Introduction to Inertial Confinement Fusion

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Princeton Plasma Physics Laboratory

2023 Introduction to Fusion Energy and Plasma Physics Course
June 5th-15th 2023

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Lawrence Livermore National Laboratory

About me

MSc in Experimental Nuclear Physics and Plasma Physics
2015| Ukraine

PhD in Applied Physics and Technology
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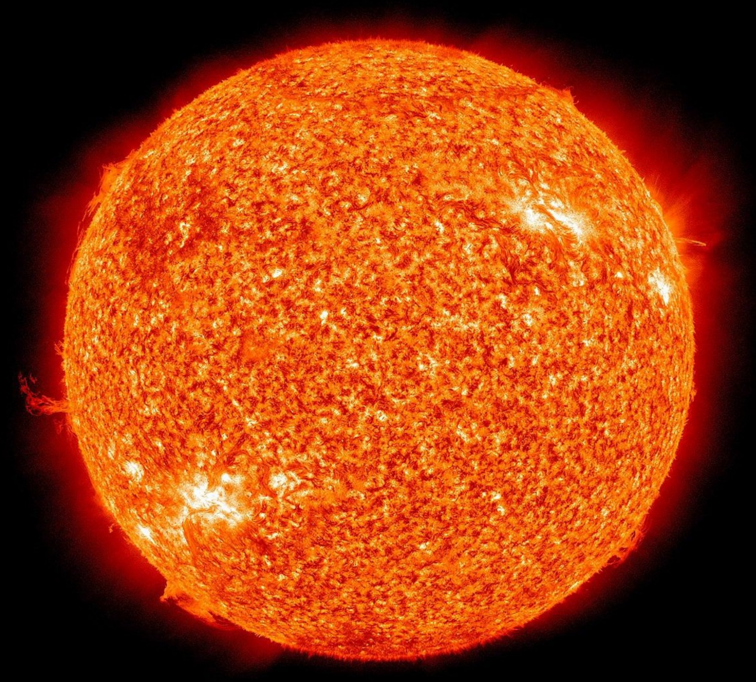
VNiVERSiDAD D SALAMANCA

Postdoctoral researcher in High Energy Density
2021 - now| USA
Vice-chair of LaserNetUS Diagnostics Committee

PPPL
PRINCETON PLASMA PHYSICS LABORATORY

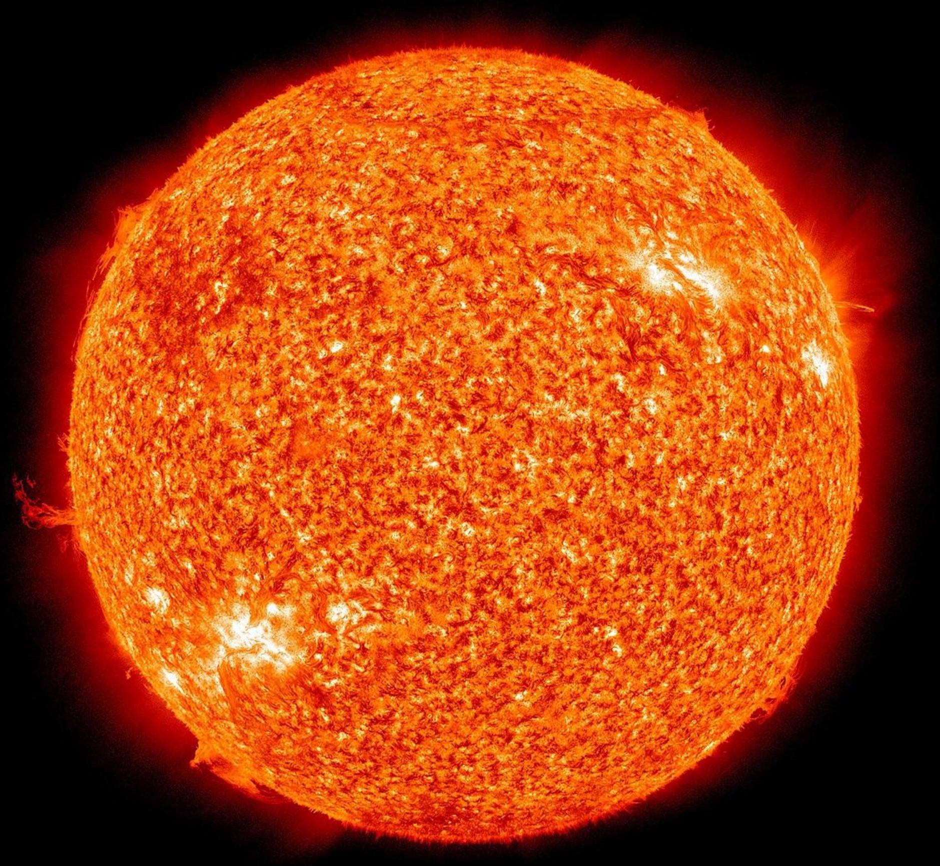
LaserNetUS



OUTLINE

1. Fusion!
2. Lasers!
3. Basics of inertial confinement fusion
4. How do we achieve fusion in the lab?
5. What's next ? Commercialization of IFE
6. Role of LaserNetUS

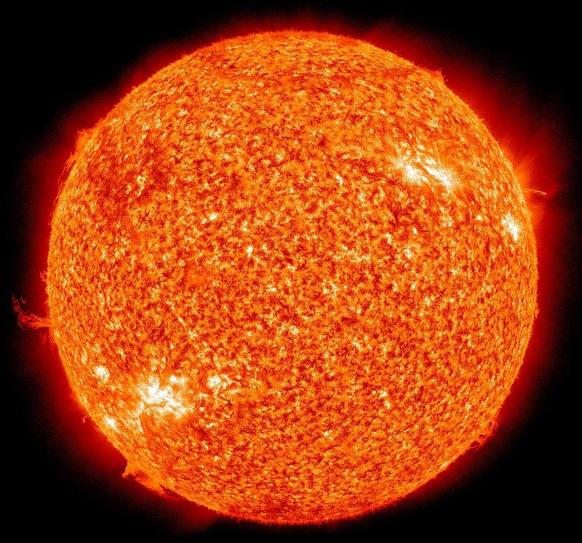
The sun and the stars are powered by thermonuclear fusion



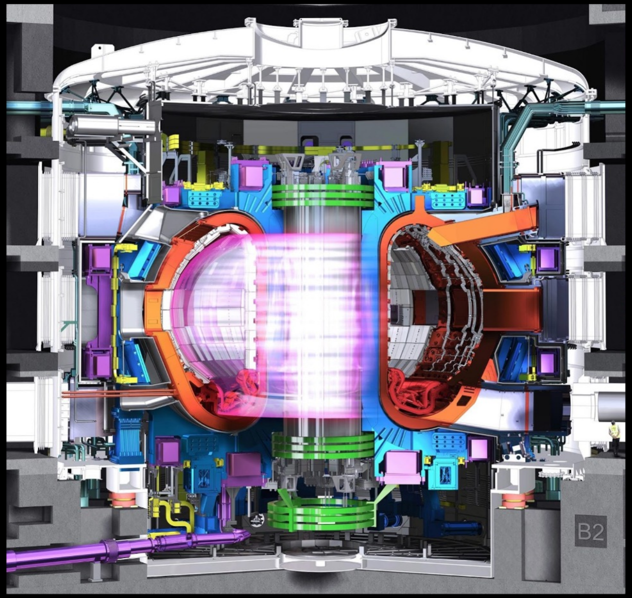
- We are essentially trying to *recreate* the conditions at the center of the sun in the laboratory

Temperature	~ 1.4 keV (15 million K)
Density	~ 150 g/cc
Pressure	~ 260 Gbar (260 billion atm)

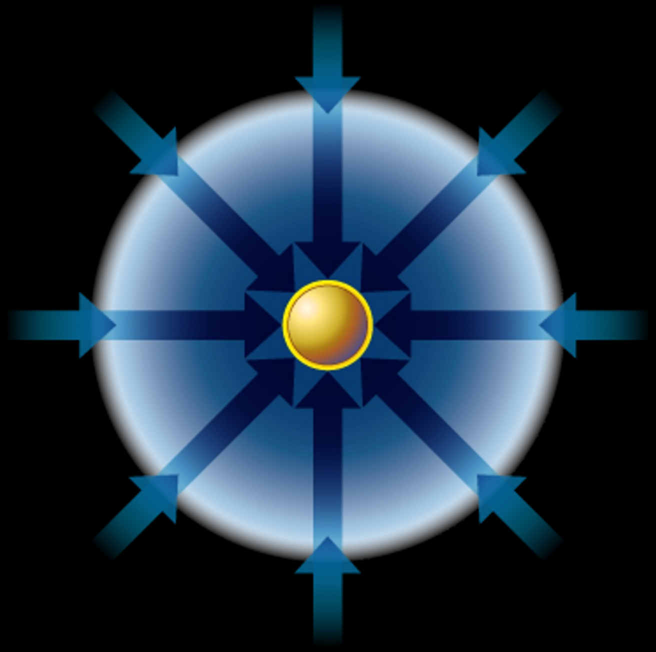
At these temperatures and pressures the plasma needs to be strongly confined



Gravitational confinement
(~ billions years)

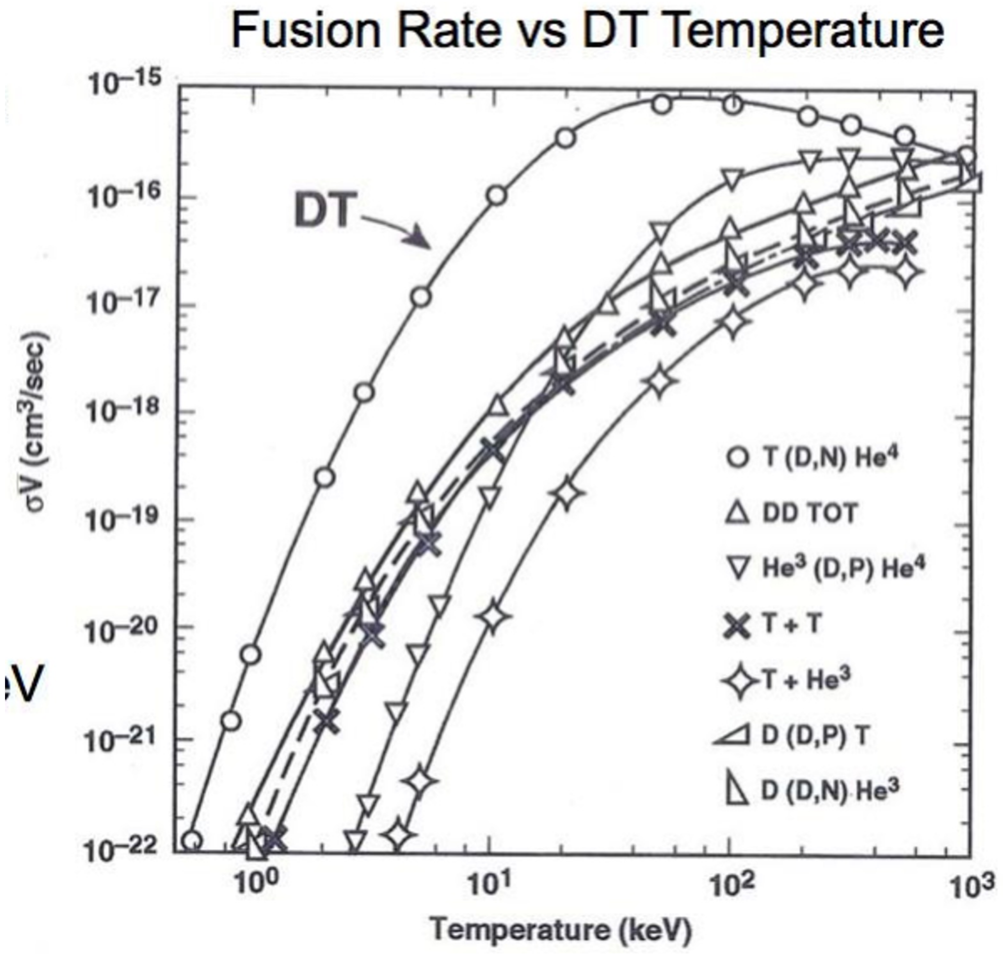


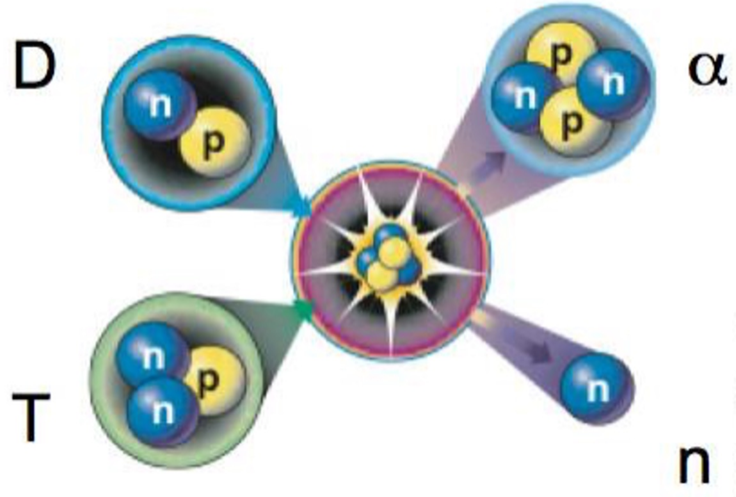
Magnetic confinement
(~ seconds)



Inertial confinement
(~ picoseconds)

In the laboratory the most practical fusion process is deuterium-tritium (DT)





$$D + T \rightarrow \alpha(3.5\ \text{MeV}) + n(14.1\ \text{MeV})$$

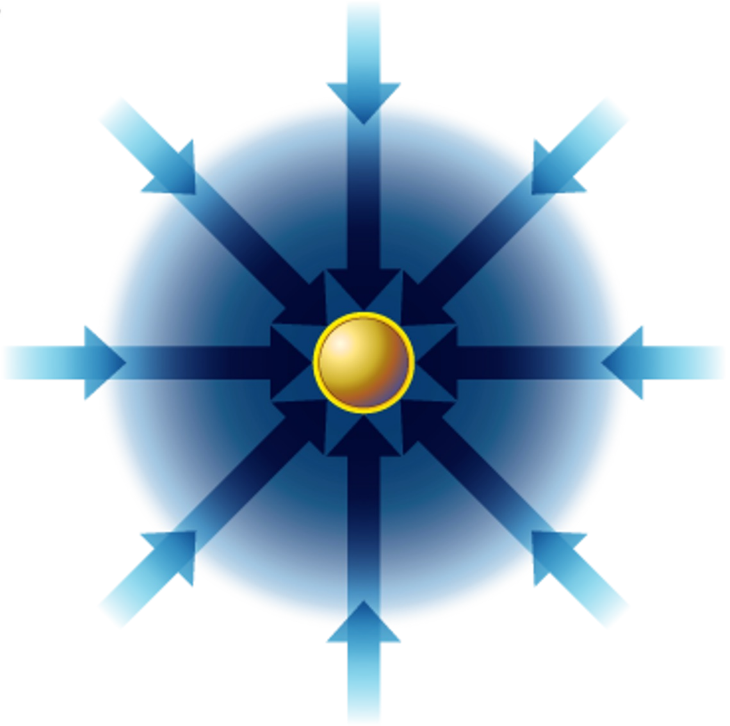
The idea of inertial confinement fusion was first published almost 50 years ago, soon after the invention of the laser

NATURE VOL. 239 SEPTEMBER 15 1972

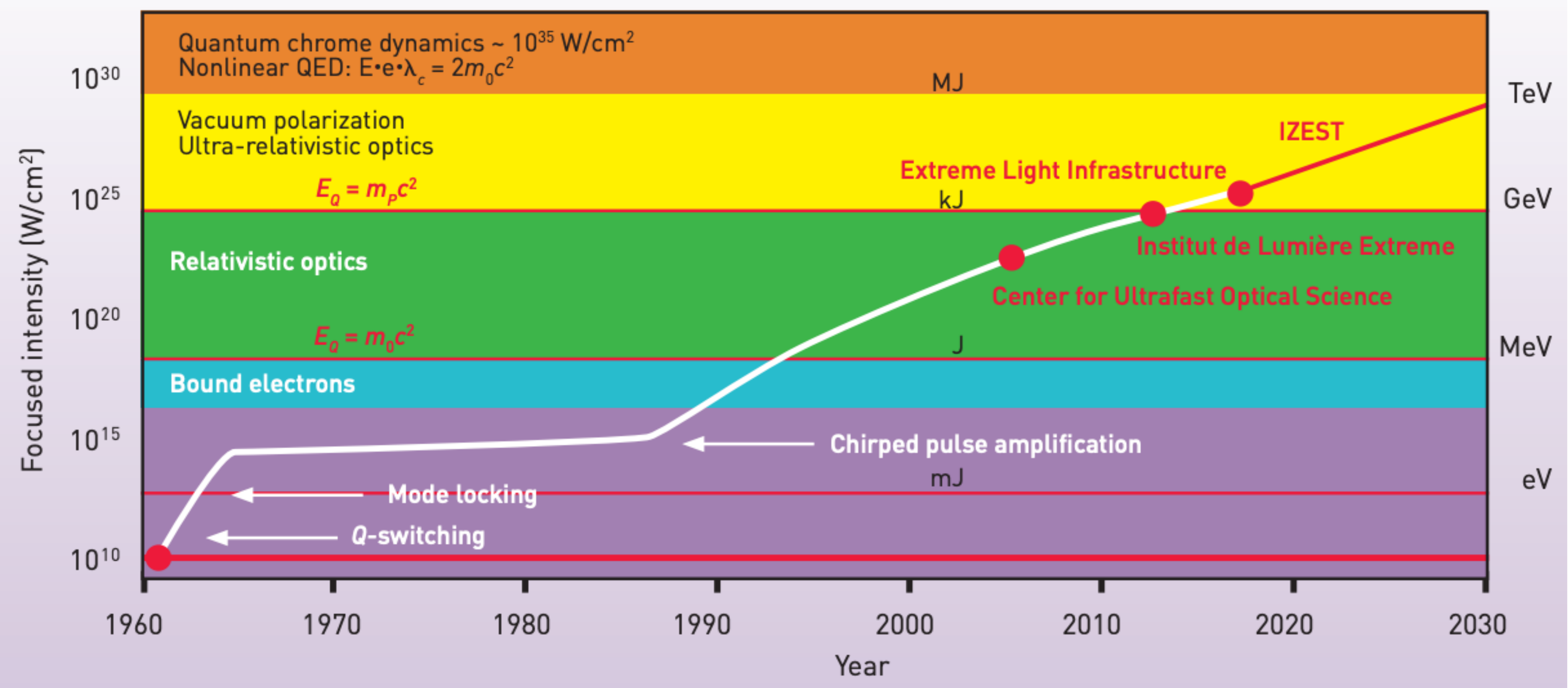
Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications

JOHN NUCKOLLS, LOWELL WOOD,
ALBERT THIESSEN & GEORGE ZIMMERMAN
University of California Lawrence Livermore Laboratory

Hydrogen may be compressed to more than 10,000 times liquid density by an implosion system energized by a high energy laser. This scheme makes possible efficient thermonuclear burn of small pellets of heavy hydrogen isotopes, and makes feasible fusion power reactors using practical lasers.

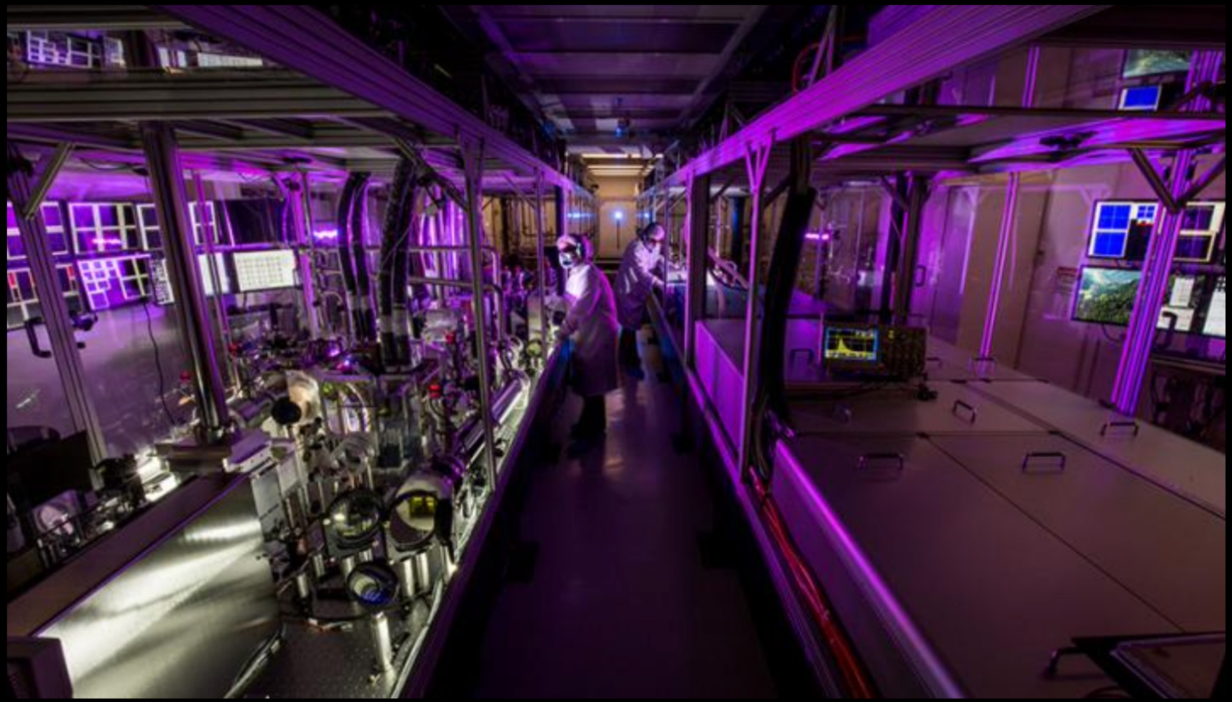


From 1960s the power laser can deliver has increased roughly by a factor of 1000 every 10 years



Adapted from T. Tajima et al., Opt Photonics News, (2013)

A "Petawatt" is many times more power than all the power delivered by all the power plants in the US

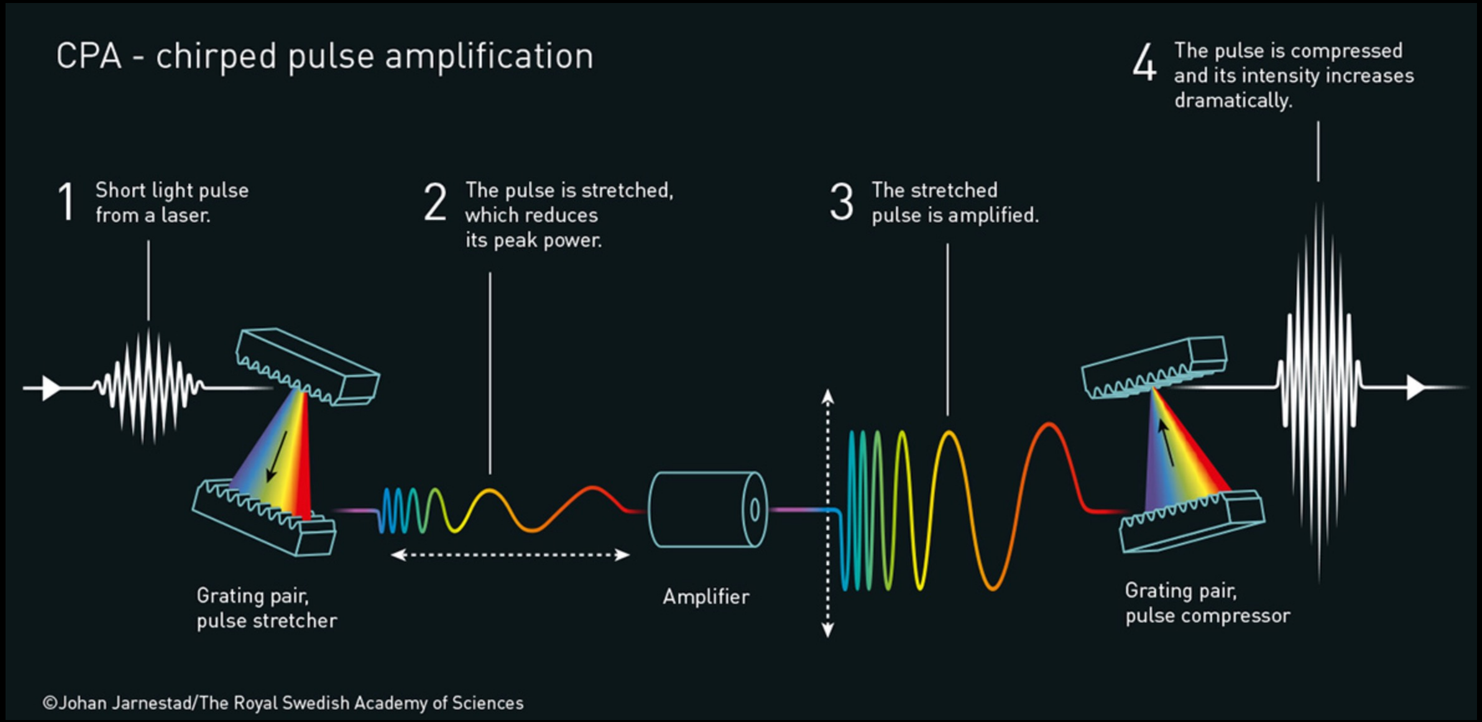


Power output of U.S. electrical grid: 0.5 Trillion watts

A state-of-the-art petawatt laser has 2000 times the power output of all power plants in the US

The power of a laser is determined by how much energy is in each pulse of light and how long each pulses is

Power [Watt] = Energy [J] / time duration [s]



The winners of the Nobel Prize in Physics 2018 are Arthur Ashkin (left), Gérard Mourou (center), and Donna Strickland (right). ILLUSTRATION: NIKLAS ELMEHAD/NOBEL MEDIA

Nobel Prize in Physics 2018

Donna Strickland, Gerard Mourou,
Compression of amplified chirped optical pulses,
Optics Communications 56 (3), 1985


Women
who changed
science
Match with a laureate
THE NOBEL PRIZE
Laureates
Explore
About
“We need to celebrate women physicists because they’re out there…
I’m honored to be one of those women.”
DONNA STRICKLAND
Nobel Prize in Physics 2018
ElectroViewer
7215

How can we use lasers for fusion?

The idea of inertial confinement fusion was first published almost 50 years ago, soon after the invention of the laser

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Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications

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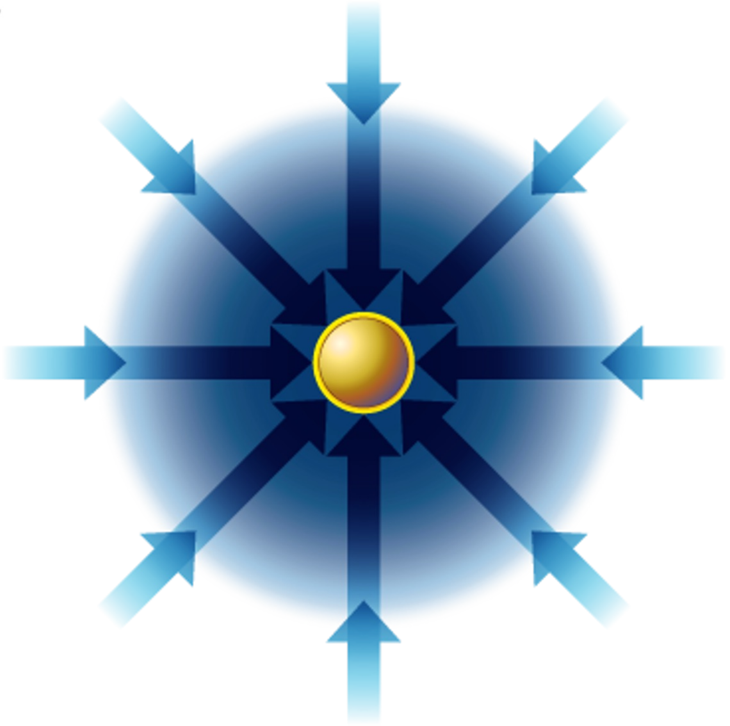
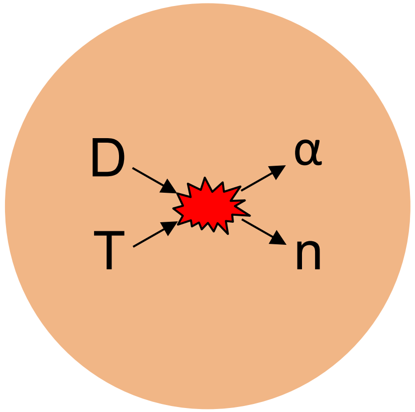


Why do we need to compress the DT fuel?

Uniform DT sphere



radius (r)
density (ρ)
mass (m)
temperature (T)

We want to maximize the fusion yield, or specifically the fusion yield per unit mass of DT (this is called the burn efficiency)

The fusion yield is: $Y = \rho_D \rho_T \sigma(T) V \tau_c$

For 50:50 DT, $Y = \rho^2 \sigma(T) V \tau_c$

Since $m = \rho V$, $Y = m\rho\sigma(T)\tau_c$

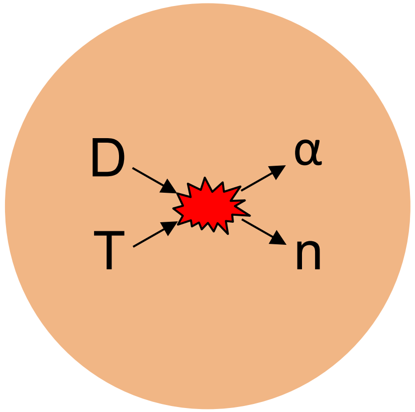
So, the yield per unit mass is: $Y/m = \rho\sigma(T)\tau_c$

Now, the confinement time is: $\tau_c \propto r$

Hence, the yield per unit mass, $Y/m \propto \rho r \, \sigma(T)$

Hence, for any temperature the burn efficiency is proportional to the areal density (ρr)
So, for high burn efficiency you want high areal density

Why do we need to compress the DT fuel?



Now, the fuel mass, m, is: $m = \rho V$

So, $m \propto \rho r^3$

Which we can rewrite as: $m = (\rho r)^3/\rho^2$

So, for a given burn efficiency (i.e., a fixed ρr),

$$m \propto 1/\rho^2$$

Hence, the higher the density, the **less DT fuel mass** you need to achieve a given burn efficiency

You need a $\rho r > 0.3$ g/cm^2 so that alpha particles can stop in the plasma, resulting in self-heating and ignition

How much DT mass and energy do you need for $\rho r > 0.3$ g/cm^2

→ solid DT
0.2 g/cm3

radius ~1.4 cm
mass ~2.3 g
energy (10 keV) ~3 GJ

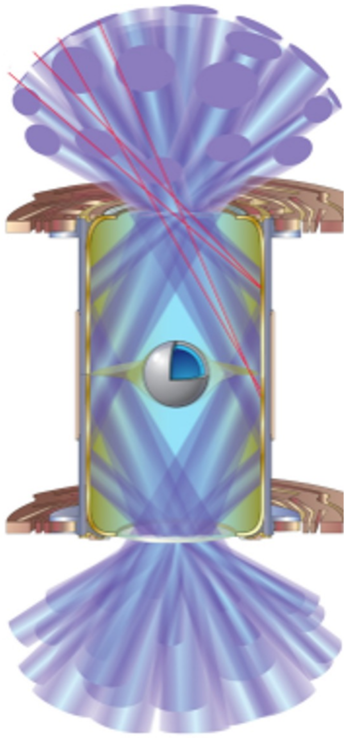
→ 1000x compressed DT

radius ~0.0014 cm
mass ~2.3 µg
energy (10 keV) ~3 kJ

Nuckolls et al. (1972) proposed using lasers to implode a spherical capsule of DT to the density and temperature needed for ignition

In the US there are three major approaches to achieving ignition and high yield through inertial fusion

Laser indirect-drive

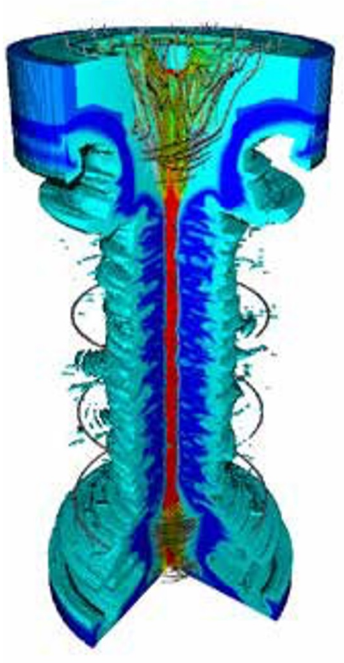


Lawrence Livermore National Laboratory

Laser direct-drive

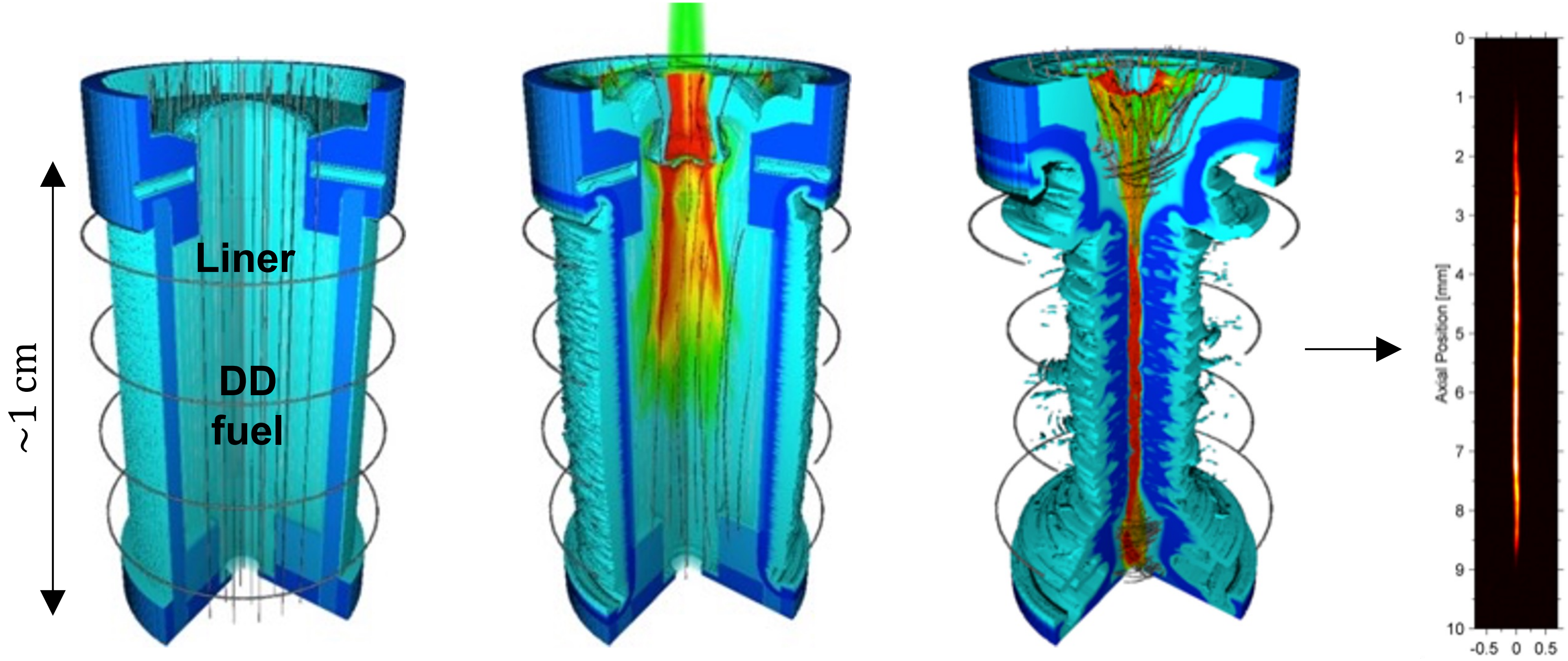
UR LLE

Magnetic direct-drive



Sandia National Laboratories

Magnetized liner inertial fusion (MagLIF)

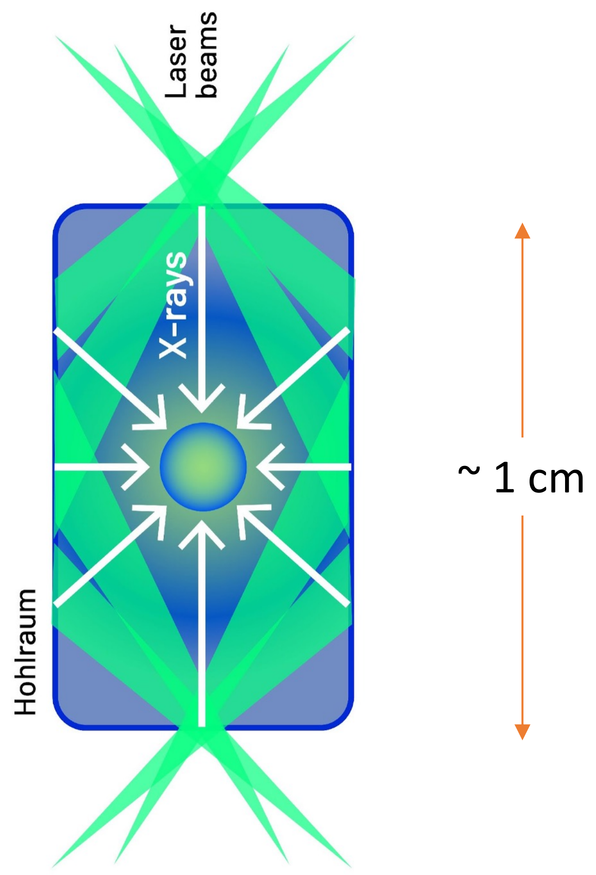


Fuel is premagnetized with an axial B-field, reducing conduction losses and trapping alpha-particles	Fuel is preheated with a multi-kJ laser to reduce convergence requirements	Fuel is **compressed** with an azimuthal B-field (J x B force)	~Gbar, multi-keV plasma

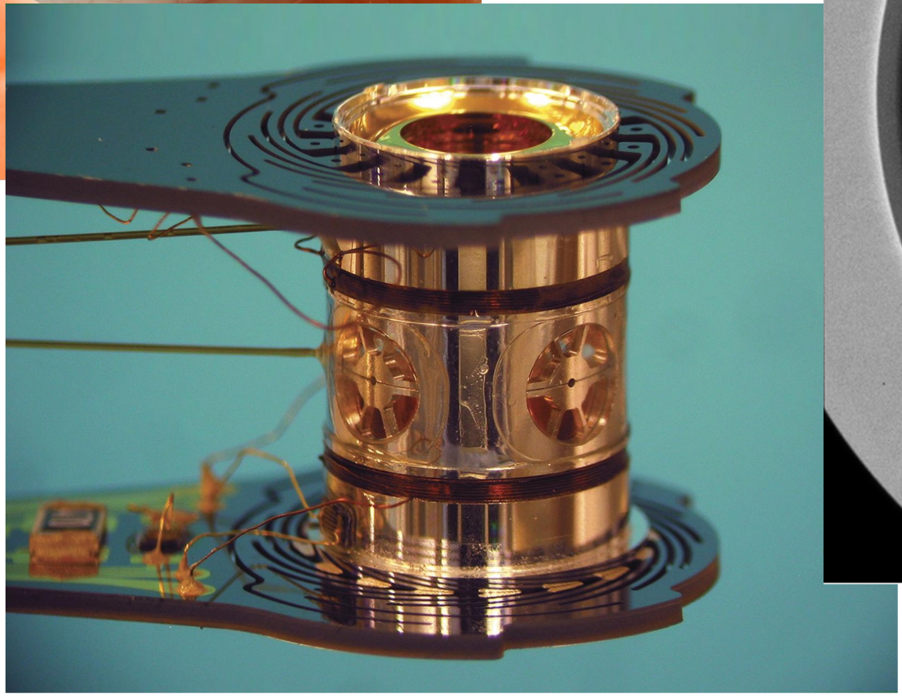
S. Slutz, Phys. Plasmas **17**, 056303 (2010)

On National Ignition Facility, the capsule is driven by x-rays produced in a cylindrical cavity called a “hohlraum”

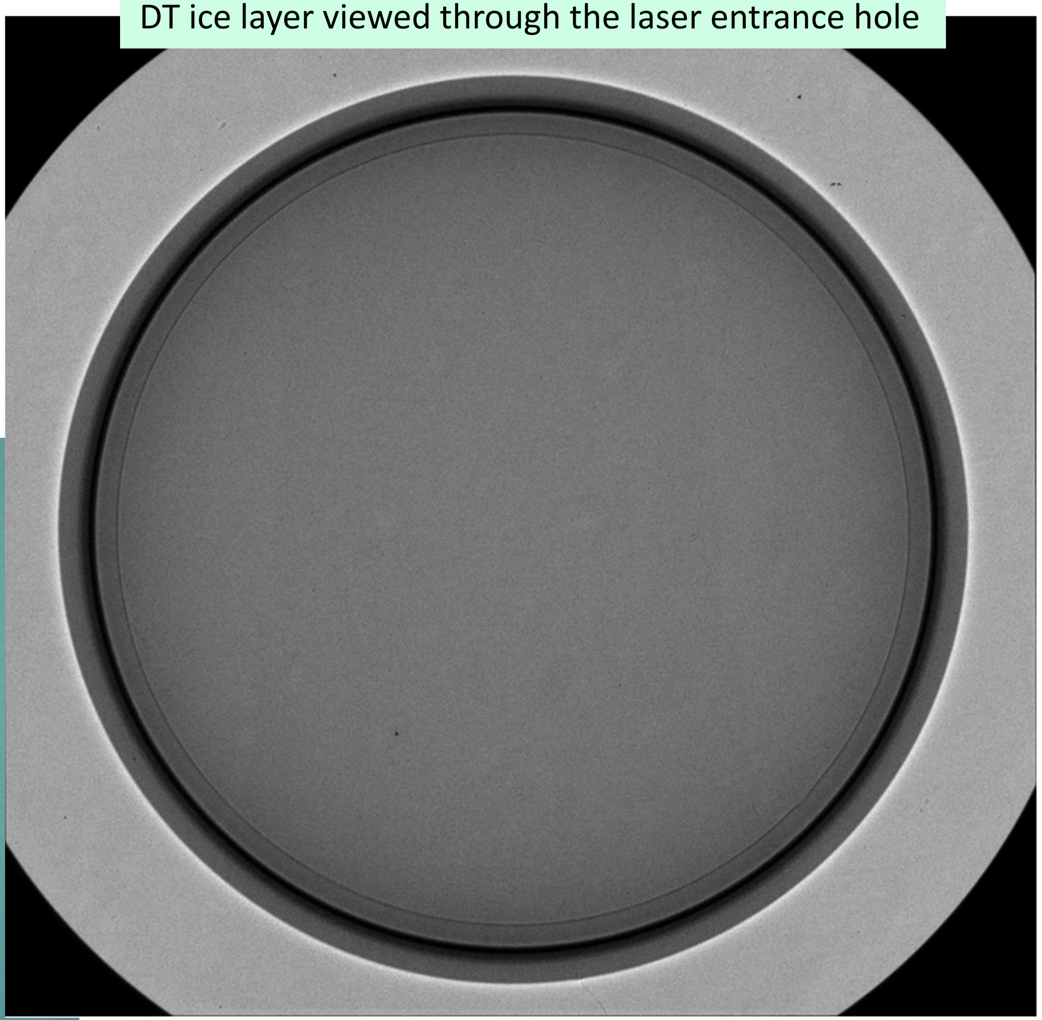
- 96 laser beams enter from the top and 96 from the bottom through a “laser entrance hole”
- Laser beams strike the inside of the hohlraum and generate x-rays
- X-rays drive the ~ 1 mm radius capsule filled with DT fuel
- Beams arranged in two cones: outer and inner to achieve symmetric drive



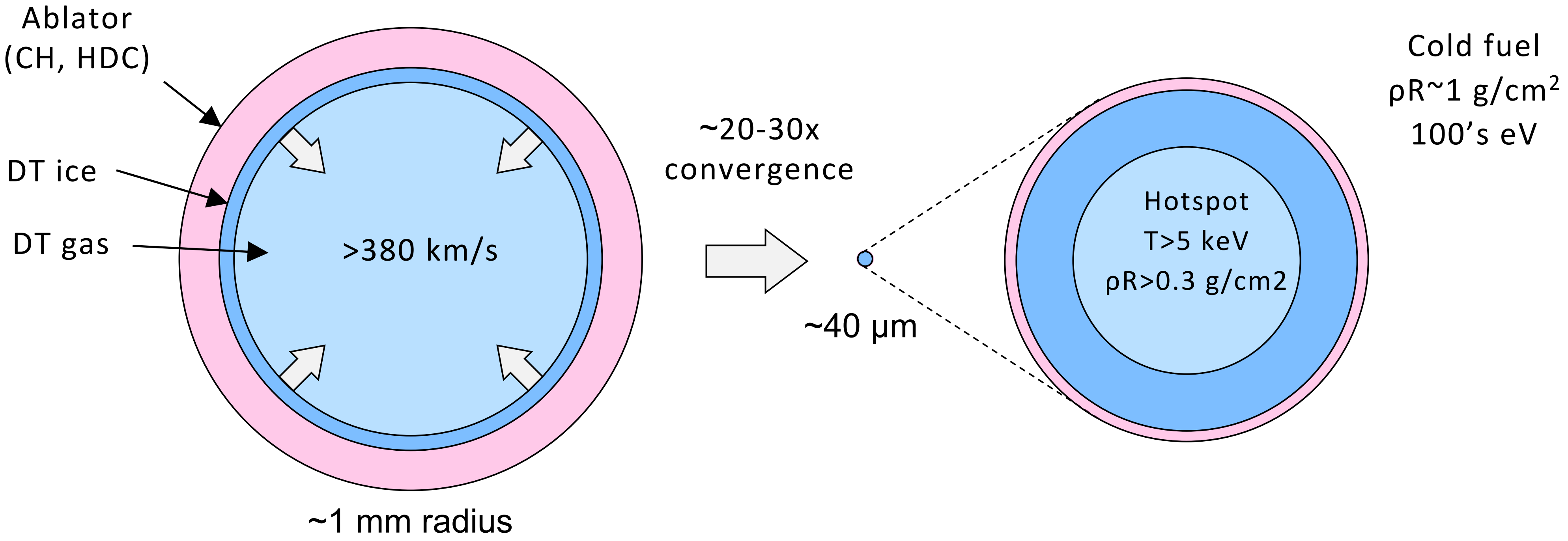
Hohlraum target at NIF



DT ice layer viewed through the laser entrance hole



The implosion at NIF forms a central core, or hotspot, surrounded by a dense shell of cold fuel



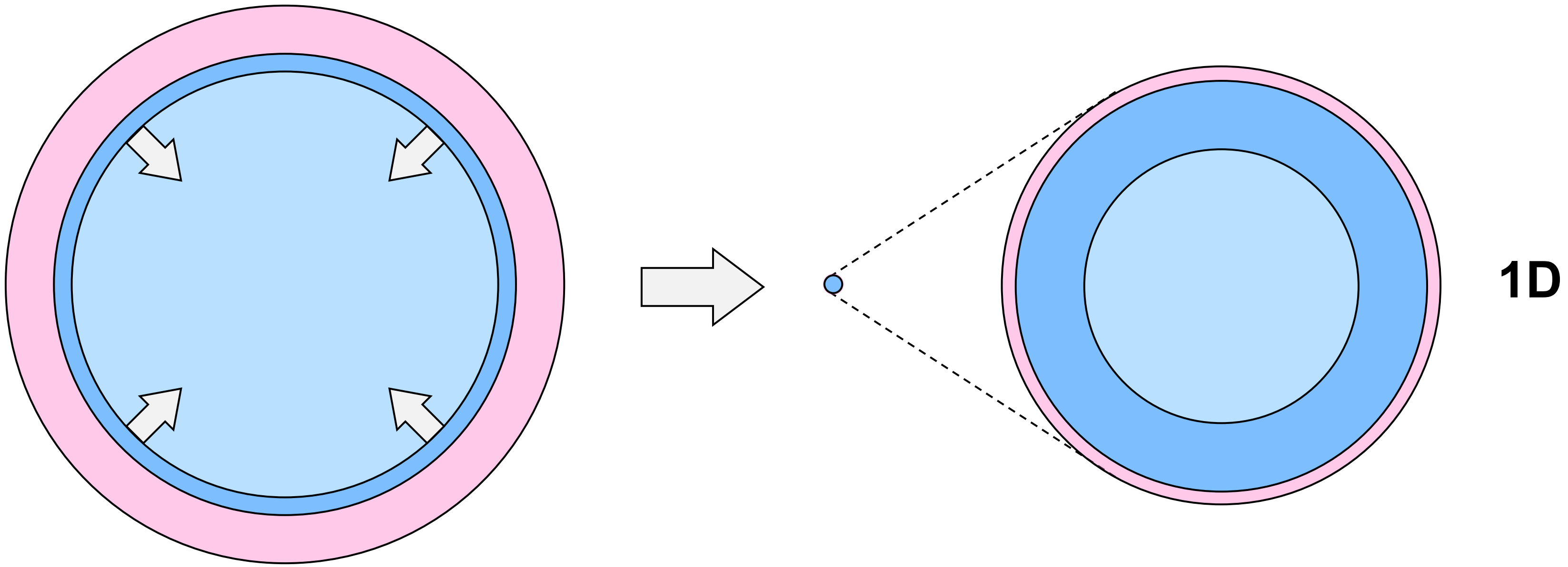
A typical NIF implosion has:

mass of DT	~200 μg
peak velocity	~380 km/s

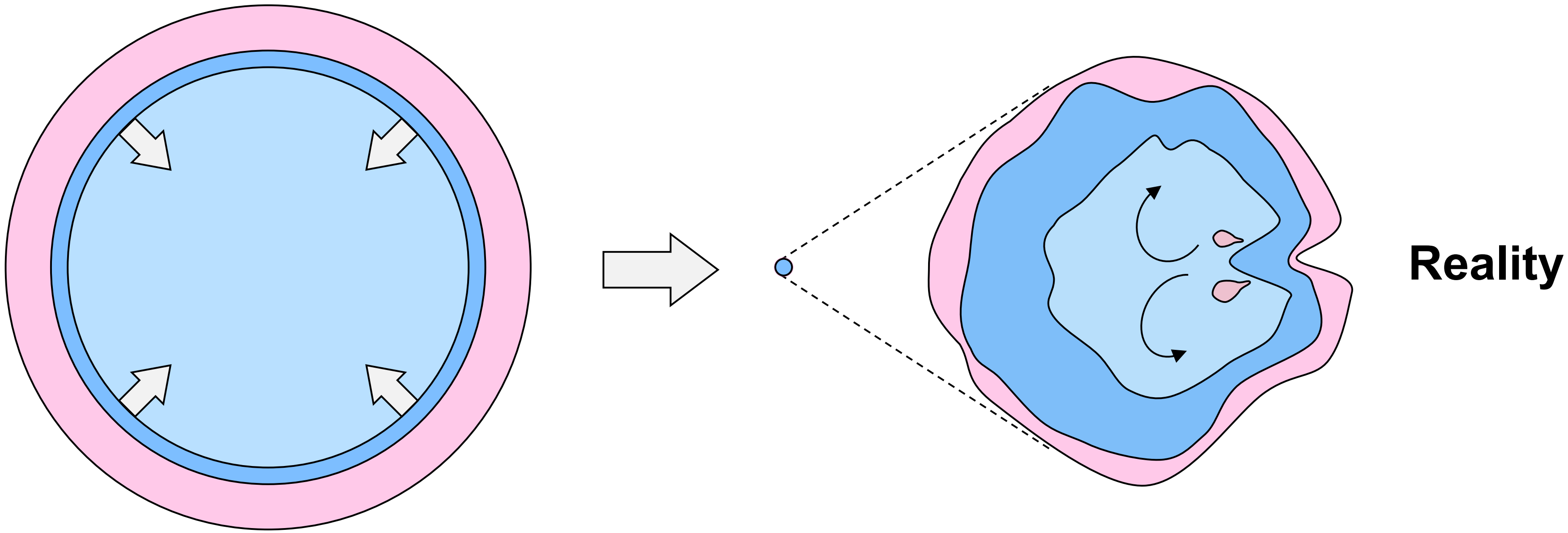
⇒ fuel kinetic energy ~14 kJ

- Energy needed to heat 200 μg to 5 keV = 116 kJ
- But, we only need to heat enough DT for ρR~0.3 g/cm^2
- If ρ_{hs}~100 g/cm3 ⇒ r_{hs}~30 μm, and m_{hs}~11 μg, so energy needed in hotspot ~6 kJ

This is a 1D picture

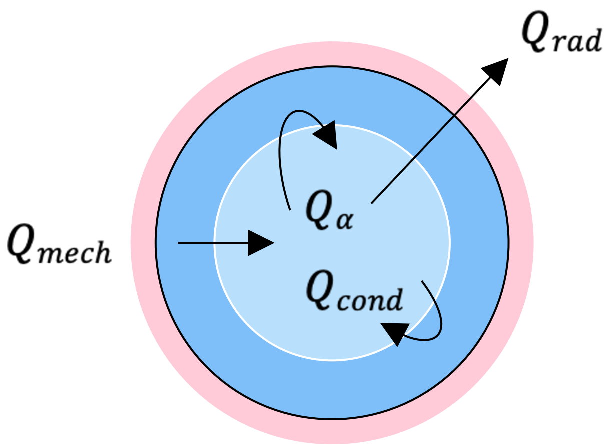


In reality a variety of 3D effects can degrade the implosion



- High-mode instability can reduce compressibility of the DT fuel
- 3D asymmetry can reduce efficiency of converting KE to internal energy
- Ablator mix in the hotspot can enhance radiation losses

Ignition conditions more in detail

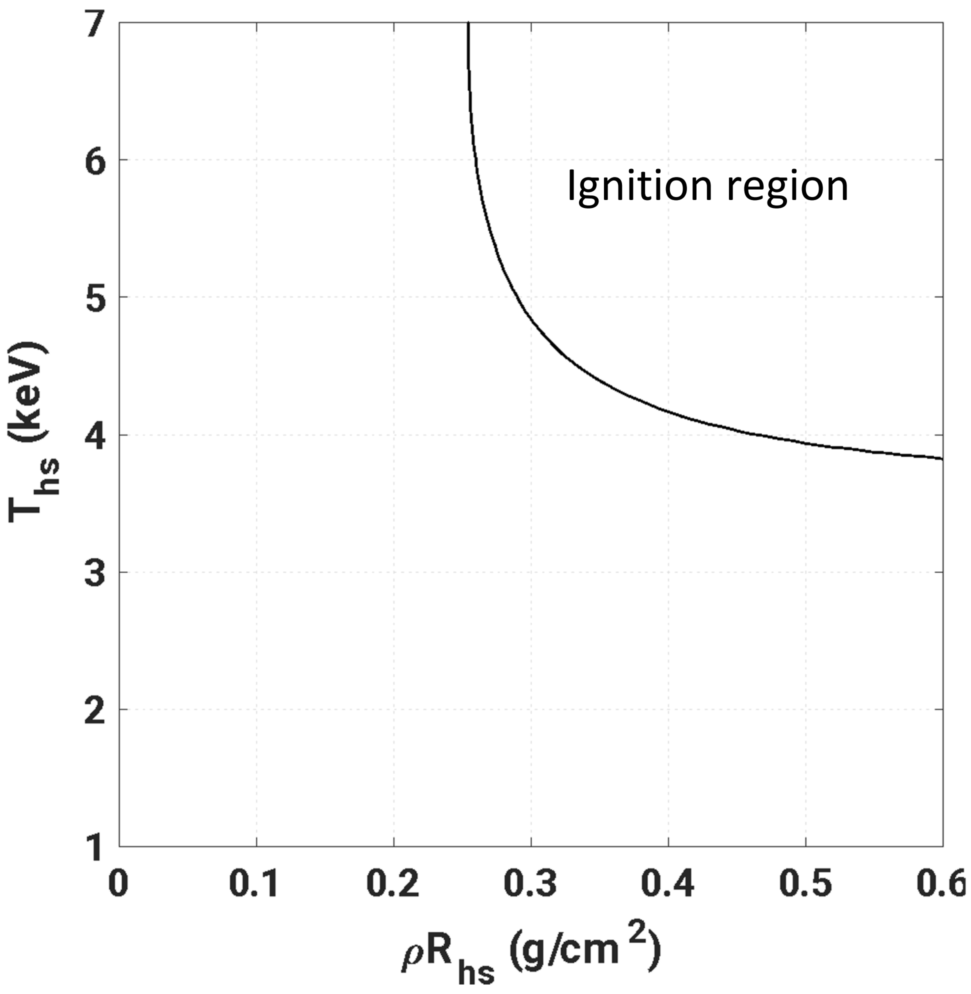


- We can consider the power balance in the hotspot
- A minimum condition for ignition is that the net power into and out of the hotspot must be positive
  - net power, Q_{net} = heating power - cooling power

$$Q_{net} = f_\alpha Q_\alpha - Q_{rad} - Q_{cond}$$

P. T. Springer, Nucl. Fusion **59**, 032009 (2019)

Ignition conditions more in detail



$$Q_{net} = f_\alpha Q_\alpha - Q_{rad} - Q_{cond} > 0$$

Plot from P. Patel (formerly LLNL, now at Focused Energy)

Diagnostics for NIF have been developed over decades by the whole HED community

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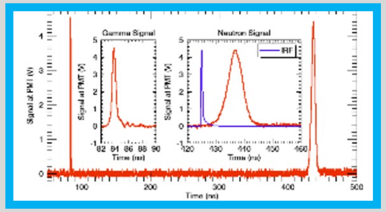
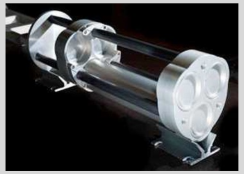
DT Ion temperature, hot spot velocity, fuel density, yield

- Five Neutron Time of Flight (nToF)'s and the Magnetic Recoil Spectrometer (MRS)

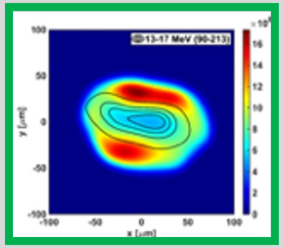


DT Neutron yield

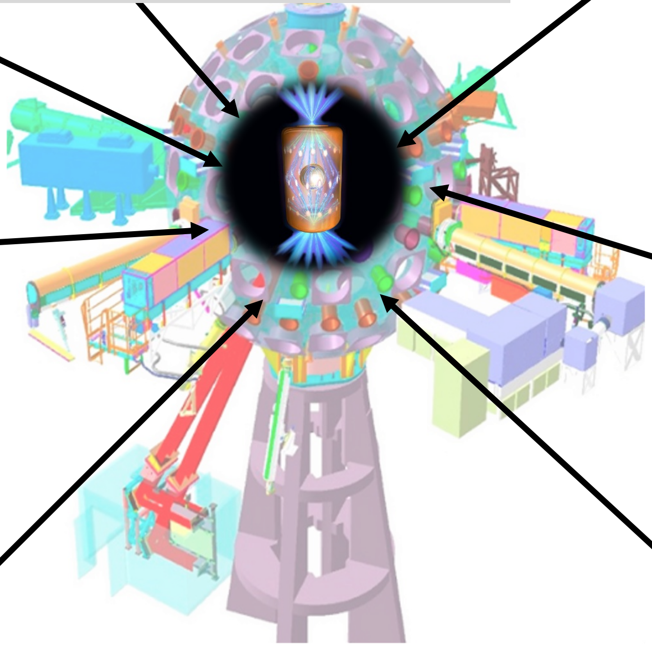


- Zirconium/Copper Nuclear activation

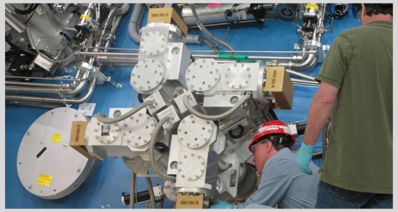
Hot spot and Fuel Shape from Neutron Imagers



- 3 Neutron Imaging (NIS) Lines of sight for 3D reconstruction of neutron hot-spot
- 2 NIS down-scatter lines of sight for fuel shape



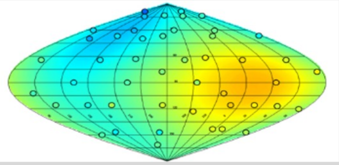
Burn width, Bang Time, DT neutron yield



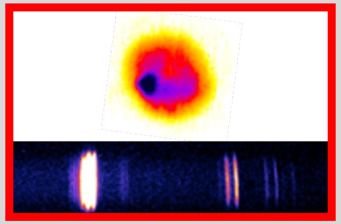
- Gamma Reaction History

DT Yield Map /Fuel uniformity

- 48 Real-Time Nuclear Activation (NAD)'s



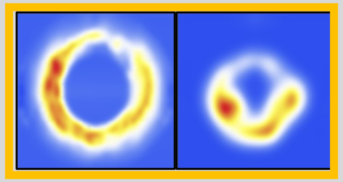
X-ray Imaging & Spectroscopy



- 3 x-ray imaging lines of sight
- X-ray spectroscopy to characterize material mixed into the hotspot

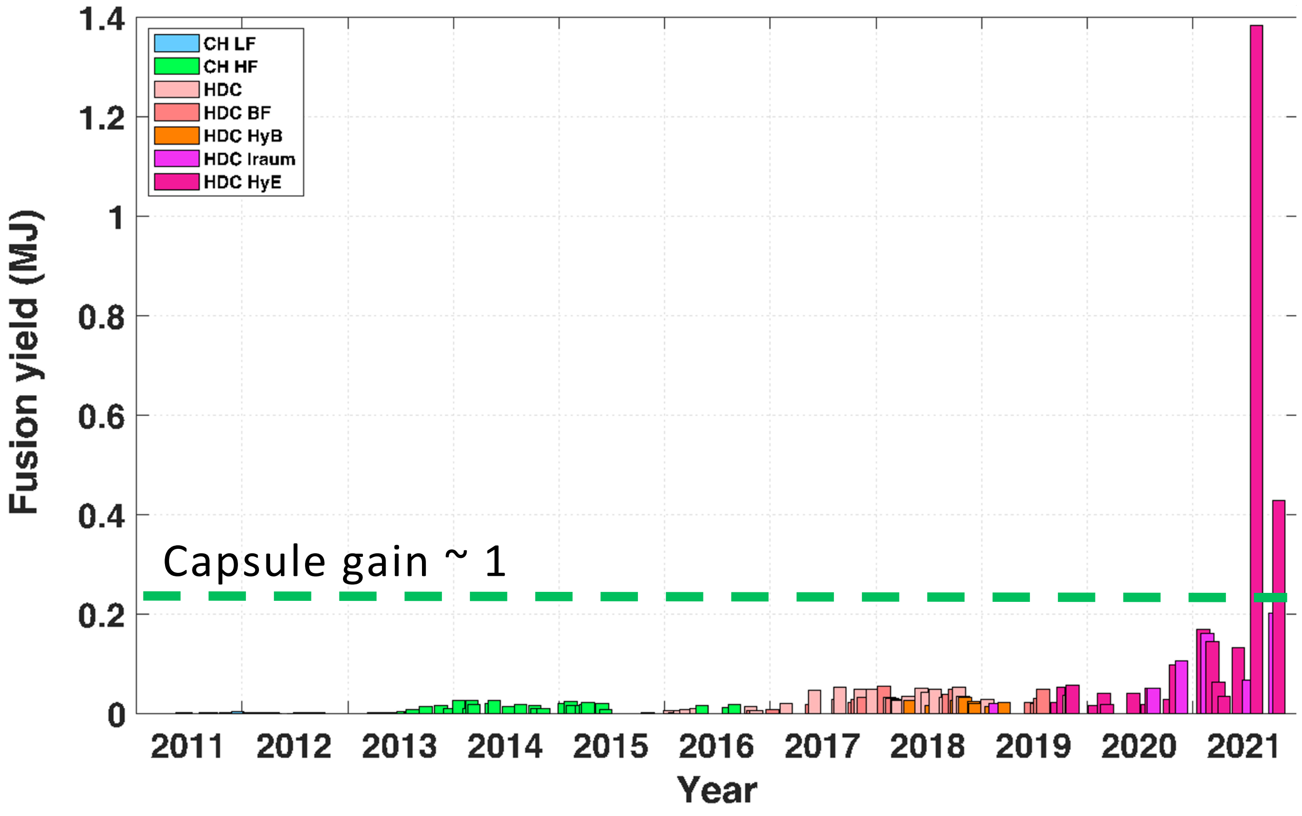
DT Fuel uniformity: Compton Radiography

- ~100keV x-rays produced by Advanced Radiography Source provide radiographs of DT fuel



From D. Callahan (formerly LLNL, now at Focused Energy)

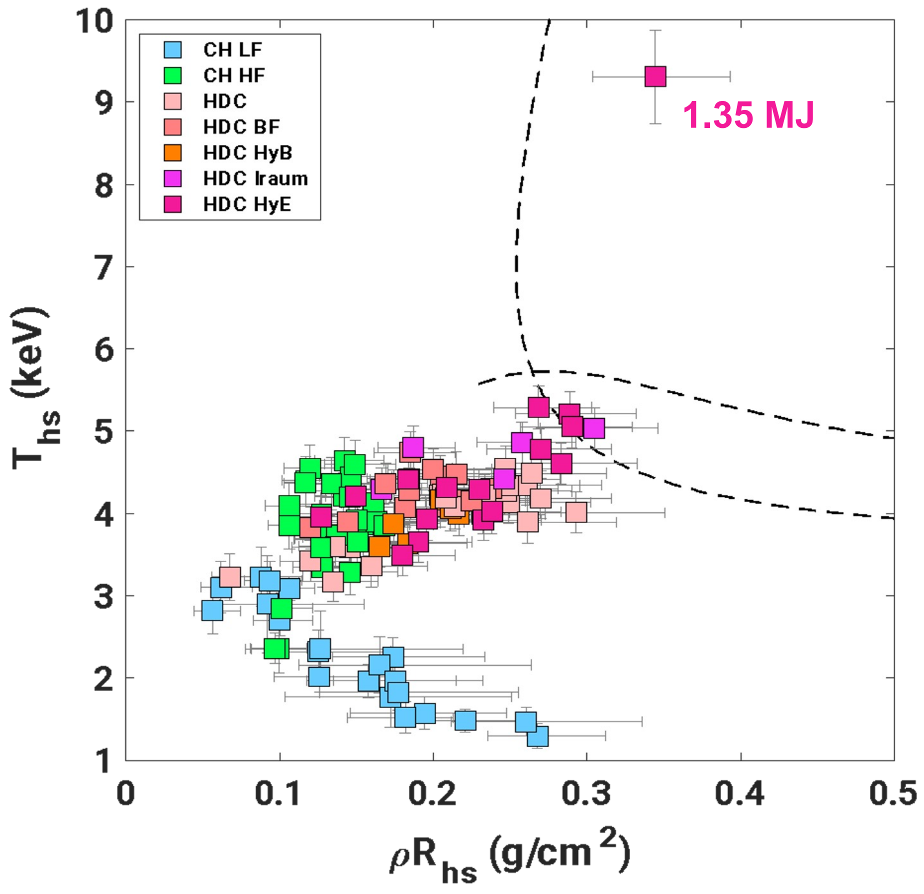
Historic advances in inertial confinement fusion have been made over the past few years



Shot achieved ignition by Lawson's criteria (scientific ignition) August 2021

Plot by P. Patel (formerly LLNL, now at Focused Energy)

Historic advances in inertial confinement fusion have been made over the past few years



Plot by P. Patel (formerly LLNL, now at Focused Energy)

Gain 1.5 was achieved in December 2022 at NIF

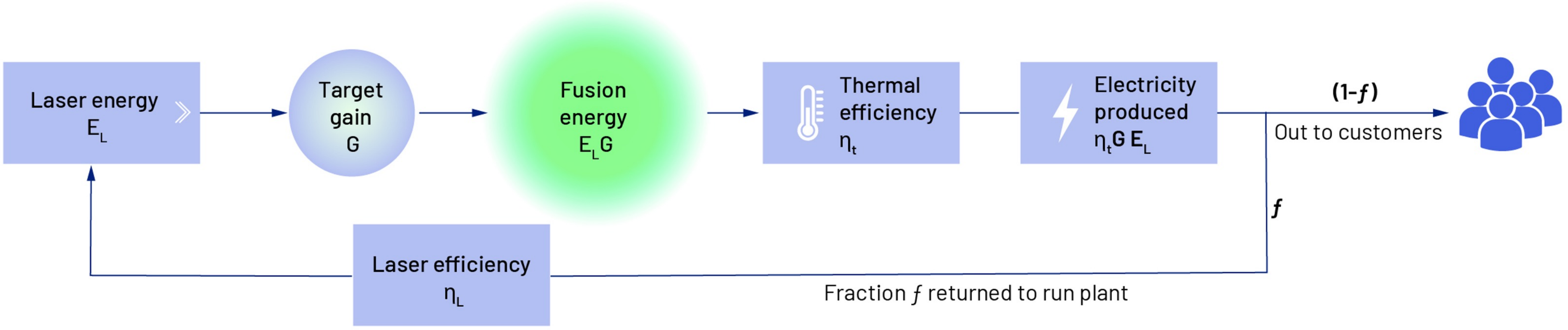
Gain 1.5 was achieved in December 2022 at NIF

Lecture by Annie Kritcher, LLNL (Tomorrow 12 PM)

What's next?

Now is the time to take the next step in inertial fusion energy

For IFE, one needs to get target gain of ~ 100 at about 10 Hz to run a power plant



- Energy to run the laser is $\mathbf{E_L / \eta_L}$
- Energy produced is $\mathbf{E_L \times G \times \eta_t}$

- If we recirculate power fraction to less than 25 % , then $\mathbf{\eta_L \times \eta_t \times G > 4}$
- If $\eta_t \approx 0.4$, then $\mathbf{\eta_L \times G > 10}$
- If $\eta_L \approx 0.1$ then $\mathbf{G > 100}$
- For **750 MW** out to the grid, we need repetition rate to be about **10 Hz** for **2.5 MJ** laser

Courtesy of P. Patel (formerly LLNL, now at Focused Energy)

Several companies are working on commercialization of IFE using various approaches

FOCUSED ENERGY

Marvel Fusion

XCIMER

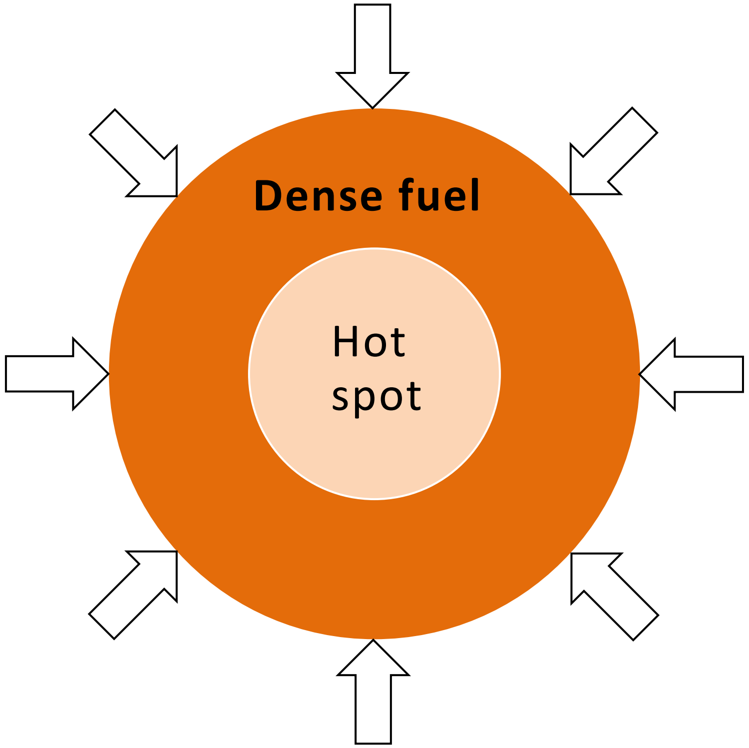
HB11 ENERGY

EX-Fusion

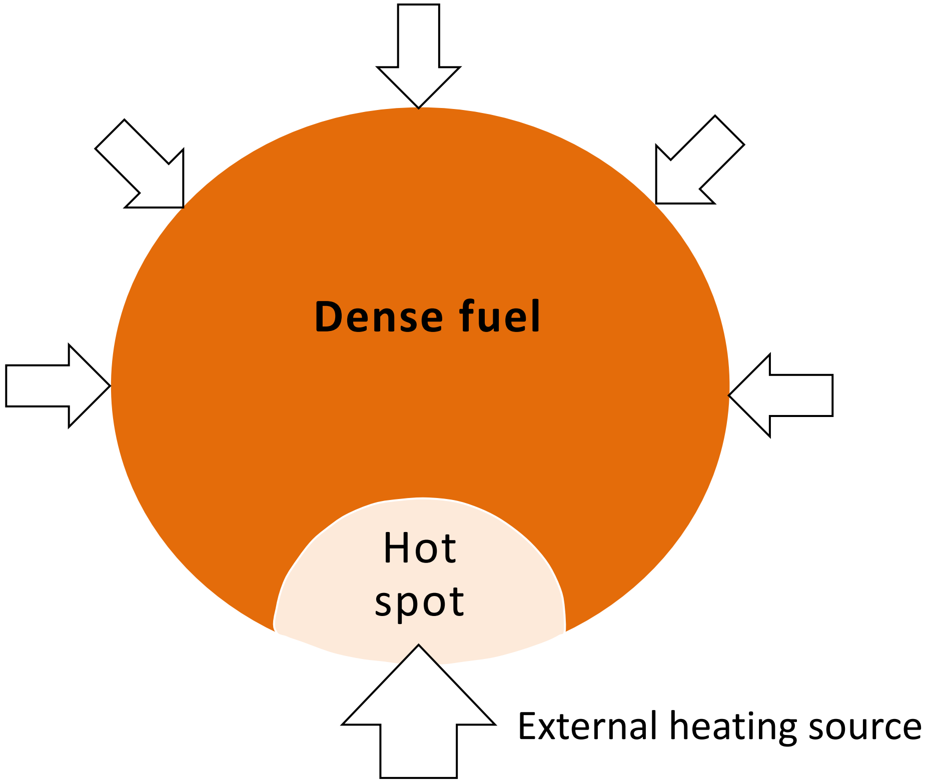
LONGVIEW FUSION
ENERGY SYSTEMS

Advanced IFE concepts are being explored: Fast Ignition

Central hot spot ignition



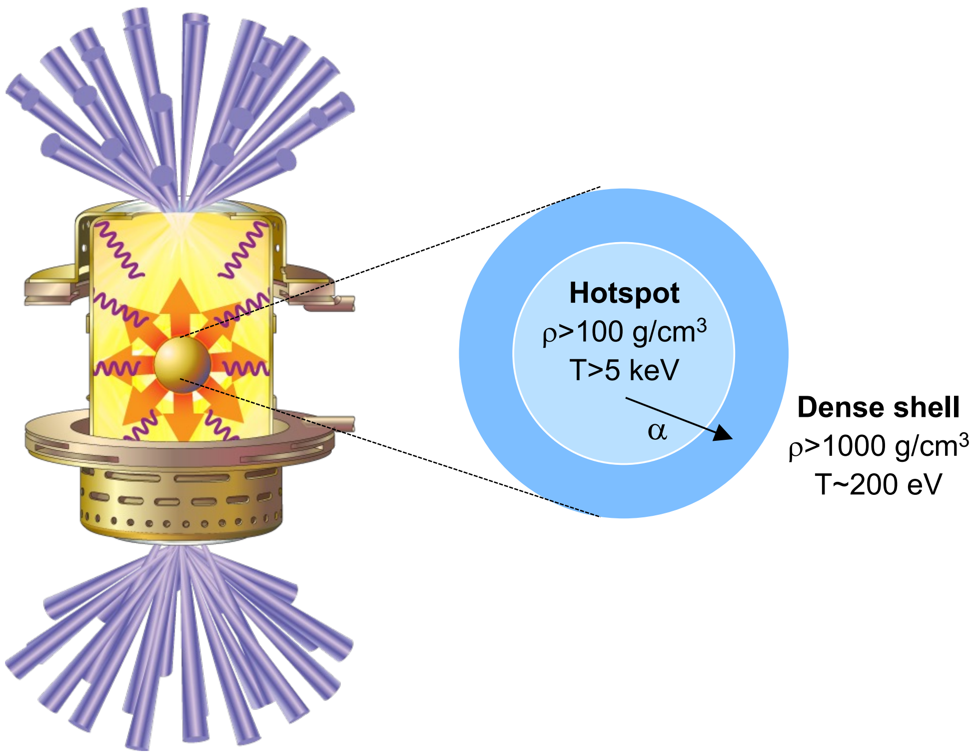
Fast ignition



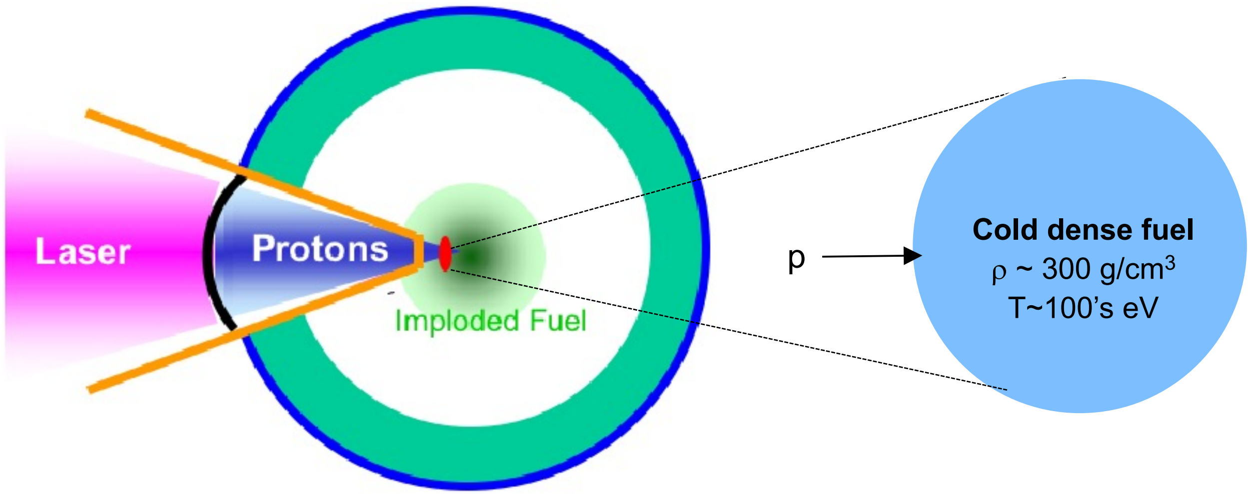
M. Tabak et al., Phys. Plasmas 1, 1626 (1994)

Advanced IFE concepts are being explored: Fast ignition

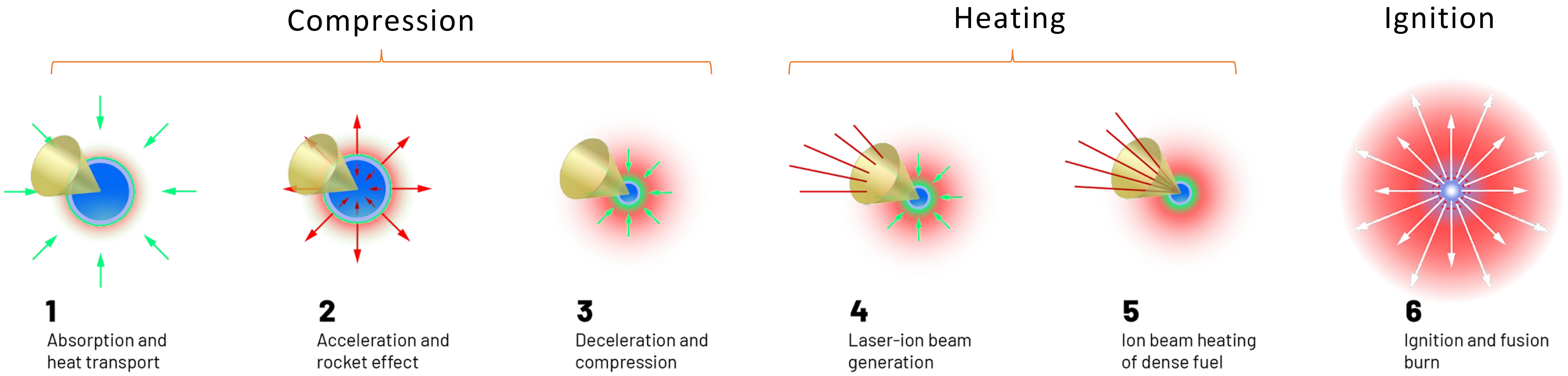
Central hot spot



Proton fast ignition



Proton fast ignition uses a short pulse laser generated proton beam to heat a hotspot to ignition temperatures



- Cone provides access to the dense core
- No longer need high fuel velocity to heat hotspot – heating is done by a separate laser source
- Challenge is to produce, focus, deposit enough protons to create hotspot

Getting from 1.5 on NIF to Gain 100

$$\text{Gain} = \frac{\text{Yield}}{\text{Laser Energy}} \sim \frac{M_{fuel}\, \eta_{burn}}{\text{Laser Energy}}$$

1.5 NIF result – gain 1.5

x 4 High velocity no longer needed so drive 4x as much fuel at ½ velocity for same kinetic energy

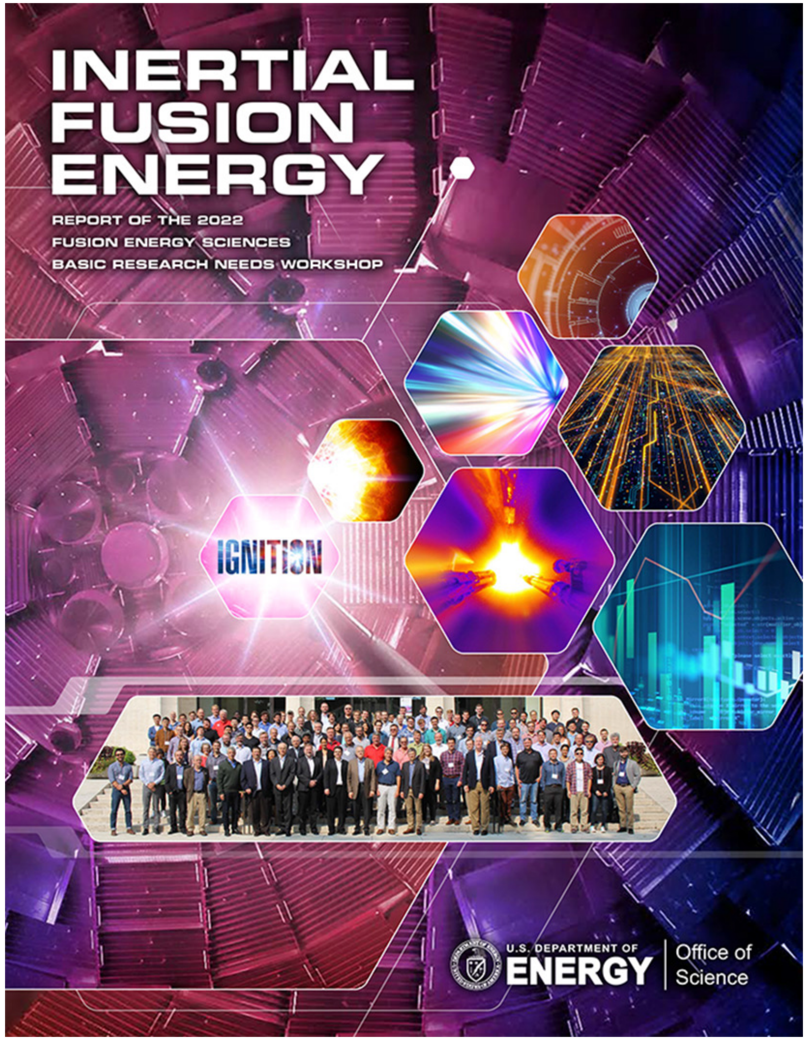
x 5 Increase burn efficiency from 4% to 20-25% by increasing fuel areal density

x 5 Direct drive compression rather than using a hohlraum (recall only 10-15% coupling in a hohlraum) ~ 5x in coupling efficiency

= 150

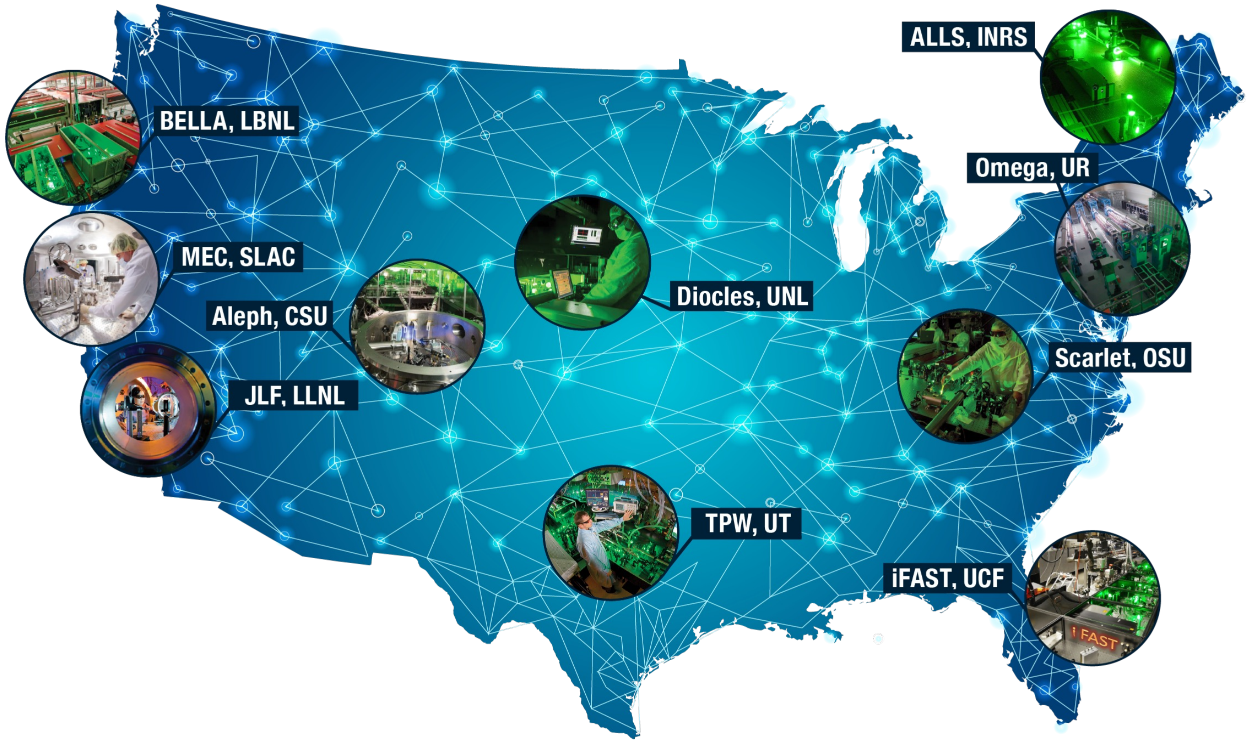
How can we address scientific
and technological questions for IFE?

Basic research needs for IFE



- Laser technology
- Inertial fusion energy target physics
- Diagnostics development
- High repetition rate operations
- Material studies
- Reactor design
- **Education and workforce development!**

THE LASERNETUS NETWORK



Our mission is to advance the frontiers of high-power laser science and applications by:

- Supporting cutting edge research
- Providing students and scientists with broad access to unique facilities and enabling technologies
- Fostering collaboration among researchers around the world

U.S. DEPARTMENT OF ENERGY | Office of Science

Mid-scale laser facilities are positioned for IFE relevant Science and Technology

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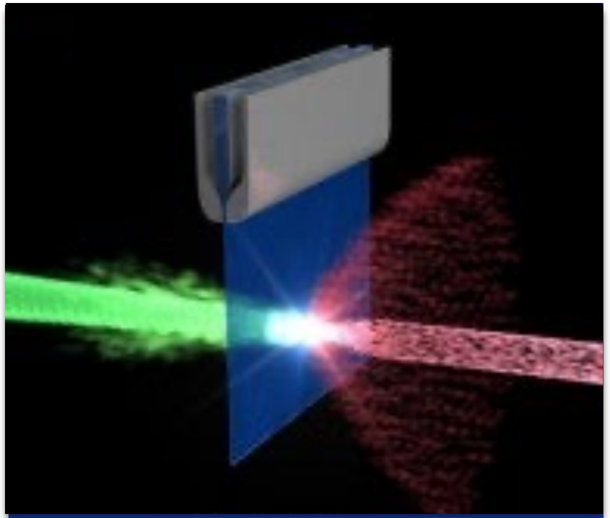
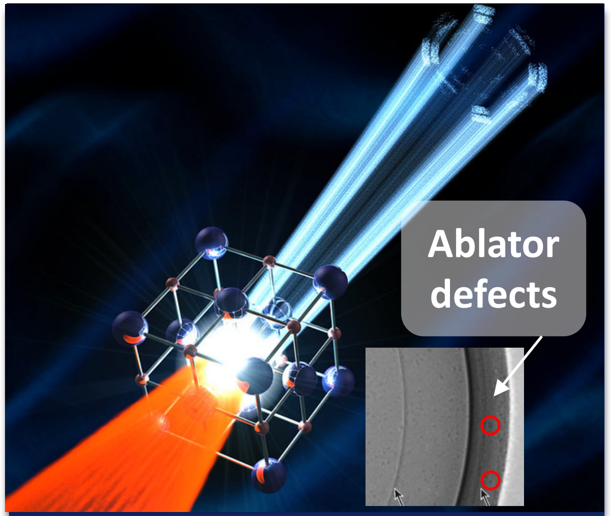
Laser-Plasma Experiments



Particle and radiation transport, laser-plasma interaction, diagnostics development, extreme states of matter

Radiation Damage & Fusion Materials



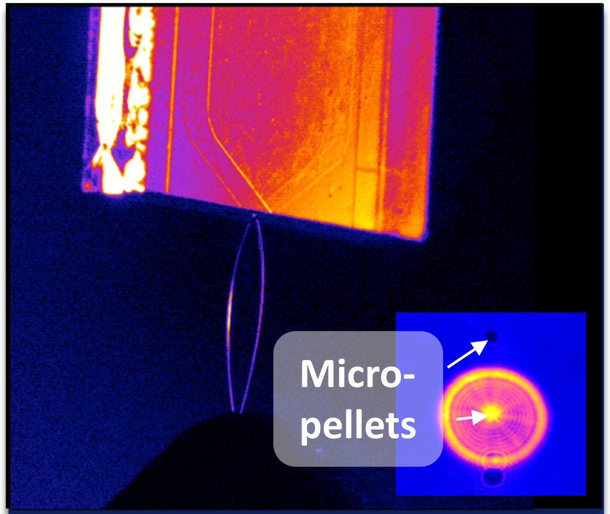
Validation of radiation damage simulations on W, or other blanket or divertor materials.

Microphysics studies of ablator and capsule materials

HRR Laser Technology

Development of high average power and high peak power laser systems operating at IFE-relevant repetition rates, e.g., 10 Hz, multi-ns, multi-kW beamlines

Fusion Technologies

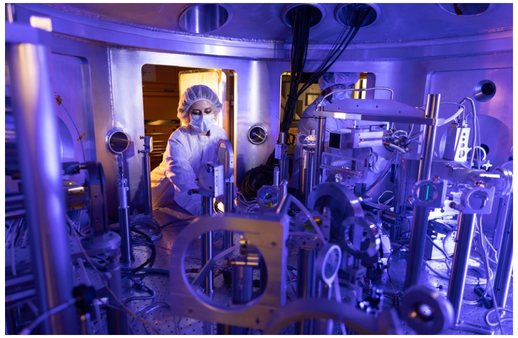
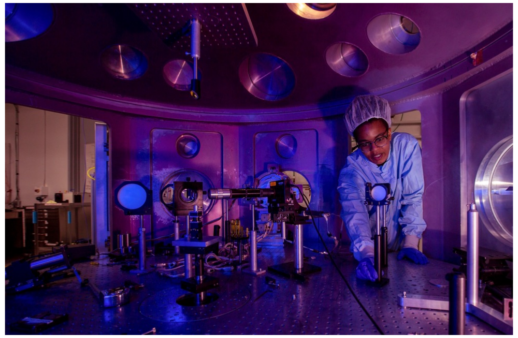
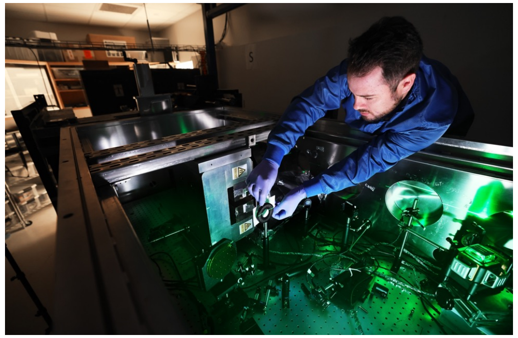
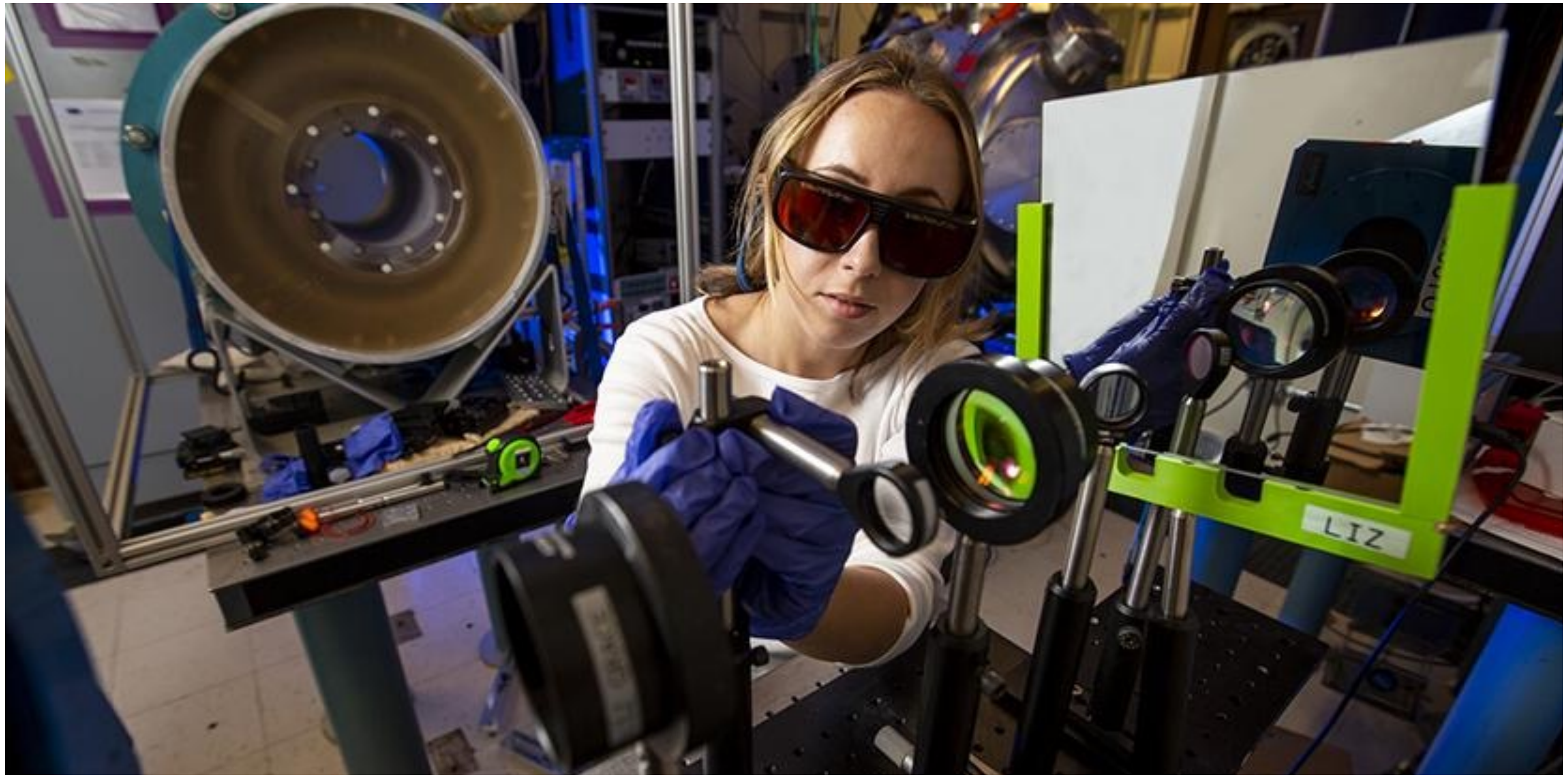


Laser plasma diagnostics, high-rep-rate targets and alignment systems, AI/ML to connect experiments and theory, integrated design and engineering for large facilities

Courtesy of C. Curry (SLAC)

BUILDING THE NEXT ENERGY SCIENCES WORKFORCE

- Encourage students and postdocs to lead experiments as PIs to cultivate new leaders
- Expose and train students and faculty at LaserNetUS facilities
- Develop capabilities and expertise at universities to create new programs
- **New initiative in development:** Undergraduate Student Research Program

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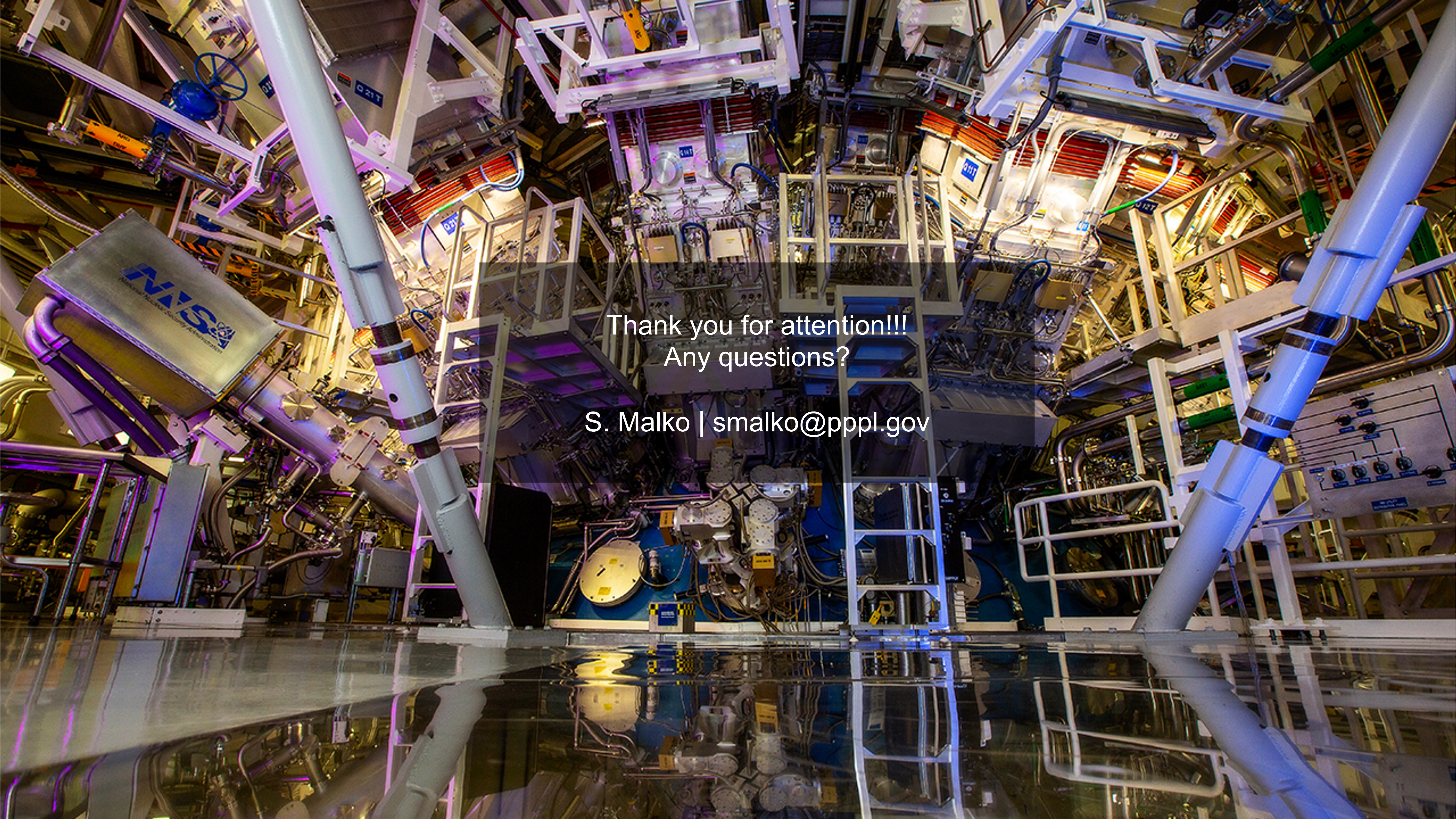
My LaserNetUS experiment at CSU ALEPH PW laser facility involved teams from 15 institutions to study ion transport in HED plasmas

PRINCETON UNIVERSITY

PPPL



Thank you for attention!!!
Any questions?

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