Update on High Energy Density Science at LLNL

Fusion Power Associates 2019

Mark C Herrmann
National Ignition Facility Director
Program Director for NIF Integration

Thanks to Rulon Linford, John Edwards, Warren Hsing, Kevin Fournier, Derrick Lassle, Doug Larson, Bruno Van Wonterghem and the entire NIF team

December 3, 2019

LLNL-PRES-XXXXXX

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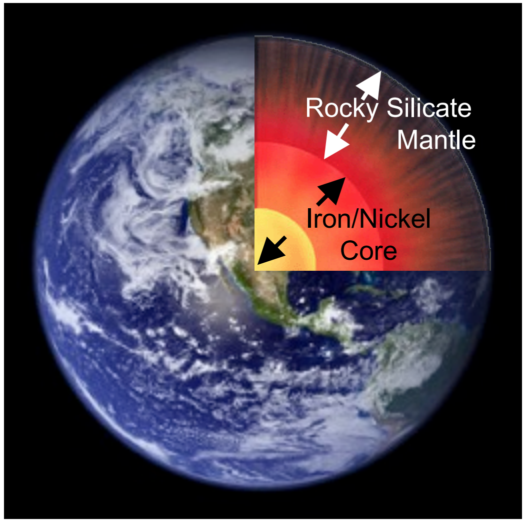
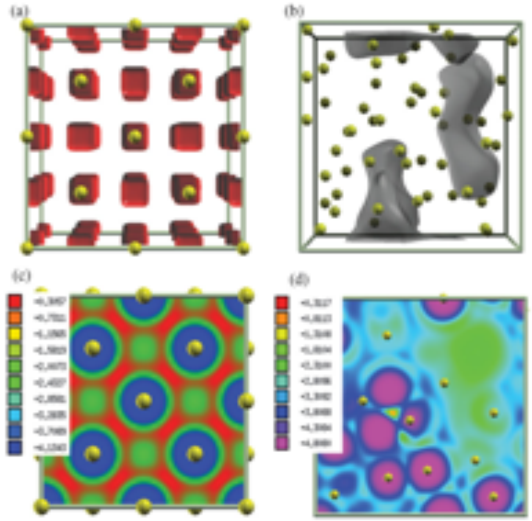
Lawrence Livermore National Laboratory

Scientists have more reasons than ever to understand matter at extreme conditions

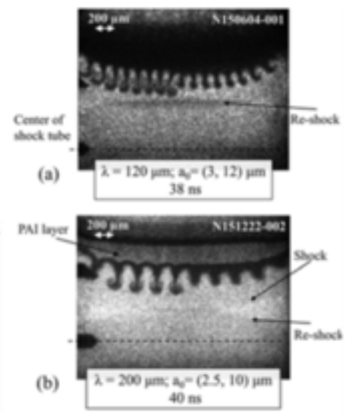
Planetary Science



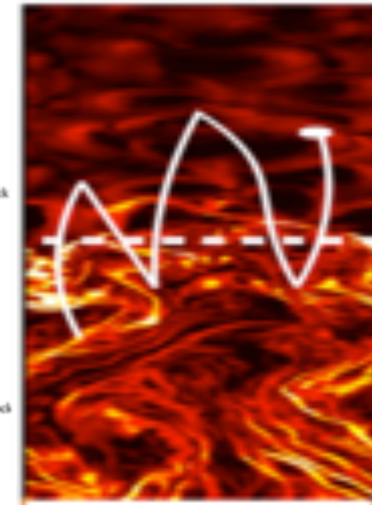
New Materials?



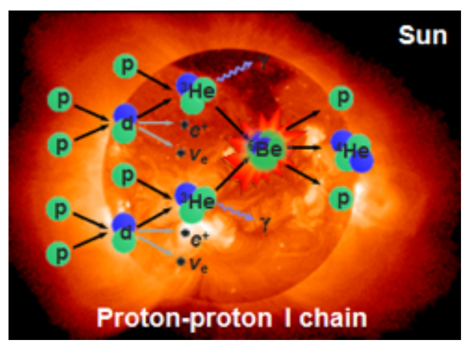
Radiation Hydrodynamics



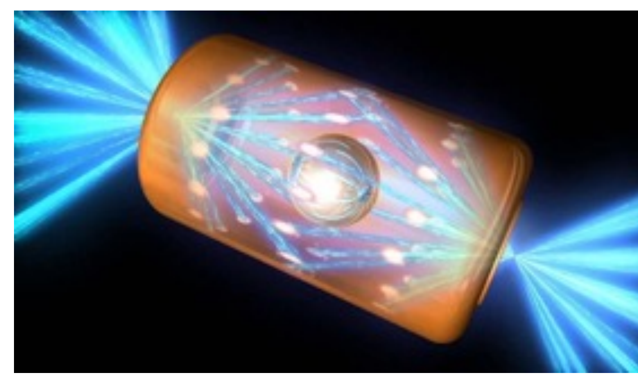
Plasma Astrophysics



Stockpile Stewardship

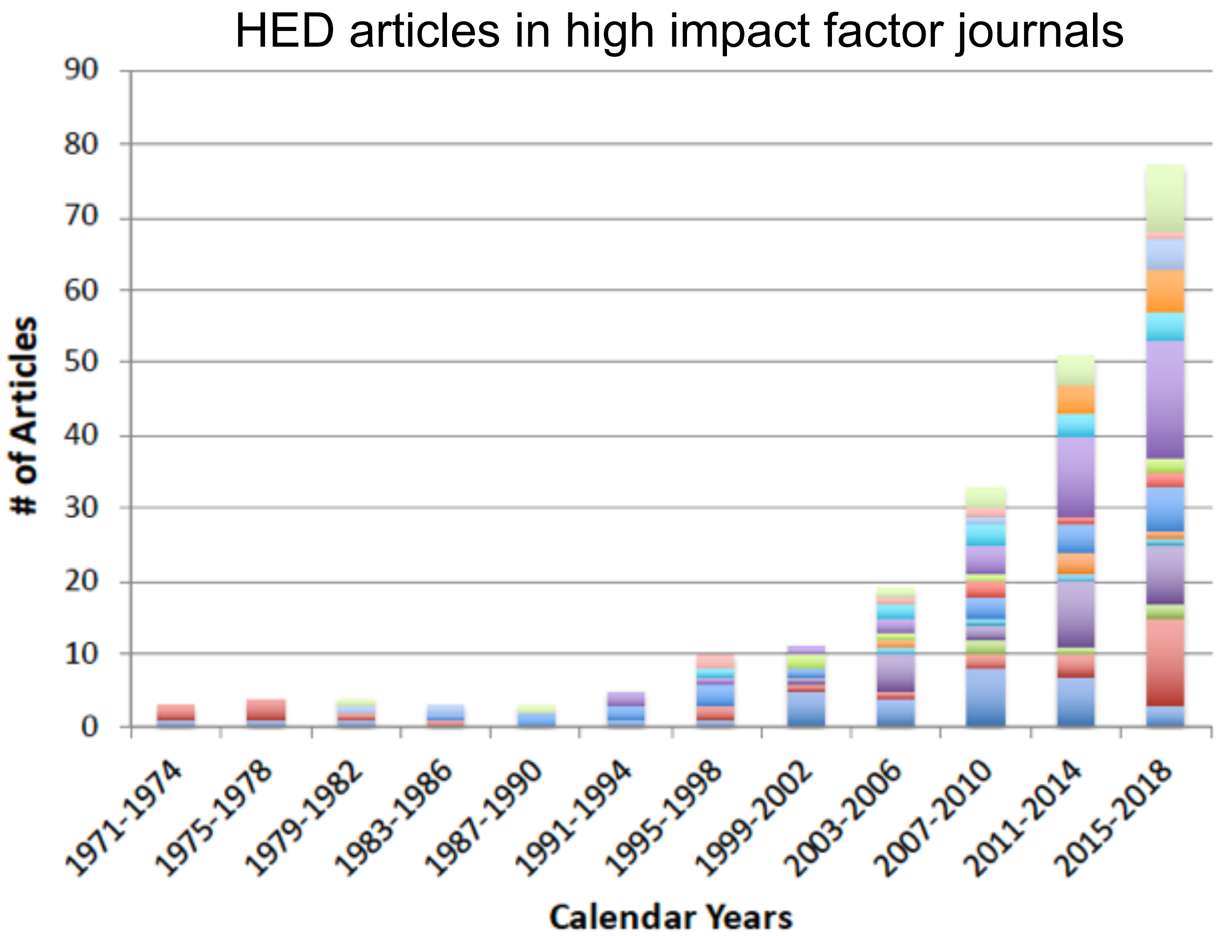


Nuclear Physics



Laboratory Fusion
Potential for Inertial Fusion Energy

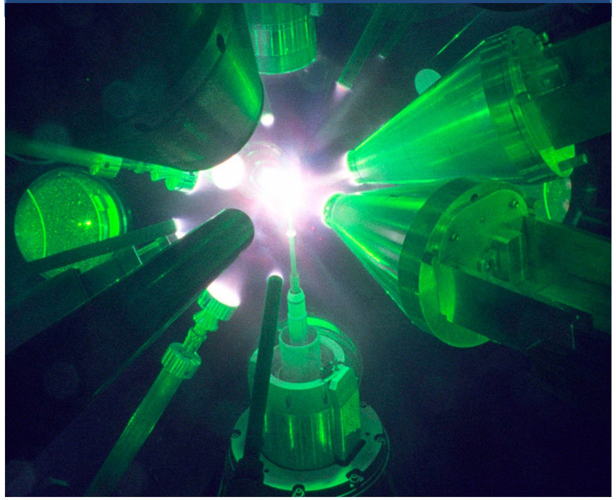
The increased interest in HED science can also be seen in the world wide growth of publications



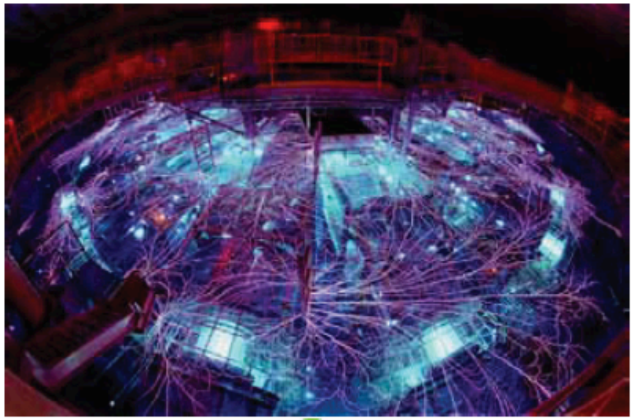
Impact factor > 10, e.g. Nature, Science, etc., Courtesy of Rulon Lindford)

The US has 4 world leading capabilities for studying matter at extreme conditions

Omega Laser Facility
U. Rochester



ZR Pulsed Power Facility
Sandia



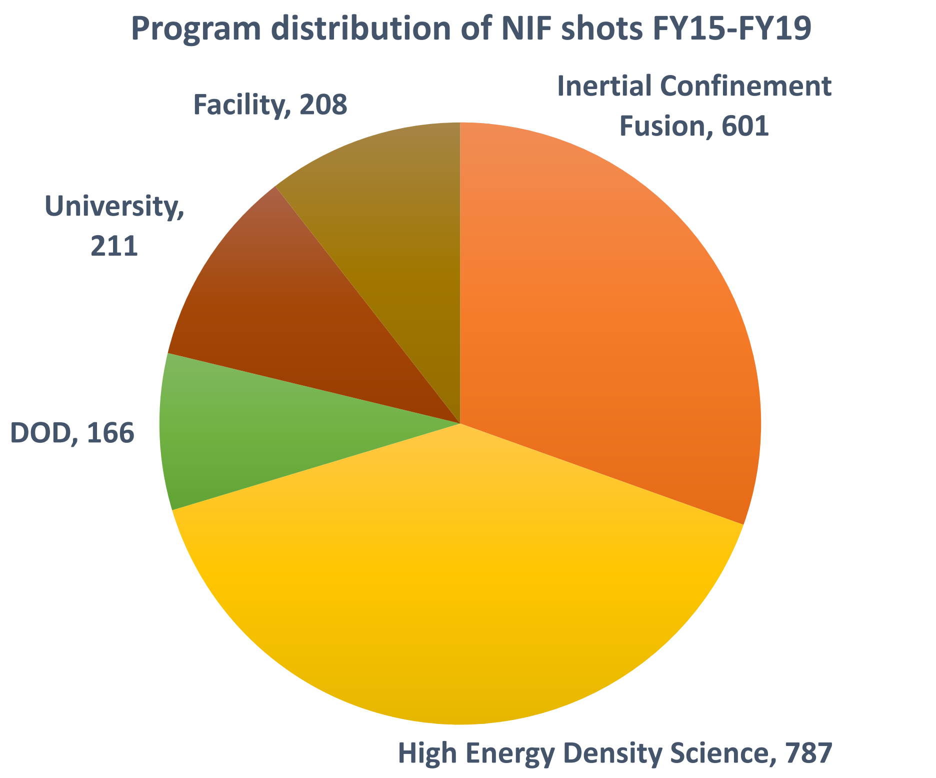
National Ignition Facility
LLNL

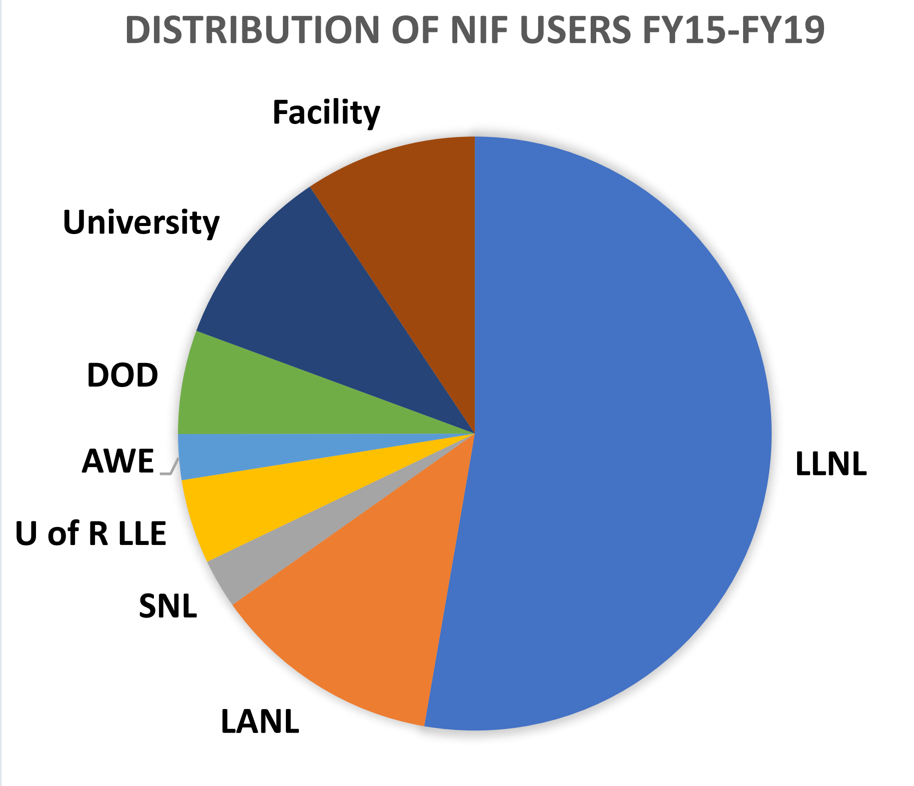
Linear Coherent Light Source SLAC

These investments all came online in the 2007-2009 timeframe

The rest of the world has significantly accelerated investment in this area

NIF recently celebrated its 10th anniversary of operations and has conducted 2800+ target experiments to date (~2000 since FY15)





- HED Science needs for the Stockpile Stewardship Program will keep NIF, Omega, and Z busy for the next 10 years
- 2020 review by NNSA and by the JASONs will help provide guidance for next steps in pursuit of fusion ignition

Experiments on NIF have lead to over 800 publications, many in some of the most prestigious journals

LETTERS
https://doi.org/10.1038/s41567-018-0331-5
nature physics

Enhanced energy coupling for indirectly driven inertial confinement fusion

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Recent experiments in the study of inertial confinement fusion (ICF) at the National Ignition Facility (NIF) in the United States have reached the so-called alpha-heating regime[1-3], in which the self-heating by fusion products becomes dominant, with neutron yields now exceeding 1×10¹⁶ (ref. [4]) However, there are still challenges on the path towards ignition, such as minimization of the drive asymmetry, suppression of laser-

Efficient energy coupling would benefit both the mainline central-hot-spot (CHS) approach, where a hot spot initiates the thermonuclear burn, and a complementary scheme for volumetric ignition using double-shell (DS) capsules[11]. In the latter, a high-Z inner shell is added to provide high inertial confinement and efficient radiation trapping. The DS approach generally provides less gain than CHS due to less fuel mass, yet it has potential benefits such as a ... laxed ... The

RESEARCH

HIGH-PRESSURE PHYSICS

Insulator-metal transition in dense fluid deuterium

Peter M. Celliers[1]*, Marius Millot[1], Stephanie Brygoo[2], R. Stewart McWilliams[3], Dayne E. Fratanduono[1], J. Ryan Rygg[1,4], Alexander F. Goncharov[5], Paul Loubeyre[2], Jon H. Eggert[1], J. Luc Peterson[1], Nathan B. Meezan[1], Sebastien Le Pape[1], Gilbert W. Collins[1,4], Raymond Jeanloz[6], Russell J. Hemley[7]

Dense fluid metallic hydrogen occupies the interiors of Jupiter, Saturn, and many extrasolar planets, where pressures reach millions of atmospheres. Planetary structure models must describe accurately the transition from the outer molecular envelopes to the interior metallic regions. We report optical measurements of dynamically compressed fluid deuterium to 600 gigapascals (GPa) that reveal an increasing refractive index, the onset of absorption of visible light near 150 GPa, and a transition to metal-like reflectivity (exceeding 30%) near 200 GPa, all at temperatures below 2000 kelvin. Our measurements and analysis address existing discrepancies between static and dynamic experiments for the insulator-metal transition in dense fluid hydrogen isotopes. They also provide new benchmarks for the theoretical calculations used to construct planetary models.

...om a mo- ...al at high ...ing focus ...e (1). The ...ties of the

properties below 2000 K and up to several hundred GPa.

Dynamic compression can explore a broad range of thermodynamic paths with time-varying manipulations of the applied pressure and con-

the choice of exchange-correlation functional used and whether zero-point energy is accounted for (1, 16). Quantum Monte Carlo (QMC) calculations should provide improved bounds on the transition pressures (16, 17), although they disagree with a recent benchmarking experiment (30). Transition pressures for hydrogen and deuterium are expected to be different because of isotope effects, but with a small relative magnitude. The transition in deuterium from QMC simulations is 30 GPa higher than in hydrogen at 600 K, decreasing to 10 GPa higher at 1200 K (16). Despite experimental support for a first-order IM transition (19, 20, 22, 23), the critical point has not been experimentally identified. Furthermore, the broad discrepancies in the measured transition pressure (20, 22, 23) and character (20–23) have made resolving the differences between the theoretical models challenging.

We completed a series of five dynamic compression experiments at the National Ignition Facility (NIF) to probe the IM transition up to 600 GPa at temperatures ranging from 900 K to 1600 K. The experiments were carried out using 168 laser beams to deliver up to 300 kJ of ultraviolet light that drove a near-isentropic reverberation compression of a cryogenic liquid deuterium sample. We adjusted the time dependence of the laser delivery (pulse shape) to control the compression sequence imposed on the sample as a ... veloc- ... istory ...

PHYSICS OF PLASMAS 25, 092708 (2018)

Probing the seeding of hydrodynamic instabilities from nonuniformities in ablator materials using 2D velocimetry

S. J. Ali,[1,a)] P. M. Celliers,[1] S. Haan,[1] T. R. Boehly,[2] N. Whiting,[2] S. H. Baxamusa,[1] H. Reynolds,[3] M. A. Johnson,[1] J. D. Hughes,[1,b)] B. Watson,[3] H. Huang,[3] J. Biener,[1] K. Engelhorn,[3] V. A. Smalyuk,[1] and O. L. Landen[1]
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PRL 112, 025002 (2014) PHYSICAL REVIEW LETTERS week ending 17 JANUARY 2014

Measurements of an Ablator-Gas Atomic Mix in Indirectly Driven Implosions at the National Ignition Facility

V. A. Smalyuk,[1] R. E. Tipton,[1] J. E. Pino,[1] D. T. Casey,[1] G. P. Grim,[2] B. A. Remington,[1] D. P. Rowl... M. Barrios,[1] L. R. Benedetti,[1] D. L. Bleuel,[1] D. K. Bradley,[1] J. A. Caggiano,[1] D. A. Callahan,[1] C. J. C... D. H. Edgell,[3] M. J. Edwards,[1] J. A. Frenje,[4] M. Gatu-Johnson,[4] V. Y. Glebov,[3] S. Glenn,[1] S. W. H... R. Hatarik,[1] W. W. Hsing,[1] N. Izumi,[1] S. Khan,[1] J. D. Kilkenny,[5] J. Kline,[2] J. Knauer,[3] O. L. La... J. M. McNaney,[1] M. Mintz,[1] A. Moore,[6] A. Nikroo,[5] A. Pak,[1] T. Parham,[1] R. Petrasso,[4] D. ... M. B. Schneider,[1] R. Tommasini,[1] R. P. Town,[1] K. Widmann,[1] D. C. Wilson,[2] and C. B. Y...
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ARTICLE

OPEN

How high energy fluxes may affect Rayleigh–Taylor instability growth in young supernova remnants

C.C. Kuranz[1], H.-S. Park[2], C.M. Huntington[2], A.R. Miles[2], B.A. Remington[2], T. Plewa[3], M.R. Trantham[1], H.F. Robey[2], D. Shvarts[4,5], A. Shimony[4,5], K. Raman[2], S. MacLaren[2], W.C. Wan[1,6], F.W. Doss[6], J. Kline[6], K.A. Flippo[6], G. Malamud[1,5], T.A. Handy[1], S. Prisbrey[2], C.M. Krauland[7], S.R. Klein[1], E.C. Harding[8], R. Wallace[2], M.J. Grosskopf[9], D.C. Marion[1], D. Kalantar[2], E. Giraldez[7] & R.P. Drake[1]

198+ Articles in Physics of Plasmas, frequently the most cited articles in that journal
50+ Articles in Physical Review Letters

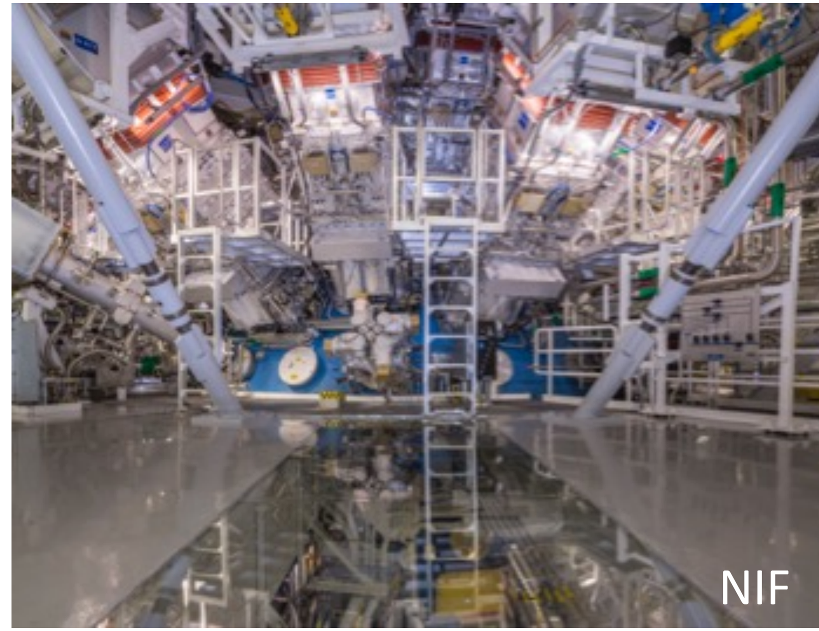
NIF is being used by stewards at all 3 labs and delivering the data needed for the Stockpile Stewardship Program

- Stockpile Modernization Program design options

- Improving our understanding of weapons science
  - Plutonium properties at high pressures
  - Radiation transport
  - Complex hydrodynamics
  - Nuclear survivability

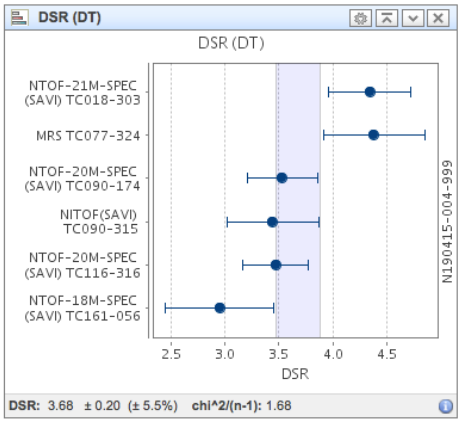
- Pursuit of ignition
  - Ignition is gateway to high fusion yields, which enable higher energy density environments for higher fidelity testing
  - Practice the ART of design

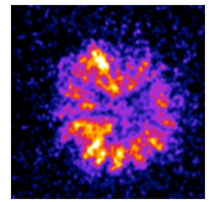
- Workforce
  - Attracting, Training, and Challenging



New measurements and understanding highlight degradation mechanisms in ICF implosions. As degradations are being understood we can work to address them

Non Uniform Fuel distribution: DSR (ntof + MRS)

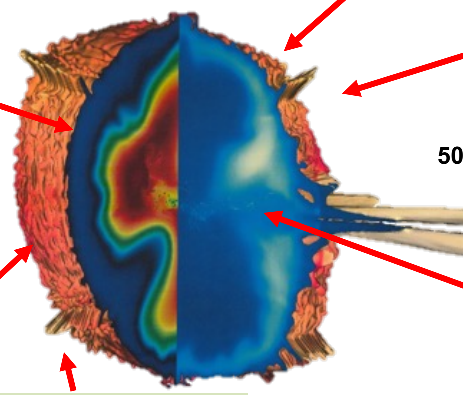




Meteors – gated x-ray imaging

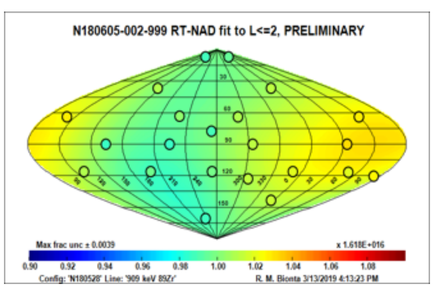
Low compression: Down-Scattered Neutrons (DSR)

3D Simulation*

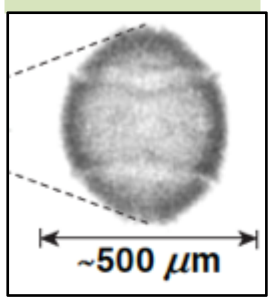


Fill tube induced mix

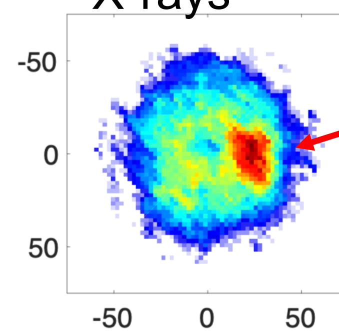
Low mode fuel shape
Un-scattered neutrons
FNADS (L<=2)



Tent Scar

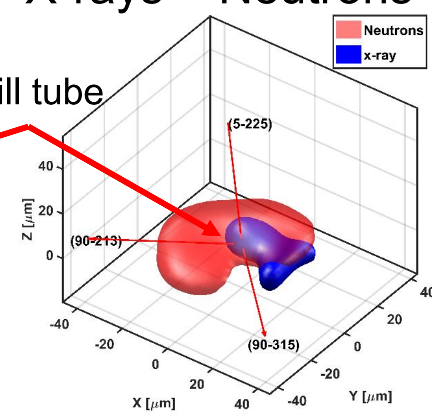


X-rays



X-rays + Neutrons

Fill tube

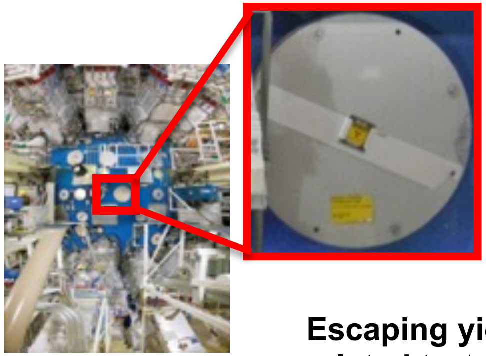


* 3D simulations of Density and temperature of N161023 at BT by Dan Clark

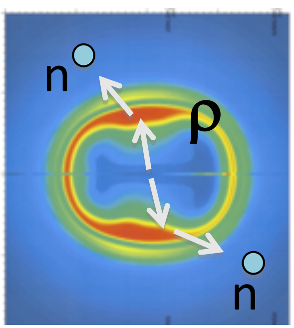
For many shots few % level variation in the distribution of laser energy correlates with the holes in the cold fuel shell and the motion of the hot spot that degrades implosion performance

Zirconium samples mounted to ports

$^{90}Zr(n,2n)^{89}Zr$

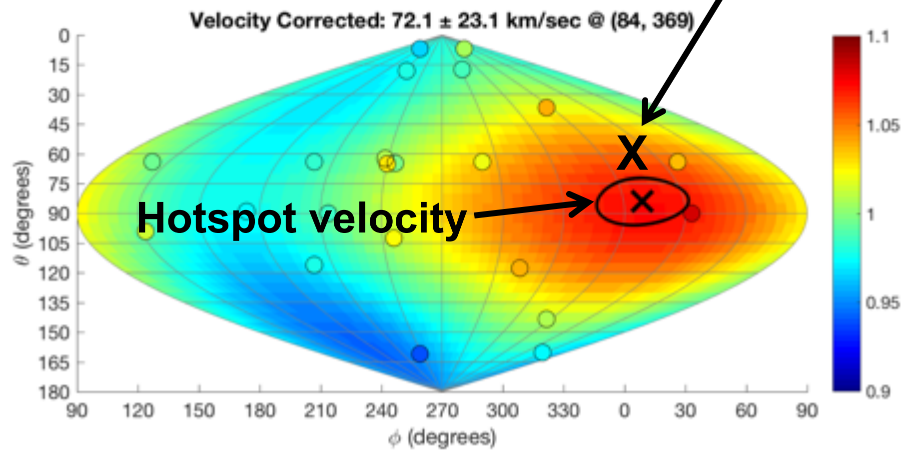


Escaping yield related to ΔρR

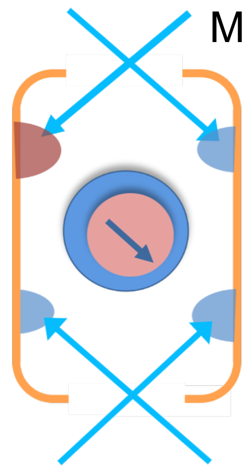


$$Y(\Omega) = Y_p e^{-\rho R(\Omega)\langle\sigma_{DT}\rangle/m_{DT}}$$

e.g. N180311 **Laser only**



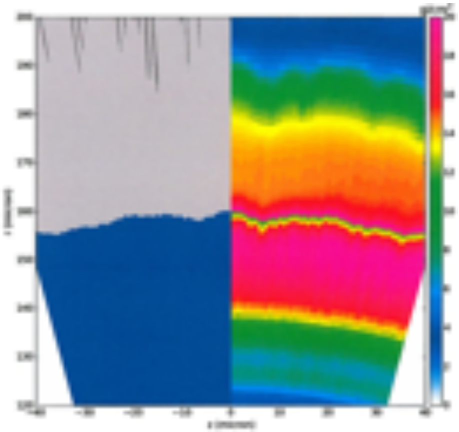
MacGowan / Rinderknecht / Landen



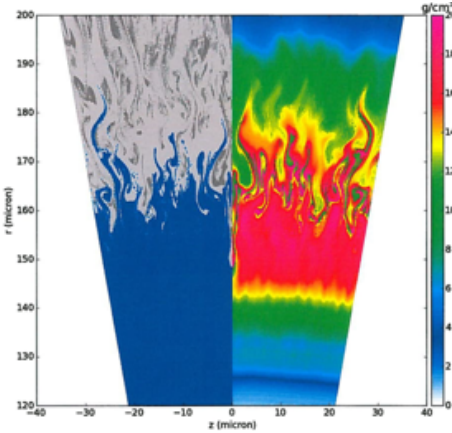
Laser to capsule model to calculate drive asymmetry

Work is underway to study pathways to improve the NIF laser power balance

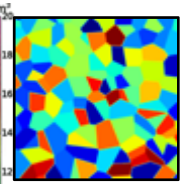
New diagnostics are enabling the study of mixing at the DT fuel-ablator interface



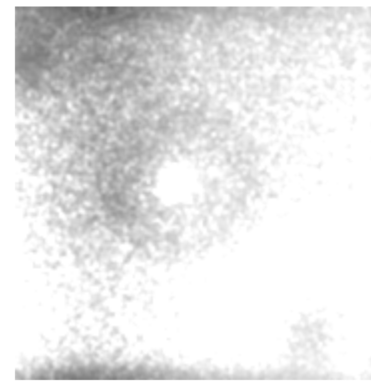
No Diamond grain boundaries



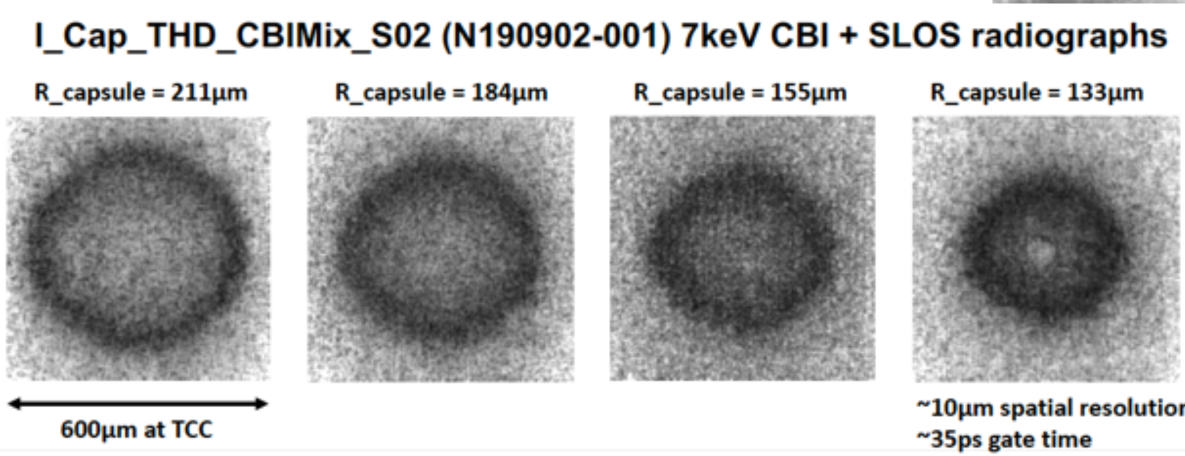
With 2D Diamond grain boundaries



0.5% density variation
1μm grains



FY18

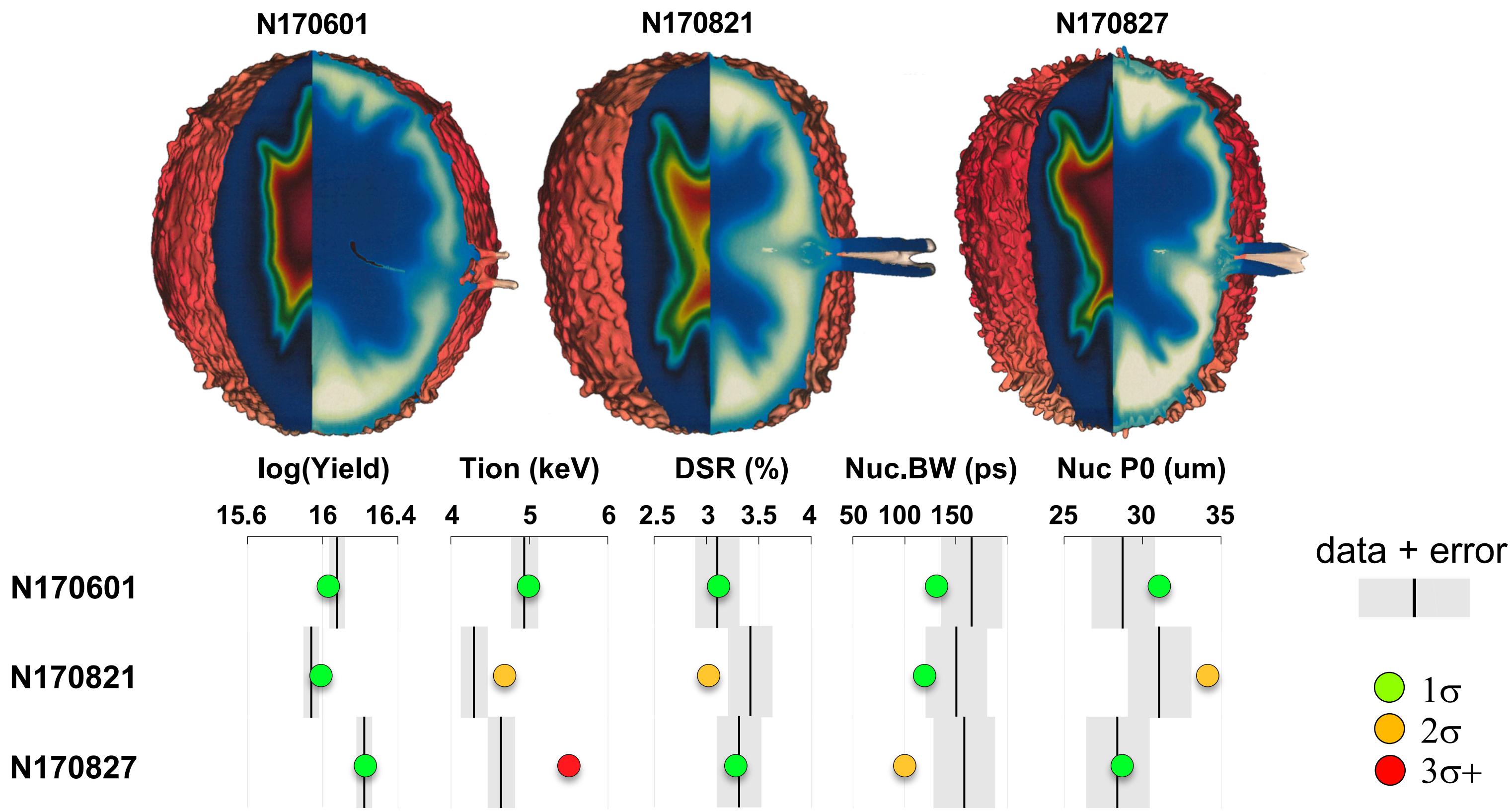


Hall, Landen, et al.

FY19

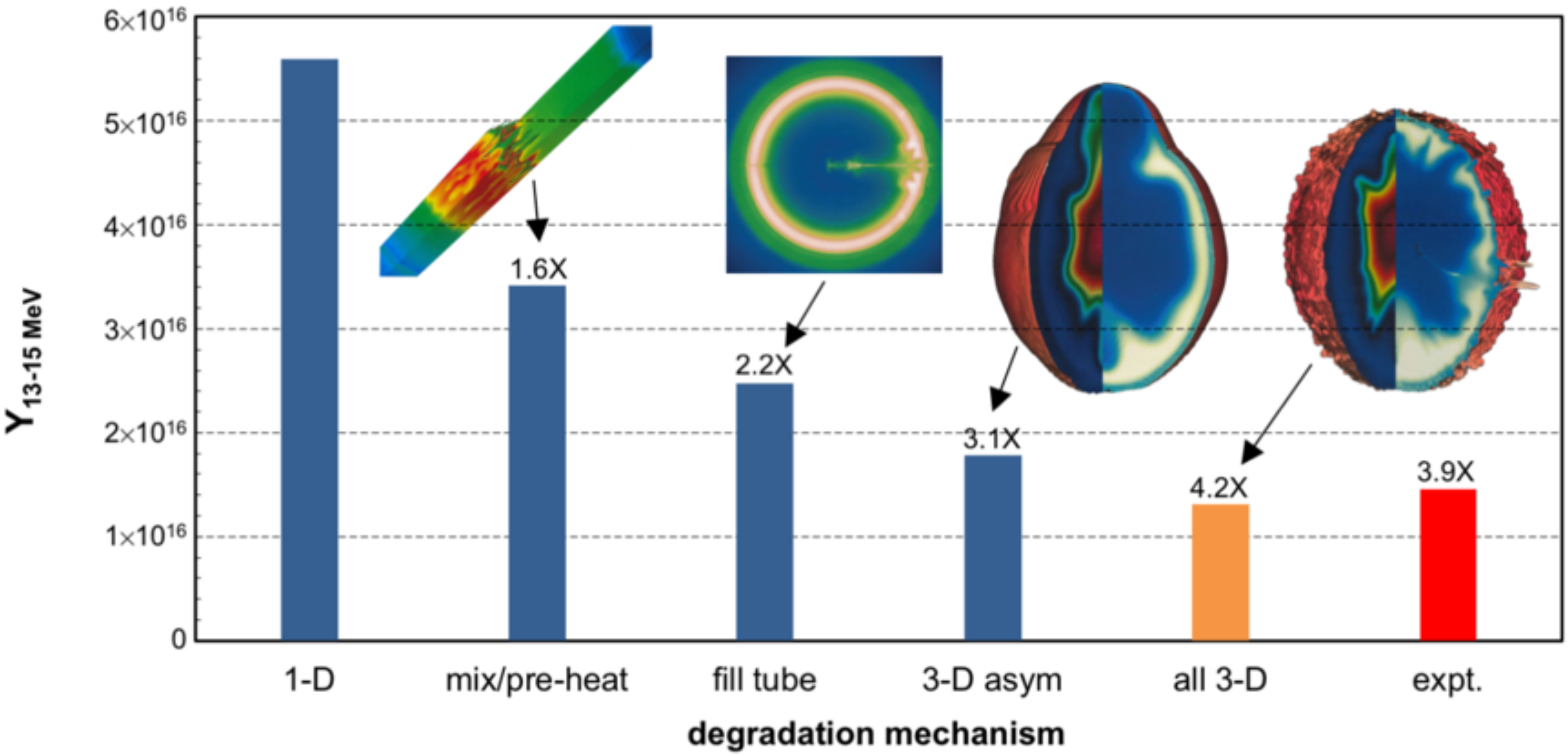
We are studying the impact of microstructure on implosions, and exploring amorphous ablator materials

3D simulations matched to many pieces of NIF data, can shed light on sensitivities to various degradation mechanisms



D. Clark, et al.

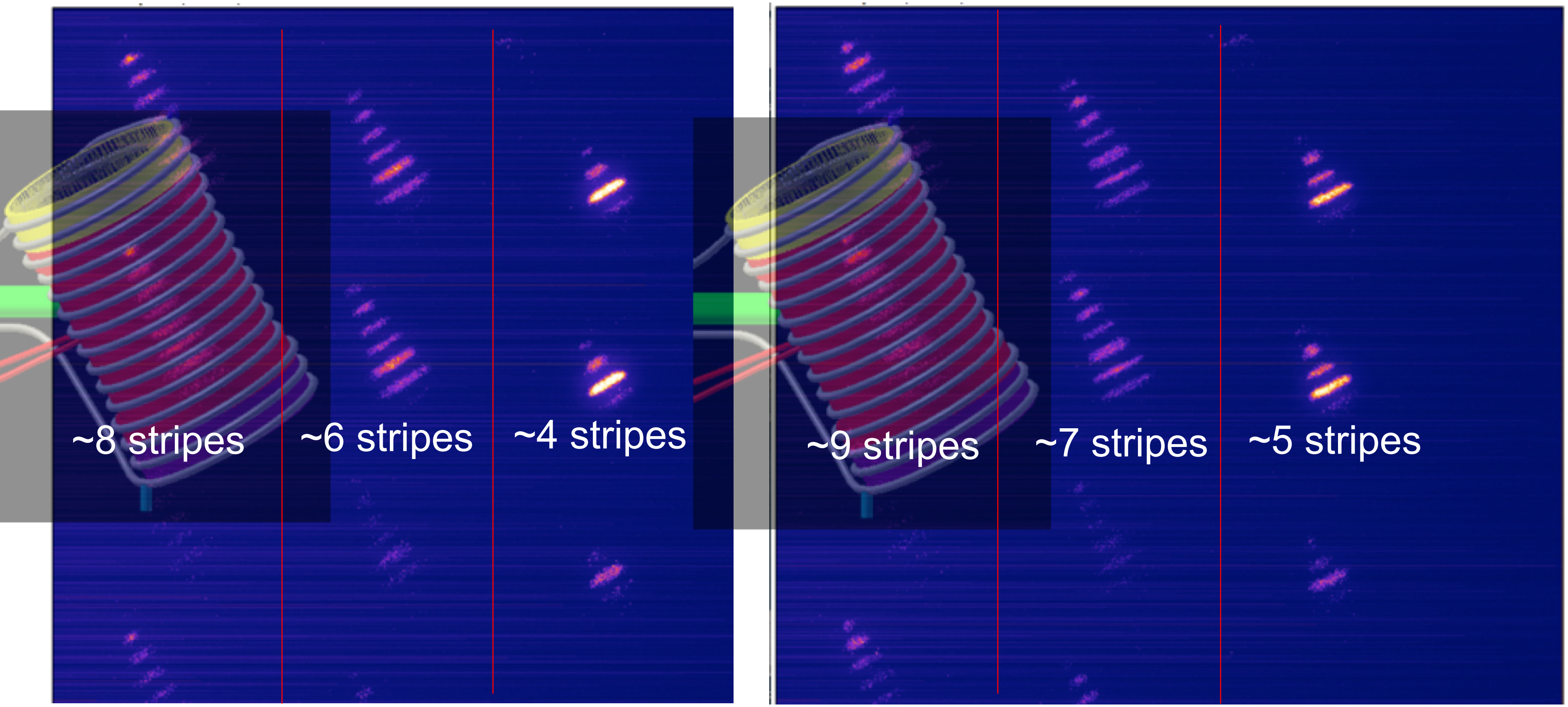
3D simulations, matched to many pieces of NIF data, can shed light on sensitivities to various degradation mechanisms



Simulations plus new measurements are providing a basis for the next steps in pursuit of ignition

D. Clark, et al.

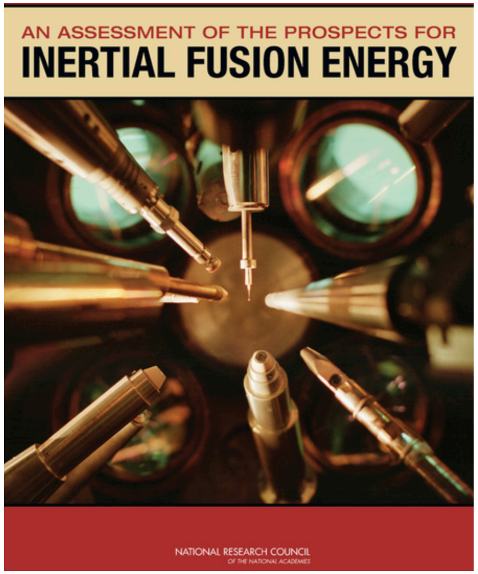
We fired our first magnetized target on NIF in May in support of Sandia’s MagLIF campaign.
Magnetized DT layered experiments will be explored



Sandia National Laboratories

As part of the APS DPP CPP, consideration should be given to reconstituting a small inertial fusion energy effort

- U.S. is clear world leader in HED, thanks to NNSA investments
- NNSA-SC partnerships have been very fruitful (e.g. Exascale)
- Current US leadership in HED research stems, in part, from historical pursuit of IFE
  - Attracted great people
  - Drove innovation
- IFE has very different risks/rewards compared with MFE
- IFE is a multi-decadal endeavor, requires innovation to enable economical energy source. Program would greatly add to
  - Innovation
  - HED research foundations (better theoretical understanding needed, long term perspective, …)
  - Workforce development
  - Future HED capabilities (e.g. rep-rated drivers, …)

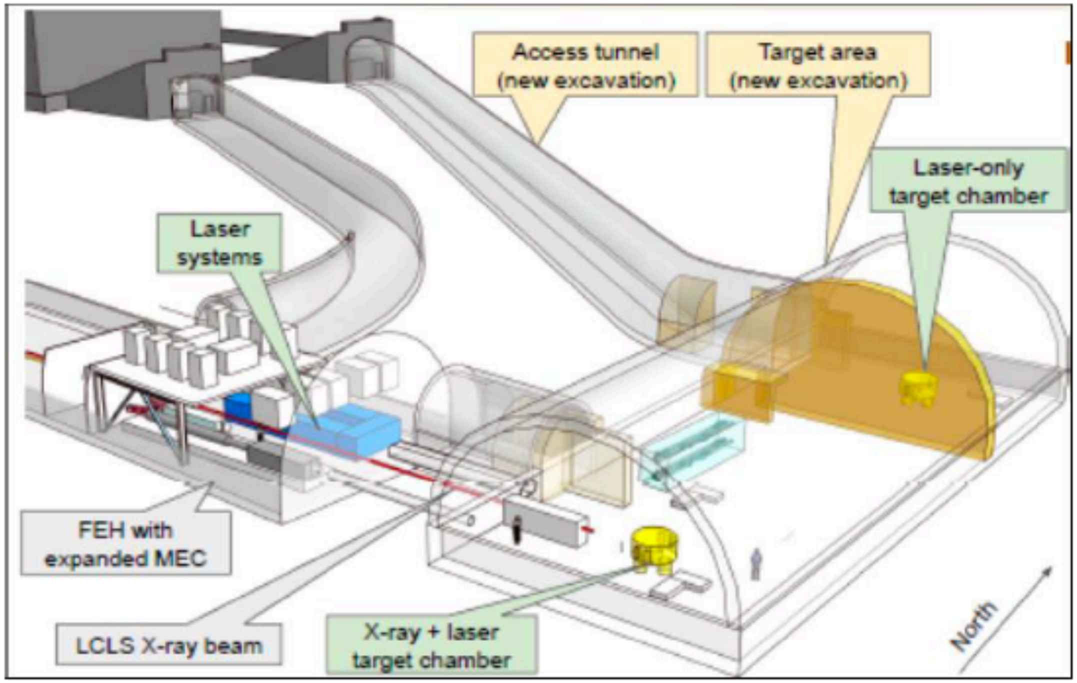


FES is exploring creating a world-leading HED science capability by coupling improved rep-rated lasers to LCLS

U.S. DEPARTMENT OF ENERGY
Office of Science

MEC Upgrade achieved Critical Decision-0 in January 2019

- **FES is considering an MEC petawatt laser facility upgrade**
  - Mission Need (CD-0) approval achieved in FY 2019
  - Addresses a recommendation in the 2017 NAS report *Opportunities in Intense Ultrafast Lasers: Reaching for the Brightest Light*



$1.6M **Allocated for the project in FY 2019**

The 192 beam, 2.8 MJ 2ω UFL-2M is well underway in Russia

Video posted on PRAVDA, April 2019

"Experiments that were conducted on a NIF facility in the United States showed that the system could not provide the necessary uniformity of irradiation of the capsule. Our irradiation system is different, it is almost spherically symmetrical. Having previous experience with the experiments, we have every chance to achieve the desired (ignition of thermonuclear reactions in targets) first in the world. "

Academician Sergei Grigoryevich Garanin, director of the Institute of Laser Physics Research at RFNC-VNIIEF.

April, 2019

The Chinese currently have the second most energetic laser in the world and are actively talking about building Shenguang IV a "facility for ignition"

❖ Introduction

High power laser in China

LFRC 激光聚变研究中心 LASER FUSION RESEARCH CENTER

Currently in China, there are laser facilities of kJ class, 10kJ class, and 100kJ class with the capability of carrying joint experiments with PW beam.

Shenguang-I

SIOM

Shenguang-II UP

SIOM

20kJ/3ns & PW/ ps

Shenguang-II

SIOM $3\omega_0$, 2 kJ, 8 beams

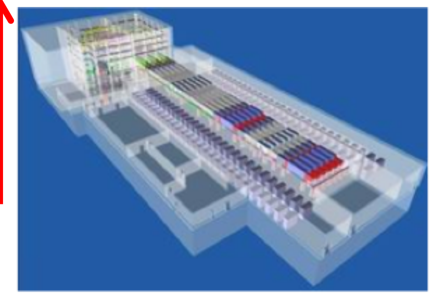
Shenguang-III

LFRC

$3\omega_0$, 180 kJ, 48 beams

Shenguang-III prototype

LFRC $3\omega_0$, 12 kJ, 8 beams



Facility for ignition

- A variety of high energy density experiments can be performed on these platforms.
- The energy scale of SG-III laser facility fills the gap between Omega and NIF which provides great opportunities to study the "missing" physics in extrapolating the acknowledge learned on Omega to that on NIF, and to increase the reliability of the ignition target design

IFSA2017

Los Alamos
NATIONAL LABORATORY
EST.1943

NNSA
National Nuclear Security Administration

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LLE

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