Overview of HEDS Experiments at LLNL

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August 3, 2023

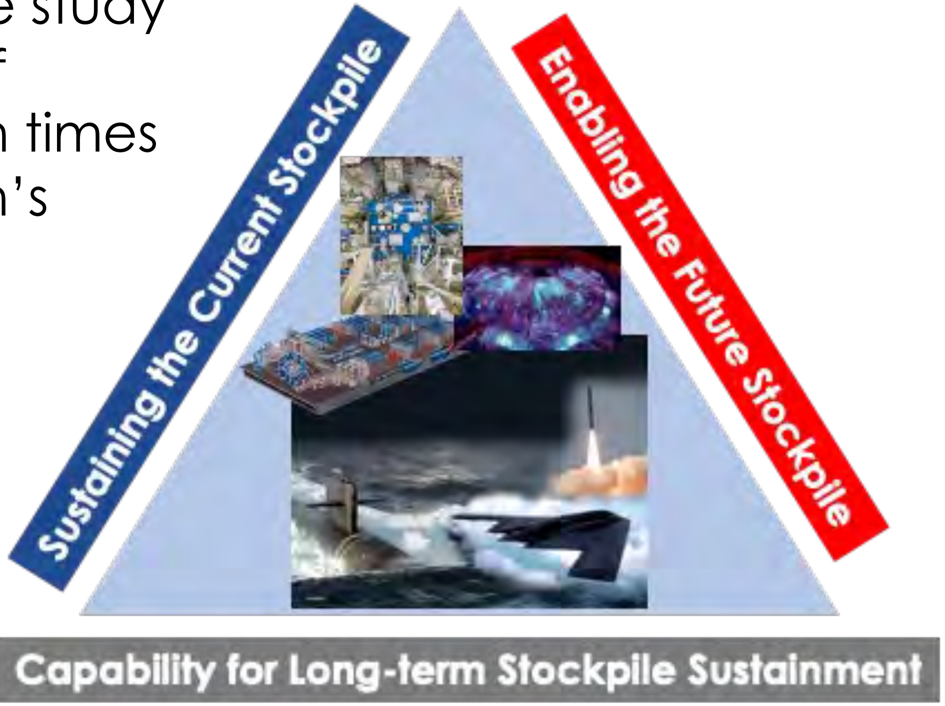
HEDS Center Seminar

Lawrence Livermore National Laboratory

Prepared by LLNL under Contract DE-AC52-07NA27344.

We use high power lasers and other technologies to create “high energy density” (HED) conditions in the laboratory

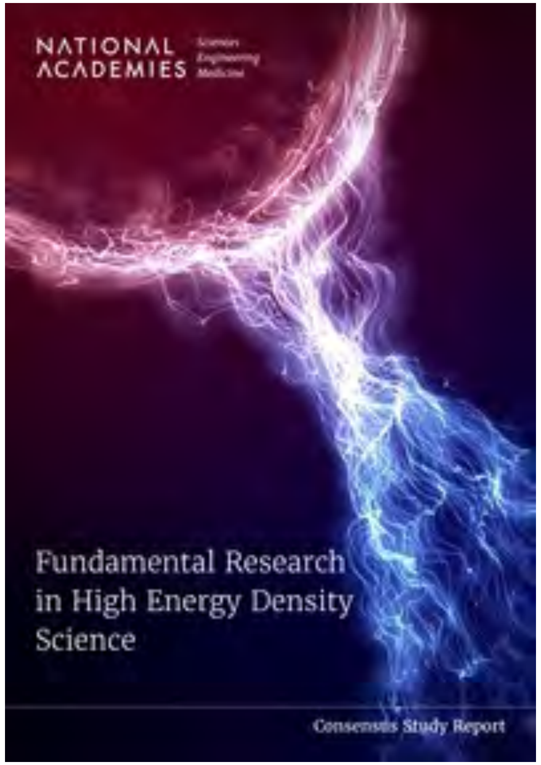
- High energy density science is the study of matter under extreme states of pressure (one million to one trillion times the atmospheric pressure at Earth’s surface, >1Mbar).
  - Stars
  - Earth’s core
  - Inertial confinement fusion
  - Fusion energy
  - Nuclear weapons science


Sustaining the Current Stockpile

Enabling the Future Stockpile

Capability for Long-term Stockpile Sustainment

https://www.energy.gov/nnsa/articles/stockpile-stewardship-and-management-plan-ssmp


NATIONAL ACADEMIES Sciences Engineering Medicine

Fundamental Research in High Energy Density Science

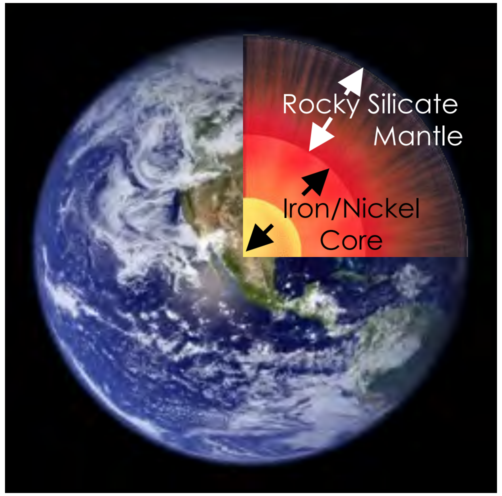
Consensus Study Report

https://nap.nationalacademies.org/resource/26728/interactive/

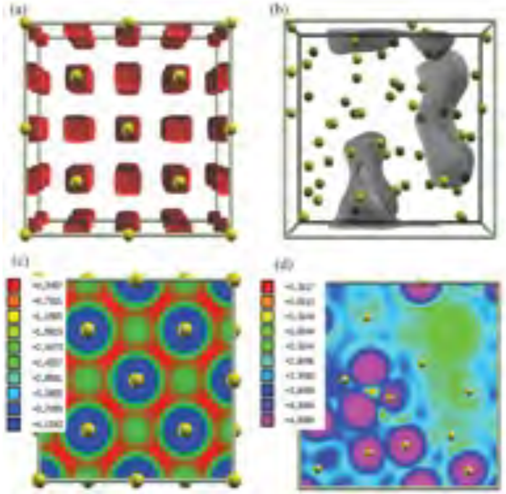
High energy density (HED) science has critical applications in areas such as inertial confinement fusion, astrophysics, nuclear science, and the stewardship of the nation’s nuclear weapons stockpile

HED experiments are focused on fundamental understanding of materials, plasmas, hydrodynamics, and radiation transport at extreme conditions

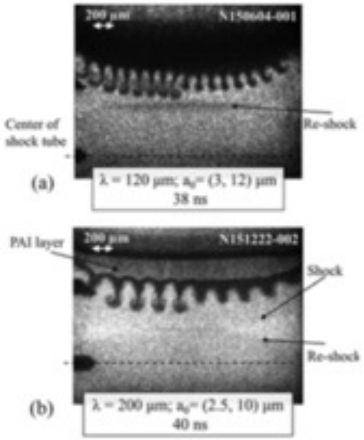
Planetary Science



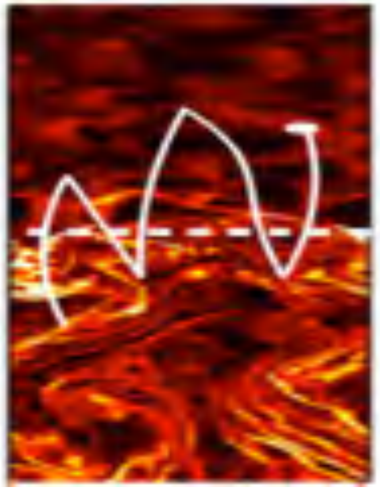
Dynamic Materials

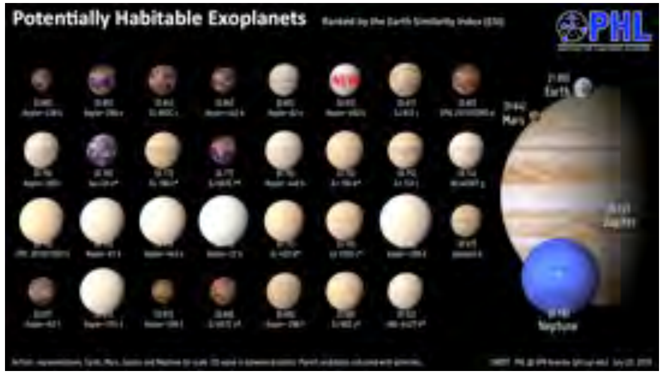


Radiation Hydrodynamics

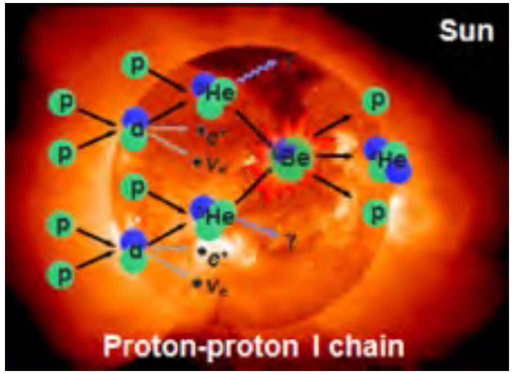


Plasma Astrophysics

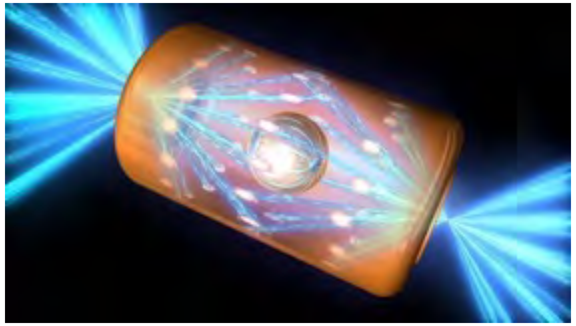




Exoplanets, cold and warm dense matter



Nuclear Physics



Material Radiation Effects (neutron, xray, gamma)

NIF is the world's largest and most energetic laser enabling the study of matter at high energy density conditions

NIF spans about 3 football fields

- Fast pulses to ~1000x more power than the US electrical grid
- Matter temperatures ~1-10x the core of the sun
- Radiation temperatures ~1000x hotter than the surface of the sun
- Densities around 100-1000x solid
- Pressures around 100 billion times earth’s atmospheric pressure
- Full suite of diagnostics (>120)

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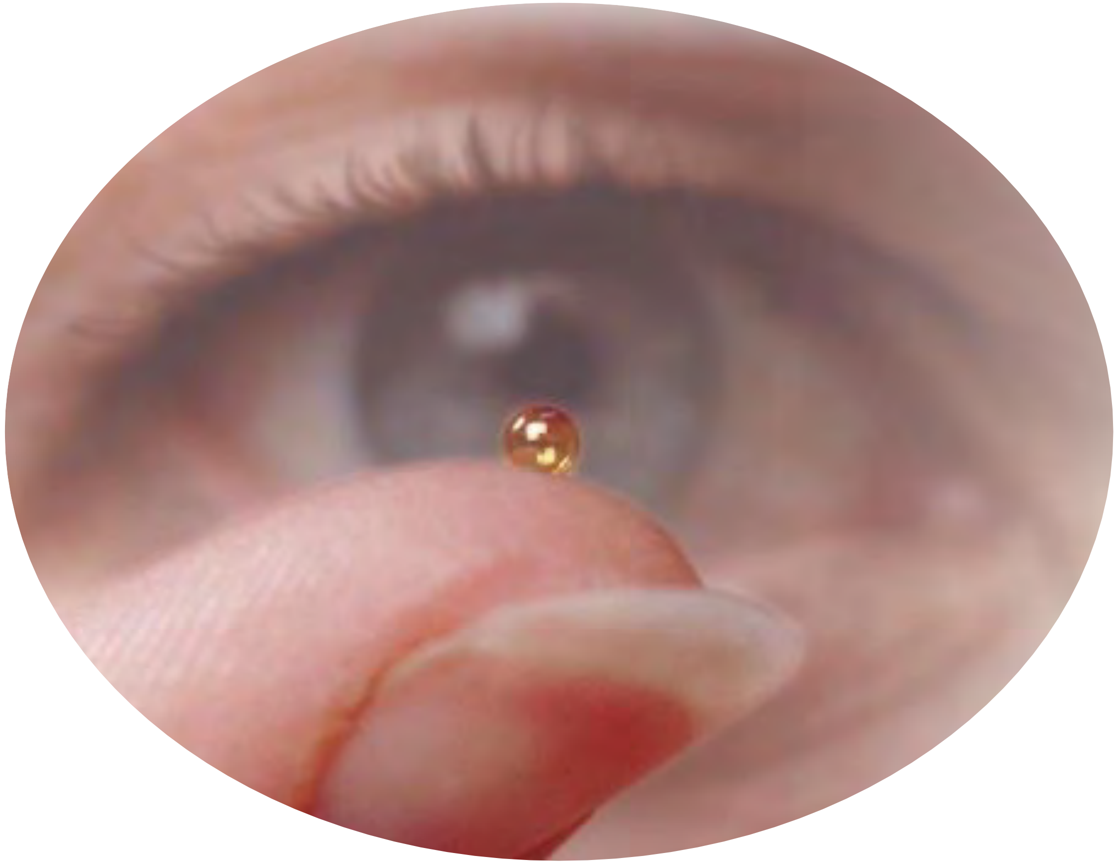
192 laser beams are concentrated into a mm^3 target

https://www.youtube.com/@LivermoreLab/playlists

At the NIF up to 2.05 MJ are delivered into a mm^3 target over ~20 nanoseconds (~500 TW peak power)



Donut energy equivalence: ignition

NIF laser used 2.05 MJ (489 kcal~2 donuts) over 20 ns to drive the ignition target

N221204 Ignition experiment produced 3.15 MJ (752 kcal~1 apple fritter and 1 donut) from fusion

The TNT equivalent of the laser energy of the NIF shot is about 1 pound,
so the December 2022 ignition shot was about 1.5 pounds of TNT equivalent.

Donut energy -> power equivalence: jogger, laser, ignition

Jogging 5 miles in one hour consuming energy at rate (power) of about **~600 Watts**.

NIF laser peak power around **500,000,000,000,000 Watts**.

The power produced by the ignition experiment is about **31,500,000,000,000,000 Watts. (3.15 MJ over ~100 picoseconds)**

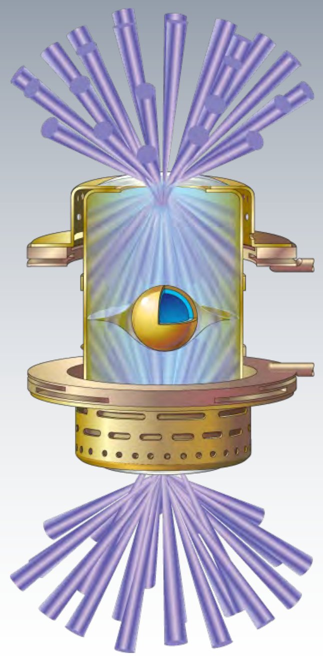
US Electrical grid >1,200,000,000,000 Watts peak capacity.

Both rate of production (power) and energy matter.

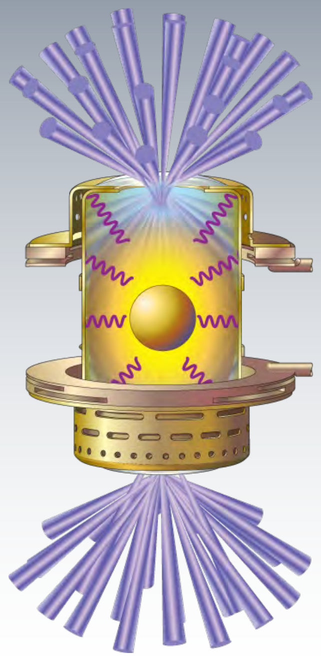
"High energy density" is achieved in the laboratory by putting energy into small amounts of material really quickly.

ICF experiments at NIF use a laser-driven hohlraum to compress a fuel pellet to achieve the conditions for ignition

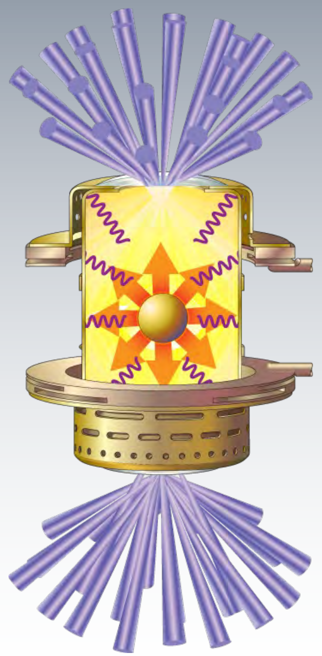
Each of the 192 laser beams are focused onto the inner wall of the hohlraum



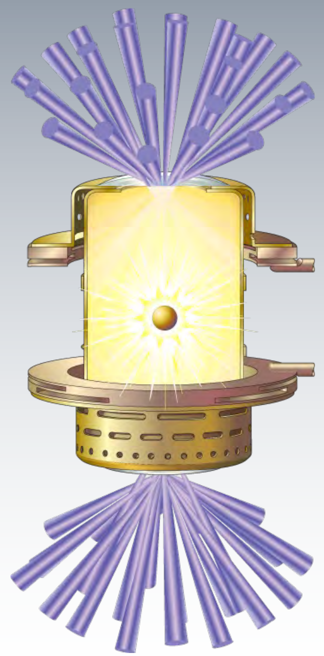
Laser beams rapidly heat the inside surface of the hohlraum creating x-rays



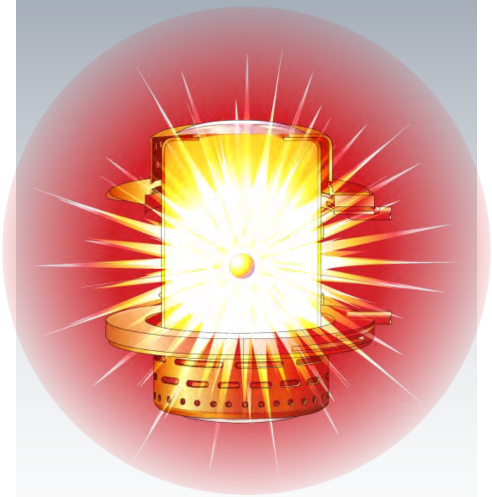
The x-rays blow off the fuel capsule wall, accelerating the fuel inward to 1 million MPH



The fuel core reaches 100 times the density of lead and ignites at 100,000,000°C

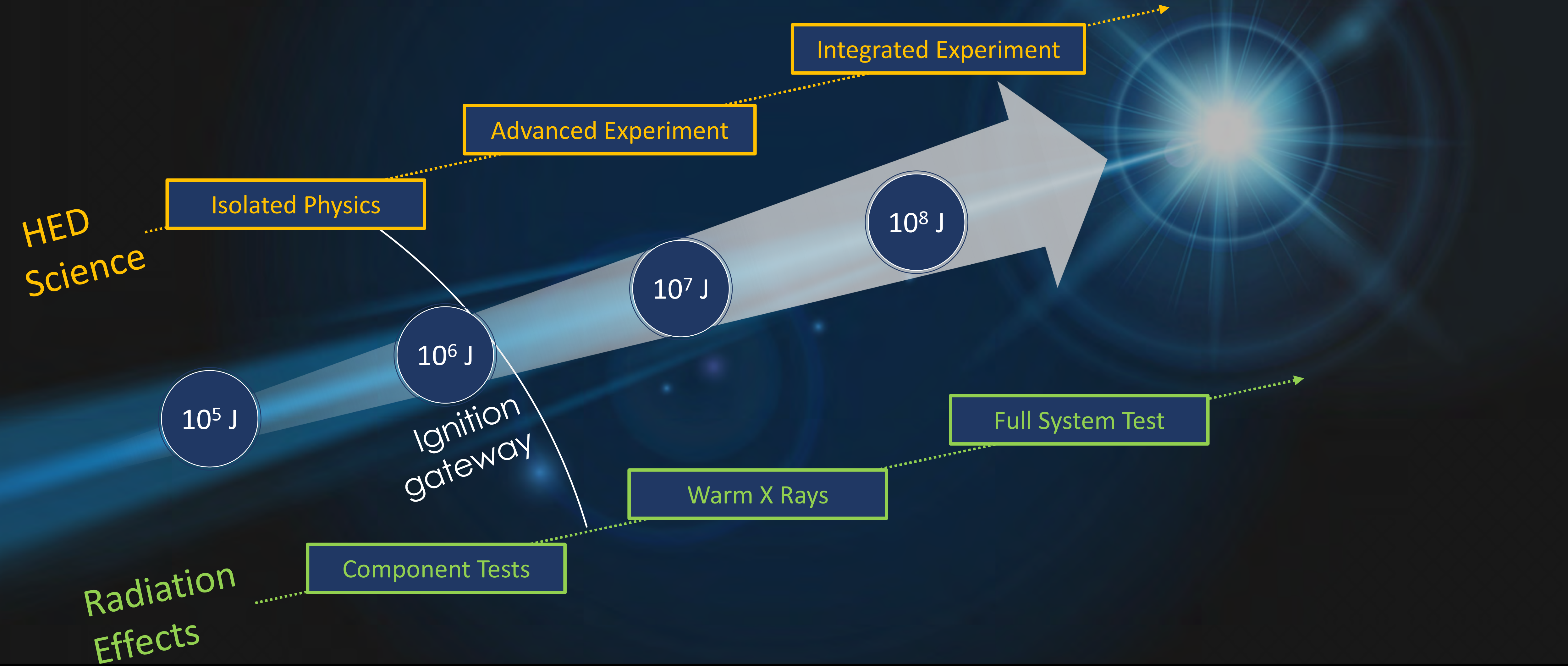


Fusion burn spreads rapidly through the compressed fuel, yielding many times the input energy



Achieving ignition in the laboratory is a Scientific Grand Challenge nearly 60 years in the making

The output of an igniting capsule is the most powerful and energetic source we can envision in the lab, opening up new capabilities for HED Science and stewardship



HED Science

Isolated Physics

Advanced Experiment

Integrated Experiment

10^5 J

10^6 J

10^7 J

10^8 J

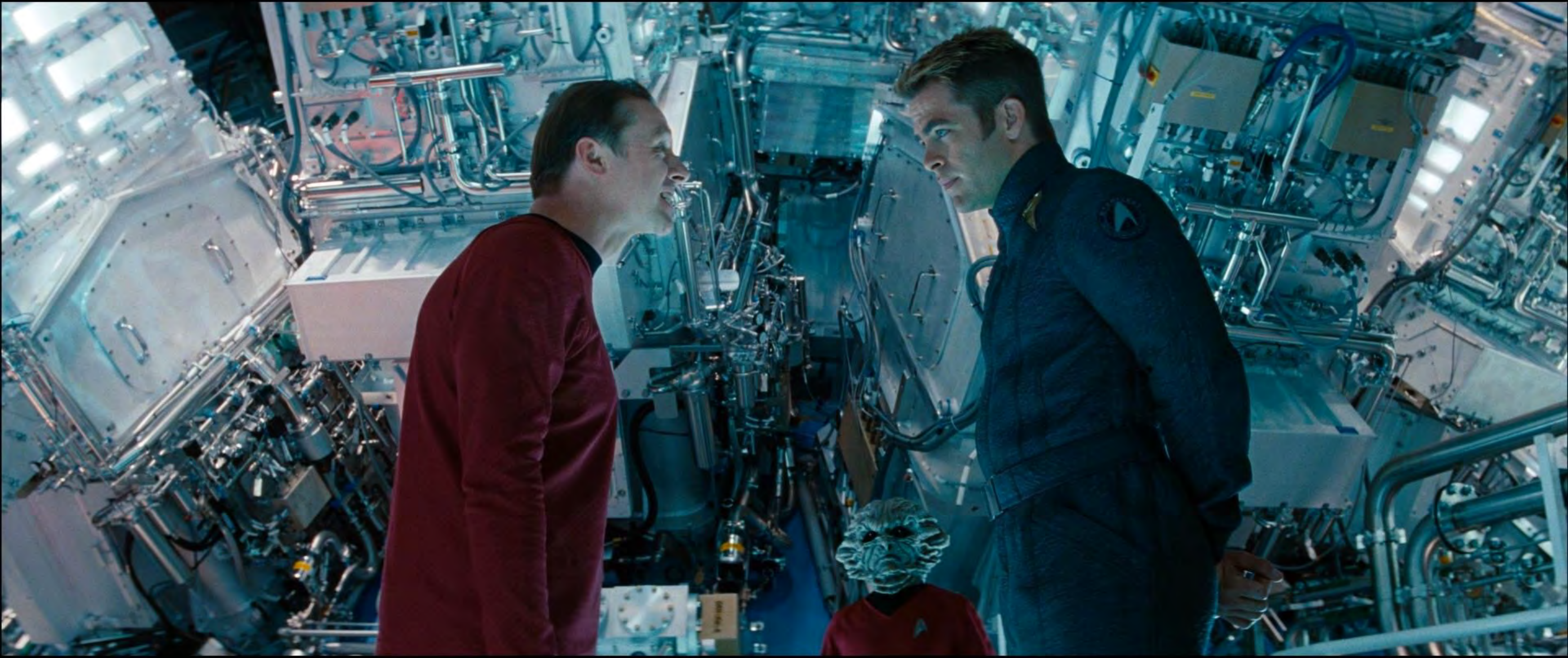
Ignition gateway

Radiation Effects

Component Tests

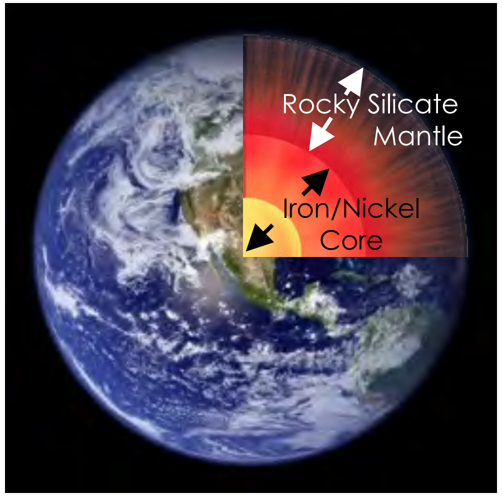
Warm X Rays

Full System Test

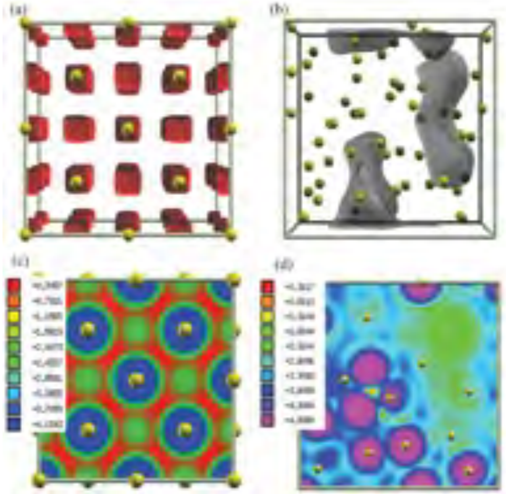


HED experiments are focused on fundamental understanding of materials, plasmas, hydrodynamics, and radiation transport at extreme conditions

Planetary Science



Dynamic Materials



A collaboration between NIF Discovery Science and the Materials IET measured the melting curve of iron to 1000 GPa

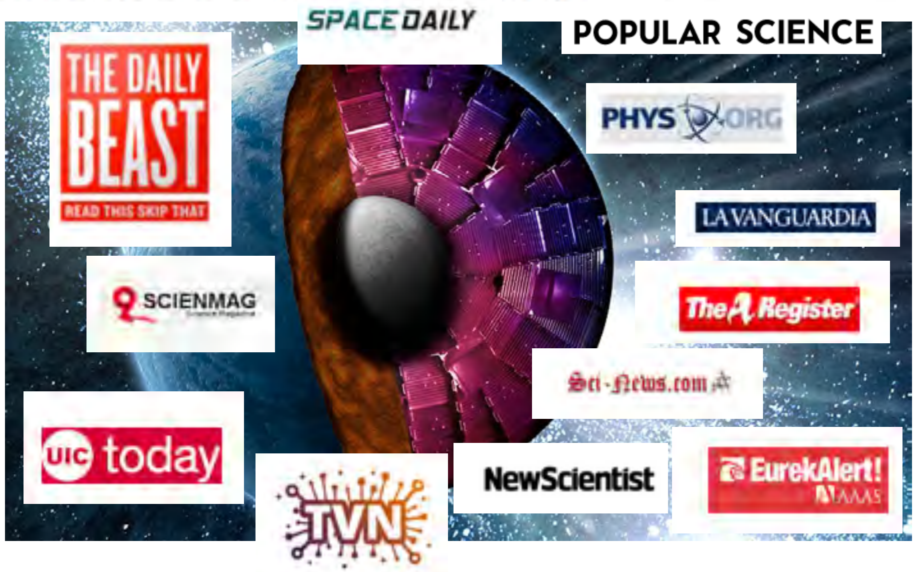
- A team of LLNL scientists developed an experimental platform at the NIF to shock iron to an initially molten state, then shocklessly compress it to pressures of 500 and 1000 GPa
- Melt is a sensitive experimental constraint on the equation of state at pressures nearly 4x greater than previous measurements.
- Experiments used x-ray diffraction to observe re-solidification on the nanosecond timescale into the hcp crystal structure, a key result for kinetics
- First data on the melting curve of iron at pressures of Earth's core and Super Earth cores, shows super Earths can have a longer lasting magnetosphere than Earth
- Platform will be applied to more programmatically relevant materials

Science

PLANETARY SCIENCE

Measuring the melting curve of iron at super-Earth core conditions

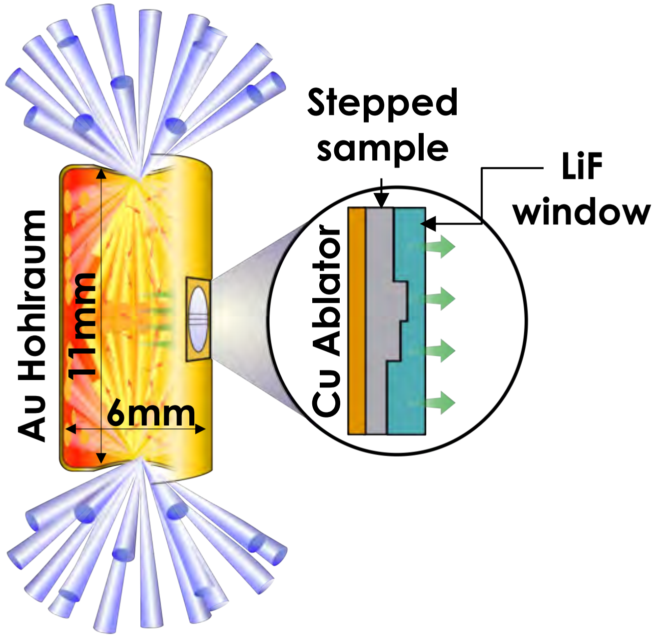
Richard G. Kraus[1]*, Russell J. Hemley[2], Suzanne J. Ali[1], Jonathan L. Belof[1], Lorin X. Benedict[1], Joel Bernier[1], Dave Braun[1], R. E. Cohen[3], Gilbert W. Collins[4], Federica Coppari[1], Michael P. Desjarlais[5], Dayne Fratanduono[1], Sebastien Hamel[1], Andy Krygier[1], Amy Lazicki[1], James Mcnaney[1], Marius Millot[1], Philip C. Myint[1], Matthew G. Newman[6]†, James R. Rygg[4], Dane M. Sterbentz[1], Sarah T. Stewart[7], Lars Stixrude[8], Damian C. Swift[1], Chris Wehrenberg[1], Jon H. Eggert[1]

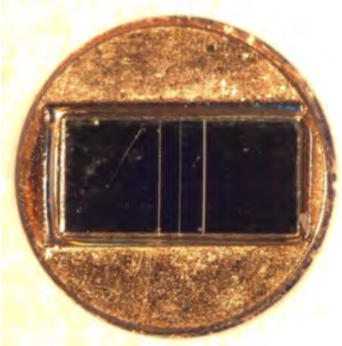


https://doi.org/10.1126/science.abm1472

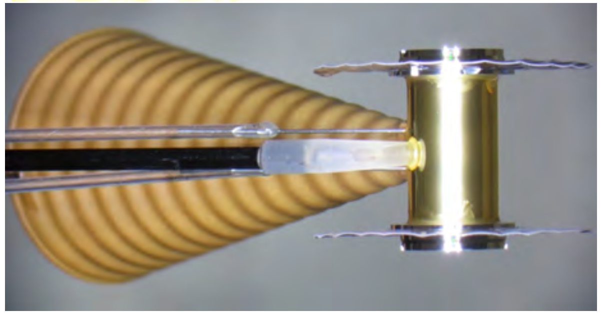
Ramp compression experiments at NIF are building new high-pressure standards for the science community

The experiments have returned “cold” compressibility data up to 20+ Mbar with 2% error on a host of materials: Copper, Gold, Platinum, Tantalum, etc.

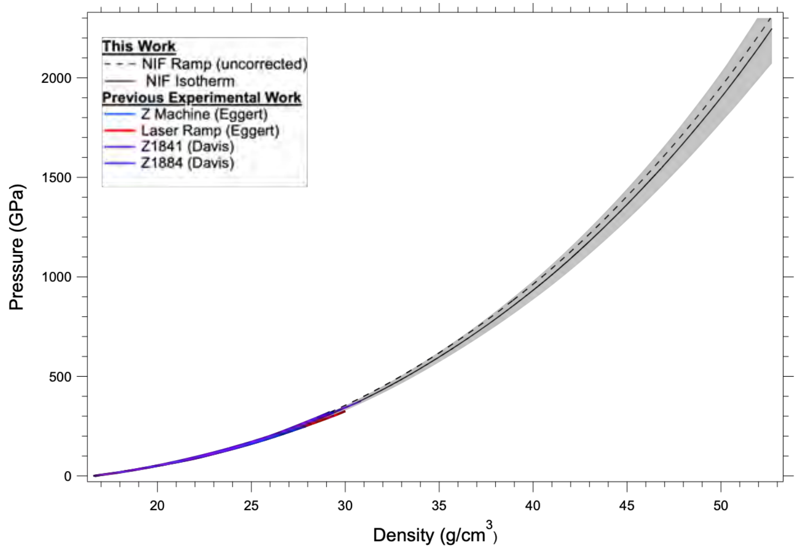




Physics package with stepped Pu sample



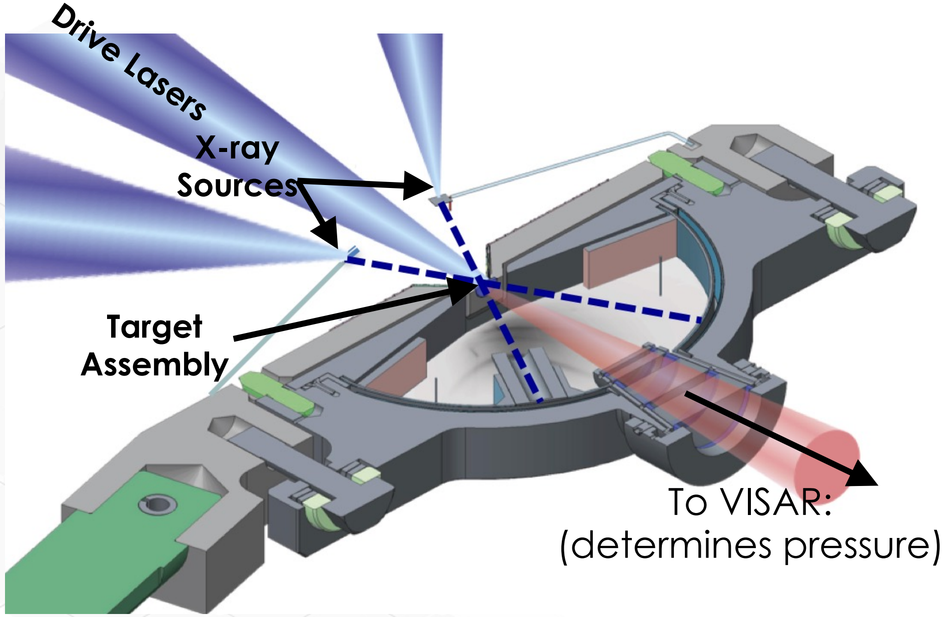
Representative tantalum result to 20+ Mbar



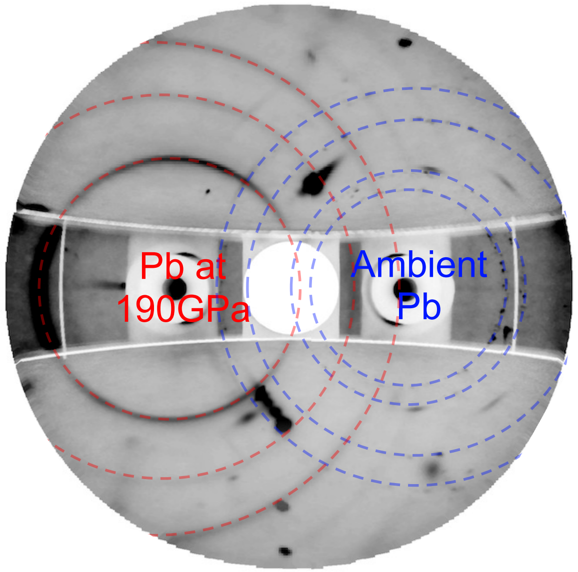
Experiments to obtain plutonium compressibility data are underway.

NIF has safely executed 18 plutonium diffraction experiments returning important scientific data on the behavior of Pu at pressure

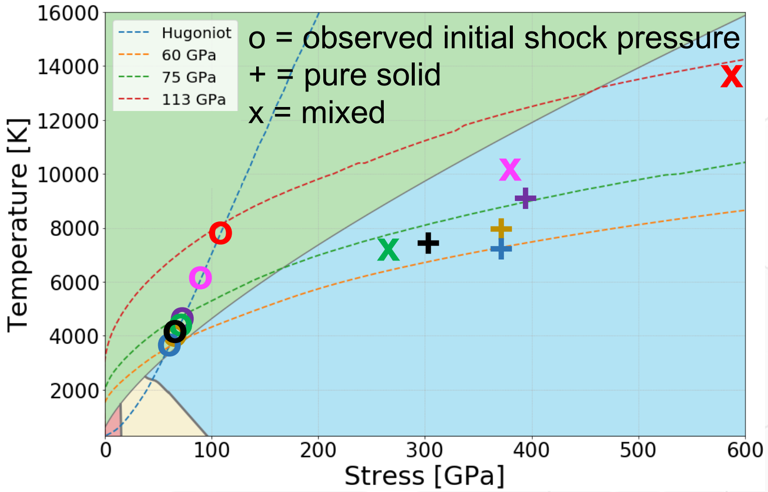
NIF X-ray Diffraction Platform



Dual exposure lead data



Shock-ramp campaign results

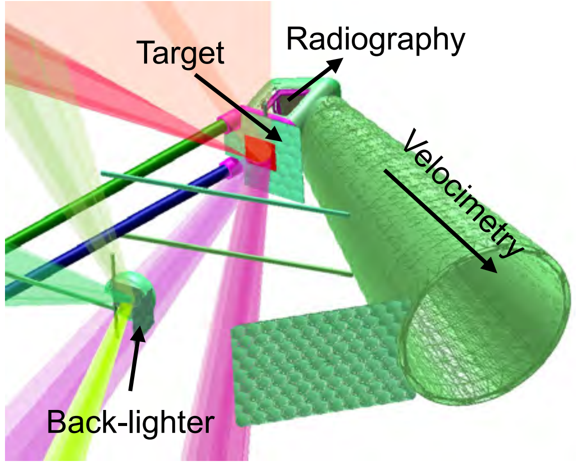


Results show re-solidification on nano-second timescales

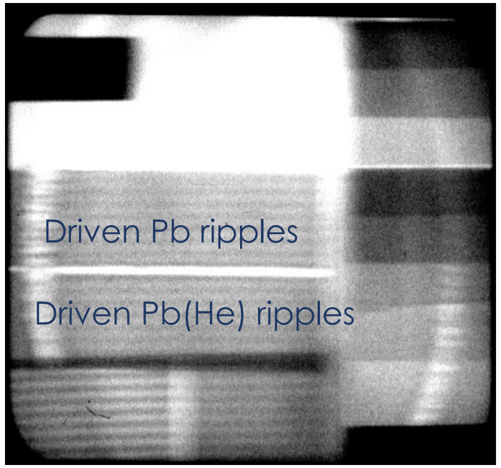
On-going plutonium experiments continue to produce data that both supports and challenges current theories used for Stockpile Stewardship. Eventual goal dynamic high-pressure data to study aged plutonium.

The effect of helium bubbles on high-pressure dynamic strength is being investigated on the Raleigh-Taylor strength platform

NIF direct-drive configuration

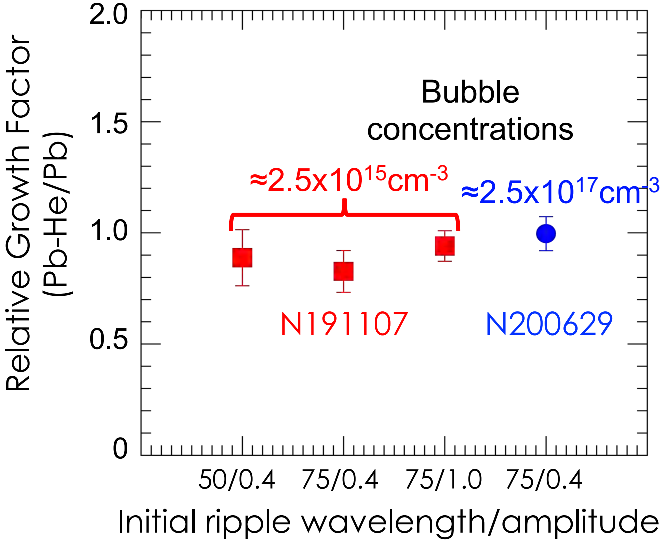


Radiography of shot N200629



TEM image of He implanted sample

Relative growth factor between two samples

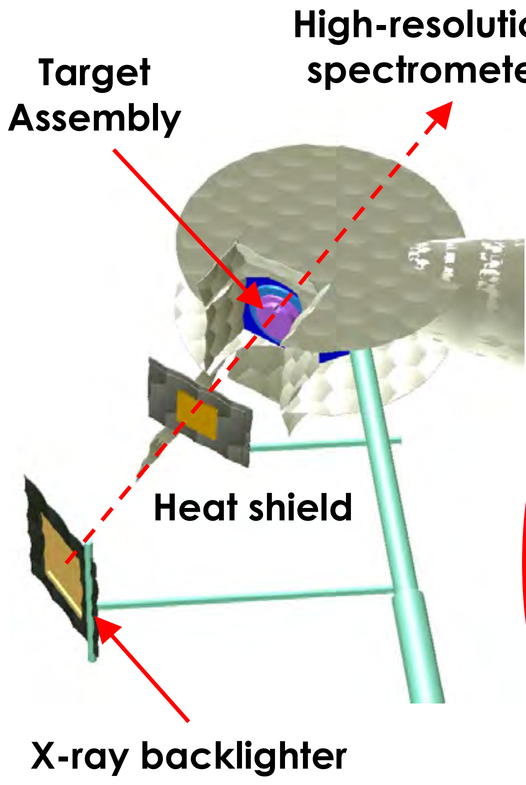


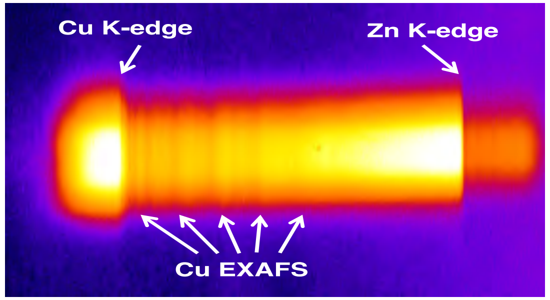
- Use of side-by-side (implanted/un-implanted) geometry increases data return rate
- To date, consistent with model predictions, no strength difference between Pb and Pb(He) samples has been seen
- Highest concentration tested had a bubble density about the same as 60 year old Pu material but with large bubble diameter

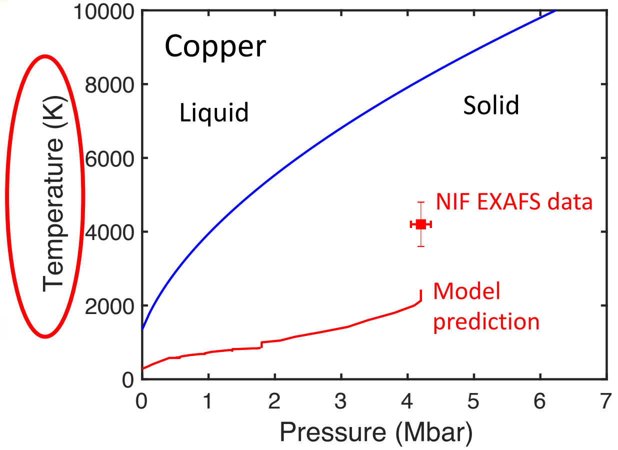
Controlled studies of strength effect on different bubble densities and bubble diameter are possible

We are developing new capabilities on NIF for measuring material properties under extreme pressures

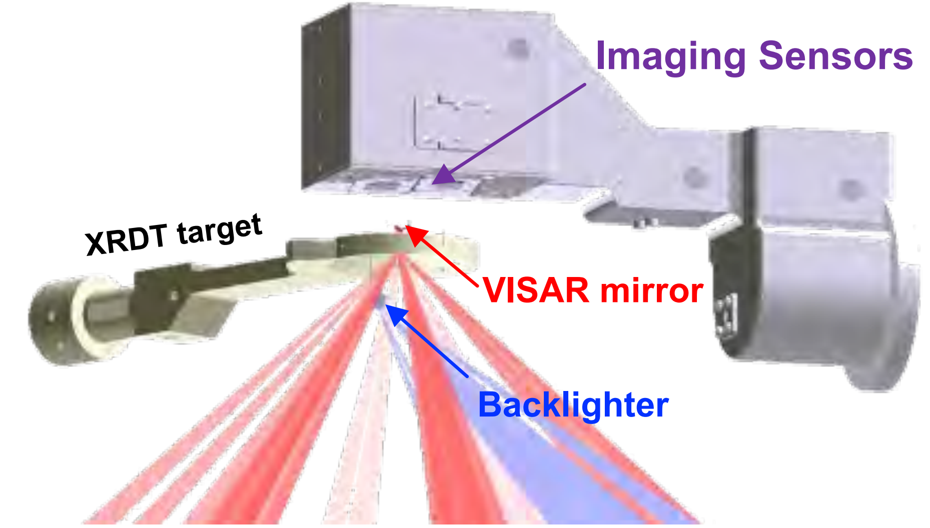
NIF EXAFS Platform

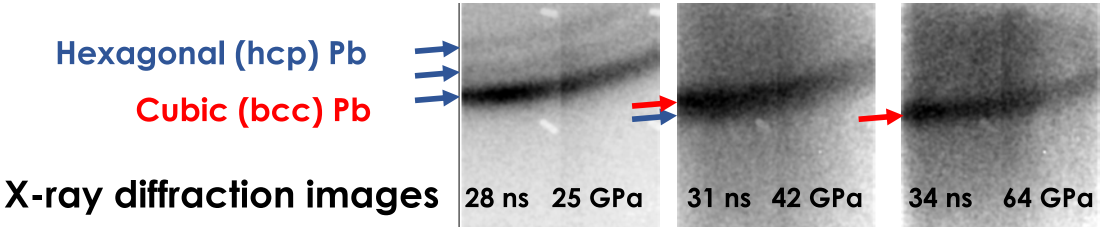






NIF time-resolved diffraction Platform

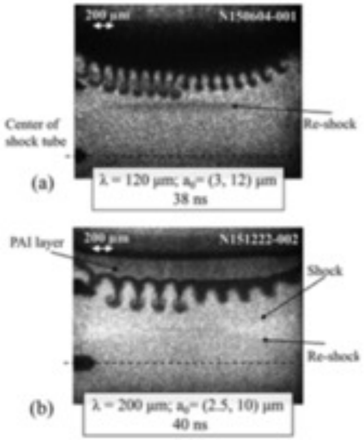




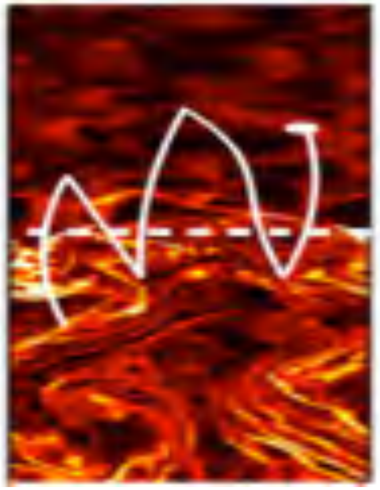
These new platforms will be applied for studying thermal states and phase transition kinetics of plutonium.

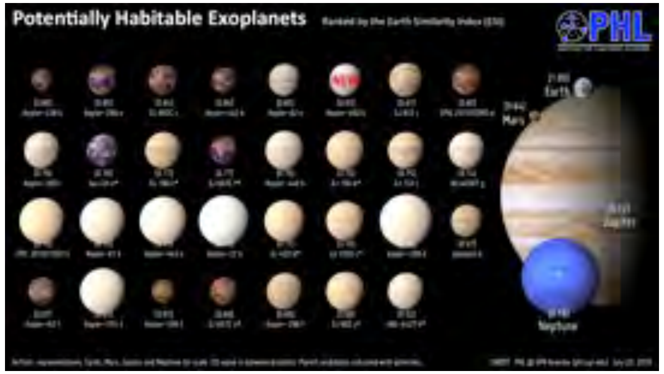
HED experiments are focused on fundamental understanding of materials, plasmas, hydrodynamics, and radiation transport at extreme conditions

Radiation Hydrodynamics



Plasma Astrophysics



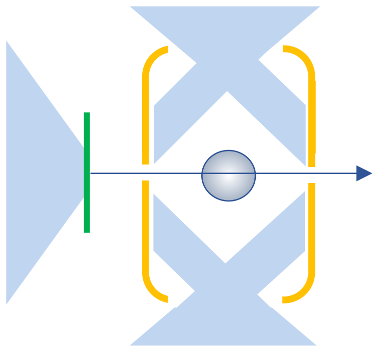


Exoplanets, cold and warm dense matter

NIF provides plasma equation of state (EOS) data in previously inaccessible pressure-temperature regimes

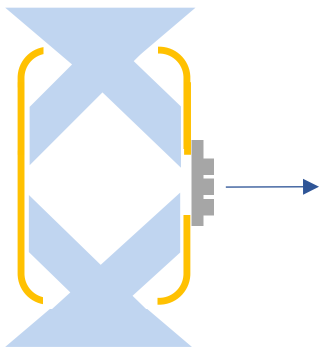
- We use the high NIF laser powers and convergent drive geometries to achieve unprecedented pressures along the Hugoniot
- Radiography of imploding shocks yields absolute EOS for low-Z materials, and shock transit time through stepped targets yields relative EOS for high-Z materials
- The next phase in plasma EOS measurements will be to access hot, off-Hugoniot states by preheating using protons and neutrons, and by shocking porous samples

low-Z, absolute



x-ray streak camera

high-Z, relative



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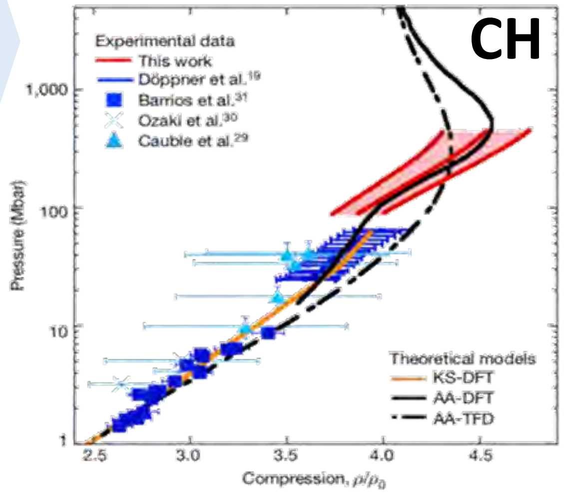
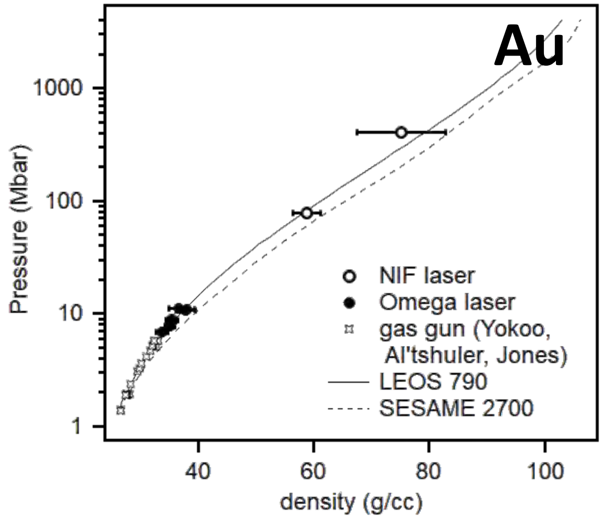


Kritcher, Nature 2020

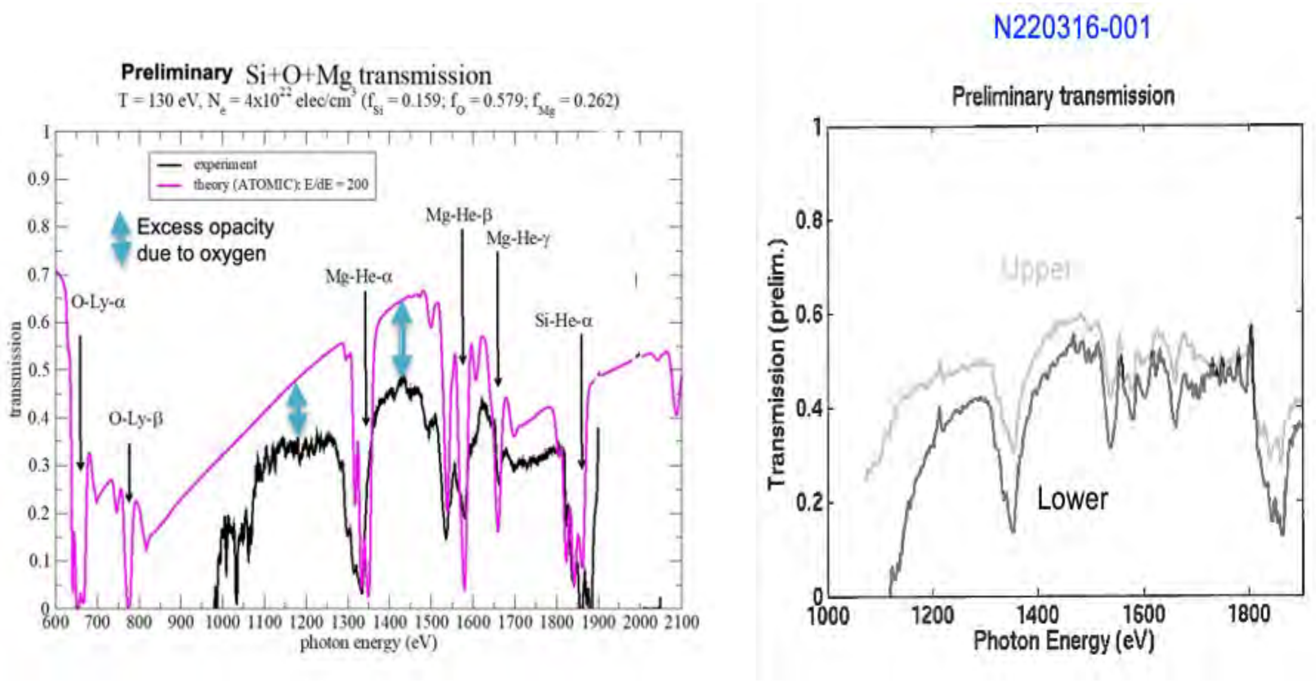


Kim, Jenei

Understanding high pressure EOS and ionization is important to ignition science and predictive capability.

NIF Opacity data for Fe:Mg & MgO:SiO_2 samples at higher plasma density ($n_e > 2x10^{22}/cm^3$) continue to show lower-than-expected transmission

- NIF Opacity campaign is beginning to repeat controversial opacity measurements previously obtained on Z, at temperatures 140-180 eV and electron densities > $2x10^{22}$ / cm^3.
- NIF data for both Fe:Mg and MgO:SiO2 samples shows unexpectedly low transmission compared with theory at the measured plasma conditions.
- Further analysis is required to correct for known systematic errors, but this is not expected to bring the observed X-ray transmission into agreement with theory.

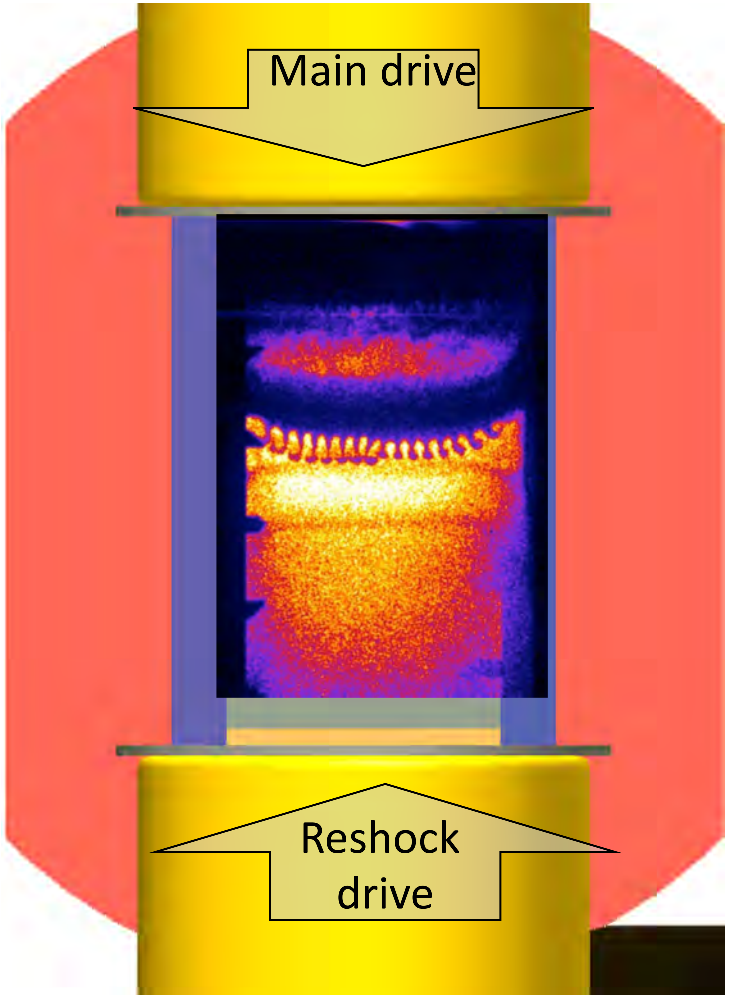


NIF X-ray transmission data from MgO:SiO2 samples taken in 2021 (left) and repeated in 2022 (right), together with theoretical expectation (left)

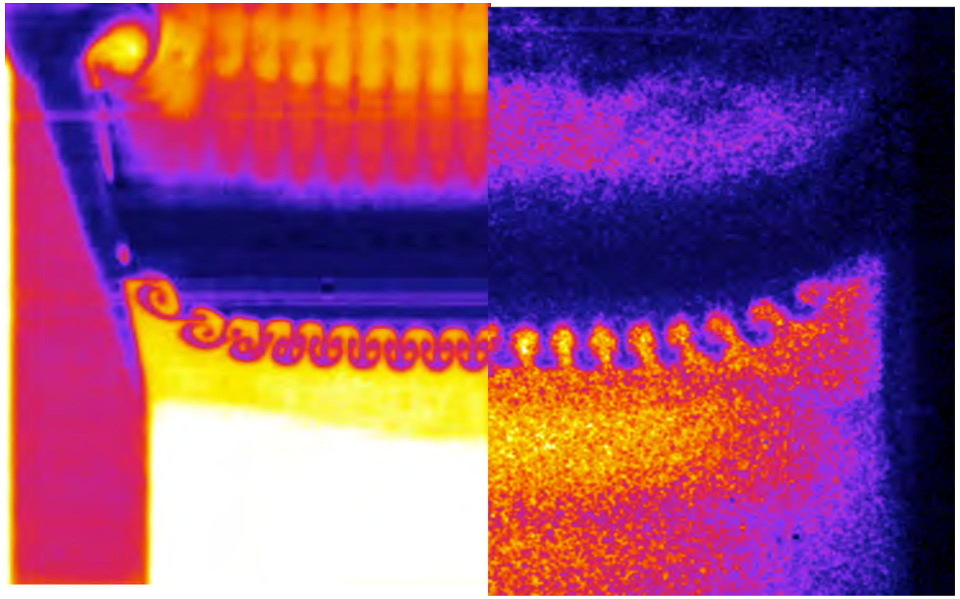
Collaboration with UT Austin, Sandia, and Los Alamos National Laboratory

We are studying the spectroscopy of astrophysically relevant plasmas in the laboratory.

The re-shock campaign gave us a controlled platform to obtain quantitative data for comparison with models and simulations



NIF's large energy enables large features to be driven and radiographed enabling detailed comparisons with simulation



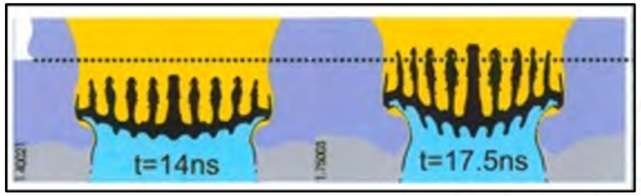
Simulation Experiment

The High Resolution Turbulence campaign is focused on improving spatial resolution of these experiments.

Simultaneous radiography and burn-through measurements at the NIF provide data to understand radiation transport at mixing interfaces

- Bound the deviation of radiation transport across plausible mixing interfaces and quantify the impact of radiation on mixing layer evolution.
- Provides data to inform uncertainty bounds for sub-zonal radiation transport in rad-hydro codes and assess the treatment of mix models in the presence of radiation.

2D simulations

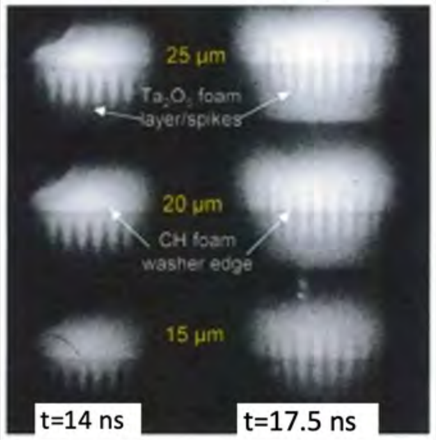


3D simulations


3D mix image


Simulated radiograph (14 ns)

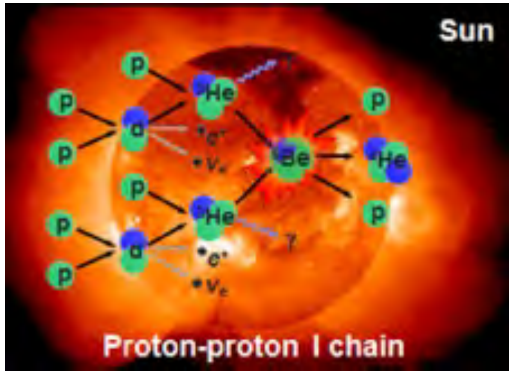
Expt. Radiographs



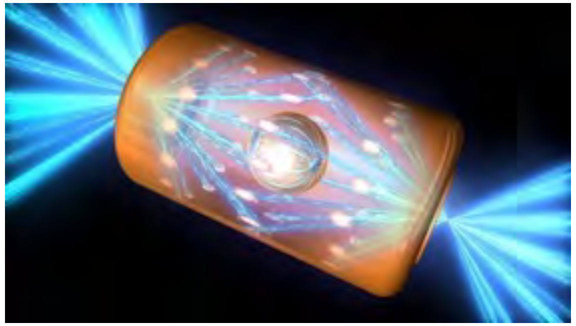
Spike lengths from simulations (left) are in good agreement with measured radiographs for platform qualification shots (right).

Future shots will provide data to validate predictive modeling capabilities for mix in the presence of radiation.

HED experiments are focused on fundamental understanding of materials, plasmas, hydrodynamics, and radiation transport at extreme conditions

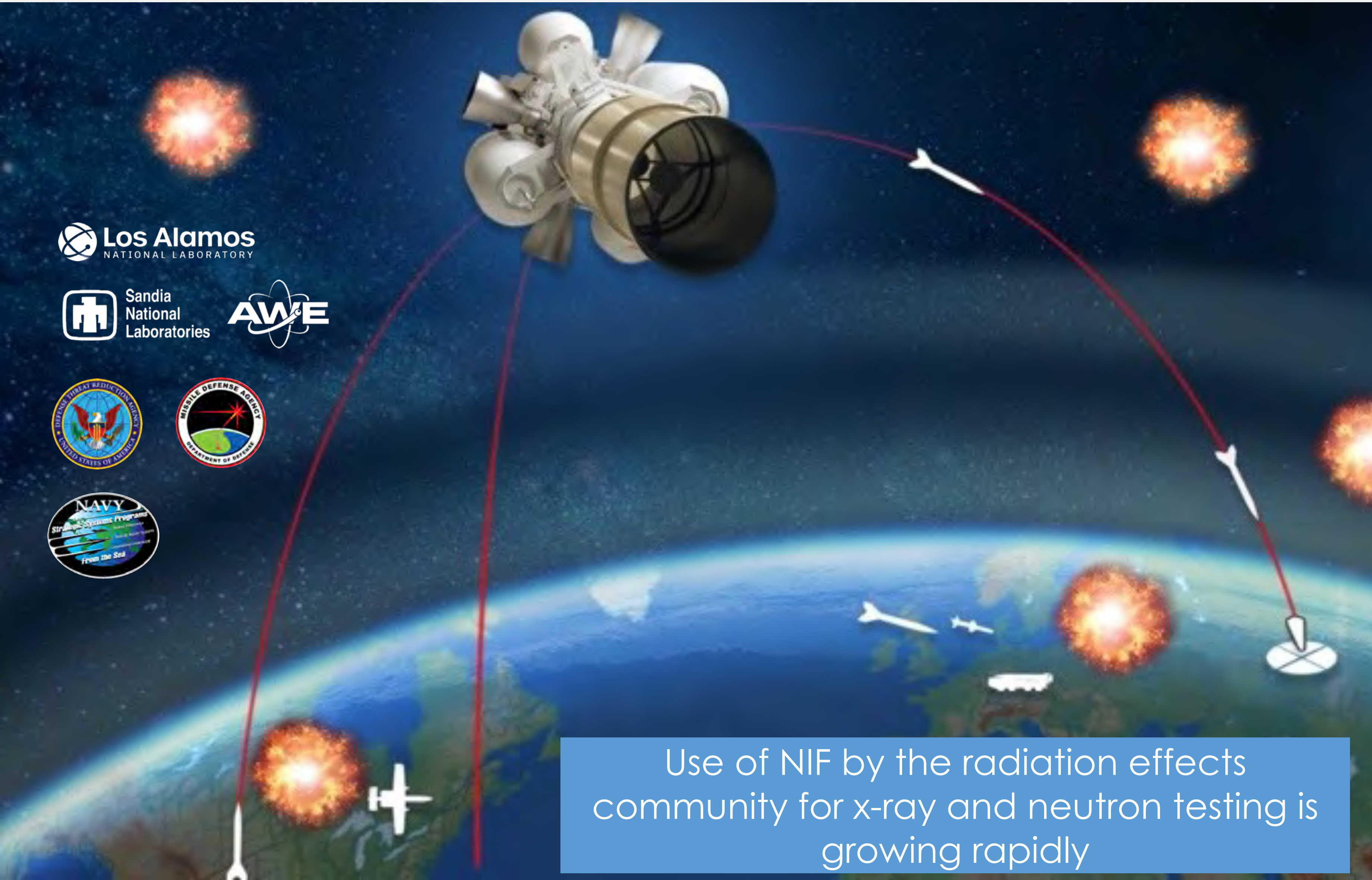


Nuclear Physics



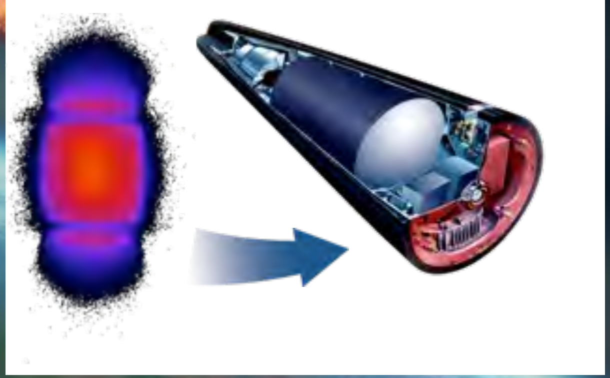
Material Radiation Effects (neutron, xray, gamma)

To maintain a credible deterrent, we must ensure our strategic systems can survive hostile encounters



NIF radiation source

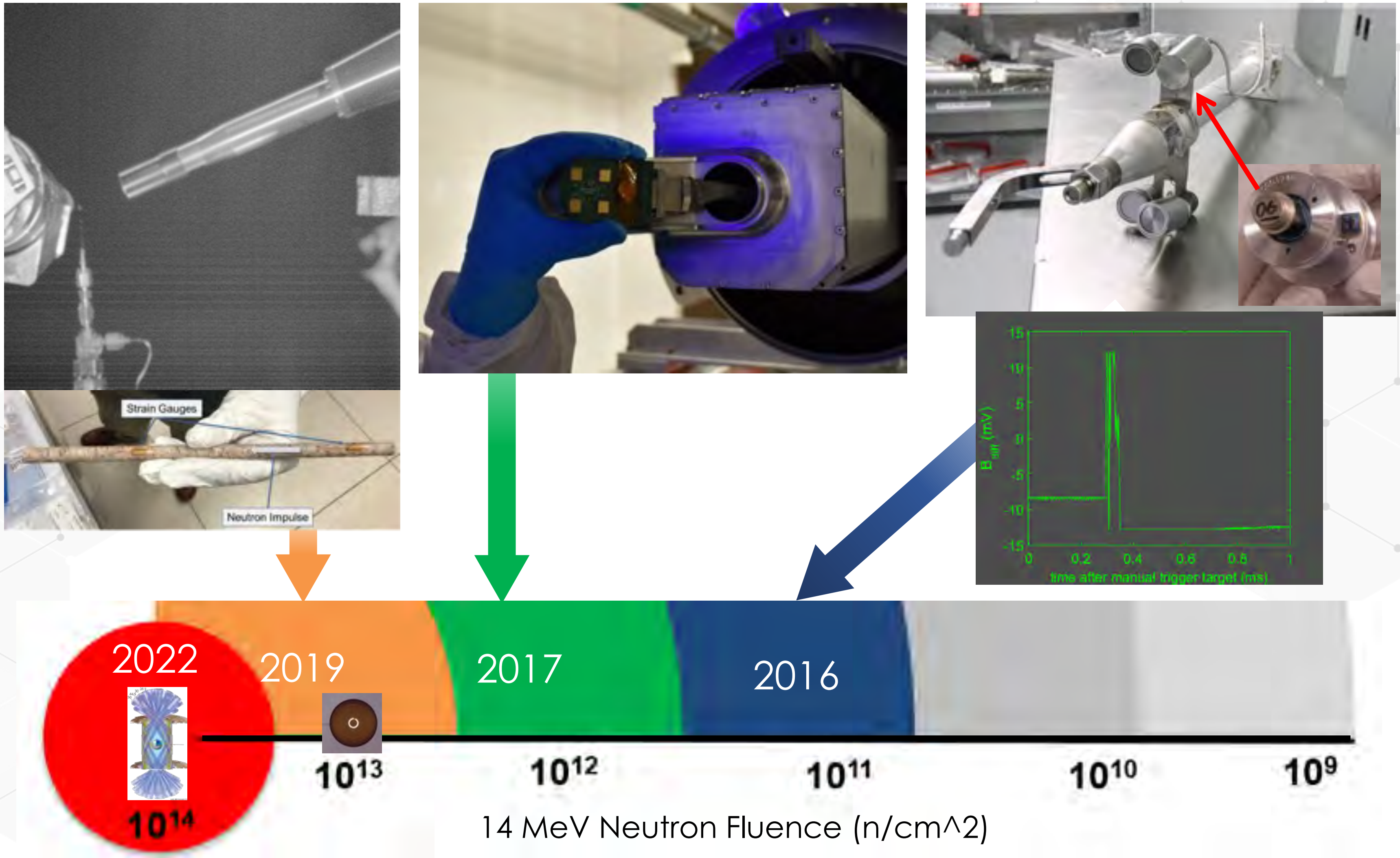
Radiation effects on materials and electronics



Use of NIF by the radiation effects community for x-ray and neutron testing is growing rapidly

Survivability

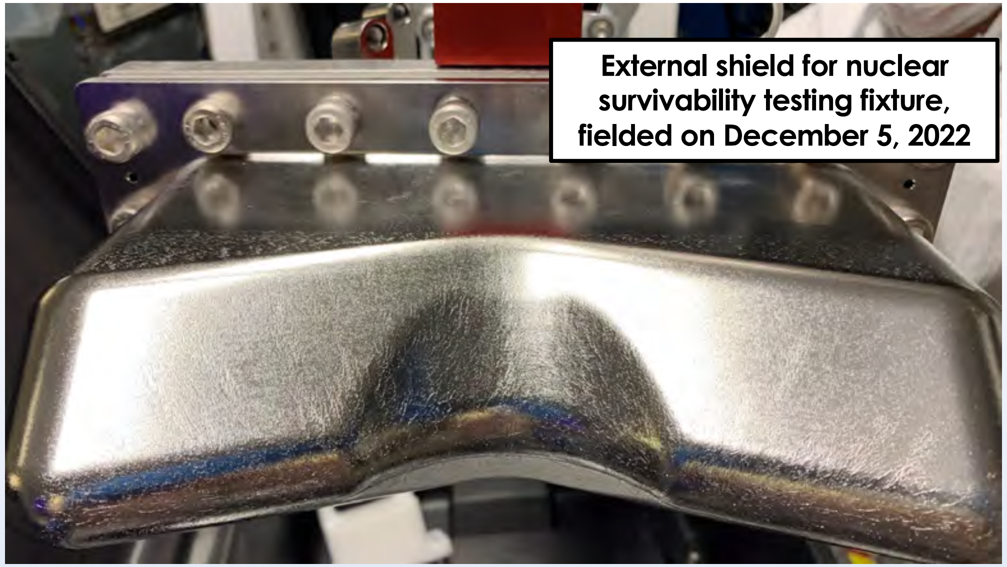
We use NIF to study how electronics and materials behave when they are exposed to extreme neutron pulses



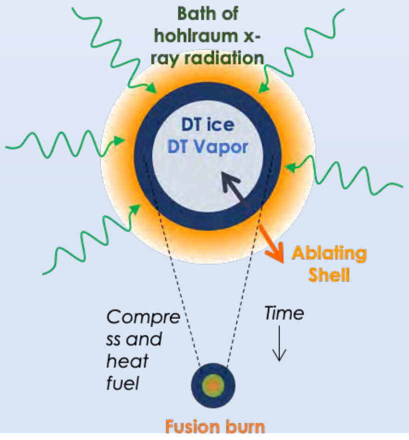
We are using ignition for survivability and material radiation effects experiments

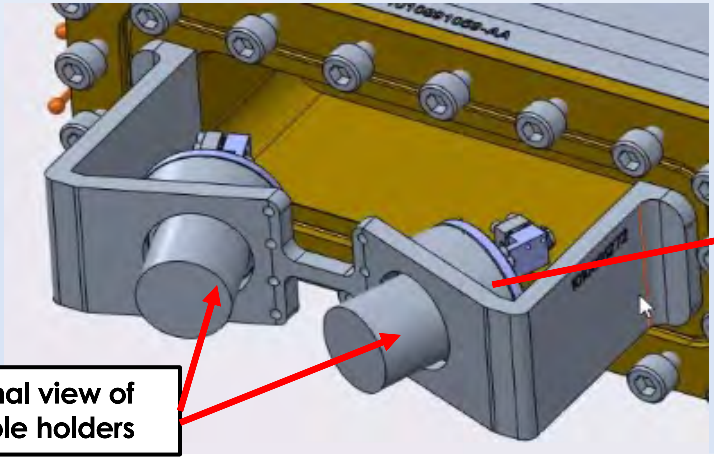
- On December 5, 2022, we fielded hardware (a "snout") that is designed to hold samples for radiation effects experiments.
- We place materials inside of this hardware to expose them to radiation, and perform both in situ and ex situ measurements of how the materials respond to neutron irradiation.

https://lasers.llnl.gov/news/ignition-experiment-advances-stockpile-stewardship-mission



External shield for nuclear survivability testing fixture, fielded on December 5, 2022





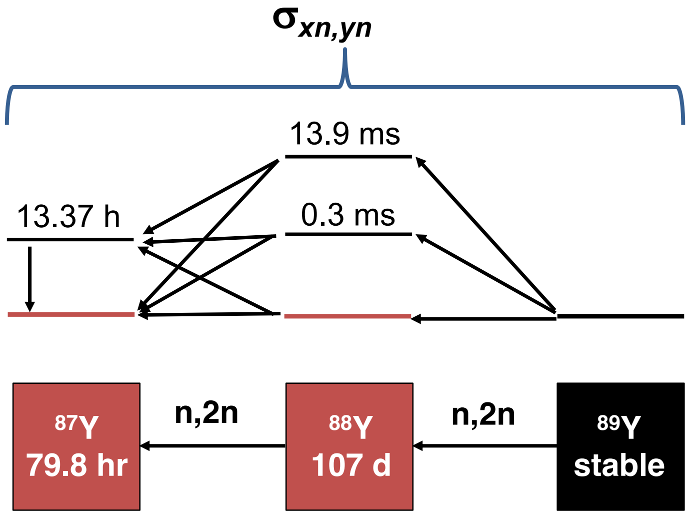
Internal view of sample holders

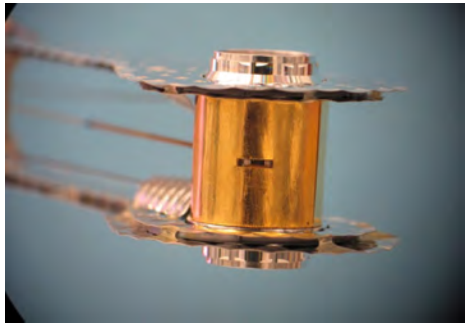
Gold-coated depleted uranium sample before (left) and after (right) ignition experiment.

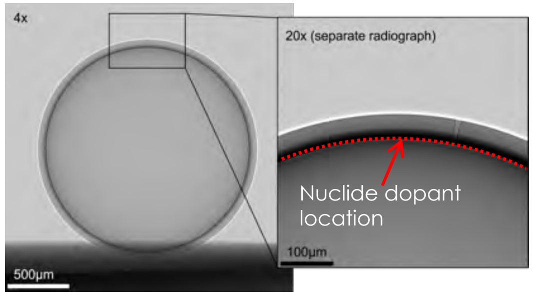
Nuclear Physics

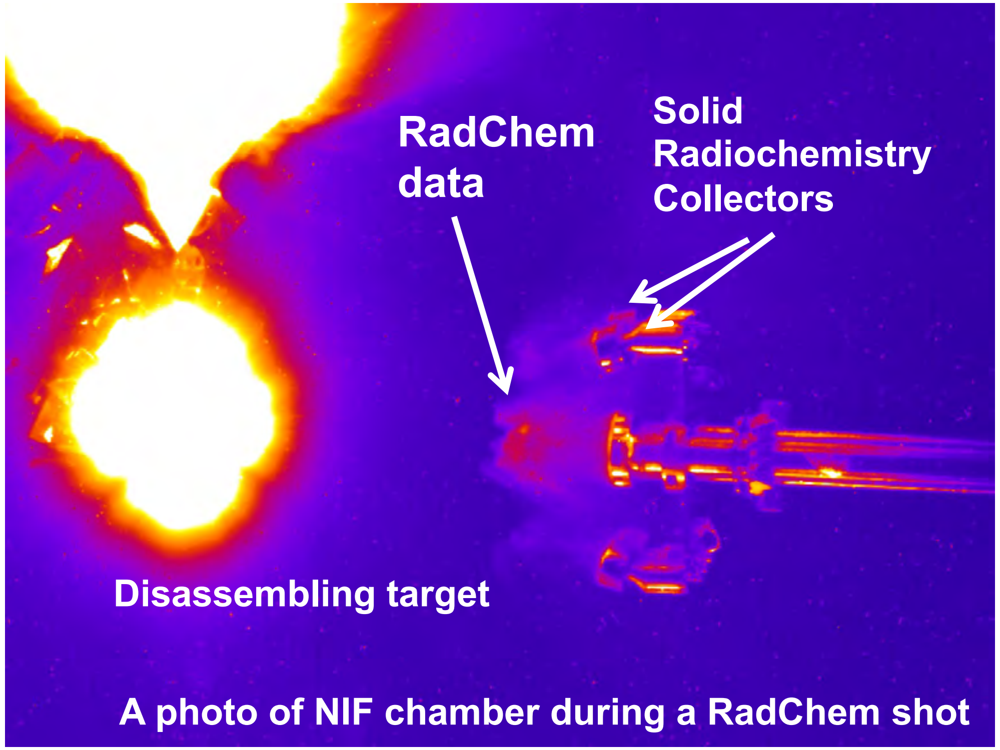
High yield at NIF enables multi-order cross section measurements for nuclear science

multiple-order n,2n reactions







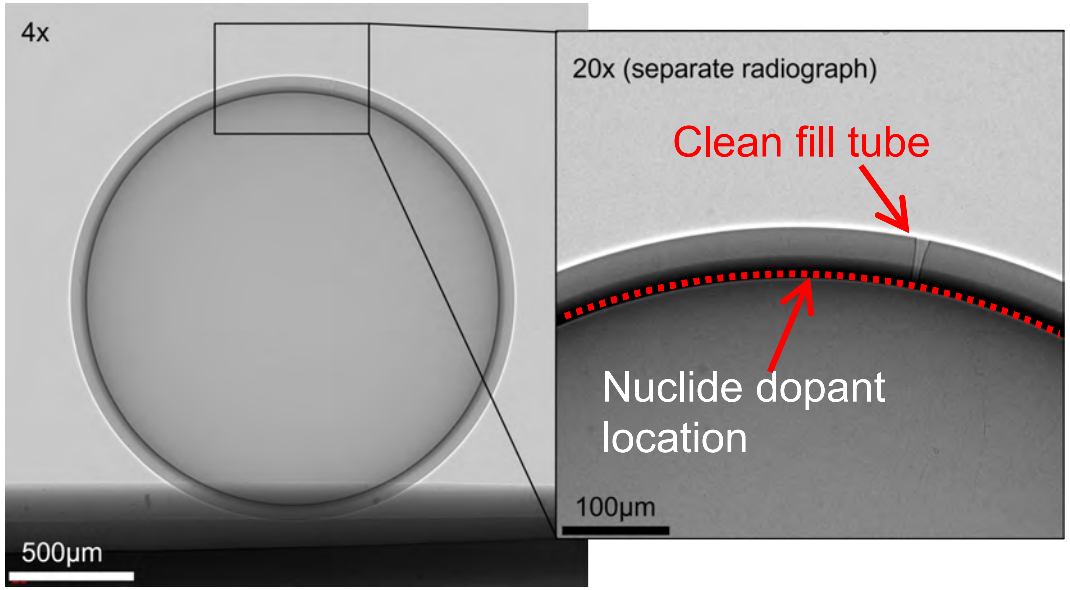


A photo of NIF chamber during a RadChem shot

Reactions on short-lived, excited states must be included in simulations of radiochemistry from underground tests.
The higher yields at NIF makes it possible to measure them in the laboratory.

RadChem shots with a radiochemical-doped HDC capsule at NIF opens possibilities for HED nuclear science

- Novel chemical methodologies and a Quality Control procedure were developed for ensuring HDC capsule fill-tube holes are not plugged with salt which caused failures in previous capsules
- Seven HDC capsules were successfully doped for fractionation shots at NIF in March, 2023
- Three NIF shots have successfully been completed to provide scientifically valuable data

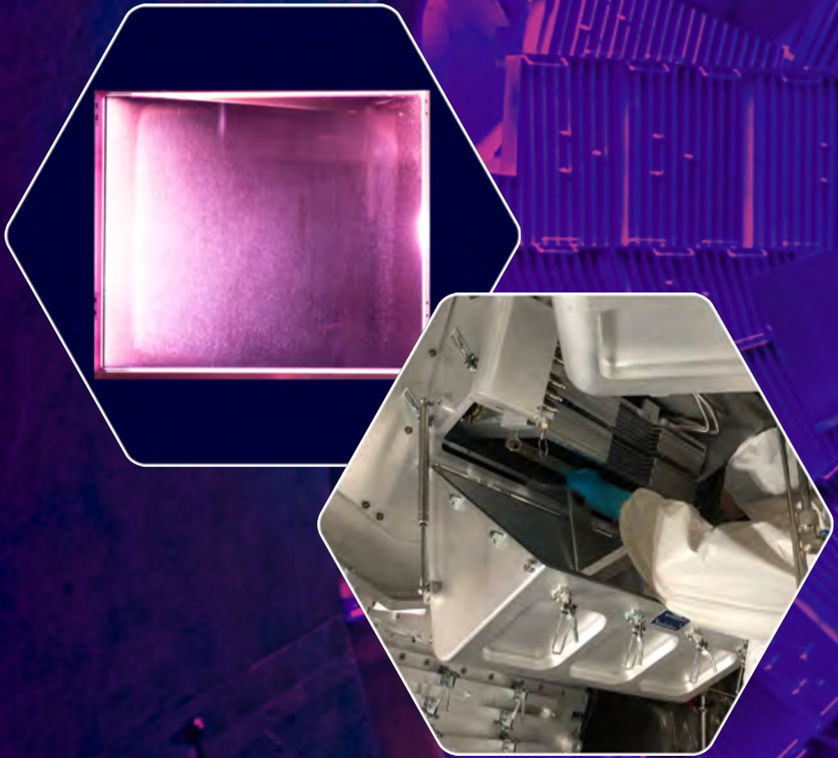


(Left) X-ray image of doped HDC capsule, showing clean fill hole (Right)

This critical capability will enable measurements of nuclear cross sections

We are undergoing activities to sustain and modernize the NIF

Laser Aging



Obsolescence

Deferred Maintenance

Higher laser energies and experiment yields are increasing the rate of degradation in some systems

Conclusions: Fusion ignition in the laboratory is a breakthrough achievement that strengthens core ST&E

- Fusion ignition in the laboratory is a grand challenge that we've been pursuing for 60 years
- Fusion occurs when two light atoms fuse together to form a larger atom and release energy in the form of neutrons, x-rays
- On December 5, 2022, we achieved fusion ignition by creating 3.1MJ of fusion energy with an input laser energy of 2.05 MJ
- Non-ignition HED experiments also continue to provide fundamental and integrated data that broaden our understanding of materials, plasmas, radiation transport, hydrodynamics, and materials radiation effects across a broad range of conditions.

The successes of HED and ICF contribute to core ST&E and provide valuable external engagement for NNSA, supporting recruitment and collaboration.

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