Recent Inertial Confinement Fusion Results from the National Ignition Facility

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On behalf of the NIF and ICF Teams

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Los Alamos National Laboratory
Lawrence Livermore National Laboratory
Sandia National Laboratories
GENERAL ATOMICS
UR LLE

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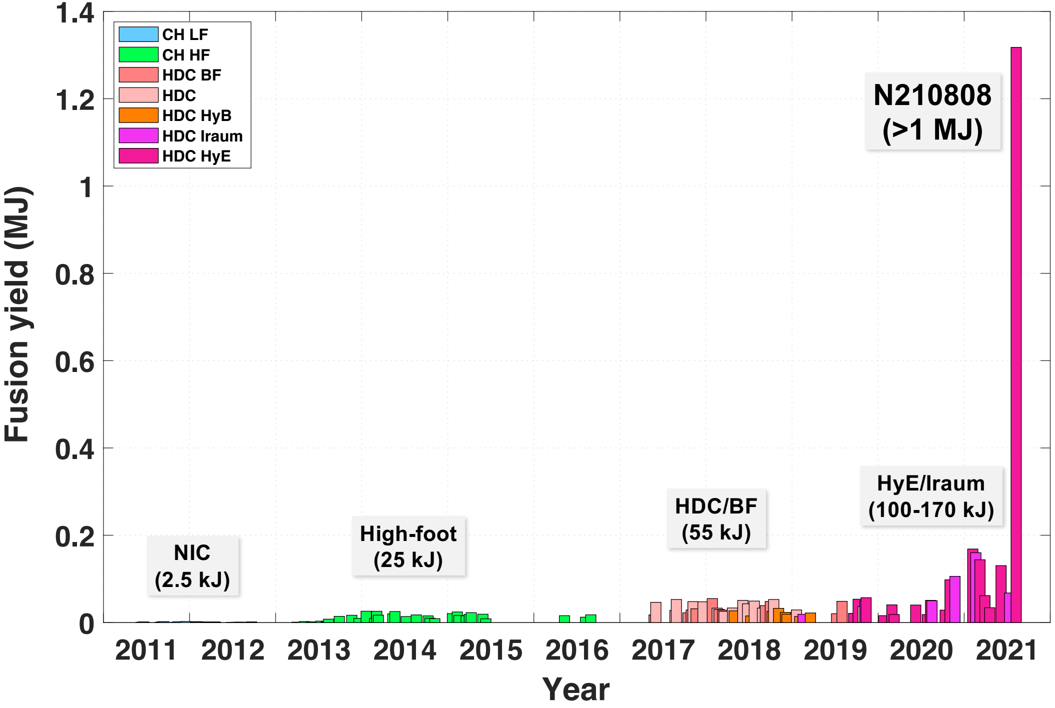
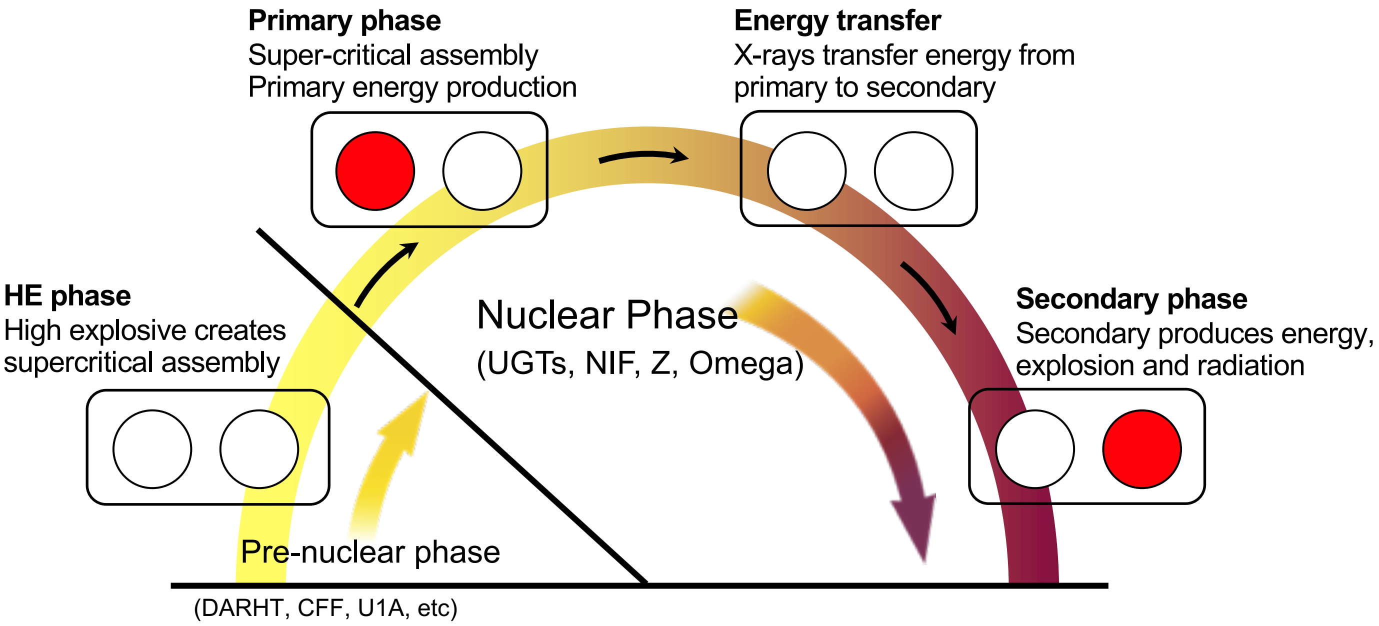
The August 8th shot on NIF yielded more than 1.3 MJ and marks a significant advance in ICF research



- By NAS 1997 Definition of Ignition, achieved gain ~0.7 (Fusion Yield/Laser Energy)
- This is the first NIF shot to achieve capsule gain (yield/absorbed energy) ~5+, E_{abs}~ 230 kJ
- All data are consistent with self-heating and burn propagating into the ice
- Repeat experiments are planned for Oct-Nov, to assess variability in this new regime
- There are many exciting possibilities for further improvements and applications to stockpile science

>99% of the yield of our nuclear weapons occurs in the high energy density state. NIF, Z, and Omega play a critical role in supporting the science-based Stockpile Stewardship Program



Primary phase
Super-critical assembly
Primary energy production

Energy transfer
X-rays transfer energy from primary to secondary

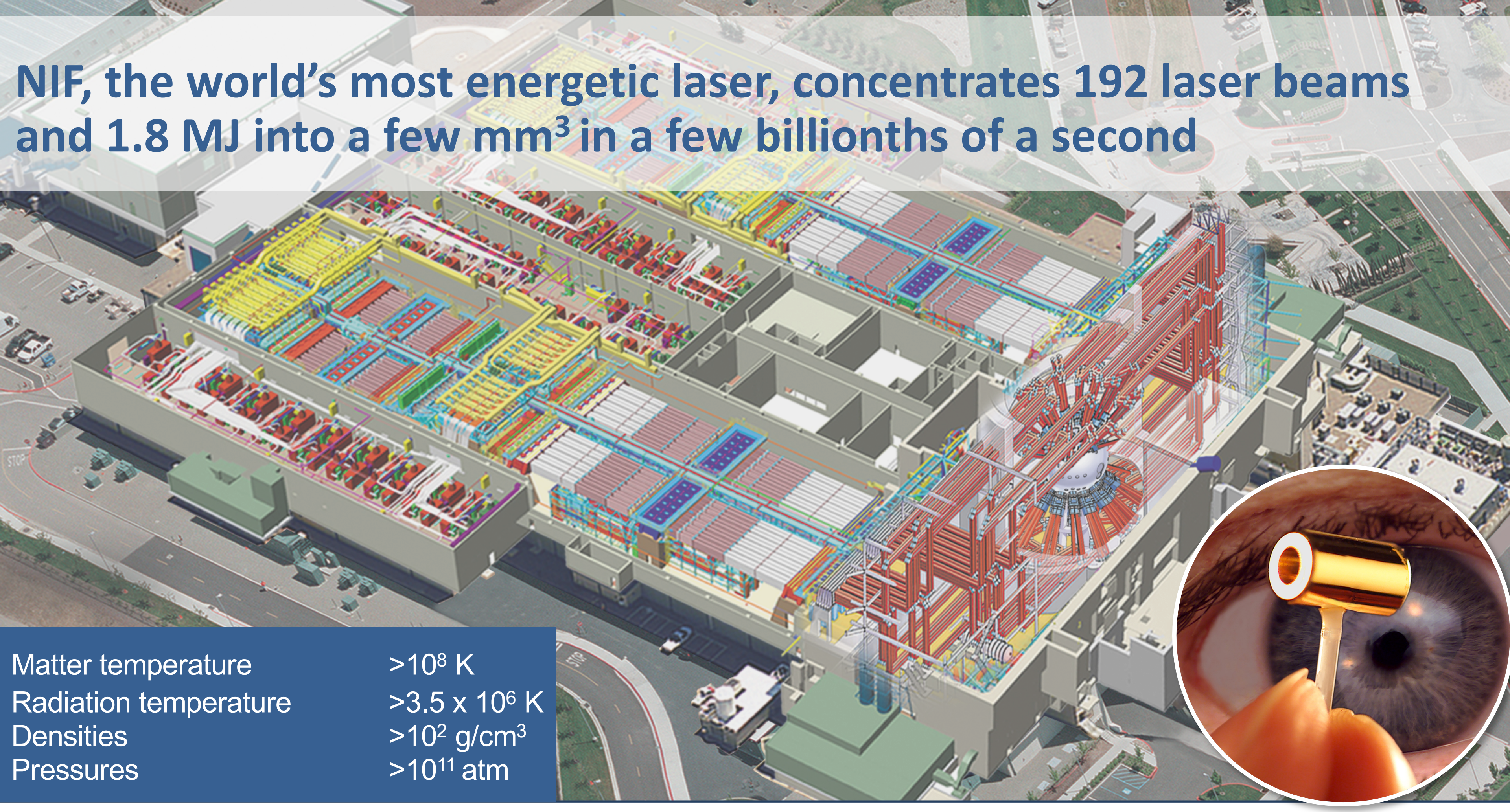
HE phase
High explosive creates supercritical assembly

Nuclear Phase
(UGTs, NIF, Z, Omega)

Secondary phase
Secondary produces energy, explosion and radiation

Pre-nuclear phase
(DARHT, CFF, U1A, etc)

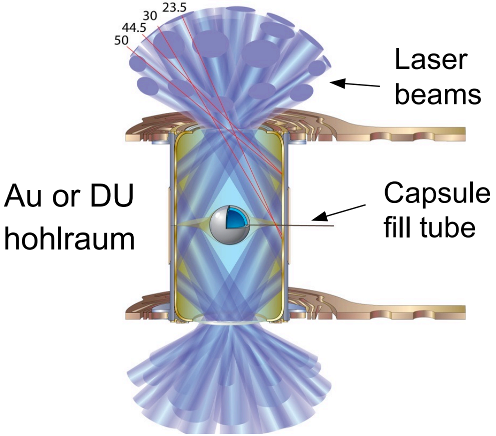
NIF, the world's most energetic laser, concentrates 192 laser beams and 1.8 MJ into a few mm^3 in a few billionths of a second



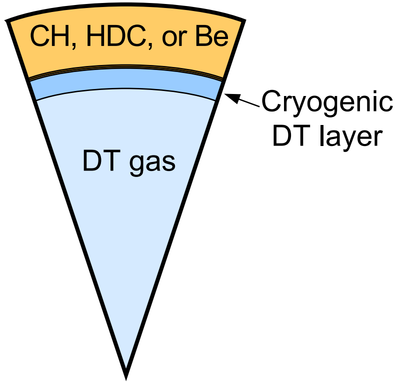
Matter temperature	>10^8 K
Radiation temperature	>3.5 x 10^6 K
Densities	>10^2 g/cm^3
Pressures	>10^{11} atm

Most fusion experiments on NIF use laser indirect drive to compress the deuterium and tritium mixture to extreme conditions

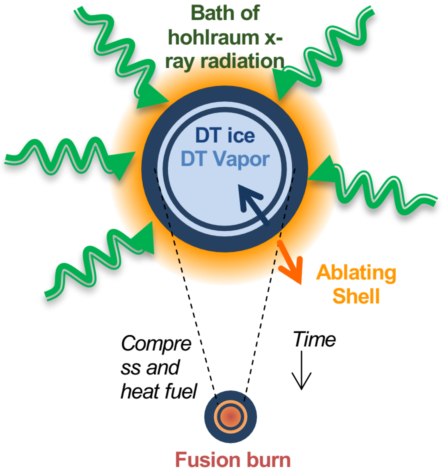
The hohlraum is a cylindrical cavity that serves as an x-ray “oven”



The fuel capsule consists of an ablator surrounding DT ice and gas

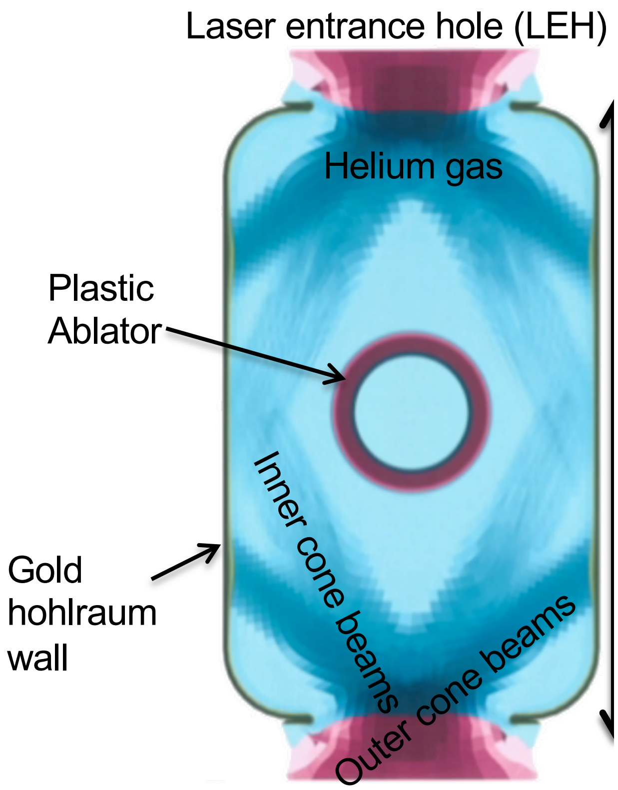


The trick of ICF is to turn 100 million atmospheres of pressure into 300 billion



Haan*, et al.*, *PoP*, 2011

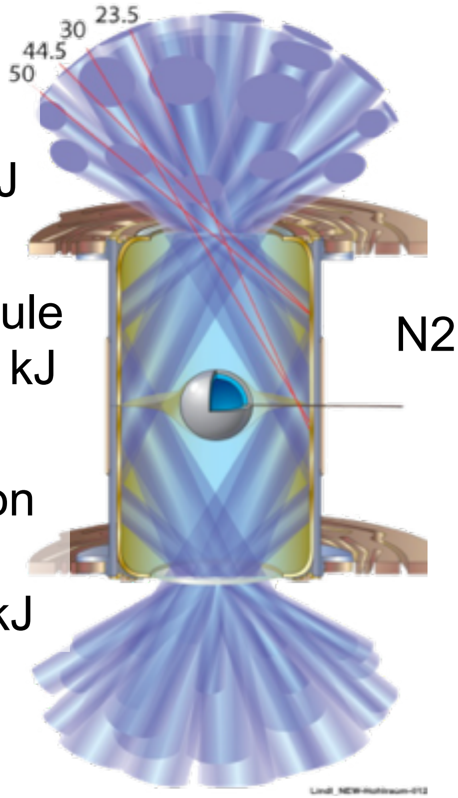
A fraction of the energy in the NIF lasers ends up in the DT fuel



Laser
1.9 MJ

Capsule
~230 kJ

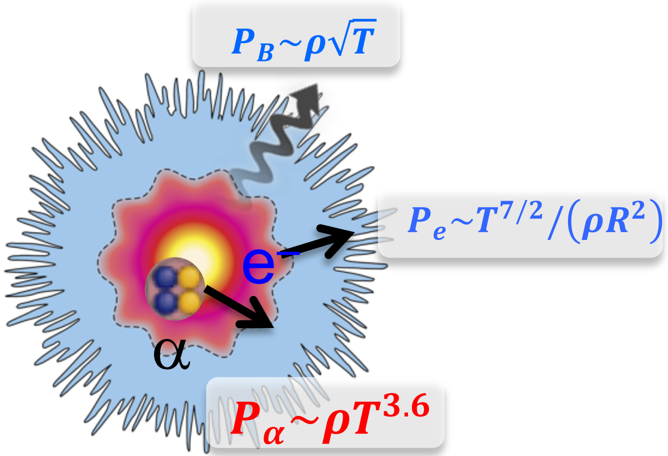
Fusion
Fuel
~23 kJ

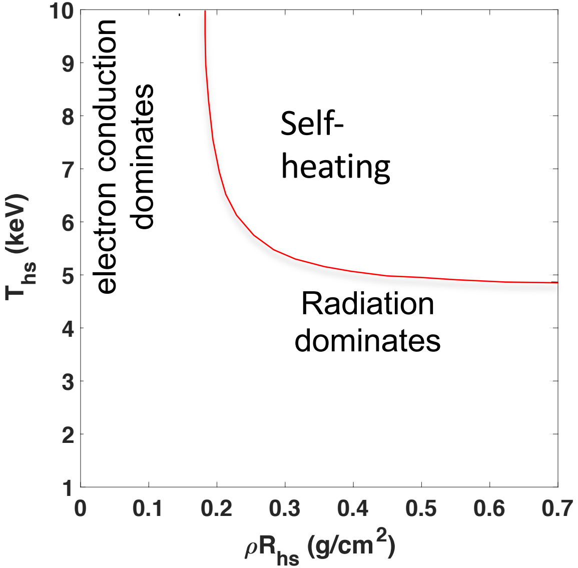


N210808 Yield=1.35MJ

At a high level, we are working to create the hottest, densest, biggest mass of DT we can (large ρr, large T)

$$c_{DT}\frac{dT}{dt} = f_\alpha P_\alpha - f_B P_B - P_e - \frac{1}{m}p\frac{dV}{dt}$$





For self heating $\rho R \gtrsim 0.3$ gm/cm^2
$T \gtrsim 5$ keV

$$E_{HS}P_{HS}^2 \propto (\varrho_{HS}R_{HS})^3 T_{HS}^3$$

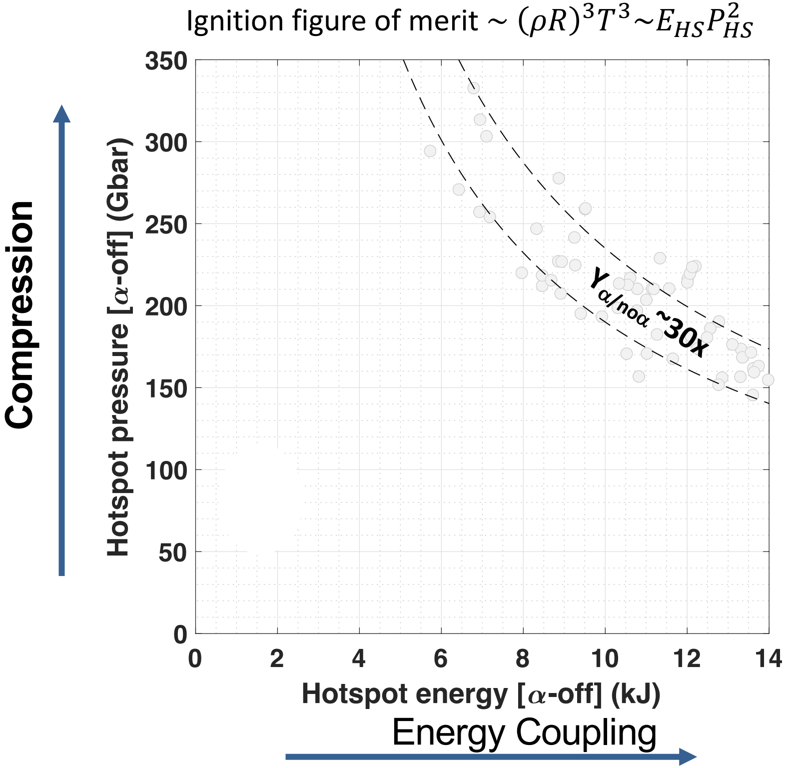
Hot spot energy and hot spot pressure are two useful

Energy available is small (~15 kJ)

Pressure must be enormous (100’s of Gigabars)

We can map out our progress over the years in E_{HS} and P_{HS} space

- Figure of Merit ~ $(\rho R)^3 T^3 \sim E_{HS} P_{HS}^2$
- Yield Amplification is simulation quantity: Yield obtained when heat is deposited by fusion reactions versus no heat deposited. $Y_{\alpha/\mathrm{no}\alpha} \sim 15 - 30$, is where burn propagation is expected to begin



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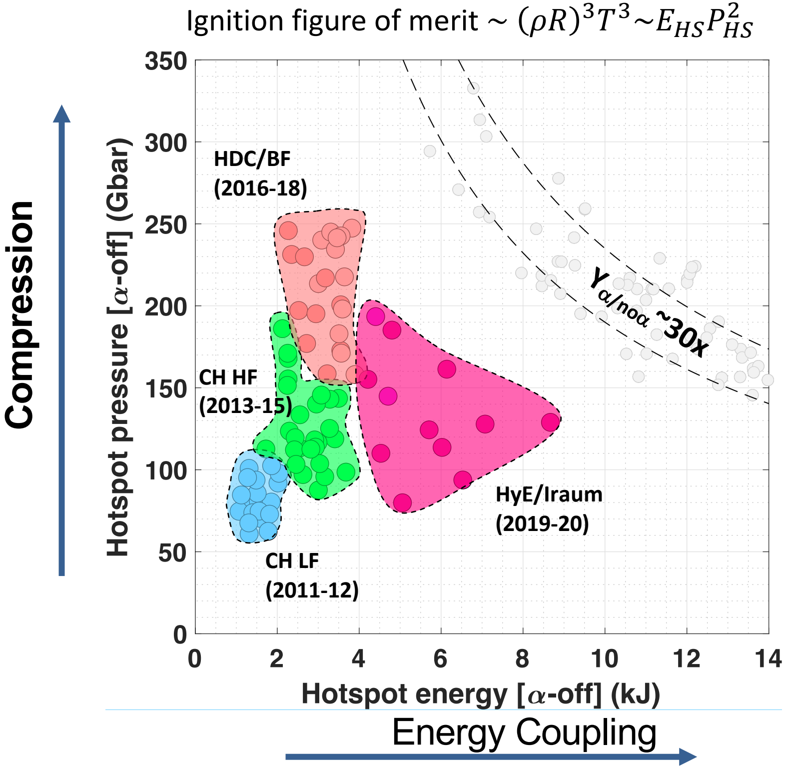
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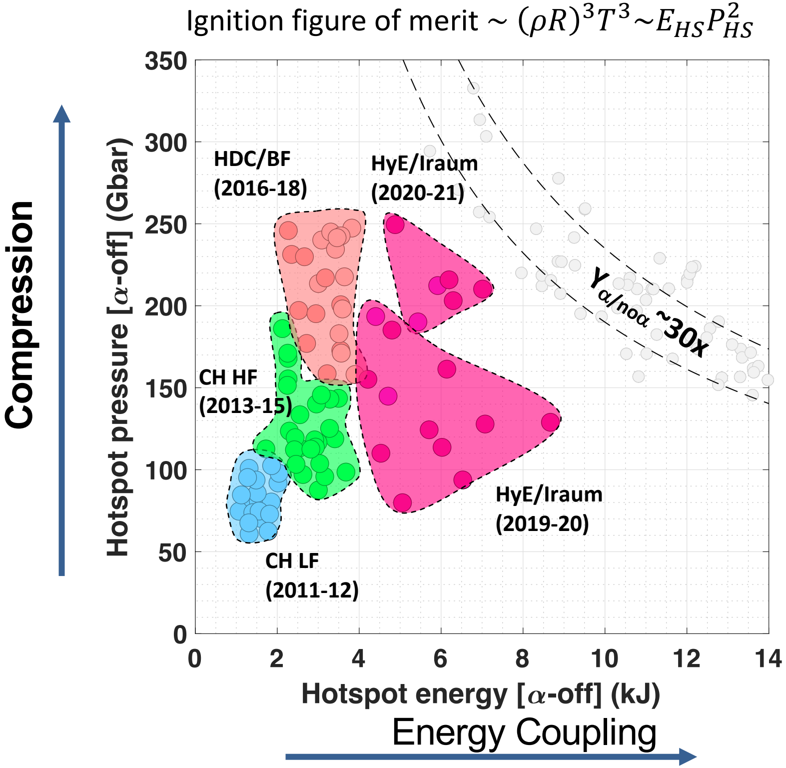
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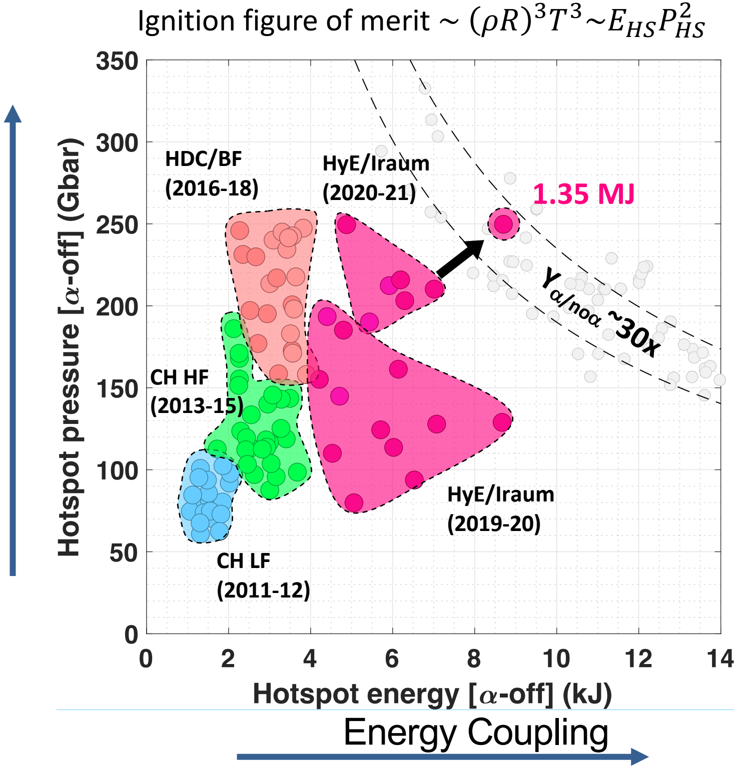
- Initial assessment suggests N210808 closed much of that gap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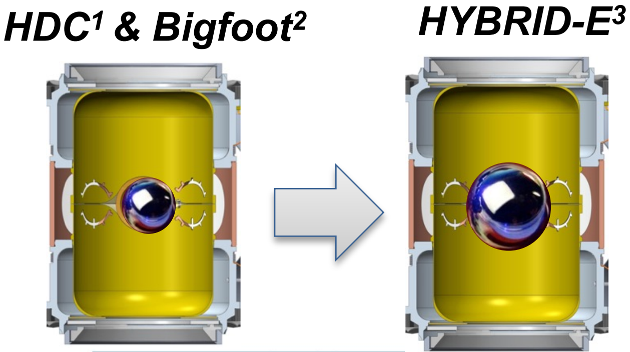
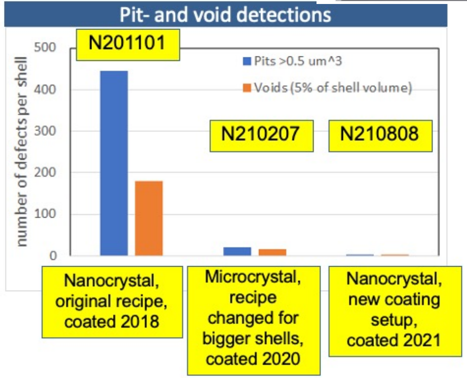
PRELIMINARY DATA– ANALYSIS UNDERWAY

Spurred on by advances in target designs, diagnostics, targets, and the NIF laser, we have made exciting progress over the last two years



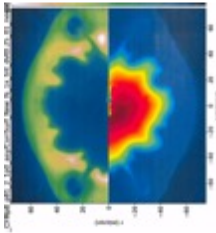


- Symmetrically imploding larger capsules that absorbed more energy
- Experimental and theoretical understanding of how to maintain pressure at stagnation as capsules were made bigger
- Better diagnostics enable us to diagnose and then fix some degradations that had appeared random
- A key challenge was targets. Even though they were technological marvels, real-world imperfections such as pits, voids, fill tube, and shell non uniformity were contributors to yield variation
- Laser variation also played a role and was addressed

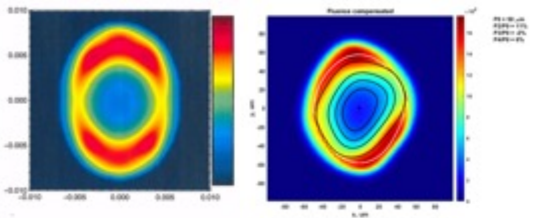
1: S. Le Pape et al., PRL 120, 245003 (2018); L.B. Hopkins et al., PPCF 61, 014023 (2018)
2: D.T. Casey et al., PoP 25, 056308 (2018); K.L. Baker et al., PRE 102, 023210 (2020)
3:O. Hurricane et al., PPCF 61, 014033 (2019); A.B. Zylstra et al., PRL 126, 025001 (2021); A.L. Kritcher et al., PoP 28, 072706 (2021)

Tuned HYDRA Hohlraum-Capsule model to N210207 predicted increase in yield for N210808 but result was higher*

N210207

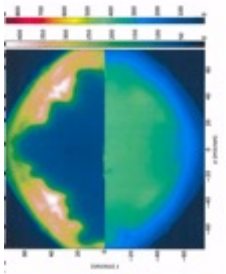


Den tion



Fluence comp

Small LEH preshot



Den press

Radiation source from integrated HYDRA simulations applied to higher resolution capsule simulations

Capsule simulations include:

- Tent, FT, Surf rough
- Laser P2 and P4
- Fall line mix model (triggers relative to atwood#)

Preshot methodology was close in matching most observables from N210207

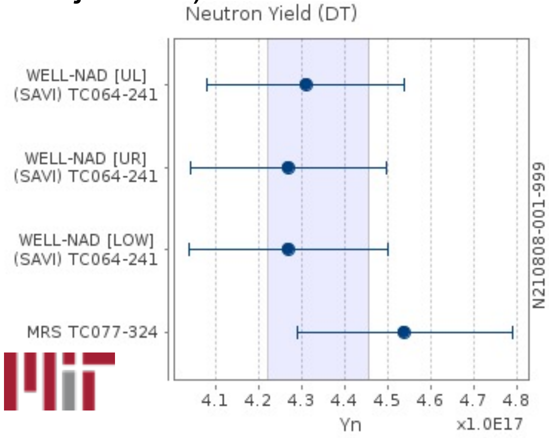
	N210207 Data	N210207 Sim	Small LEH preshot	Data
Yield (tot)	6.07e16	6.15e16	1.7e17	PRIMARY 4.3x10^{17}
Bang time	9.09-9.125	9.07	9.4	9.28
Tion (DT,DD) (keV)	5.67;5.23	6.2;5.44	7.8;7.6	11.3 / 8.9
4pi DSR (%)	3.16	3.744	3.7	2.72
P0 (um), P2um	~43;~5	35	34;-3	77.3
PNI P0,P2 (um;um)	42	41	41;6.15	51 ; -5um
DSNI P0	61	61	59	T.B.D.
Vel (km/s)		389	391	
Burn width, (ps)	110-130	120	95	89
Injected mix @ BT	>100	23	47	T.B.D.
Hot spot velocity	70km/s	4	-3	75 km/s
Yamp		5.54		25-30x

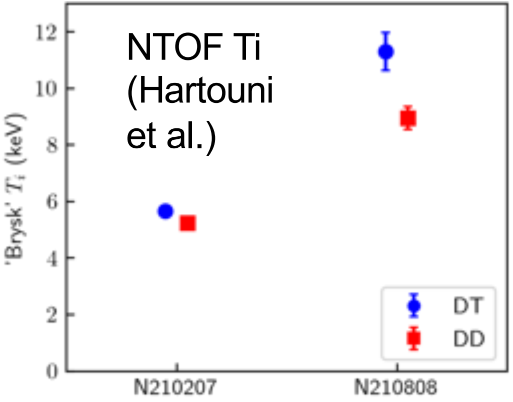
Yield increase in sims from reduced coast and better stability

*Lead Designer A. Kritcher, Lead Experimentalist A. Zylstra

Nuclear data on N210808 show a primary yield ~4.3e17 with high ion temperature, short burn width, and increased volume

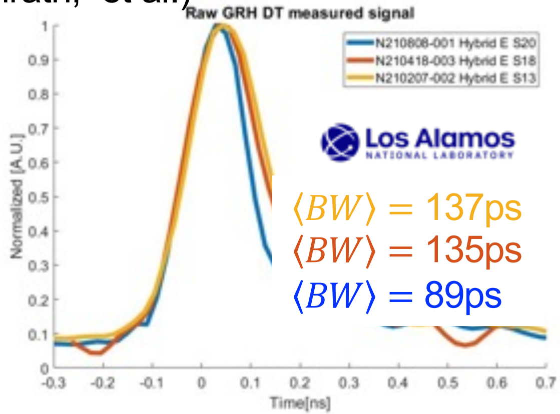
Nuclear yield from activation (Hahn, Bionta, et al) and MRS (Gatu Johnson, Frenje et al.)





NTOF Ti (Hartouni et al.)

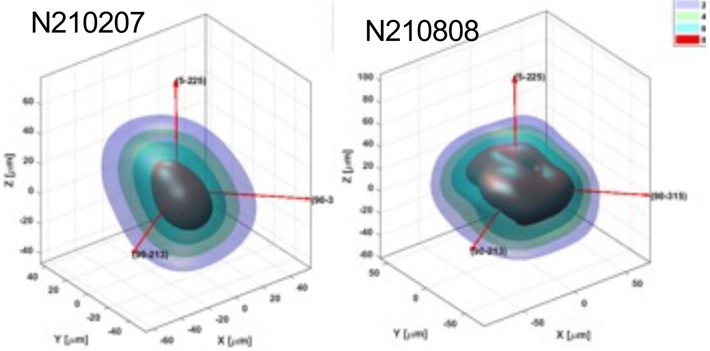
GRH burn width (Meaney, Geppert-Kleinrath, et al.)



$\langle BW \rangle = 137$ps

$\langle BW \rangle = 135$ps

$\langle BW \rangle = 89$ps



NIS primary images (Volegov, Fittinghof, Lamb, Birge, Geppert-Kleinrath, …)

1.35 MJ in 89 ps= 15 Petawatts ~10% of total solar irradiation on earth from a plasma that fits In a cube 100 um on a side!!!

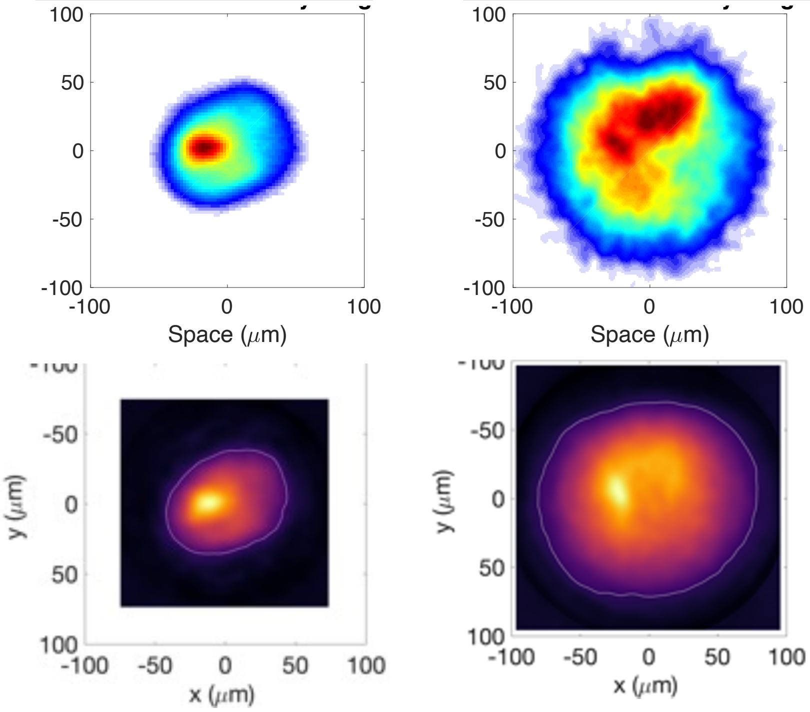
X-ray diagnostic data also shows larger size, higher temperature

Predecessor

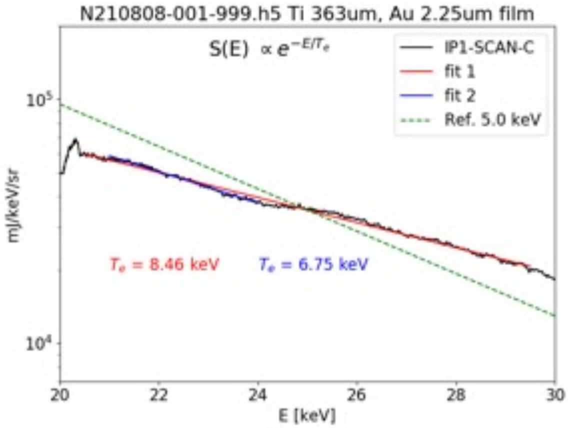
N210808

Pinhole imaging (Pak) E_{photon} centered at 13 keV

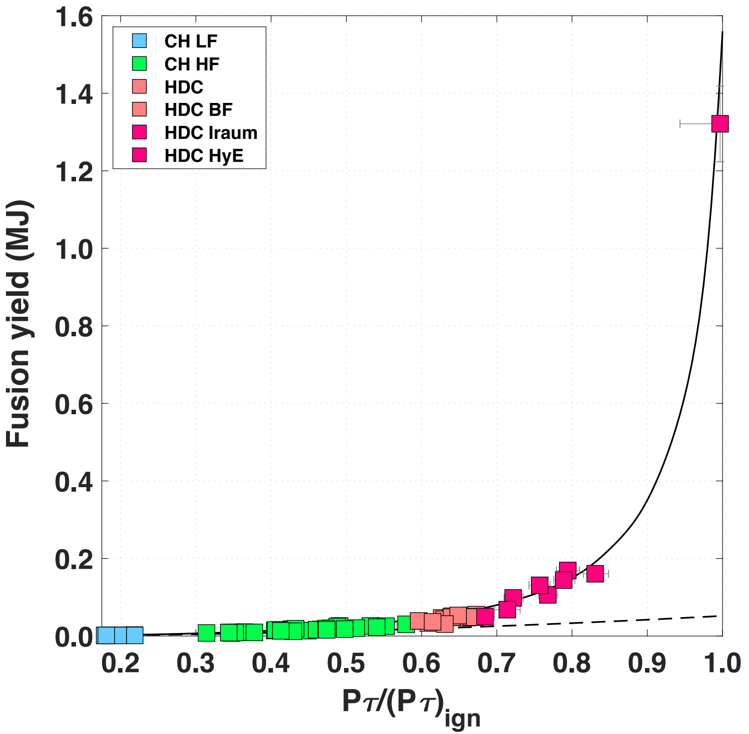
Penumbral imaging (Bachmann) E_{photon} centered at 25 keV

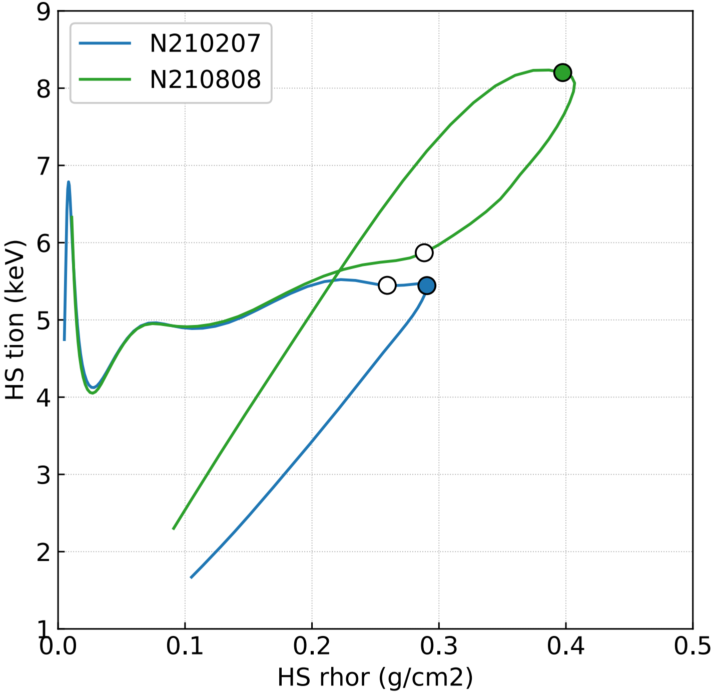


T_e from continuum spectrometer (Stoupin, MacPhee, …)



Yield vs. Generalized Lawson criterion shows the progress over the last year and the sensitivity to changes

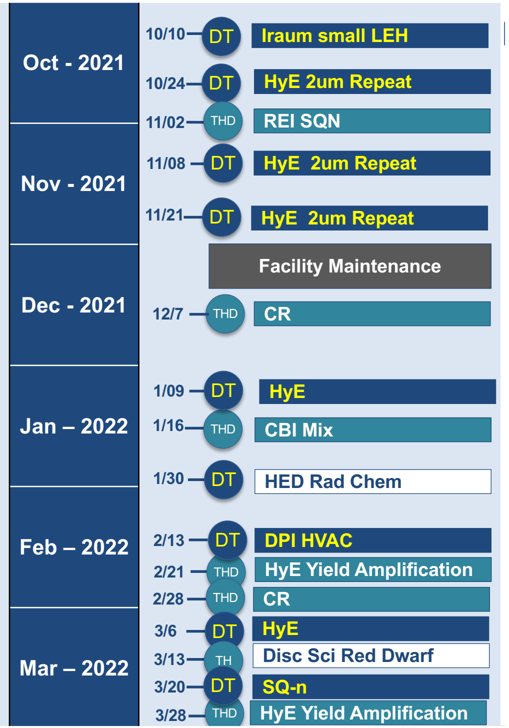




*Preliminary analysis by P. Patel

PRELIMINARY DATA– ANALYSIS UNDERWAY

We've adjusted the FY22 Q1/Q2 NIF shot schedule to get near term opportunities to assess variability in this new regime



Oct - 2021	10/10	DT	Iraum small LEH
	10/24	DT	HyE 2um Repeat
Nov - 2021	11/02	THD	REI SQN
	11/08	DT	HyE 2um Repeat
	11/21	DT	HyE 2um Repeat
Dec - 2021			Facility Maintenance
	12/7	THD	CR
Jan – 2022	1/09	DT	HyE
	1/16	THD	CBI Mix
	1/30	DT	HED Rad Chem
Feb – 2022	2/13	DT	DPI HVAC
	2/21	THD	HyE Yield Amplification
	2/28	THD	CR
Mar – 2022	3/6	DT	HyE
	3/13	TH	Disc Sci Red Dwarf
	3/20	DT	SQ-n
	3/28	THD	HyE Yield Amplification

Fusion ignition is a runaway process

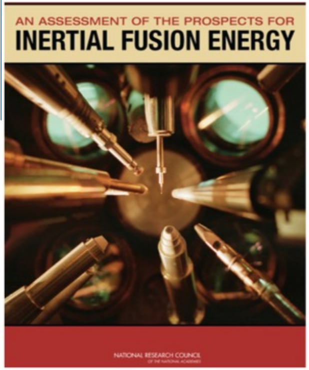
We expect variability in initial experiments

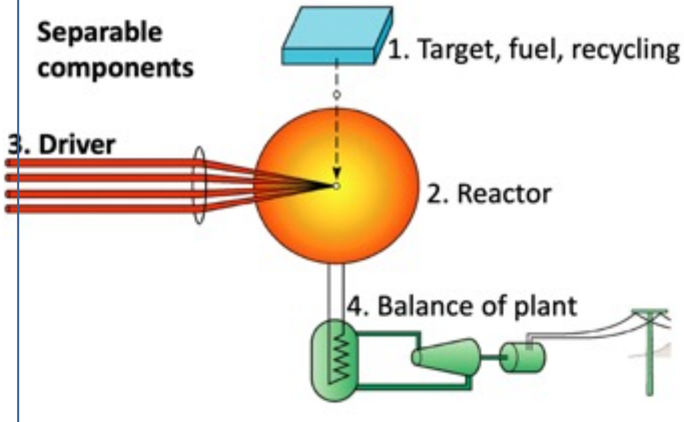
Over time we will develop understanding of what drives variability and improve both the design and the technology

Longer term our goal is to increase the yield further to create even more extreme environments for stewardship applications

This exciting advance also prompts a discussion, already underway, about the path forward for inertial fusion energy

- IFE is not part of the NNSA mission
- There are many, many technical challenges!
- However, there are potential system advantages, and diversified risks

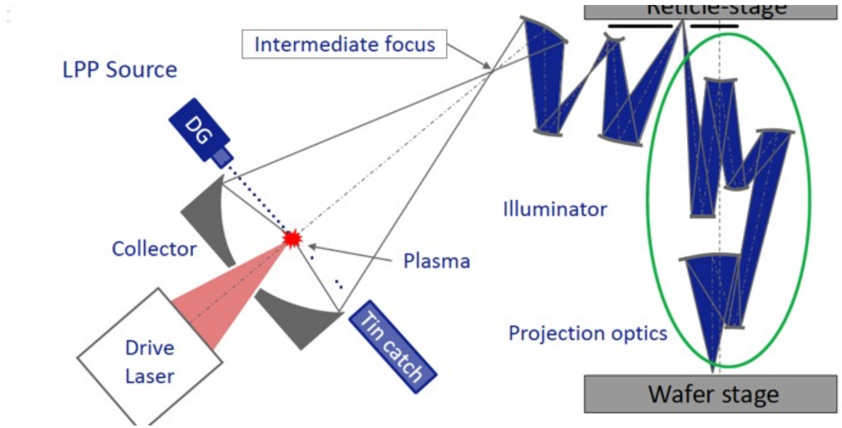

AN ASSESSMENT OF THE PROSPECTS FOR
INERTIAL FUSION ENERGY



Key components of an IFE system:
- Drivers
- Target fabrication
- Target injection
- Engagement
- Chamber technologies
- Final optics
- Tritium processing
- Economics

NAS 2013 Study:
“The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program within DOE would be when ignition is achieved.”

It is interesting to compare an EUV Lithography system to what would be needed for an inertial fusion energy plant



	EUVL	IFE
High Rep-rate laser	40 kW 10.6 μm	10-30 MW 200-500 nm
High Rep Rate Targets	30 μm tin 50 kHz	Ignition target 10 Hz
Harsh Environment (X-rays and Debris)	250W x-ray, 5 mg/sec, vacuum/gas	200 MW x-ray, 800 MW neutron, 10 g/sec
Long Lifetime Optics	Gigashot	Gigashot+

There are many exciting challenges and opportunities ahead!

- **Analysis of the shot is still in progress! Stay tuned**
  - Data analysis
  - Post-shot models
  - Inferred quantities and metrics
- **Continued experiments to understand and build upon this result**
  - Variability assessments in Oct/Nov
  - THDs for ‘burn off’ baseline
  - Understanding of sensitivities
  - Continued design improvements
- **Applications to important problems in stockpile stewardship**
  - Improving understanding of thermonuclear burn processes, nuclear survivability
  - Pushing to higher yield for applications
  - Increasing confidence in a future high-yield facility


Team NIF

Kudos to an incredible team (both today and over the decades) who worked through innumerable challenges to enable this exciting result

WPD

Weapon Physics
& Design Program