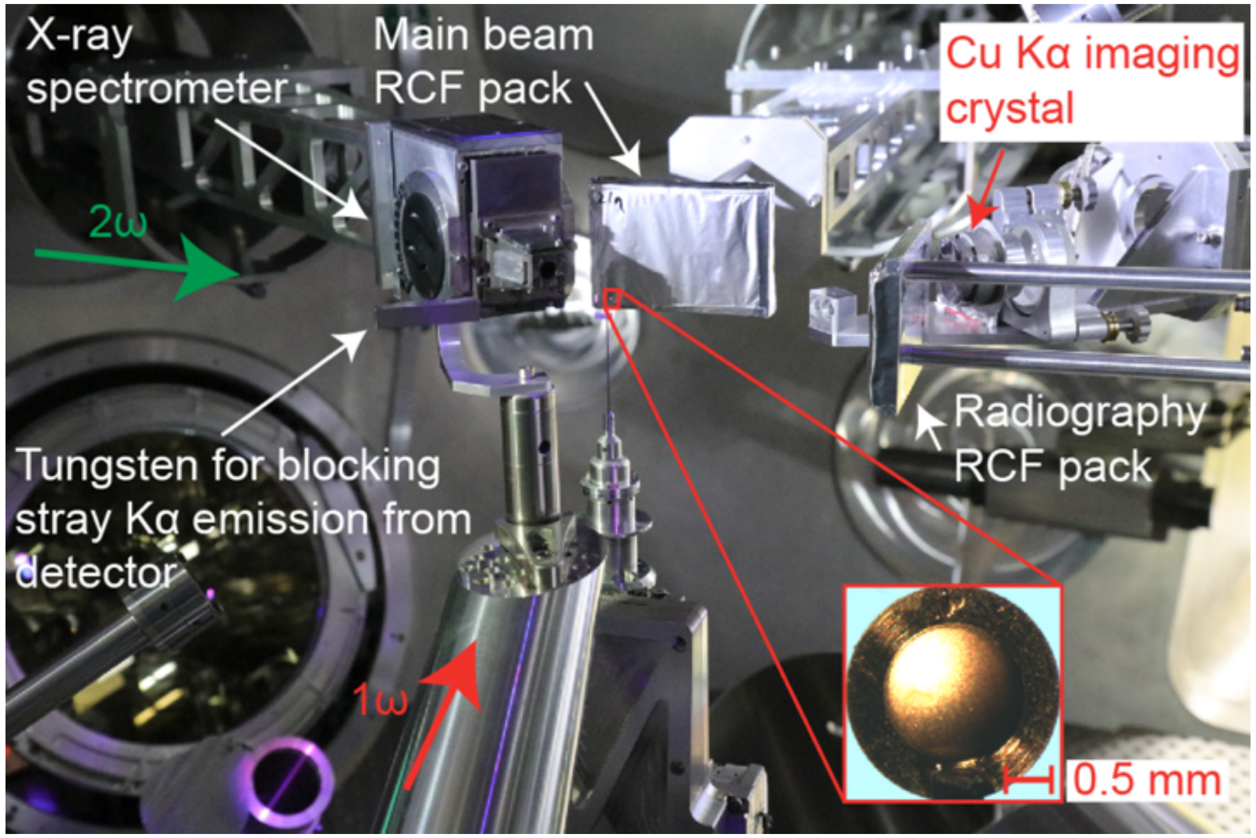


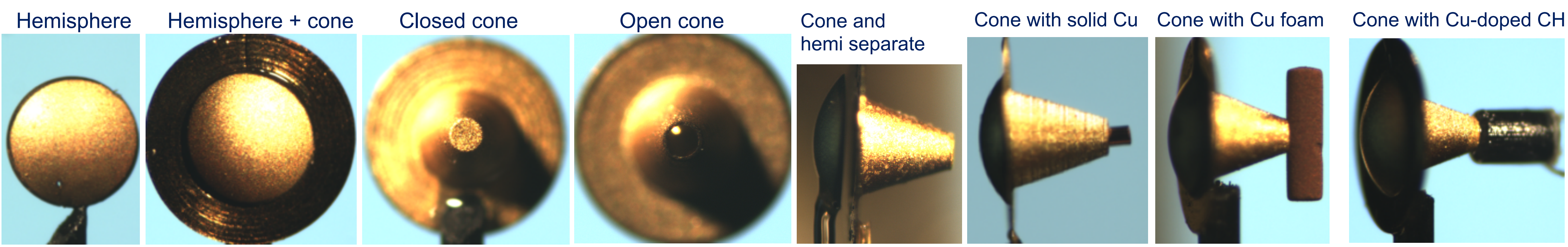
<u>Parameters used</u>

- Main driver beam 500 J, 0.5 ps (1ω)
- Proton backlighter laser beam 200 J, 0.5 ps (2ω)
- 4x LP 50 J, 2 ns
- Gold targets: 10 μm-thick hemispherical targets, 15 μm-thick cone walls

Experimental Setup

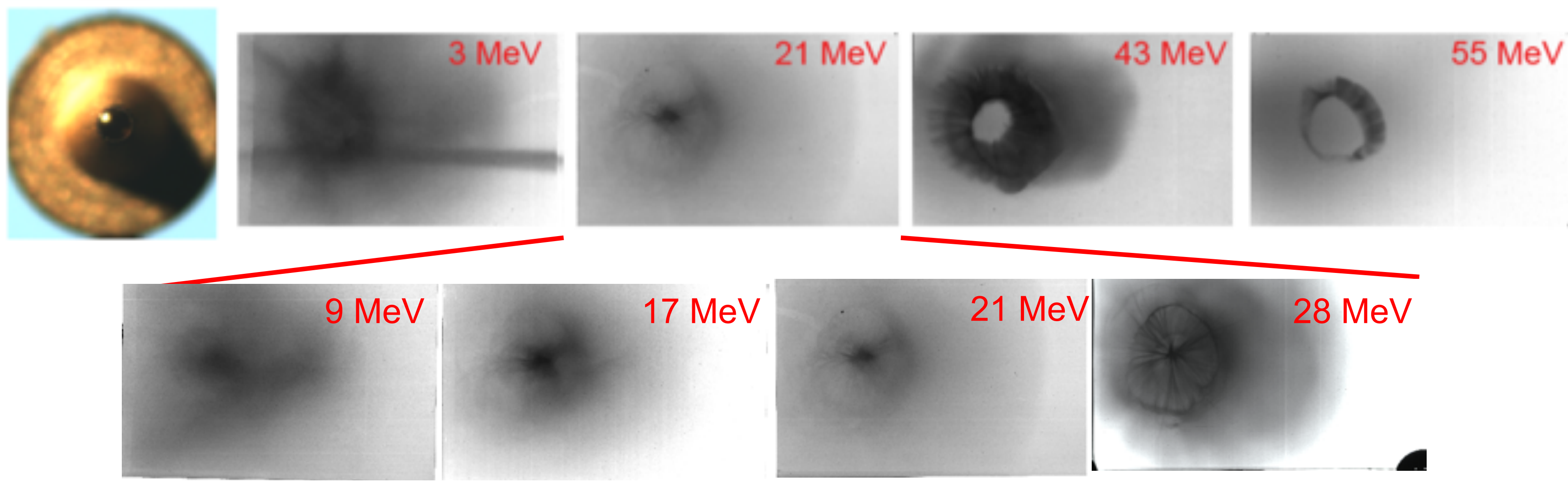




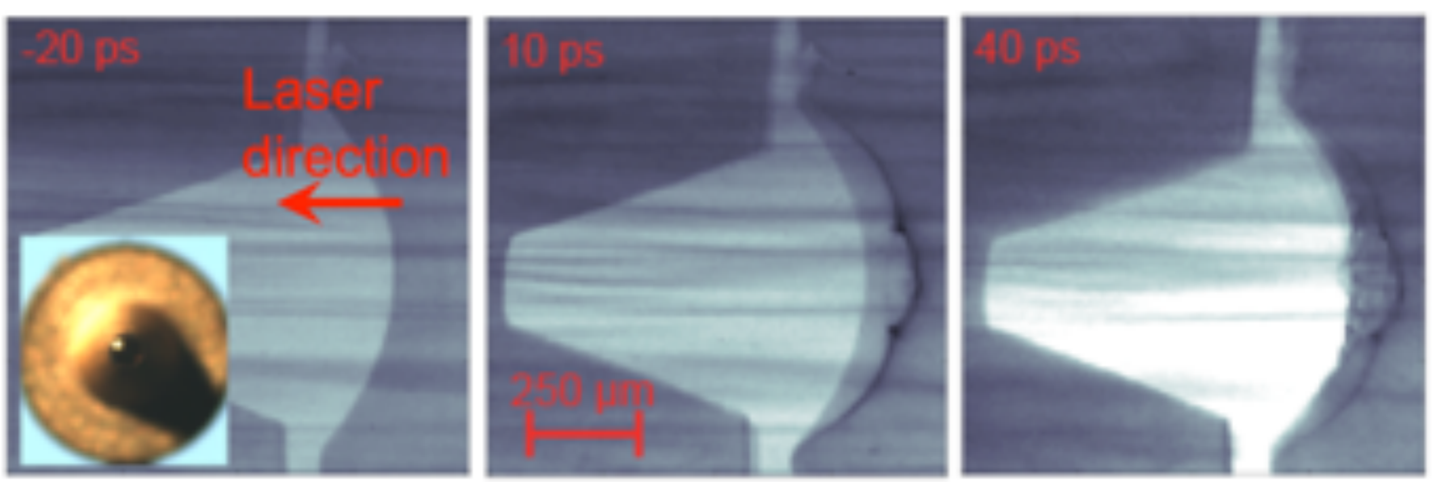


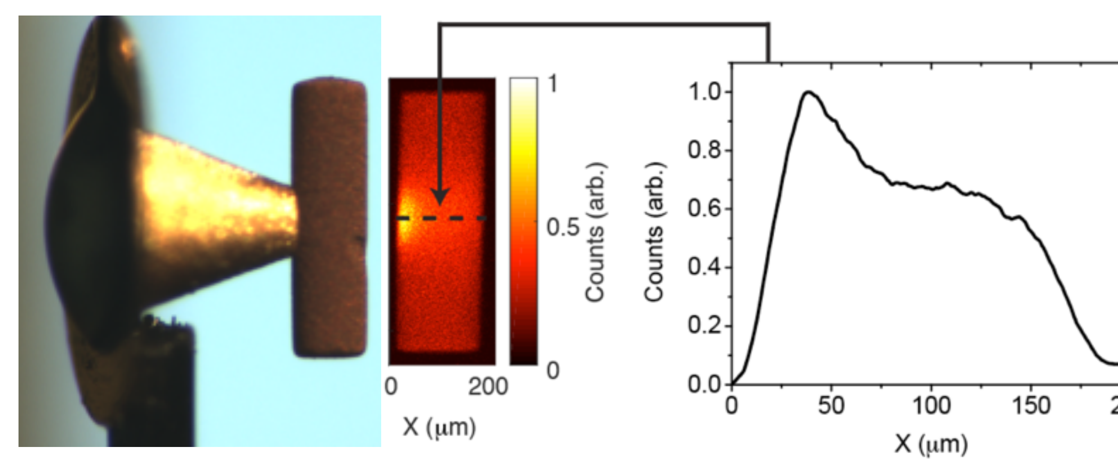
Results

Hemi with open cone



- An open cone exhibits clear proton focusing, between ~ 10 and 30 MeV





•Diagnosed is a long-lived field, not seen in the hemisphere-only case, which may be acting to confine and focus the lower energy protons

•Two component emission indicates a focused beam of protons heating the sample, as opposed to only electron/X-ray heating

Conclusion

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- Understanding and mitigation of laser plasma instabilities has pushed the yield to a point, where α -particle heating becomes visible
- HDC ablator and lower gas fill in the Hohlraum results in similar neutron yield at half the laser energy
- Enlarging the Hohlraum results in α -particle heating with twice the kinetic energy of the capsule and close to compensating bremsstrahlung and conduction losses
- fast ignition facilities become available in US, Europe and Asia
- Recent proton fast ignition experiments show focusing, transport and heating of intense laser driven beams and so far no show stoppers for the concept