MATLAB for Control of Cryogenic DT Fuel for Nuclear Fusion Ignition Experiments

MATLAB EXPO

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Suhas Bhandarkar

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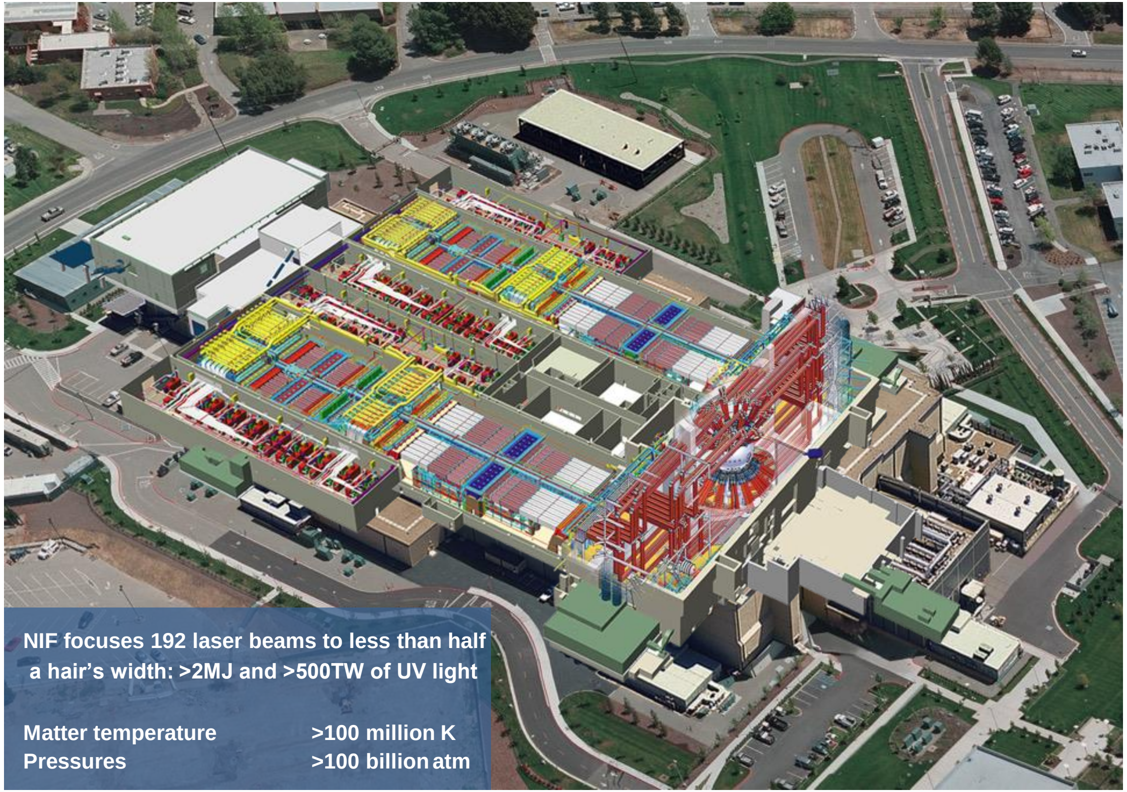
On Dec. 5, 2022, we demonstrated an igniting fusion reaction, where nuclear energy out > optical energy in: a breakthrough achievement

Achieving ignition in the laboratory is a Scientific Grand Challenge over 50 years in the making

The National Ignition Facility (NIF) is a flagship facility at Lawrence Livermore National Lab (LLNL) to study high energy density science

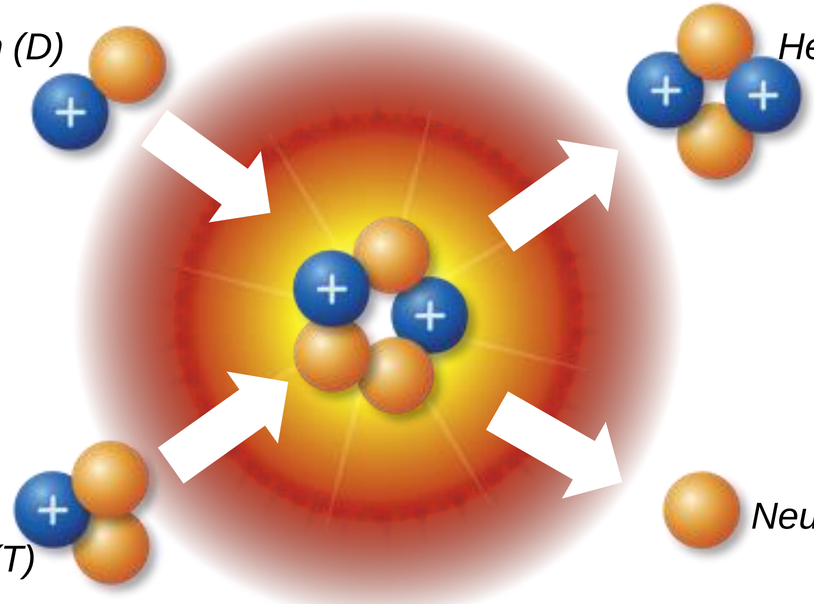
The NIF is the world's most powerful laser that delivers over 2MJ of 351nm UV light with very high precision of pointing



NIF focuses 192 laser beams to less than half a hair's width: >2MJ and >500TW of UV light

Matter temperature	>100 million K
Pressures	>100 billion atm

It can be used to investigate nuclear fusion, the reaction that powers the sun and the stars

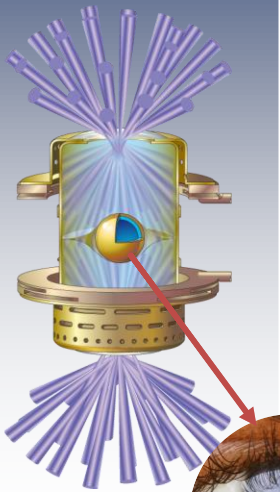


$$Q_{fusion} = 3.3 \times 10^{11}\ \mathrm{J/g}$$

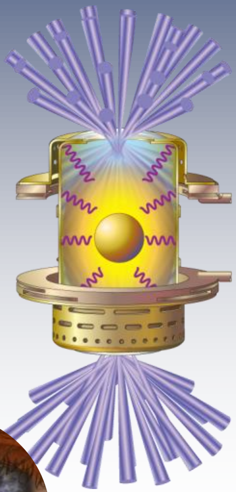
For comparison: Combustion of gasoline: 4.6x10^{3}J/g

NIF’s laser energy is used to compress a spherical fuel-filled capsule to investigate conditions for controlled and sustained nuclear fusion

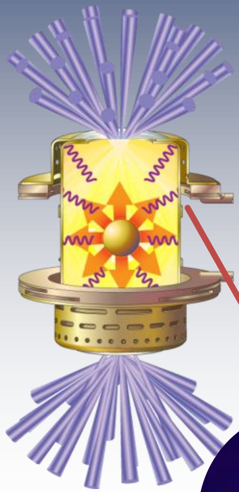
Each of the 192 laser beams is focused onto the inner wall of the hohlraum

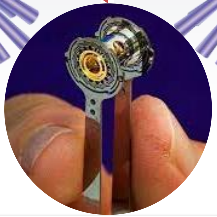


Laser beams rapidly heat the inside surface of the hohlraum creating X-rays

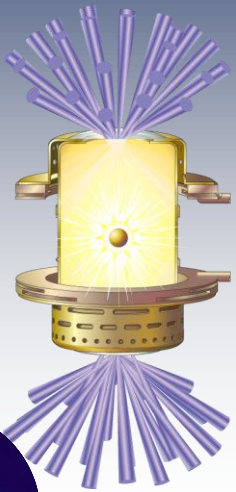


X-rays blow off (ablate) the fuel capsule wall, compressing the fuel at ~500 km/s

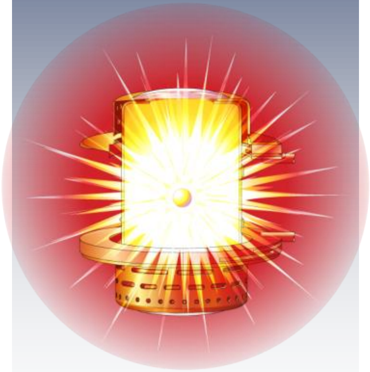




Fuel core reaches 100 times the density of lead and temperature of 100M°C

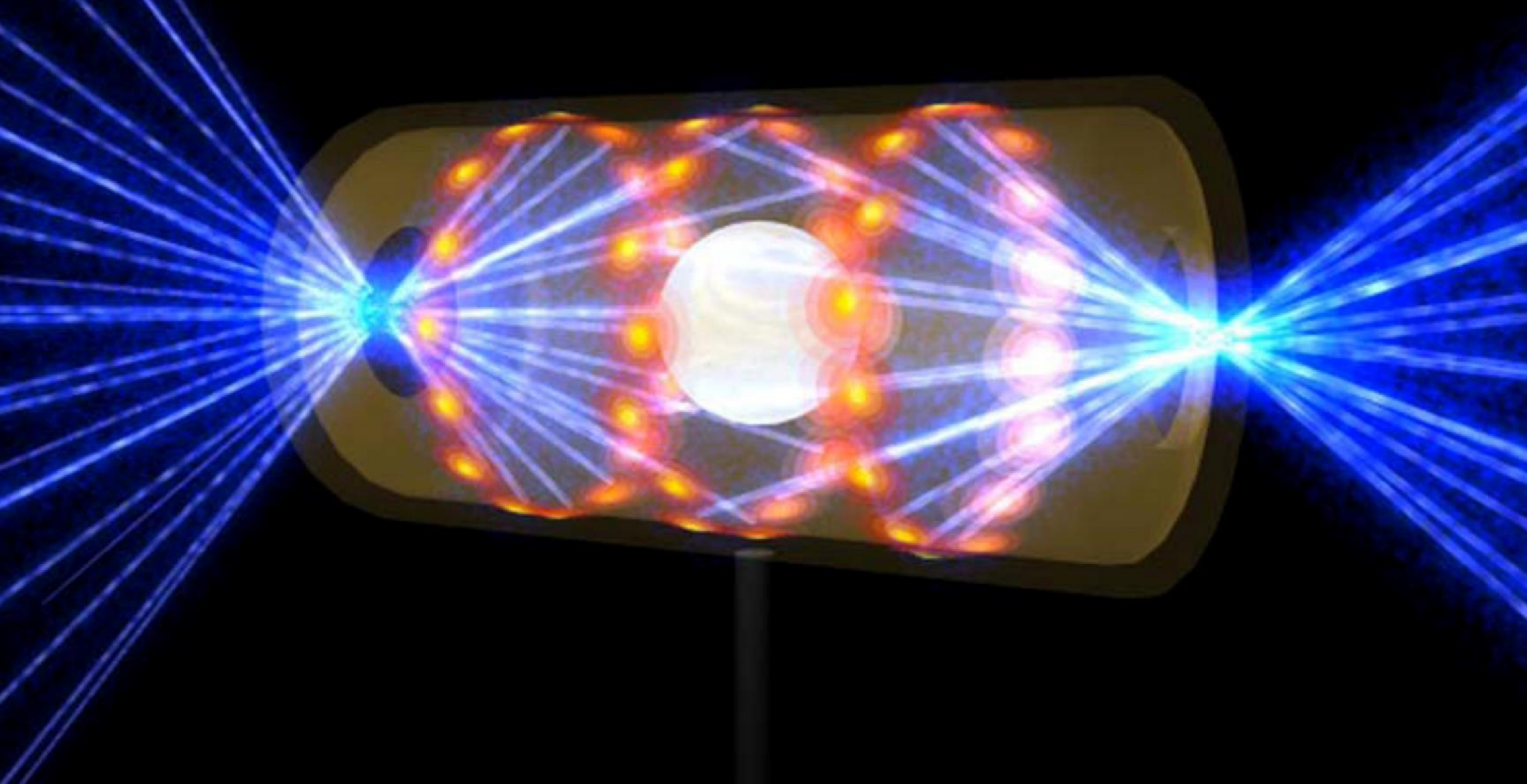


Fusion burn spreads rapidly through the compressed fuel which can yield many times the input energy



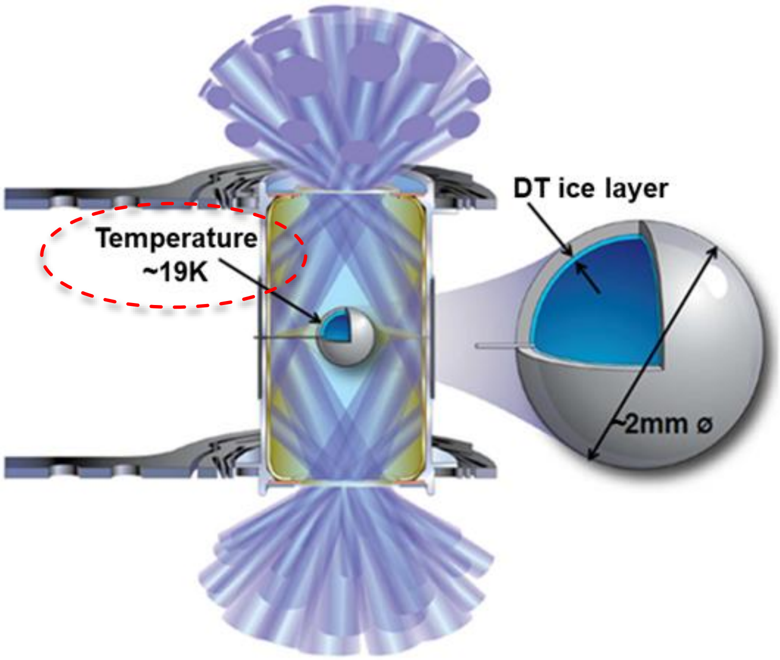
J. Lindl, *PoP*, 1995; S. Haan, *et al.*, *PoP*, 2011
J. Nuckolls et al., *Nature*, 1972

An experiment at the National Ignition Facility



Fuel for the nuclear fusion experiment is a mixture of deuterium & tritium (DT)

- This fuel is in the form of a thin solid layer capsule
  - thickness is about hair's width
- Solid DT ice layer needs to be *near-perfect*
  - have very uniform thickness (to within ~0.5µm)
  - extremely homogeneous & smooth
- Defects act as sites for hydrodynamic instabilities to form and disrupt uniform compression of the fuel



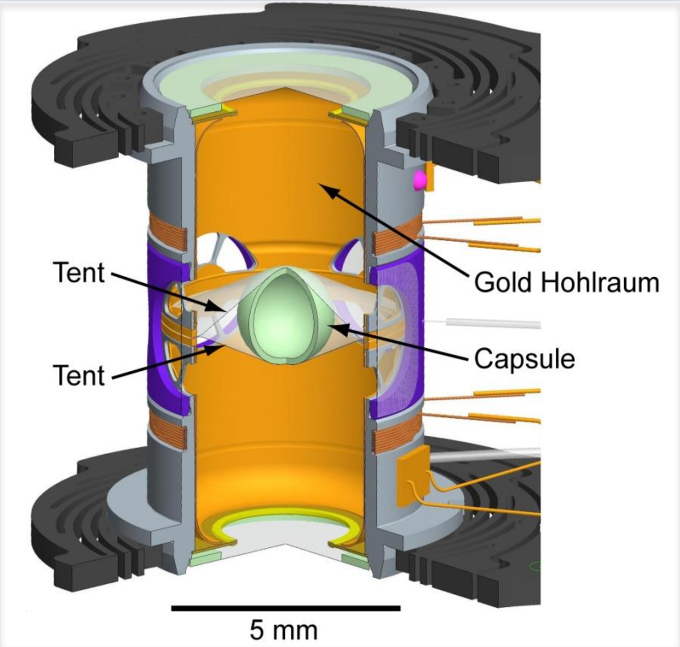
The *target* for doing cryogenic ignition experiments is an ultra-precise micro-assembly with carefully designed materials

- Cryogenic layering requires sub milli-Kelvin control of temperatures

- So, while basic components are the capsule and the hohlraum, the final experimental article called the 'target' is complex

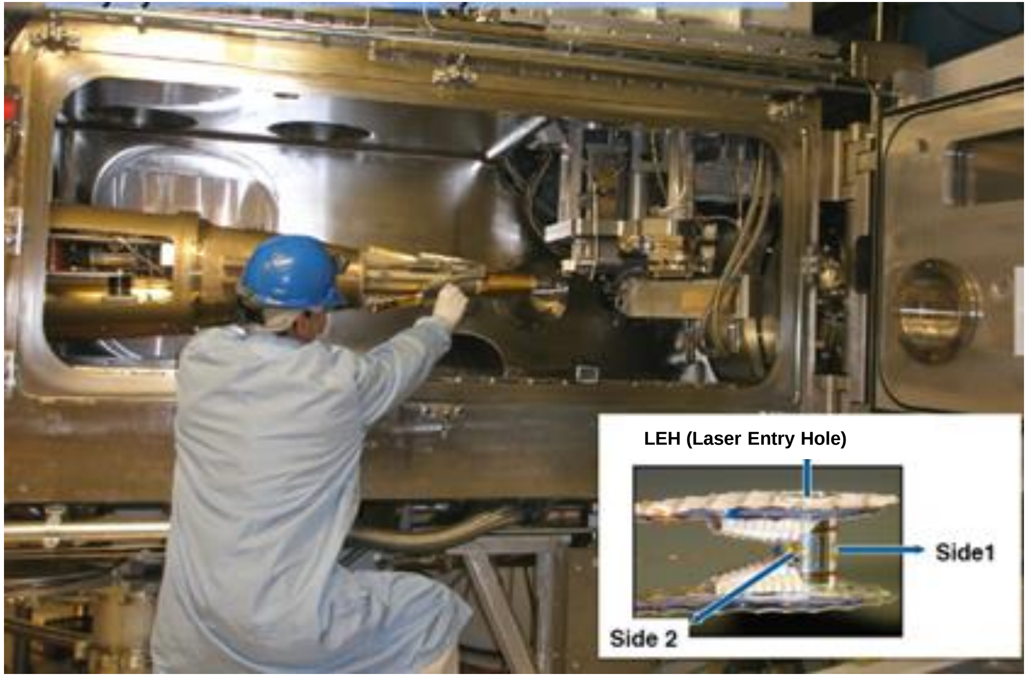
- Capsule is optically opaque, so we use X-rays to image from
  - Top
  - Side

Core components of the ignition target

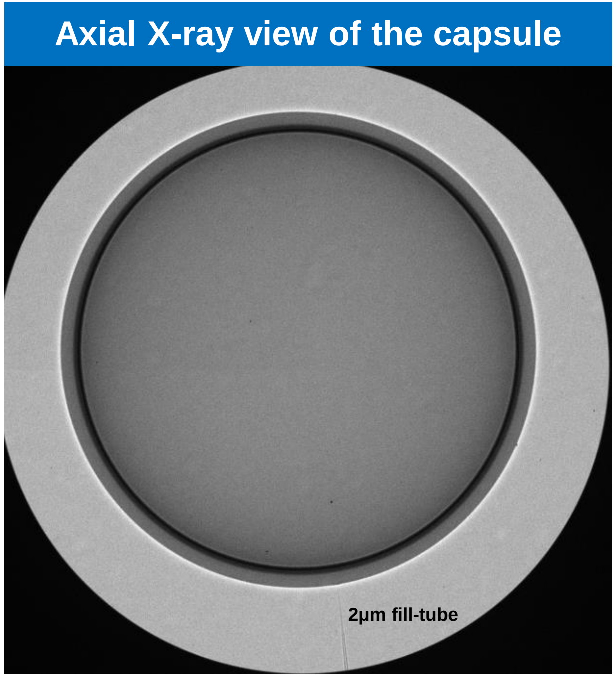


X-ray imaging is used to guide the formation of the DT fuel layer

Growth of the DT ice layer is monitored using X-ray radiographs from 3 directions



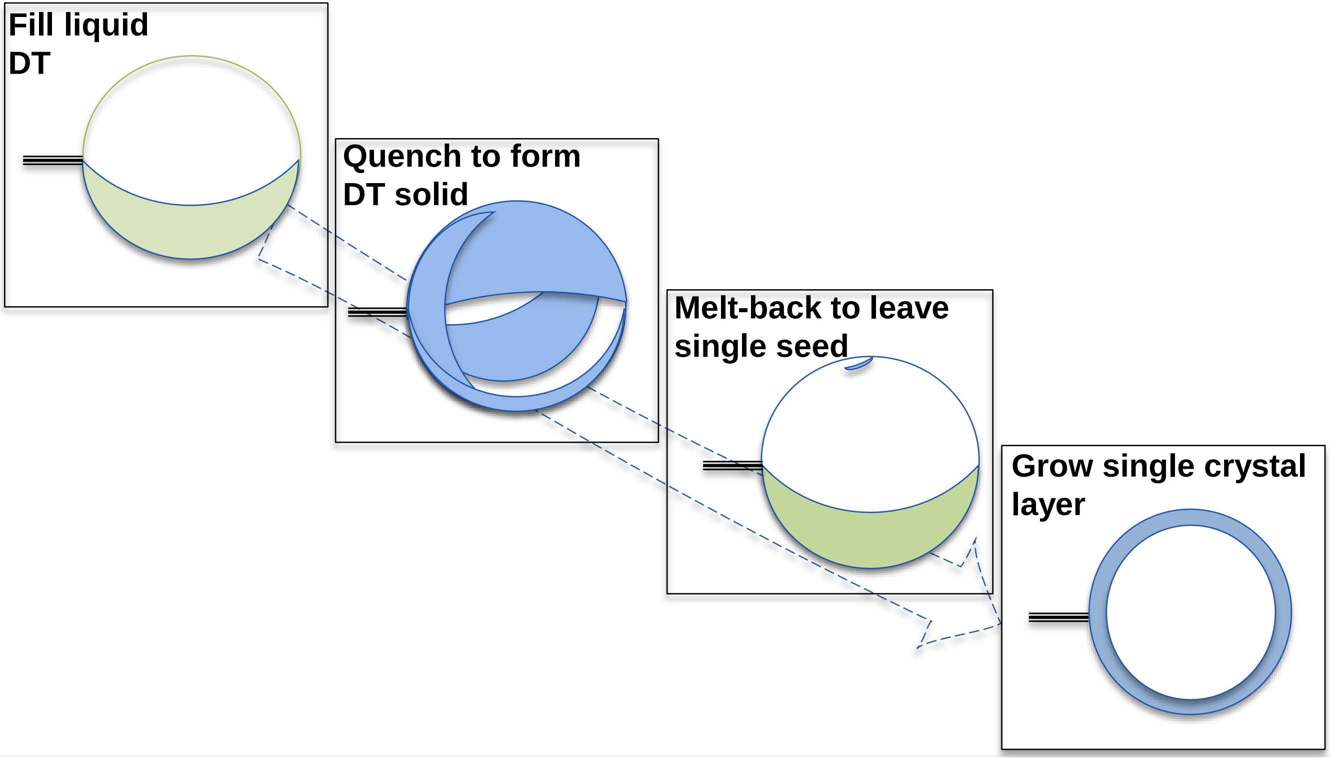
DT is introduced into the capsule through a small fill tube with a diameter of 2µm



Making the DT layer with stringent specifications is a finely tuned process with several steps, which we have automated using MATLAB

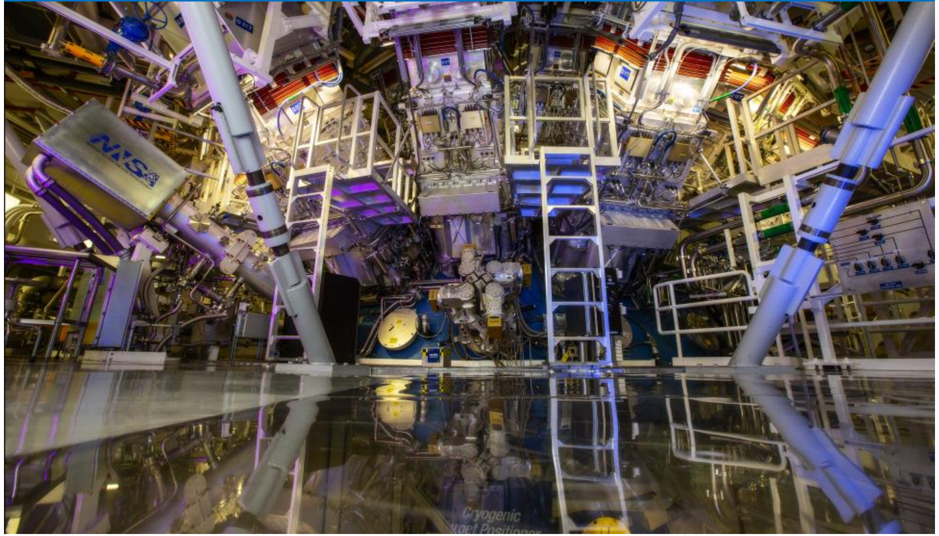
- **Formation of defect-free spherical single crystal layer at 19K is challenging**

- **We used MATLAB to automate the whole process**
  - ***Press "start" and we get a layer at the end***
  - ***MATLAB does***
    - ***system control***
    - ***image acquisition***
    - ***image analysis***
    - ***make decisions to advance each step***



The fine synchronization of the many sub-systems and diagnostics needed for a NIF laser shot is controlled using customized code

Chamber where the laser experiments are conducted



We use MATLAB to communicate with the instruments via a Java interface to the custom Integrated Computer Control System (ICCS)

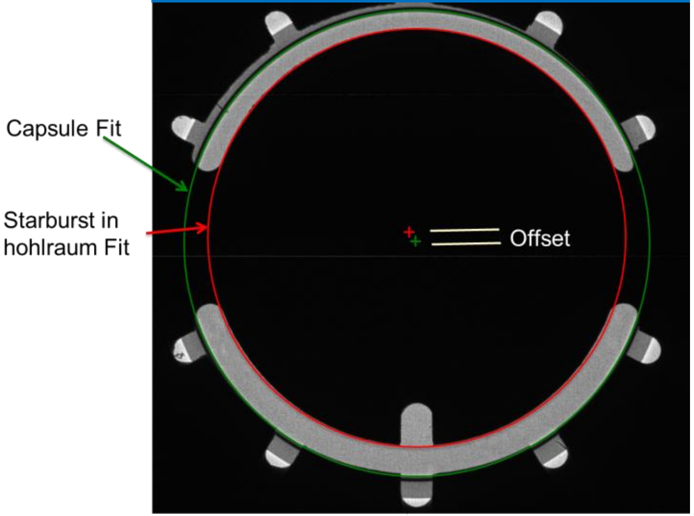
- Cryostat control system
  - Turn cryostat on and off at selected times
- Temperature controllers
  - Read and set temperatures
- Camera servers
  - Take large format images

Data derived from images drive the DT layer formation process

- *Image analysis is a major MATLAB operation*
  - Take periodic sets of images
  - Align each set and stack
    - Vibration from cryostat causes significant image shift between subsequent images

- *MATLAB performs important QC checks as a gate for proceeding further into the process*
  - Confirm centering of the capsule to resolution of better than a micron
  - Detect and quantify micro-defects such as foreign particles

Capsule needs to be well-centered in the hohlraum

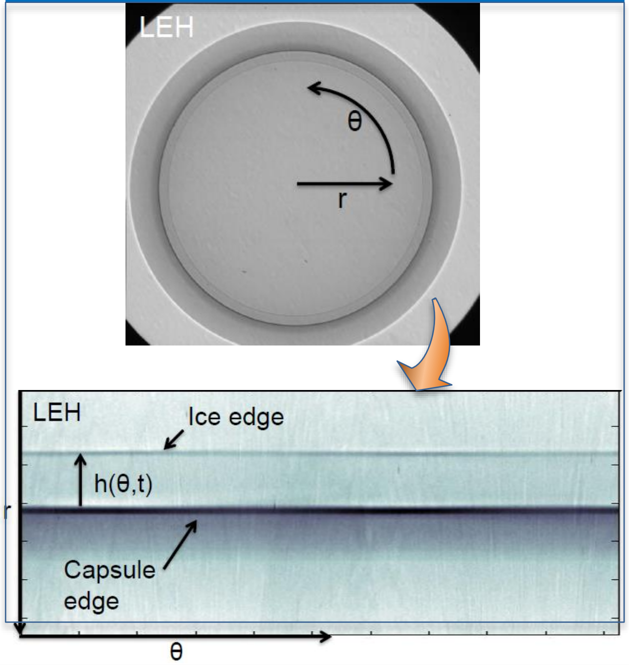


MATLAB is used to make process decisions based on image analysis to monitor and control layering process

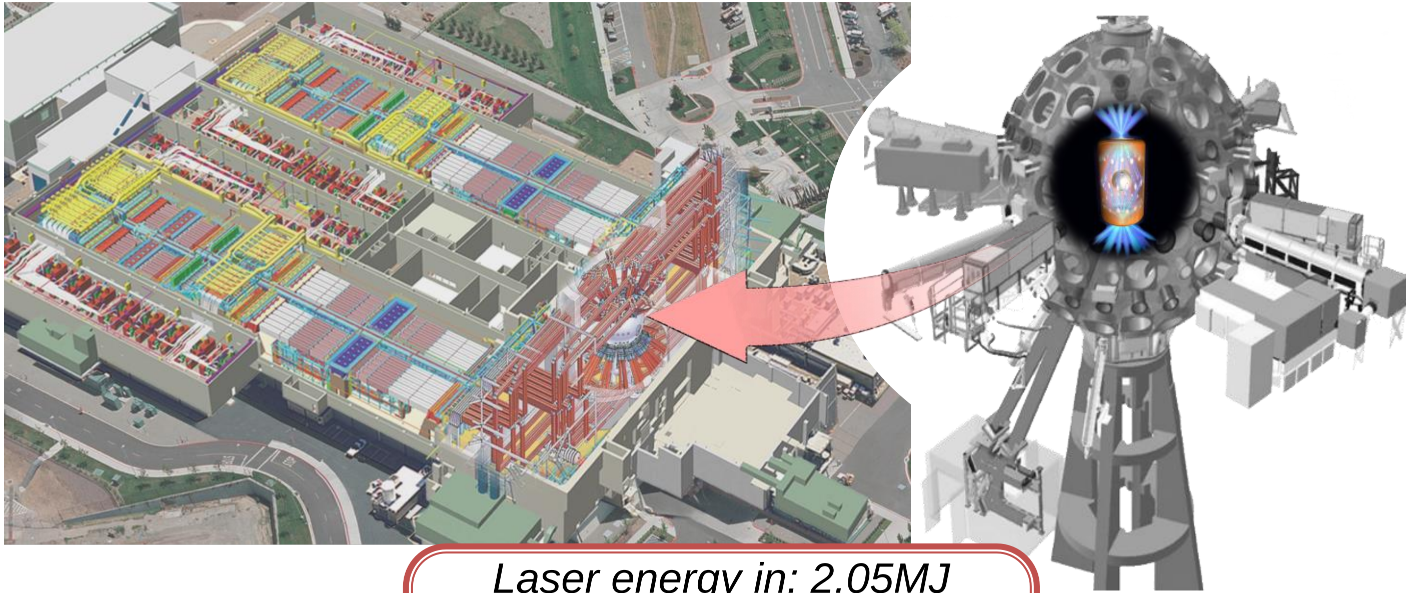
- Key element of the image analysis: detect the DT interface amidst the multiple layers of the capsule
  - Control fill to with 1µm to form a solid layer of exactly the desired thickness

- Unwrap and analyze the image for layer quality to prepare reports for go-ahead decisions & post-shot simulations
  - Layer quality parameters
    - Low modes (deviations from sphericity: sub-micron)
    - Power spectrum (micro-roughness at different scales)
    - Isolated defects (e.g. ppm level vapor etched grooves)

Processing of the X-ray image for extraction of important parameters

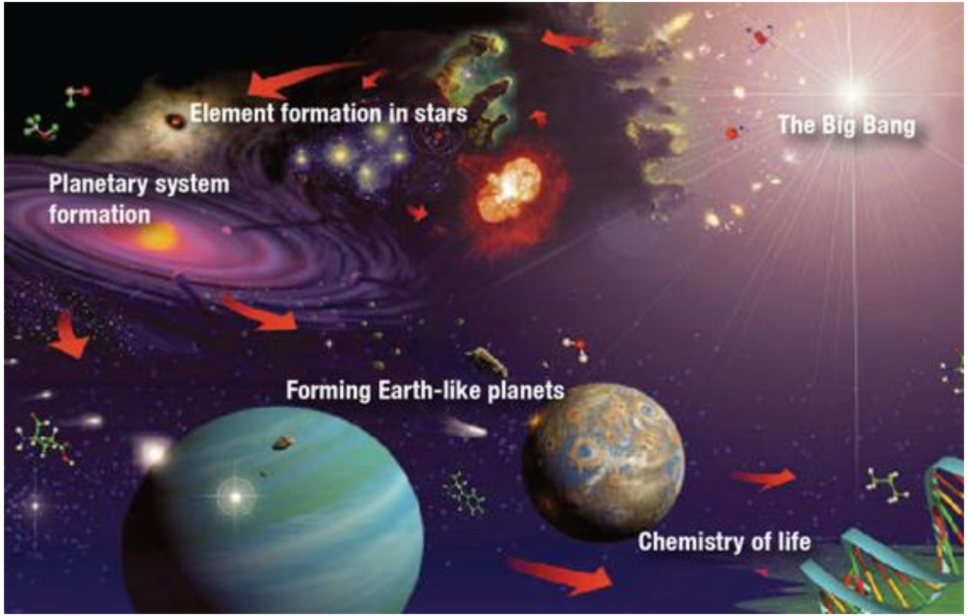


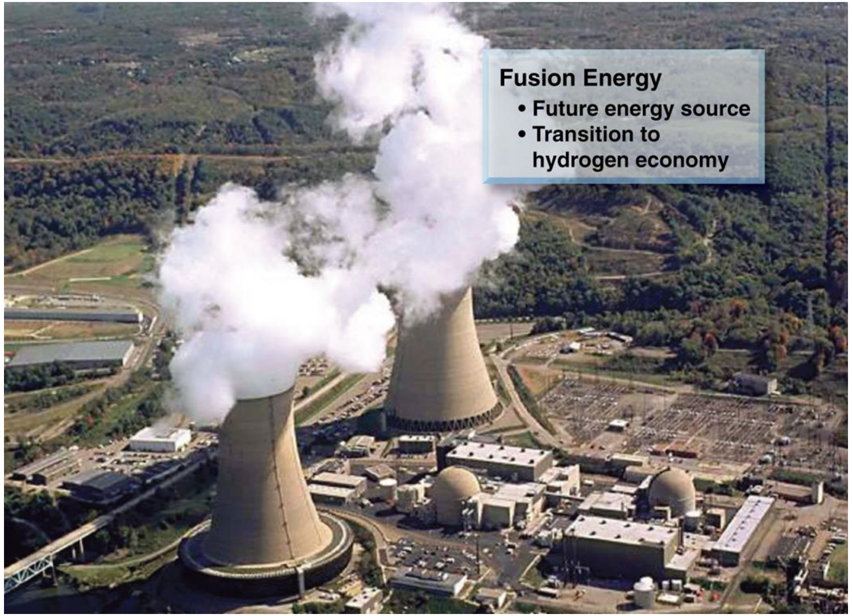
Having demonstrated an igniting fusion reaction, we are now embarking on pushing the gain to even higher levels



Laser energy in: 2.05MJ
Fusion energy out: 3.15 MJ
Gain: ~1.5x
Seeking higher gains next

Beyond supporting our nation's stockpile stewardship mission, NIF enables unique science in frontier astrophysics & clean fusion energy





Ignition provides fresh impetus and the scientific foundation for inertial fusion energy (IFE)

- Fusion Energy is the holy grail of clean energy and the next grand challenge

- This will require developing a lot of new technologies and new talent

LLNL seeks to accelerate IFE in support of DOE's decadal vision of enabling the commercialization of fusion energy

Thank you

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