Status of and Progress on the National Ignition Facility

Fusion Power Associates

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National Ignition Facility Director
and the NIF Team

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Lawrence Livermore National Laboratory

NIF is delivering for the Stockpile Stewardship Program

- Stockpile stewards are using NIF to obtain the data needed for SSP, including the ongoing stockpile modernization. We frequently make discoveries that challenge our simulations, our assumptions, and our stockpile stewards.

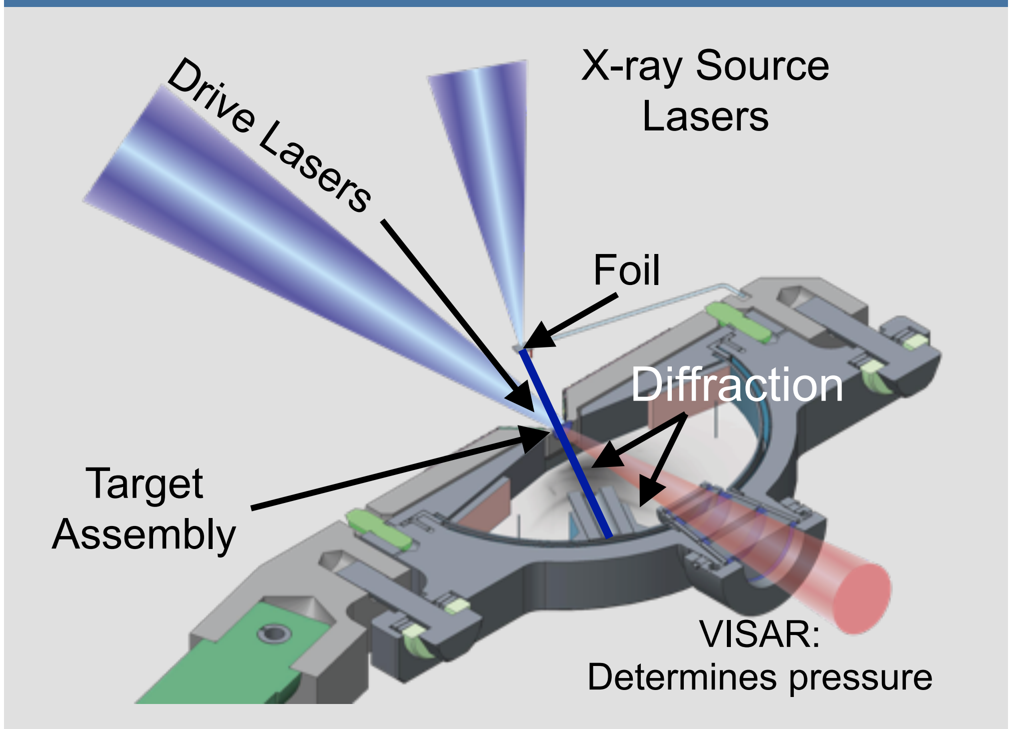
- The increase in NIF shot rate has enabled significantly more experiments for all users, enabling faster progress in ICF, HED, and the NIF Discovery Science Program

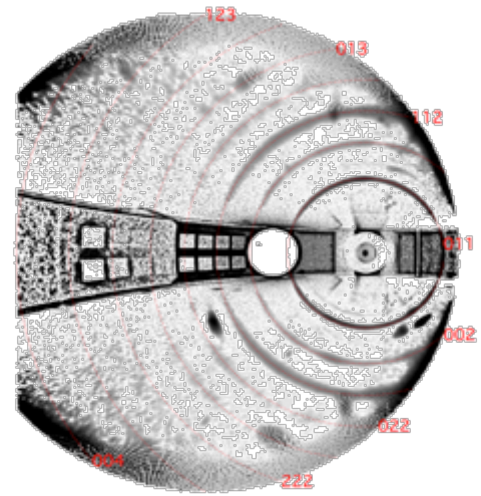
- Achieving inertial confinement fusion ignition in the Laboratory is a grand scientific challenge.
  - Progress is being made on understanding and improving inertial confinement fusion target performance
  - New diagnostics are providing critical insights that will lead to further progress
  - Path forward involves reducing perturbations from engineering features, increasing capsule/hohlraum size, enhancing understanding, and exploring higher energy/power NIF operations

It is an exciting time on the NIF

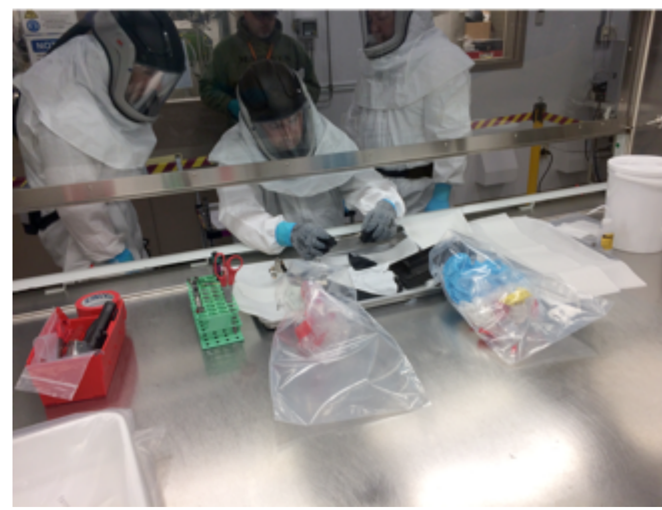
Dynamic x-ray diffraction and experiments studying material strength have returned important scientific data on the behavior of Pu at high pressures

NIF X-ray Diffraction Platform



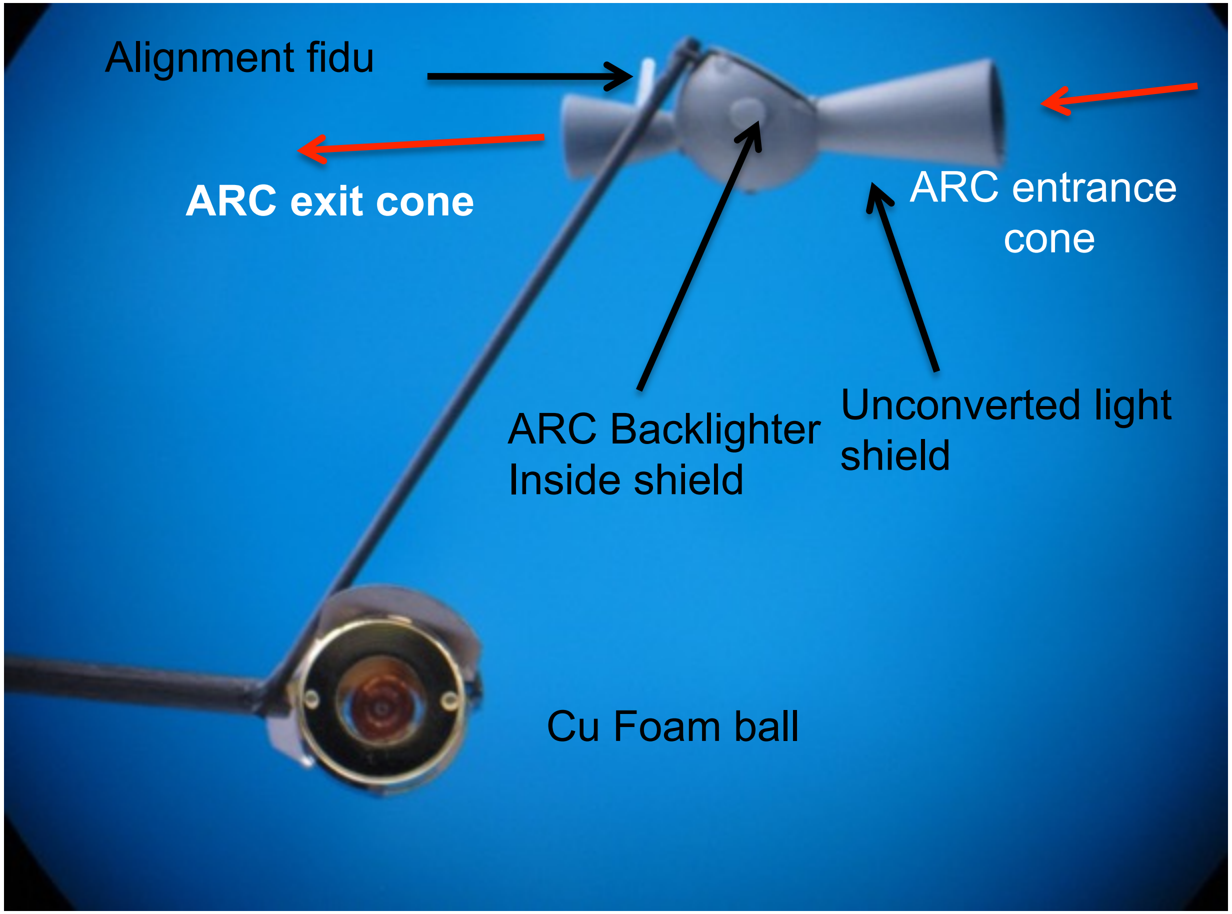


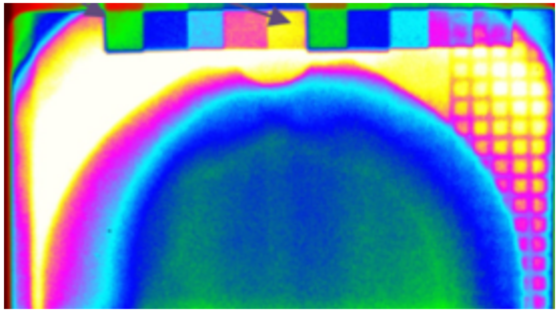
Lead data

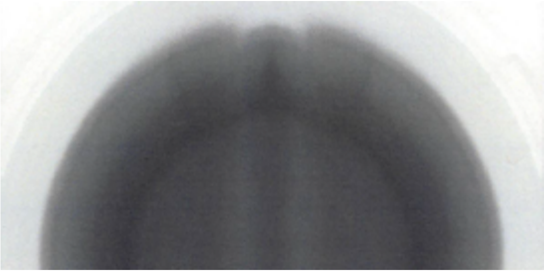


Eggert, et al.
Park, et al.

A new platform is returning important data on complex hydrodynamic phenomena using the Advanced Radiographic Capability (a short pulse laser on NIF) for high photon energy x-ray radiography



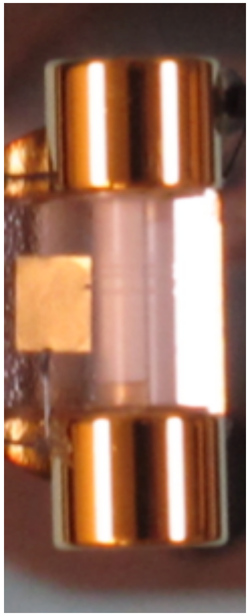


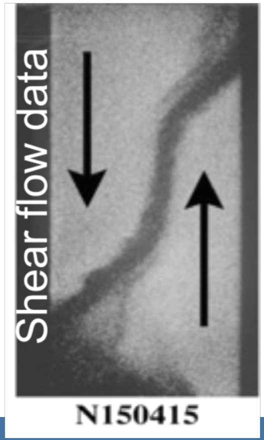


D. Martinez and ARC IPT

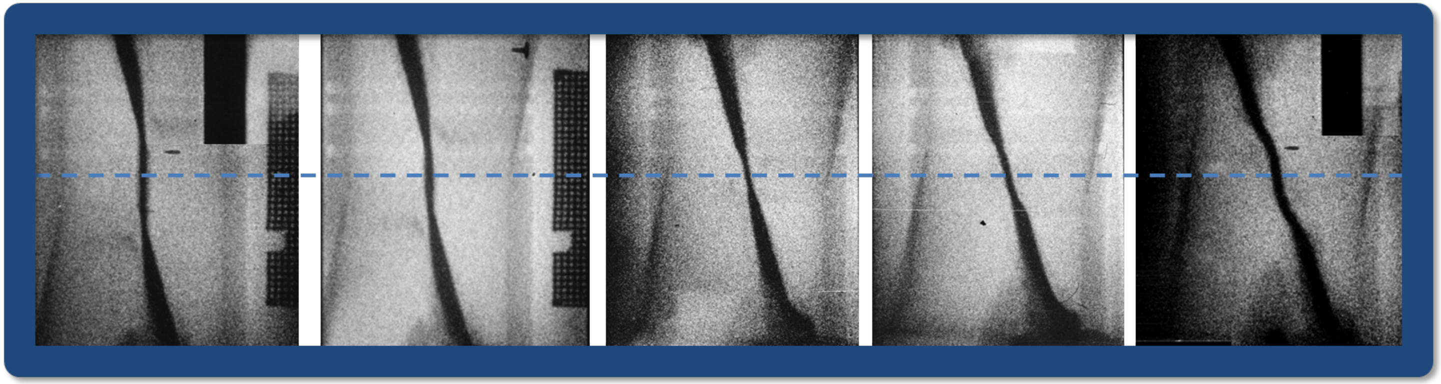
Los Alamos recently completed a 63 shot campaign to understand mixing in the presence of shear

Los Alamos
NATIONAL LABORATORY
EST. 1943

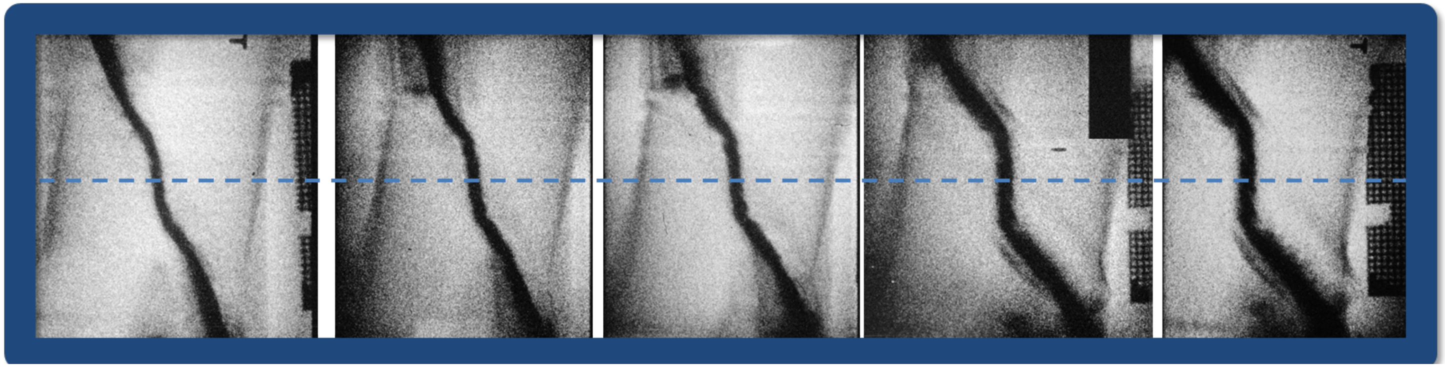




16.4 ns, S01-1 | 18.6 ns, S01-2 | 19.4 ns, S05-1 | 20.8 ns,S05-2 | 21.8 ns, S03-1



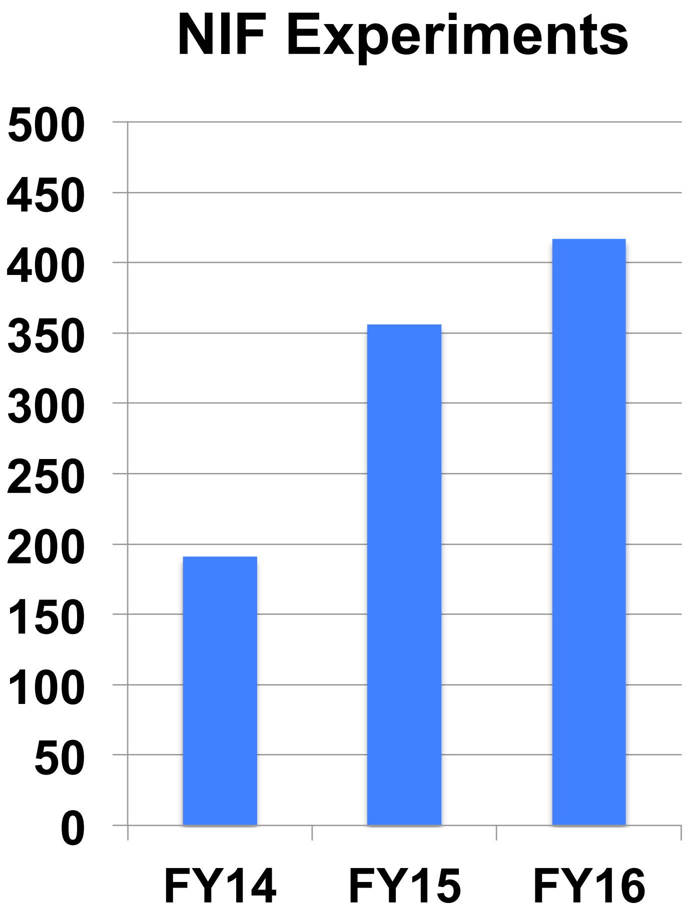
23.0 ns, S03-2 | 24.4 ns, S06-1 | 25.6 ns, S06-2 | 27.2 ns, S02-1 | 28.4 ns, S02-2



Doss *et al* POP **22** 056303 (2015), Flippo *et al* RSI **85** 093501 (2014), Ping *et al* POP **22** 112701 (2015), Flippo *et al* JPCS **688** 012018 (2016), Flippo *et al.* JPCS **717** 012062 (2016), Doss *et al.* JPCS **717** 012059 (2016), Capelli *et al* Fusion Sci Tech **70** 316 (2016), Flippo *et al* PRL **117** 225001 (2016), Doss et al. PRE **94** 023101 (2016)

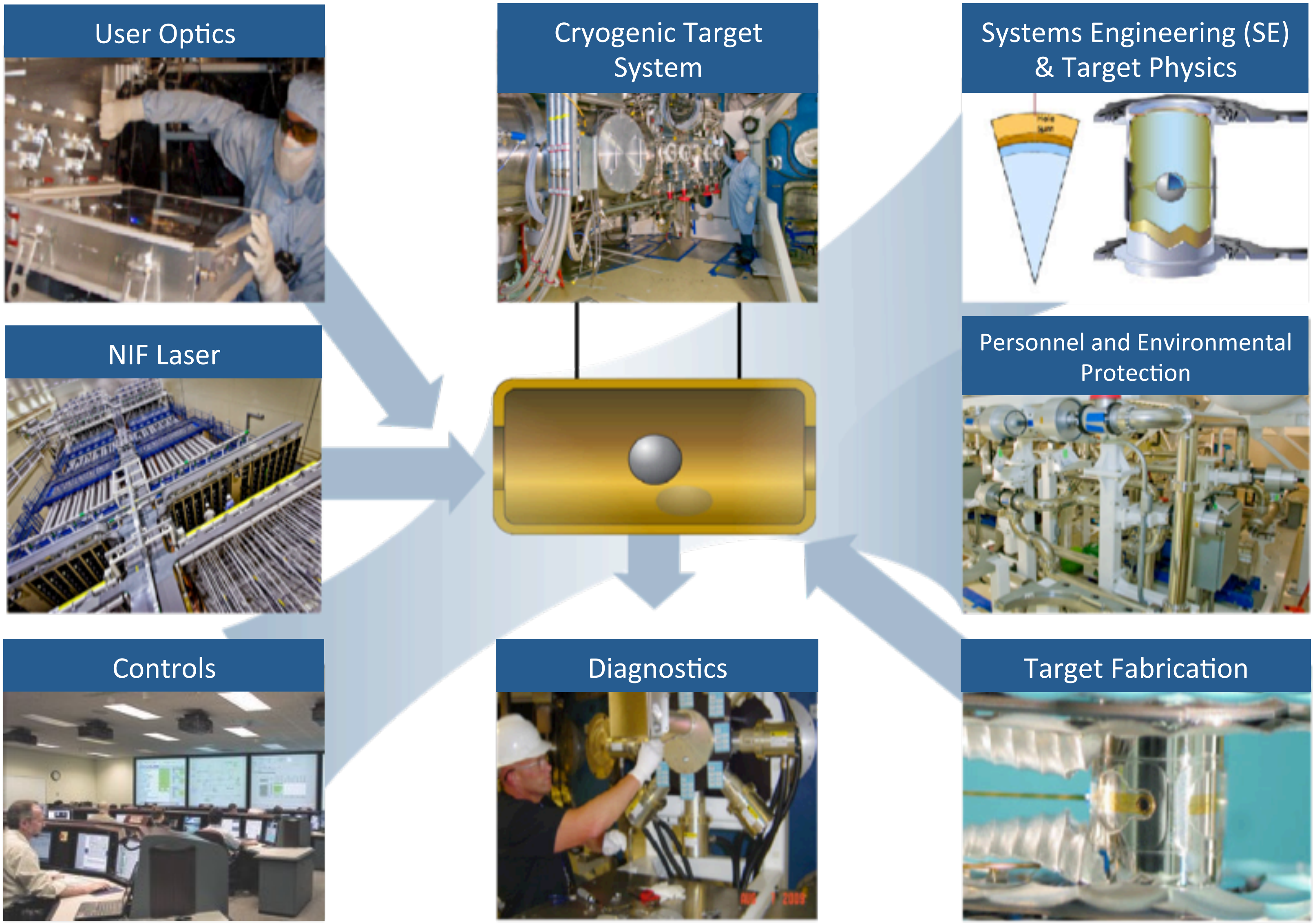
This work relies heavily on NIF's precision and shot to shot reproducibility

We significantly increased the scientific productivity of NIF from FY14 through FY16



- NIF is highly oversubscribed, every program would like more experimental opportunities
- Scientific publications with NIF data are increasing
- We increased the number of experiments from 191 in FY14 to 356 in FY15 to 417 in FY16 with fixed funding by implementing over 80 efficiency improvements.
- Percentage of experiments meeting expectations has remained high(>90%) as the number of shots has increased
- We have brought several new diagnostics on line (11 in FY16) and deployed new experimental capabilities enabling new measurements

Every system on NIF was improved in order to increase number of experiments with fixed funding

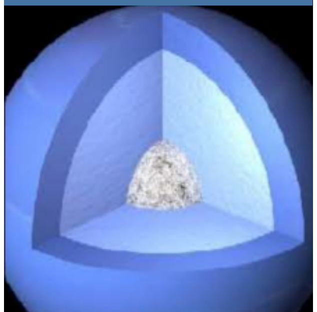


The large increase in shots has benefited all of NIF's users

User	FY14 Total	FY15 Total	FY16 Total	FY17 Total
LLNL	131	195	210	221
LANL	13	51	63	60
SNL	5	4	8	8
AWE	4	5	12	7
LLE	8	10	26	17
DTRA, MDA, Navy, C7, …	4	17	25	19
Discovery Science	8	44	38	47
Facility	18	30	35	29
Grand Total	**191**	**356**	**417**	**408**

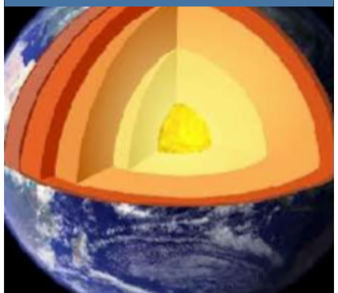
The Discovery Science Program is hitting its stride

High pressure phases of carbon



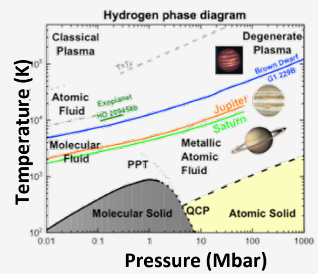
Wark (Oxford)

C, Fe EOS at planetary interior pressures



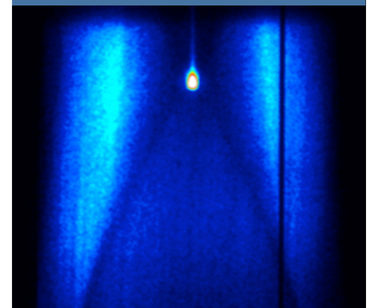
Duffy (Princeton), Jeanloz (UCB)

High pressure hydrogen properties



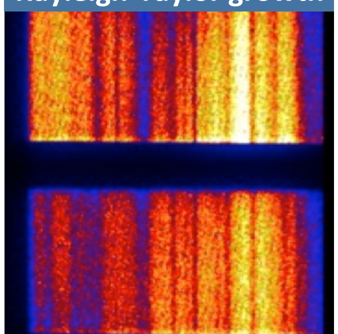
Jeanloz (UCB), Hemley (CIW)

CH and carbon at near Gbar pressures



Falcone (UCB), Neumayer (GSI)

Planar ablation front Rayleigh-Taylor growth



Casner (CEA)

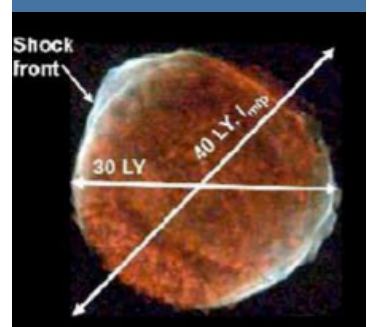
Molecular cloud radiative dynamics

Pound (Maryland)

Supernova explosion radiative hydrodynamics

Kuranz (Michigan)

Collisionless astrophysical shocks

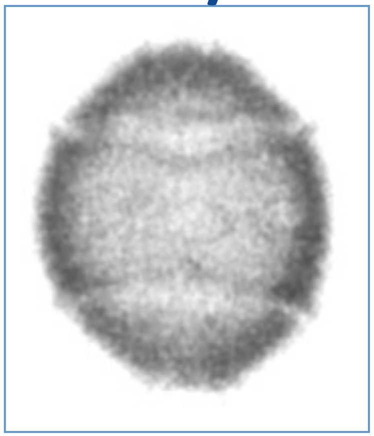


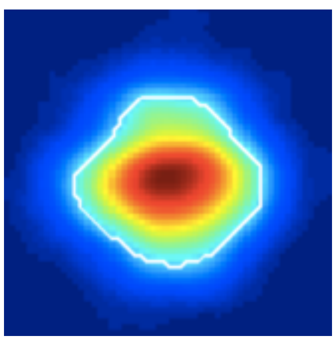
Sakawa (Osaka)

- Annual calls oversubscribed
- Excellent data obtained
- High impact publications submitted and published
- Programmatic spinoffs
- Strong staff engagement and recruiting opportunities
- External recognition

We are making progress in controlling inertial confinement fusion implosions

2012/13

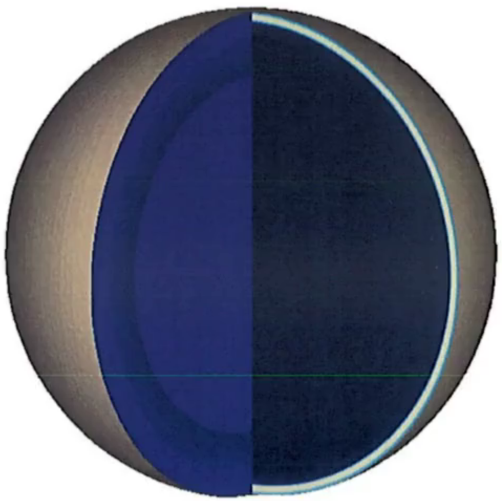




Yield ~ 2 kJ
Pressure ~ 150 GB
(7e14 DT neutrons)

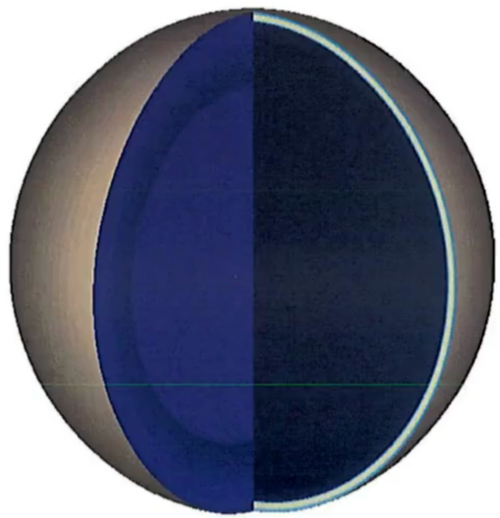
Initial experiments on NIF were strongly affected by implosion asymmetries and instability growth

1D



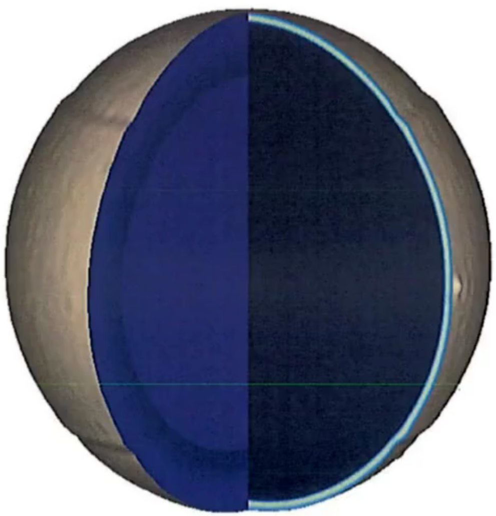
1D
500 zones
1 CPU
5 minutes runtime

3D, including low modes



3D low-res.
7,000,000 zones
1536 CPUs
1 day runtime

3D, including all perturbations



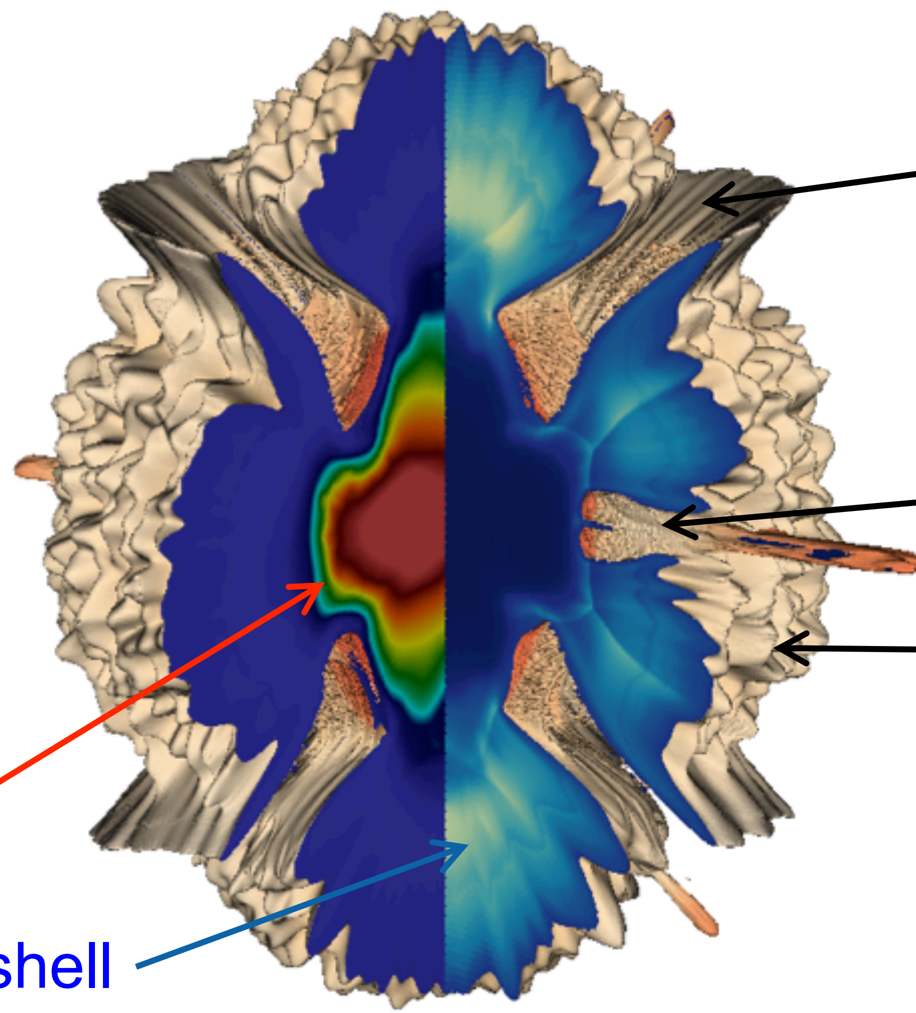
3D full-res.
400,000,000 zones
6144 CPUs
1 month runtime

Post-shot simulation of N120405
D. Clark et al.

Simulations provide critical insight. A grand challenge is to diagnose these implosions and constrain modeling in these extreme conditions

D. Clark –
3D Simulation of low foot N120405

C. Weber –
Postprocessed movie



We are making progress in controlling inertial confinement fusion implosions

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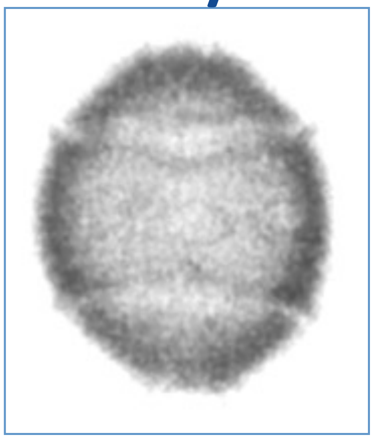
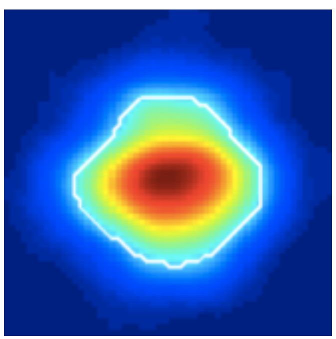
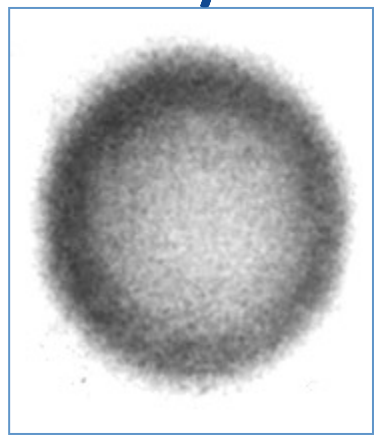


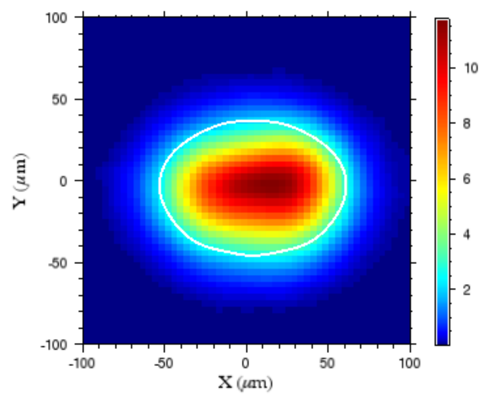


Yield ~ 2 kJ
Pressure ~ 150 GB
(7e14 DT neutrons)

Better hydro

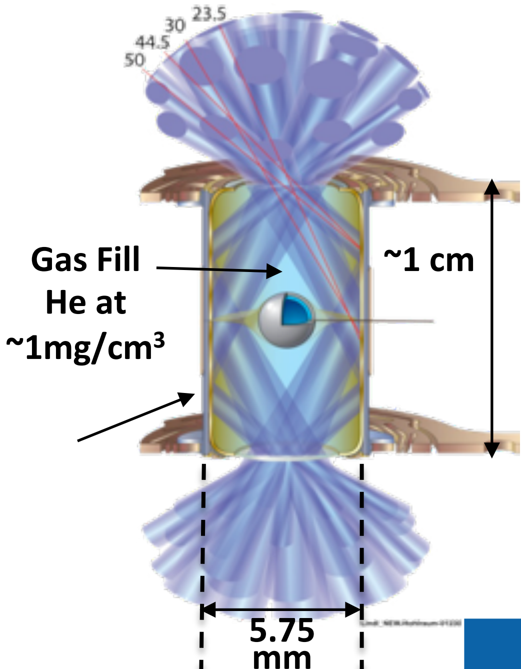
2014/15

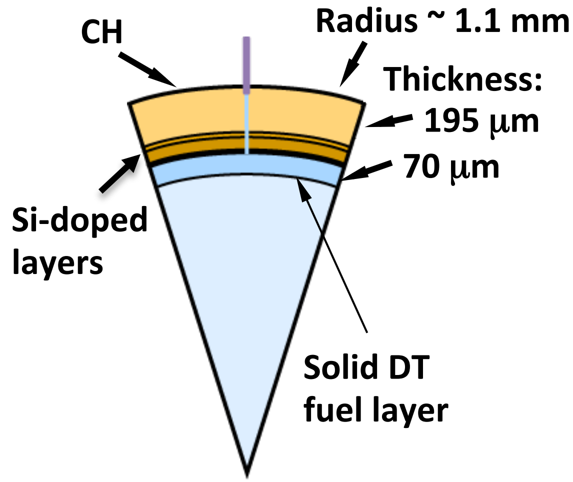


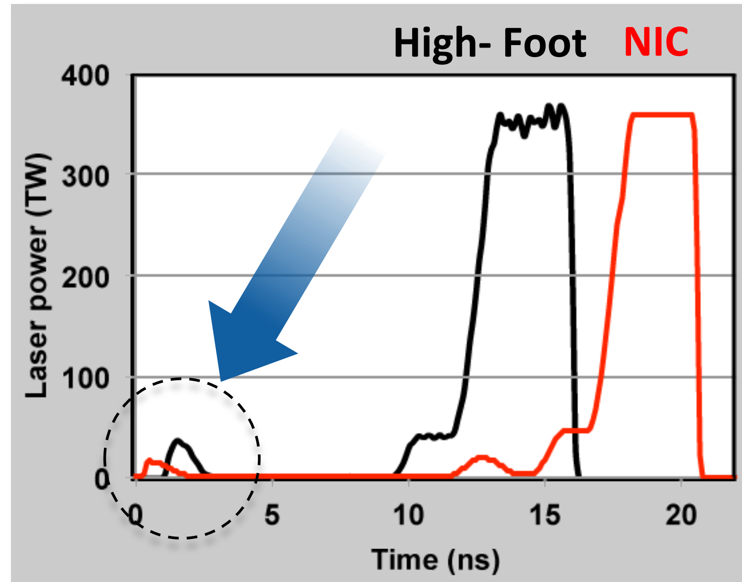


Yield ~ 27 kJ
Pressure ~ 250 GB
(9 e15 DT neutrons)

The “High-foot”* is a pulse-shape modification designed to reduce hydrodynamic instability



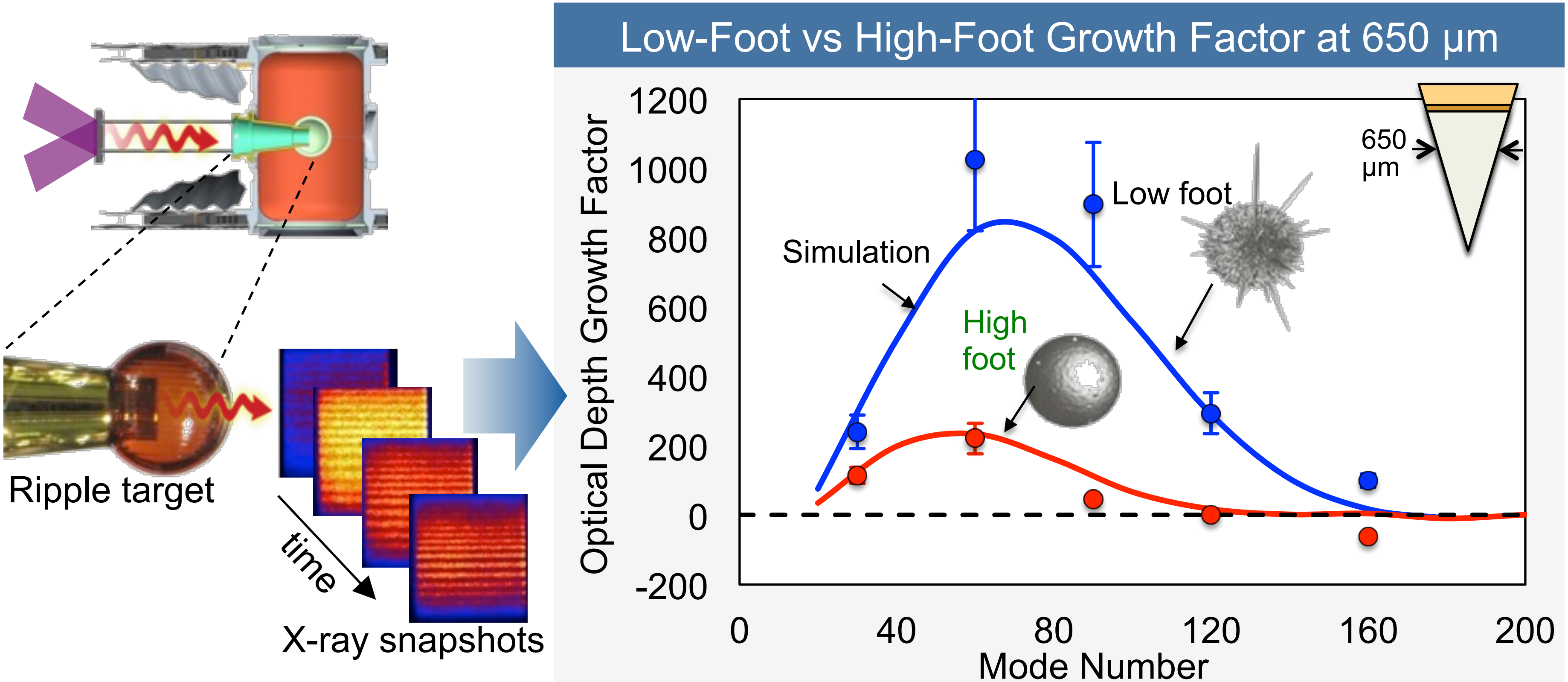




	NIC Low-foot	High-foot
Adiabat (a measure of entropy)	~1.5	**Increased to:** ~2.5
In-flight aspect ratio, (IFAR)	~20	**Reduced to:** ~10
Convergence	~45	**Reduced to:** ~30

*Dittrich et al., *PRL, **112***, 055002 (2014); Park et al., *PRL, **112**,* 055001 (2014); Hurricane et al., *Nature*, ***506***, 343 (2014); Hurricane et al., Phys. Plasmas, Vol. **21**, No. 5 (2014)

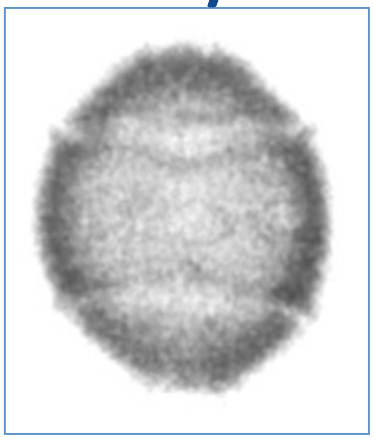
Raising the foot reduces the growth rate of hydrodynamic instabilities

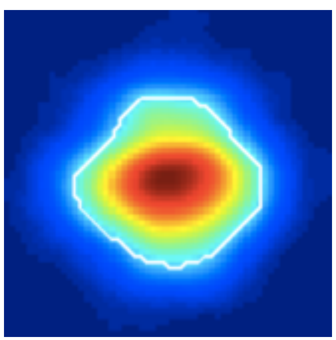


Raman, Peterson, Smalyuk, Robey

We are making progress in controlling inertial confinement fusion implosions

2012/13

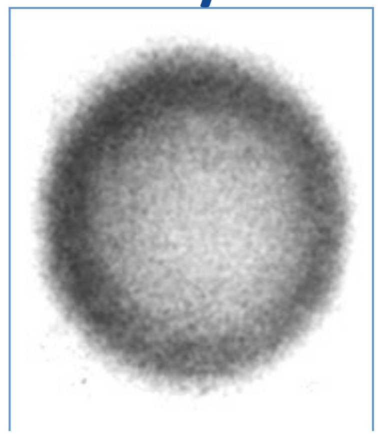


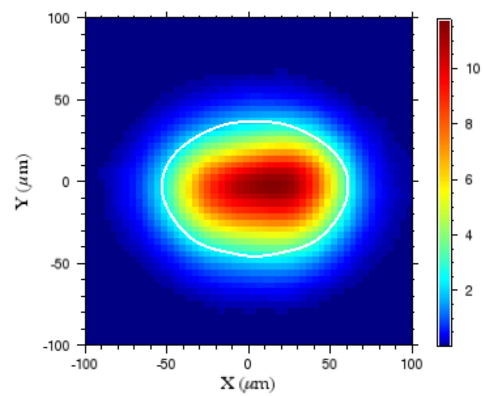


Yield ~ 2 kJ
Pressure ~ 150 GB
(7e14 DT neutrons)

Better hydro

2014/15

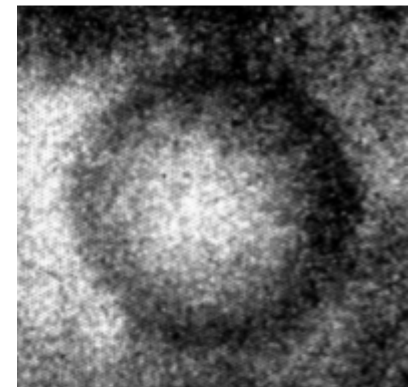


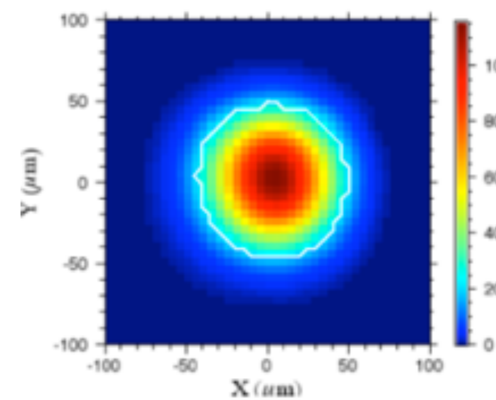


Yield ~ 27 kJ
Pressure ~ 250 GB
(9 e15 DT neutrons)

Better LPI, symmetry
Reduce fill tube

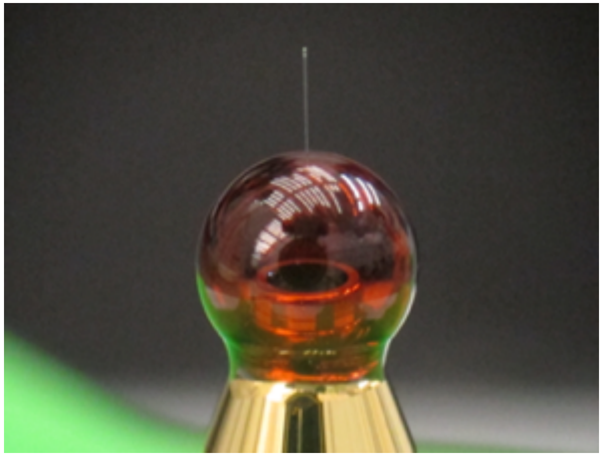
2016/17

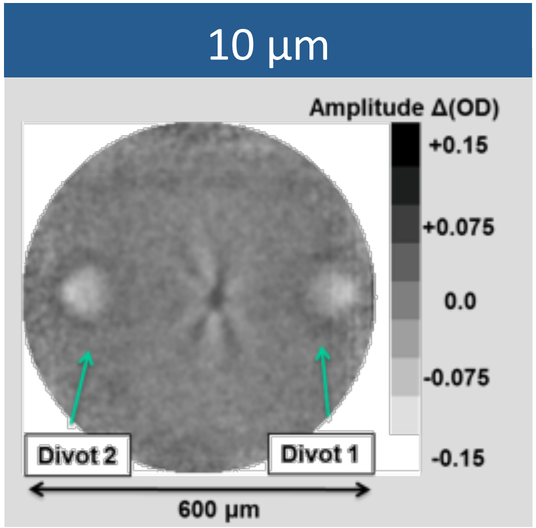


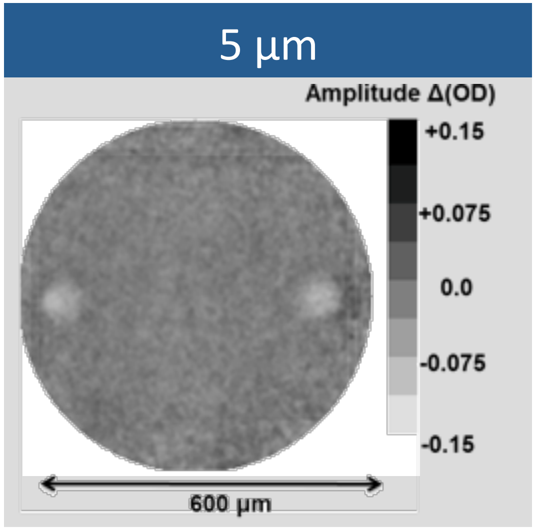


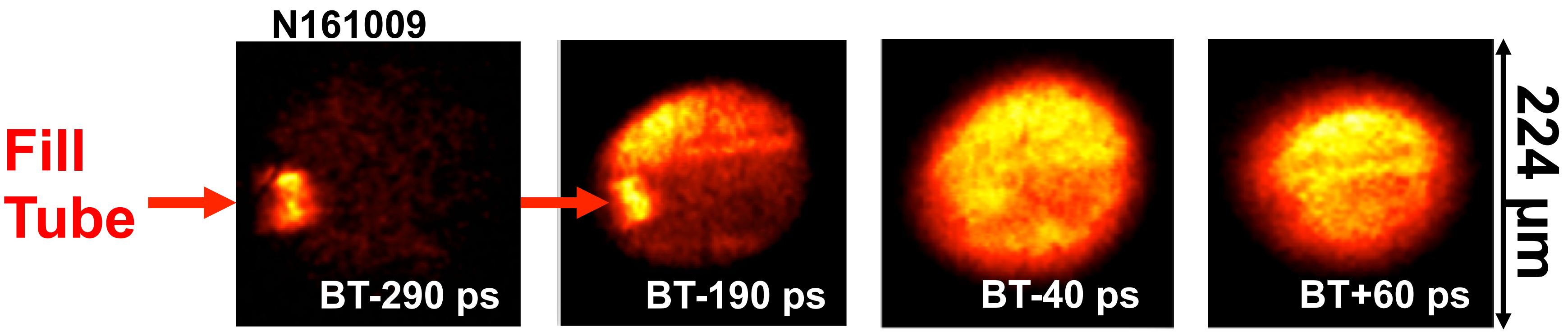
Yield ~ 57 kJ
Pressure ~ 350 GB
(2 e16 DT neutrons)

New measurements have highlighted that the perturbation from the fill tube is many times bigger than expected



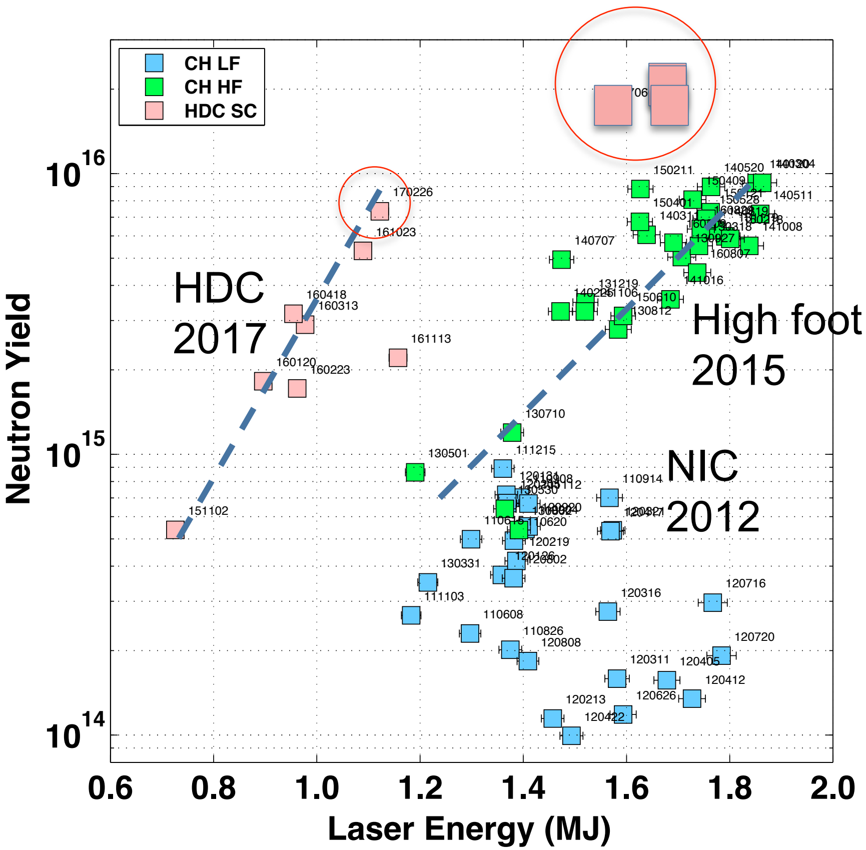


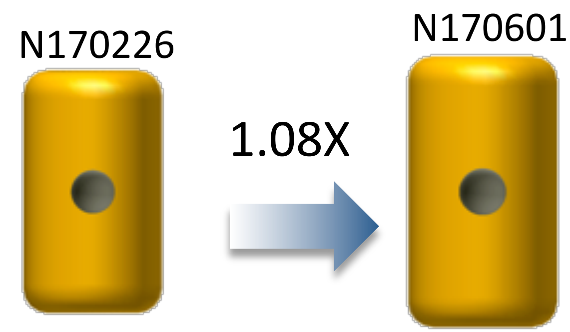




MacPhee, et al, Pickworth, et al.

Recent scaled up diamond experiments with 5 micron fill tubes (1.08x) significantly exceeded previous NIF yield records (47kJ, 53 kJ, and 57 kJ ~ 2.e16)

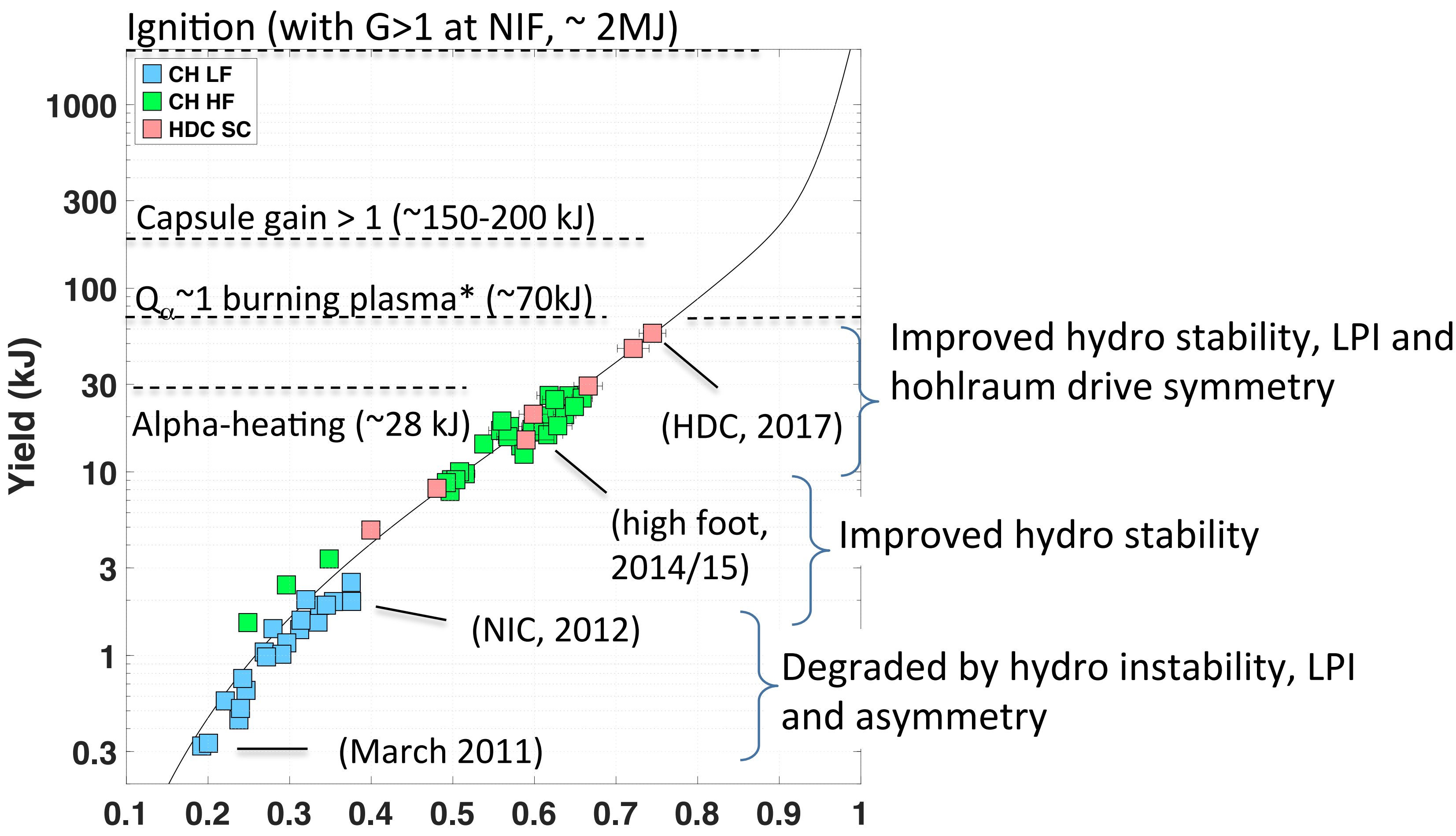




Y~47kJ, 53 kJ, 57 kJ versus 27kJ previous record

N170601	
E_{laser} (MJ)	1.57
P_{laser} (TW)	465
Y_{total} (#)	1.7×10^{16}
T_{Brysk} (keV)	4.7
ρR_{fuel} (g/cm^2)	0.64
ρR_{hs} (g/cm^2)	0.22-0.24
P_{stag} (Gbar)	300
$Y_{\alpha}/Y_{no\text{-}\alpha}$	~2.5
velocity (km/s)	~380

Our goal is ignition (fusion energy out = laser energy in)



Lawson Criterion, χ $\chi = (P\tau / P\tau_{IGN})$

Betti R. et al., PRL **104**, 135002, (2010).

*Betti R. et al., PRL **114**, 255003, (2015).

P-tau has improved significantly in the last year

Lawson like power balance

$P \sim 2nT$

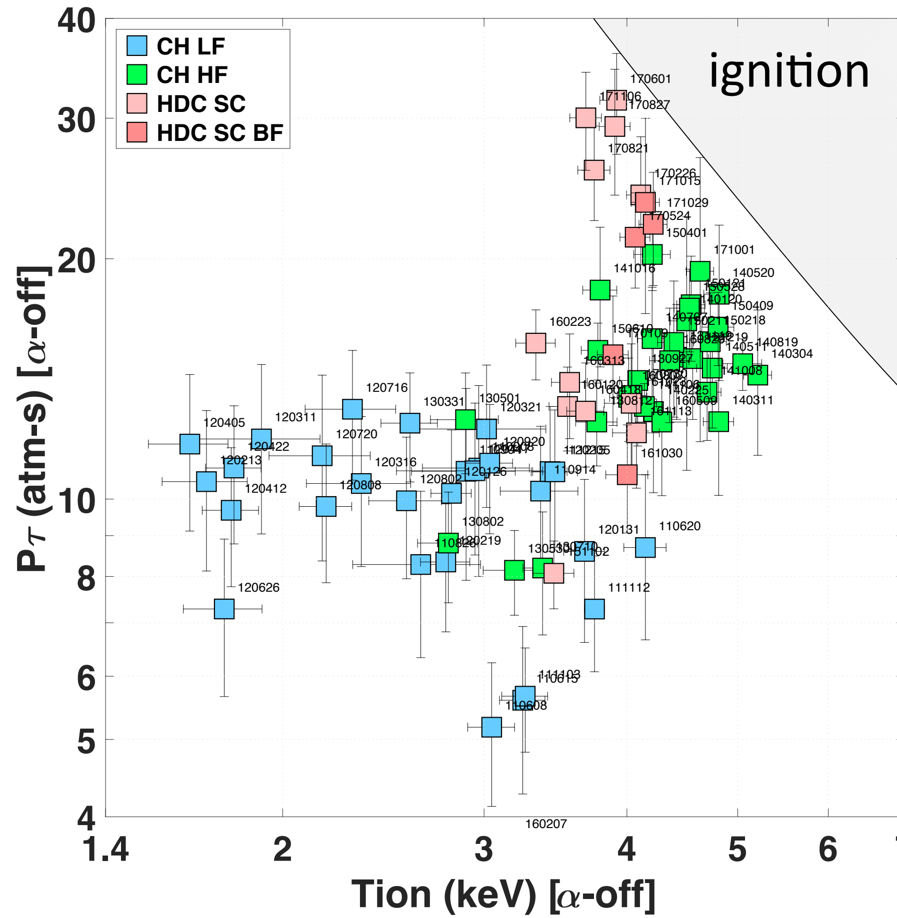
$$\frac{n^2}{4} \langle \sigma v \rangle V \varepsilon_\alpha > \frac{3}{2} \frac{PV}{\tau}$$

$$P\tau > \text{const.} \frac{T^2}{\langle \sigma v \rangle} \sim \frac{1}{T^{\sim 2}} = P\tau_{ign}$$

$\langle \sigma v \rangle \sim T^{\sim 4}$

$$\chi_{no\text{-}\alpha} = \frac{P\tau}{P\tau_{ign}} = 1 \quad \text{for ignition}$$

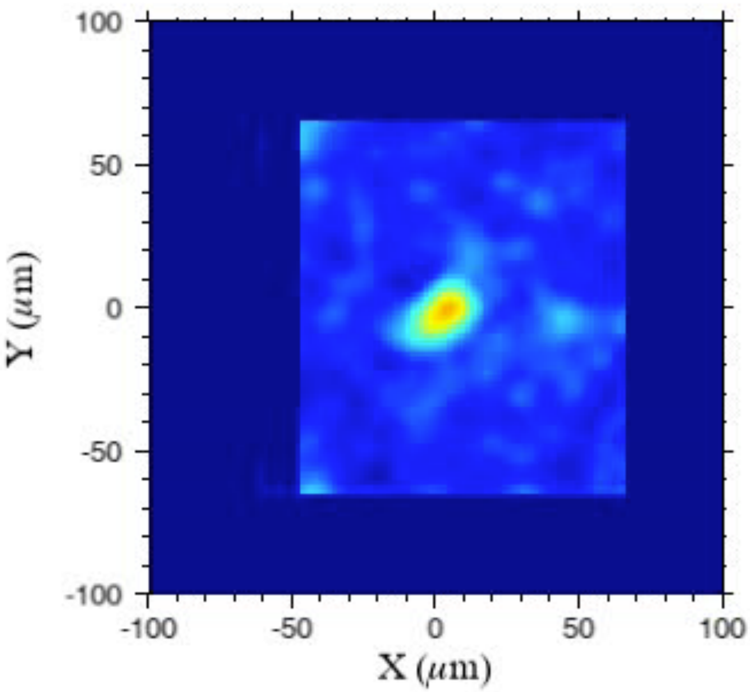
$$E_{ign} \sim \chi^2_{no\text{-}\alpha}$$

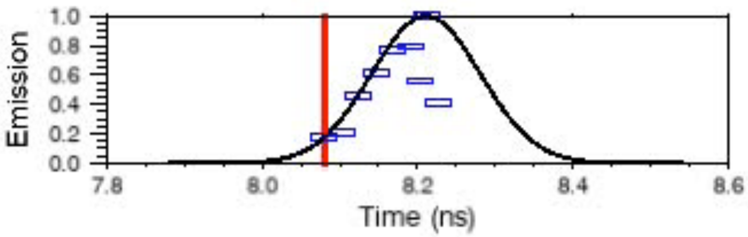


New diagnostics capture the dynamics on a 10x faster time scale than was previously possible

X-ray movie of the Implosion

DIXI recorded an x-ray movie of implosion

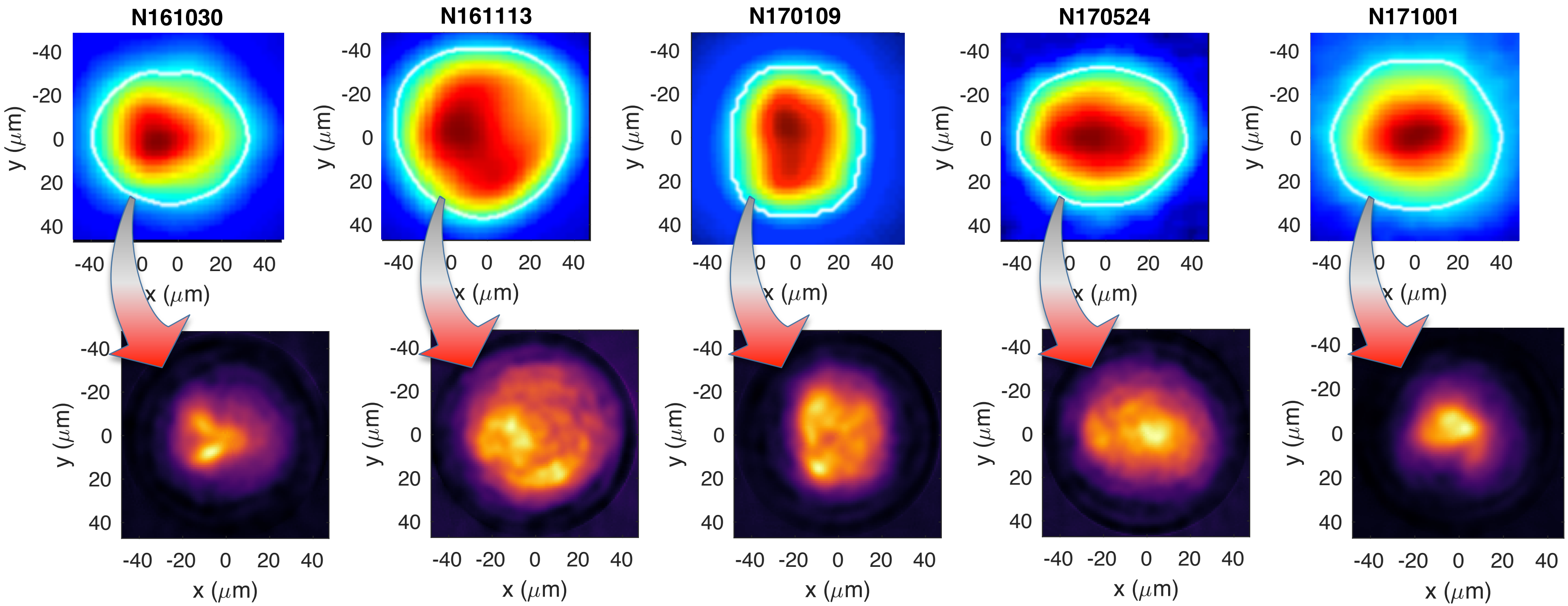




Diagnosing 3-D morphology with high spatial and temporal resolution in combination with the burn history is critical for all approaches

New diagnostics, like penumbral imaging, are giving new insights into implosion performance

Low Resolution Pinhole Images (standard pinhole res. ~ 14 μm, 90-78 LoS)

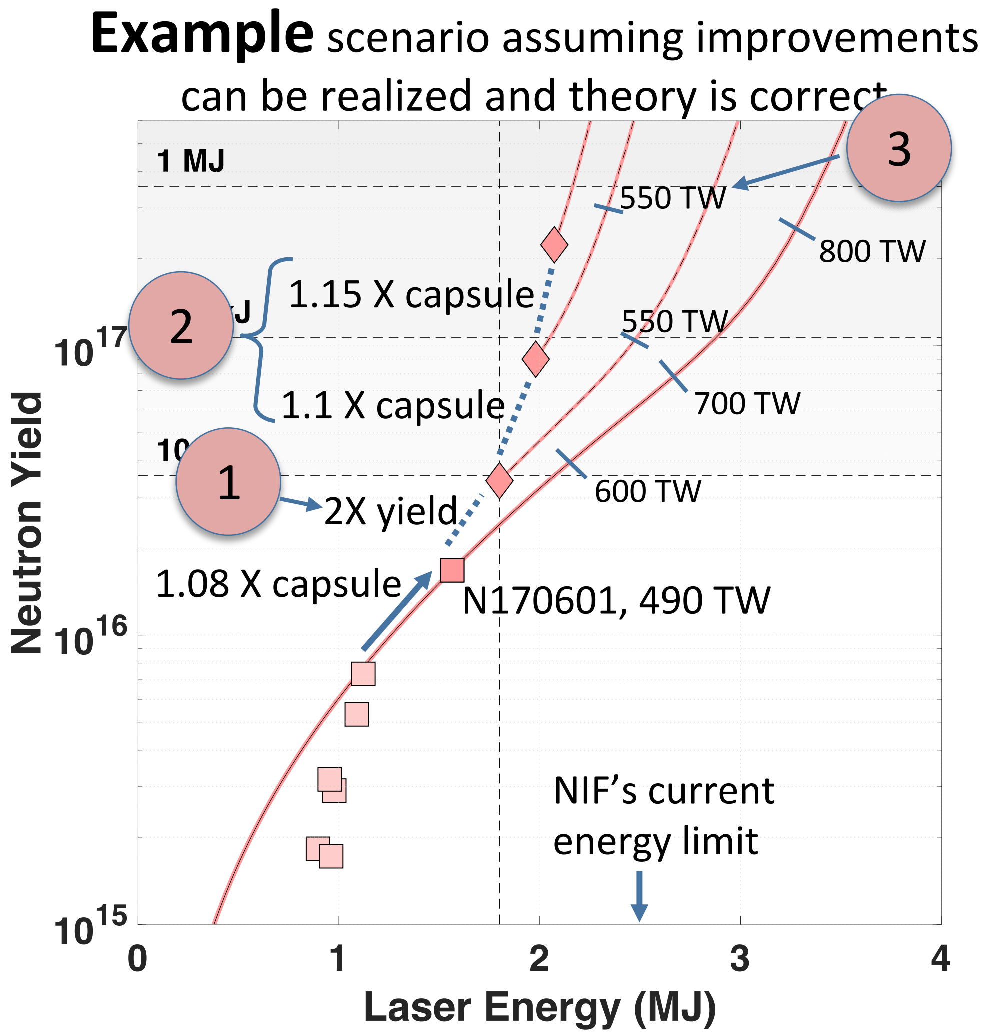


High Resolution Penumbral Images (~ 5 μm, 90-100 LoS)

Bachmann et al.

4

There are several steps to explore on the path forward



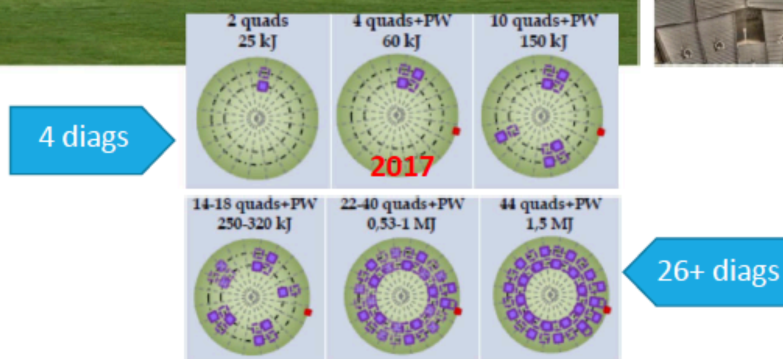
1) **Optimize current designs**: capsule size, engineering features, residual asymmetry, at full power and energy

2) **Improve the hohlraum** to admit larger, more robust capsules

3) **Increase laser power and energy**

France's Laser Megajoule has performed its first experiments and will be ramping up the number of beams over the next few years

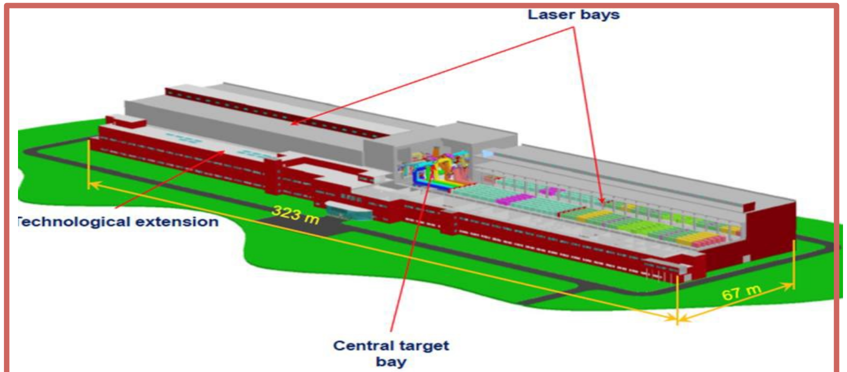
LMJ ramps up power gradually, allowing a robust roadmap towards ignition



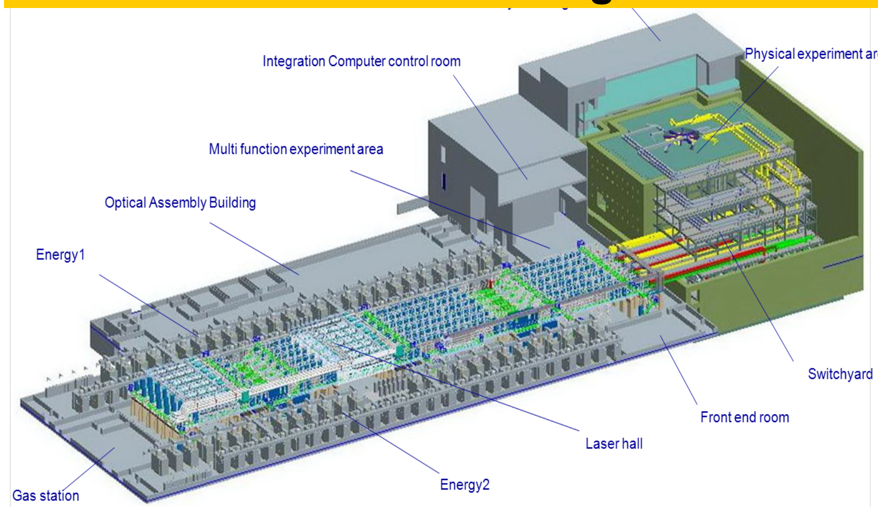
- Plan has 40 beams coming on line in 2019 eventually 176
- CEA-NNSA agreement has been renewed and there is increasing outreach and coordination
  - Optics
  - Laser modeling
  - Diagnostics
  - Infrastructure (particularly cryo positioner)
  - Operations
- Specific mutually beneficial activities in each area

Both Russia and China are investing significantly in the area of lasers for high energy density physics

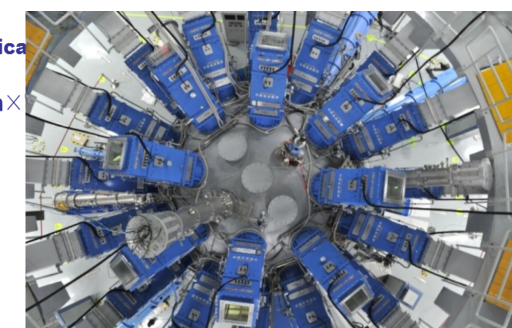
UFL-2M
- **192 beams, 2.8 MJ (1.5x NIF energy)**
- **Construction underway**



Shenguang III (180 kJ) is now operating
- **48 beams arranged in polar configuration**
- **80 diagnostics**
- **World's second most energetic laser**



2. Optica
72.8m×



NIF is delivering for the Stockpile Stewardship Program

- Stockpile stewards are using NIF to obtain the data needed for SSP, including the ongoing stockpile modernization. We frequently make discoveries that challenge our simulations, our assumptions, and our stockpile stewards.
- The increase in NIF shot rate has enabled significantly more experiments for all users, enabling faster progress in ICF, HED, and the NIF Discovery Science Program
- Achieving inertial confinement fusion ignition in the Laboratory is a grand scientific challenge.
  - Progress is being made on understanding and improving inertial confinement fusion target performance
  - New diagnostics are providing critical insights that will lead to further progress
  - Path forward involves reducing perturbations from engineering features, increasing capsule/hohlraum size, enhancing understanding, and exploring higher energy/power NIF operations

It is an exciting time on the NIF

Lawrence Livermore National Laboratory