Inertial Confinement Fusion and Energy: A Cleaner and Safer Energy Solution

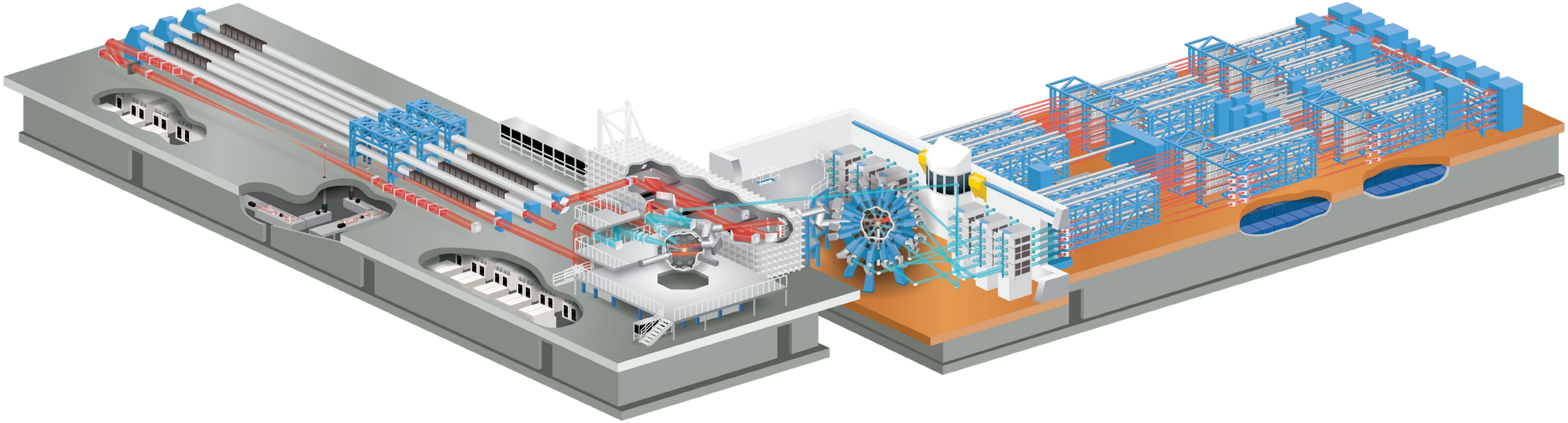
Chris Deeney, P. B. Radha, facility researchers, staff, and operational teams

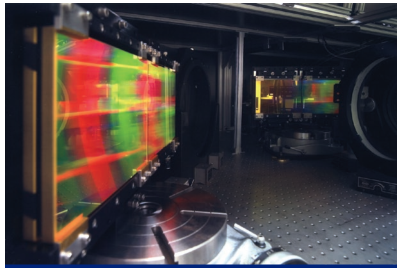
University of Rochester
Laboratory for Laser Energetics

Huang Speaker Series

Rochester, NY
June 13, 2023

The leading academic institution advancing laser technologies, fusion, and high-energy-density science at scale





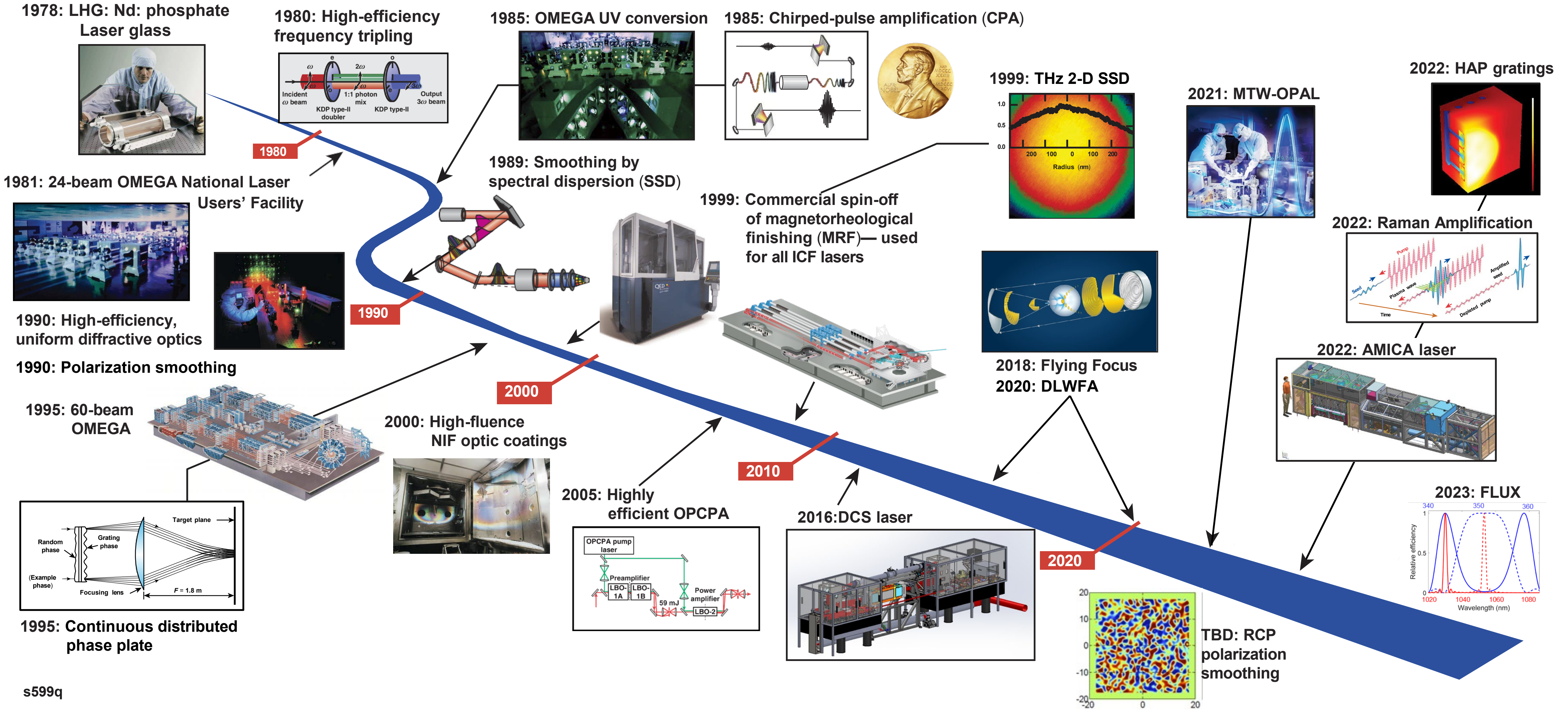
Innovation

Leadership in S&T

Education

Building S&T and scientists for the future

Innovation at LLE as an example



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The LLNL panel for announcing “Ignition” on 12/13/22 is comprised of scientists with a long history of research on Omega

UR LLE
UNIVERSITY of ROCHESTER

Mark Herrmann
Program Director for Weapon Physics and Design
LLNL

Alex Zylstra
Lead Experimentalist
MIT PhD 2015 (OMEGA)
615 OMEGA
<u>248 OMEGA EP</u>
863 shots

Annie Kritcher
Principal Designer
85 OMEGA shots

Art Pak
Team Lead, Stagnation Science
69 OMEGA
<u>151 OMEGA EP</u>
220 shots

Tammy Ma
Lead Inertial Fusion Energy Institutional Initiative
106 OMEGA
<u>68 OMEGA EP</u>
174 shots

Panel participants were PI or co-PI on 1,342 shots at LLE

Jean-Michel Di Nicola
Chief Engineer for NIF Laser Systems

Michael Stadermann
Program Manager, Target Fabrication

Fusion powers the Earth, keeps the peace, and will be sustainable local energy in the future

Department of Energy/ National Science Foundation

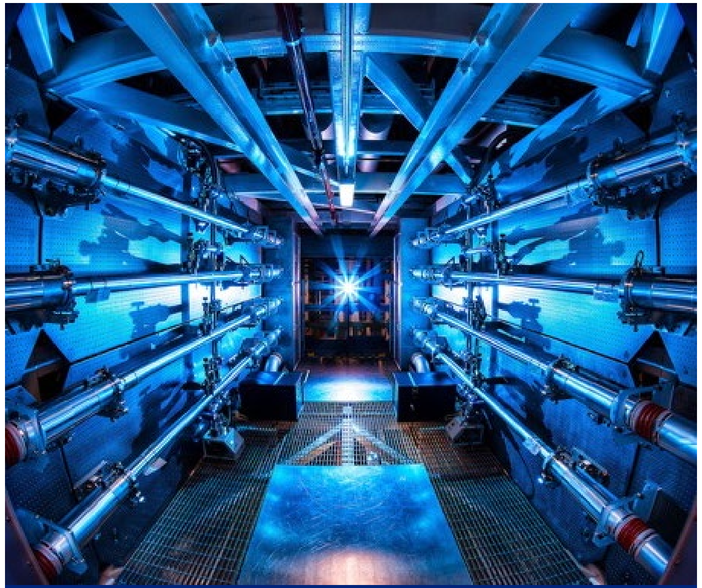
National Nuclear Security Administration

Fusion "Kitty Hawk:

Prototype: SPARC
Q > 2, P_{fusion} > 50 MW
~2021 to 2025

Department of Energy/ Industry

Why does DOE have three major ICF facilities? Unique roles, technical competition, innovation, education, and risk management

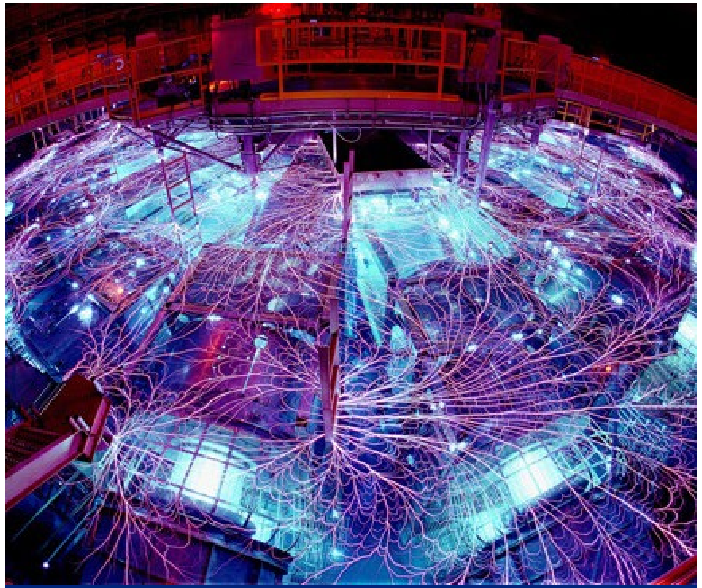


Ignition Capable

Indirect-Drive ICF

2100 Shots per year

Direct-Drive ICF

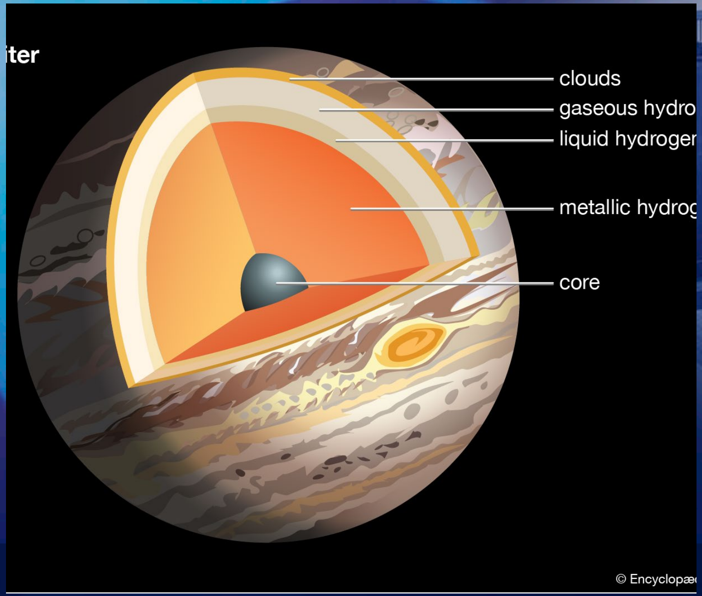


Engineering scale samples

Magnetically Driven ICF

Applications of high-power lasers

Laboratory Astrophysics



Probes and Materials at Extreme Conditions

Fusion

Nuclear fusion is the process by which stars produce energy

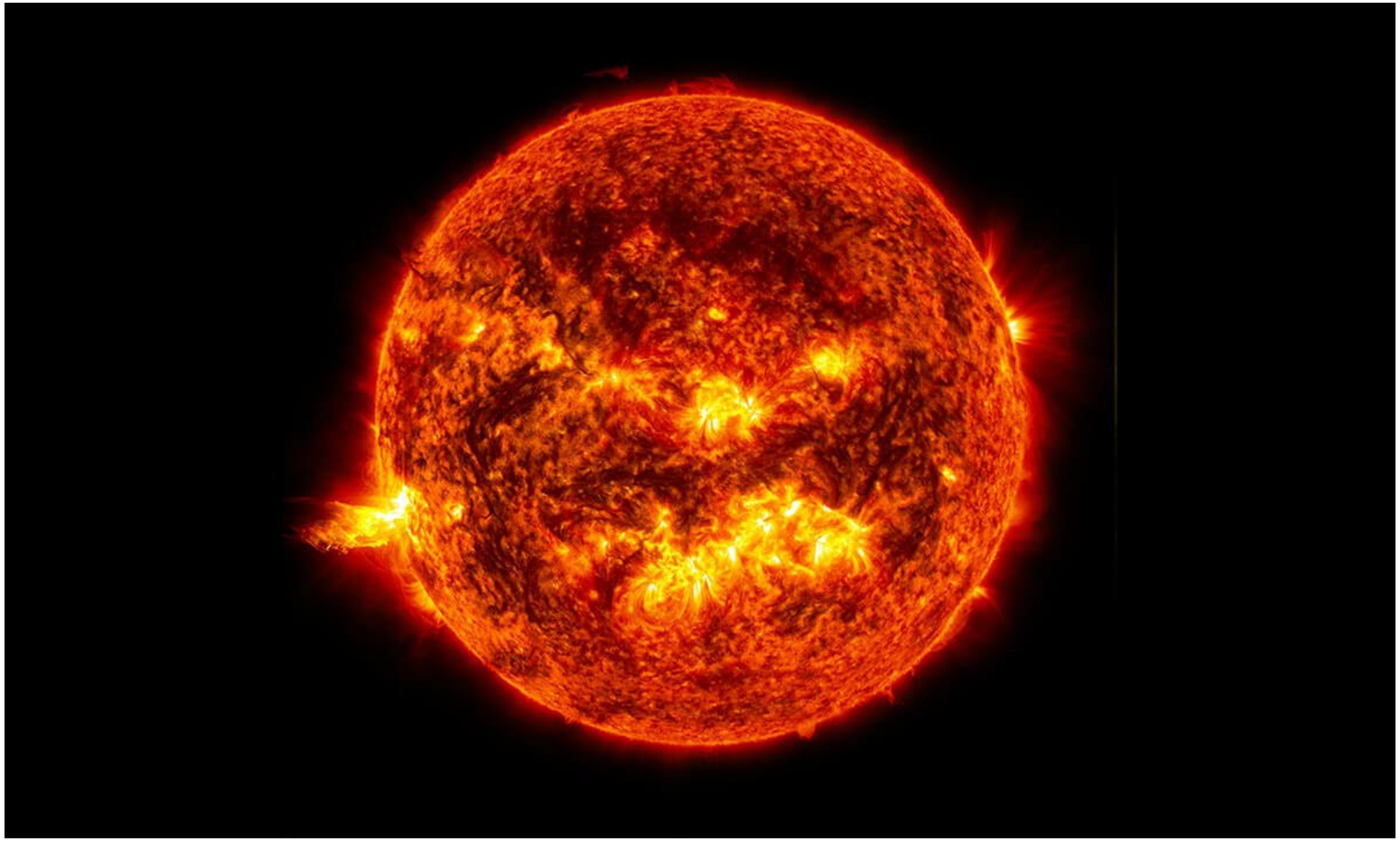
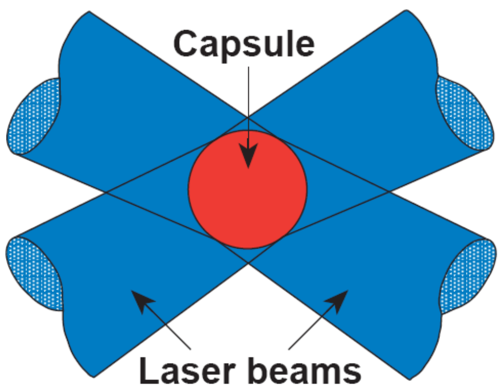


Image: NASA Solar Dynamics Laboratory

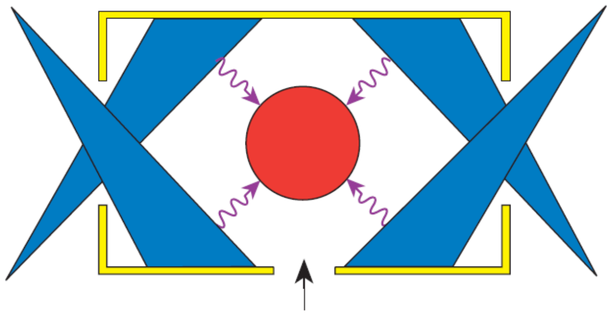
- Fusion requires very high Temperatures (approximately 10s – 100s of millions of degrees)
- Matter under these conditions (plasma) is very hard to confine
- The Sun’s gravity confines the plasma at these very high temperatures

Two approaches are being pursued on OMEGA and the National Ignition Facility

Direct-drive target



Indirect-drive target

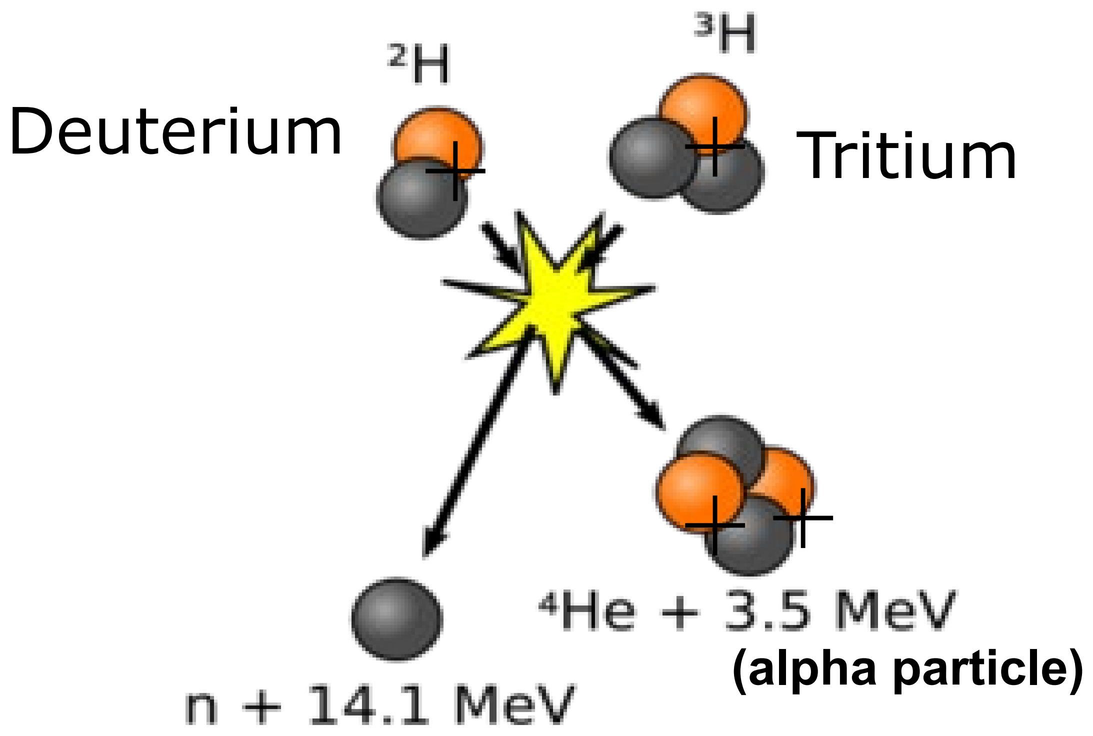


Hohlraum using
a cylindrical high-Z case

Direct-drive couples nearly 4 times more of the laser energy onto the capsule than indirect drive

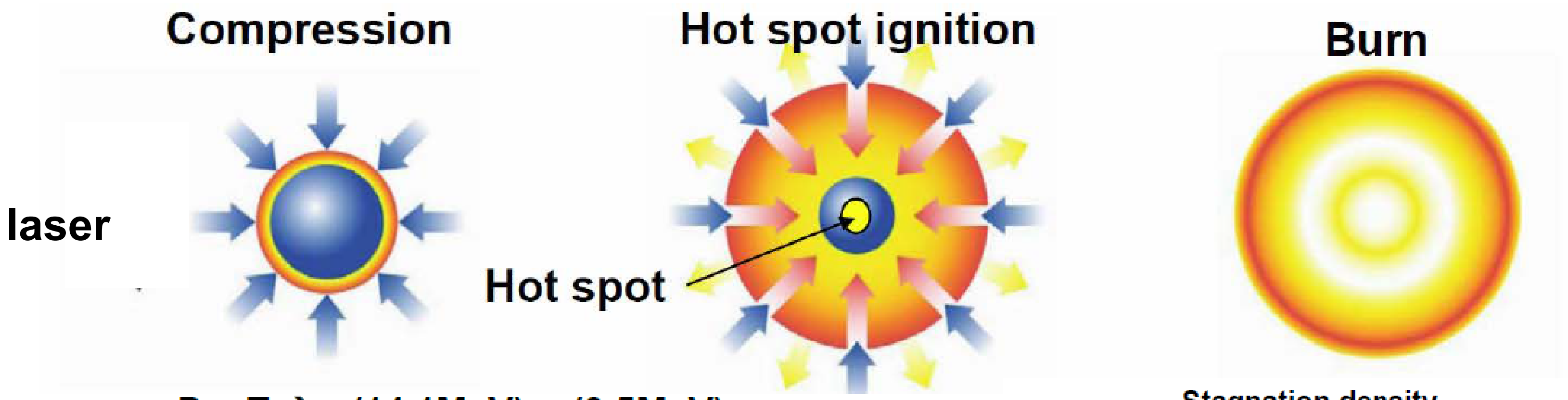
Indirect-drive is less sensitive to the nonuniformity of each individual laser beam

Deuterium and tritium (heavier isotopes of hydrogen) fusion are the best studied on laser facilities



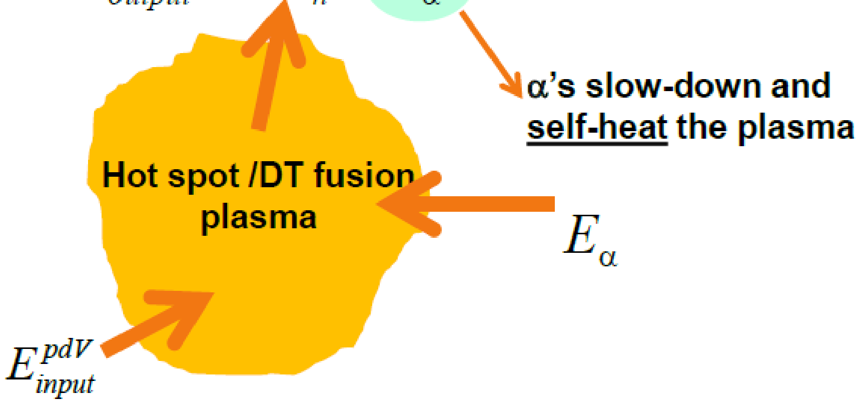
Deuterium-tritium fusion has the highest reaction probability under the conditions we can achieve today on high-power lasers

Inertial Confinement Fusion (ICF) implodes capsules to develop conditions for a robust hotspot and propagating burn resulting in “high” neutron yields

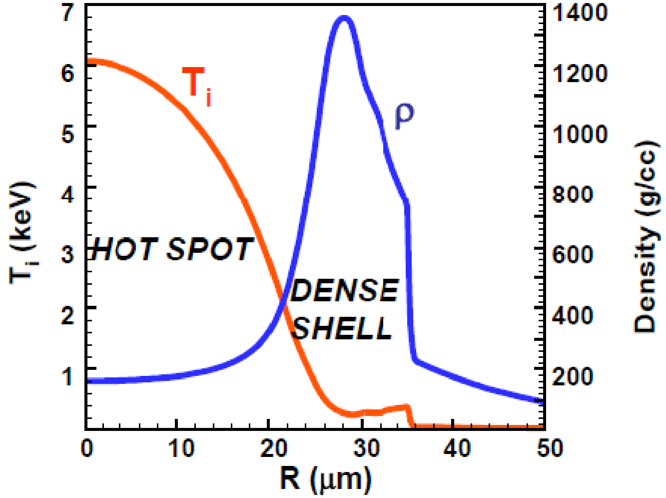


D + T → n(14.1MeV)+α(3.5MeV)

$$E^{nuclear}_{output} = E_n + E_\alpha$$

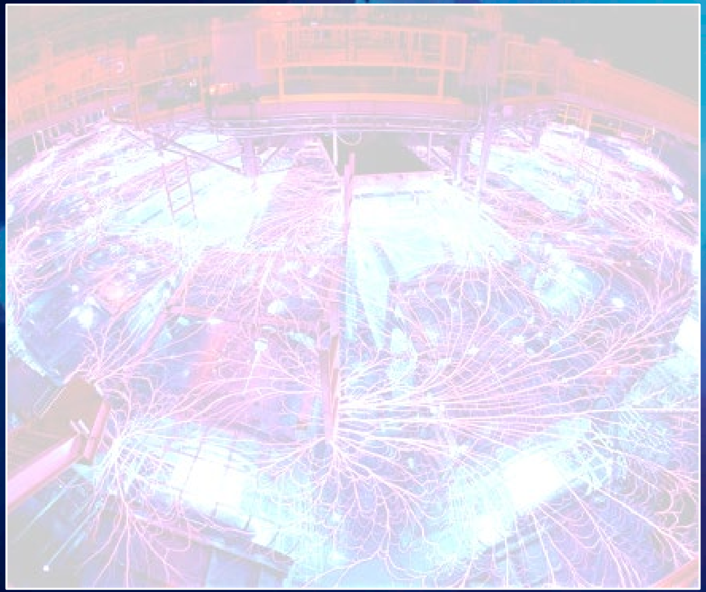


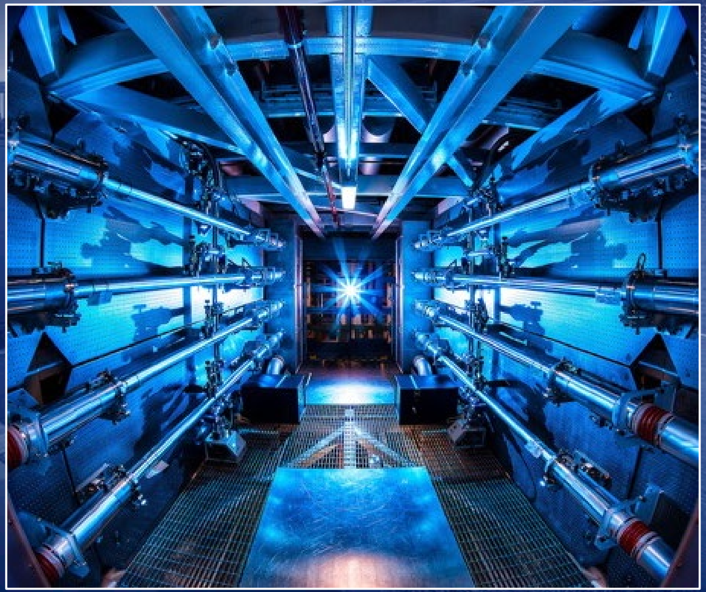
Stagnation density and temperature



$$G = \frac{E_{fus}}{E_{laser}}$$

Ignition is the process
In which the alpha particles
are stopped in the hotspot and
produce more fusion reactions

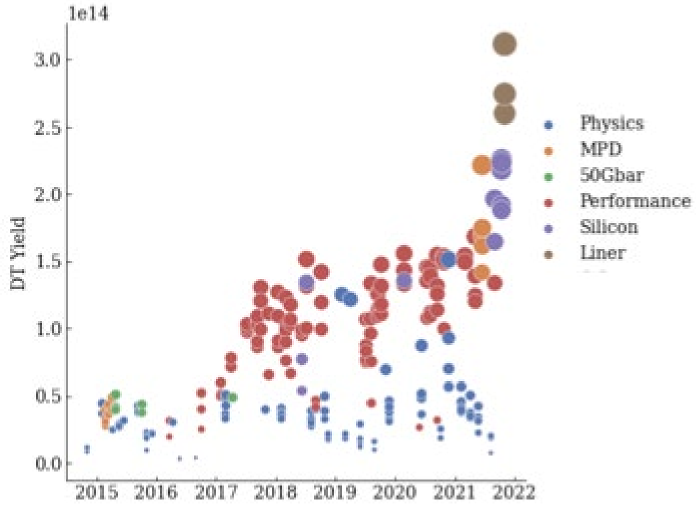




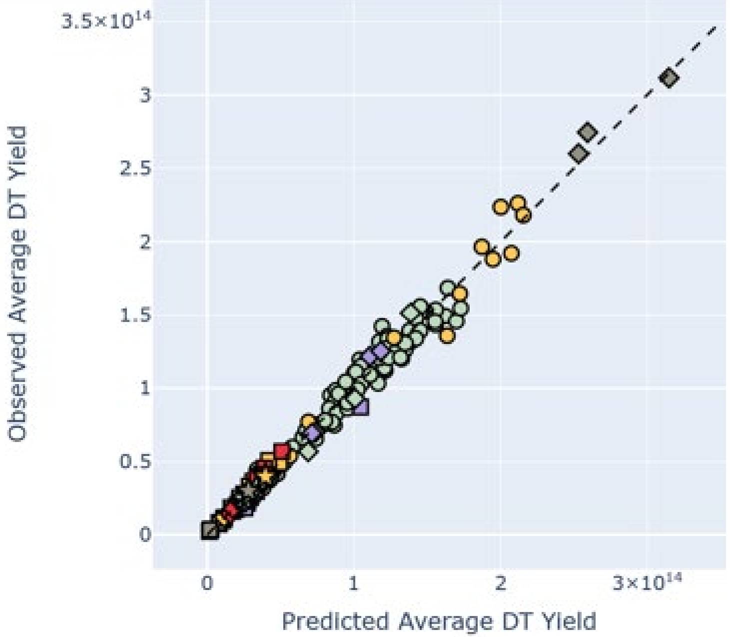
Recent accomplishments: OMEGA, and NIF

Physics-informed data science techniques are leading to significant improvements in fusion yields on OMEGA

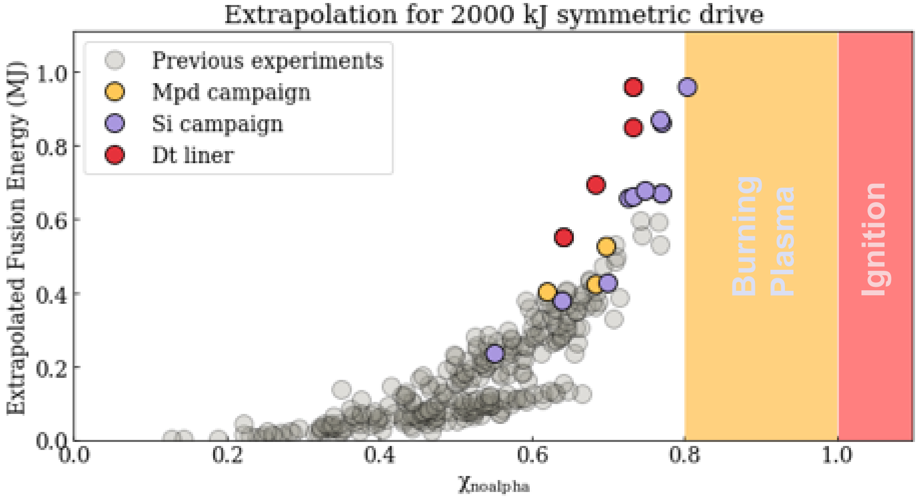
Measured neutron yield vs. time



Statistical modeling (SM) predictions* vs. Measured neutron yield

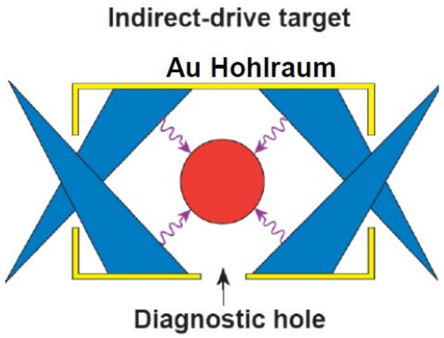


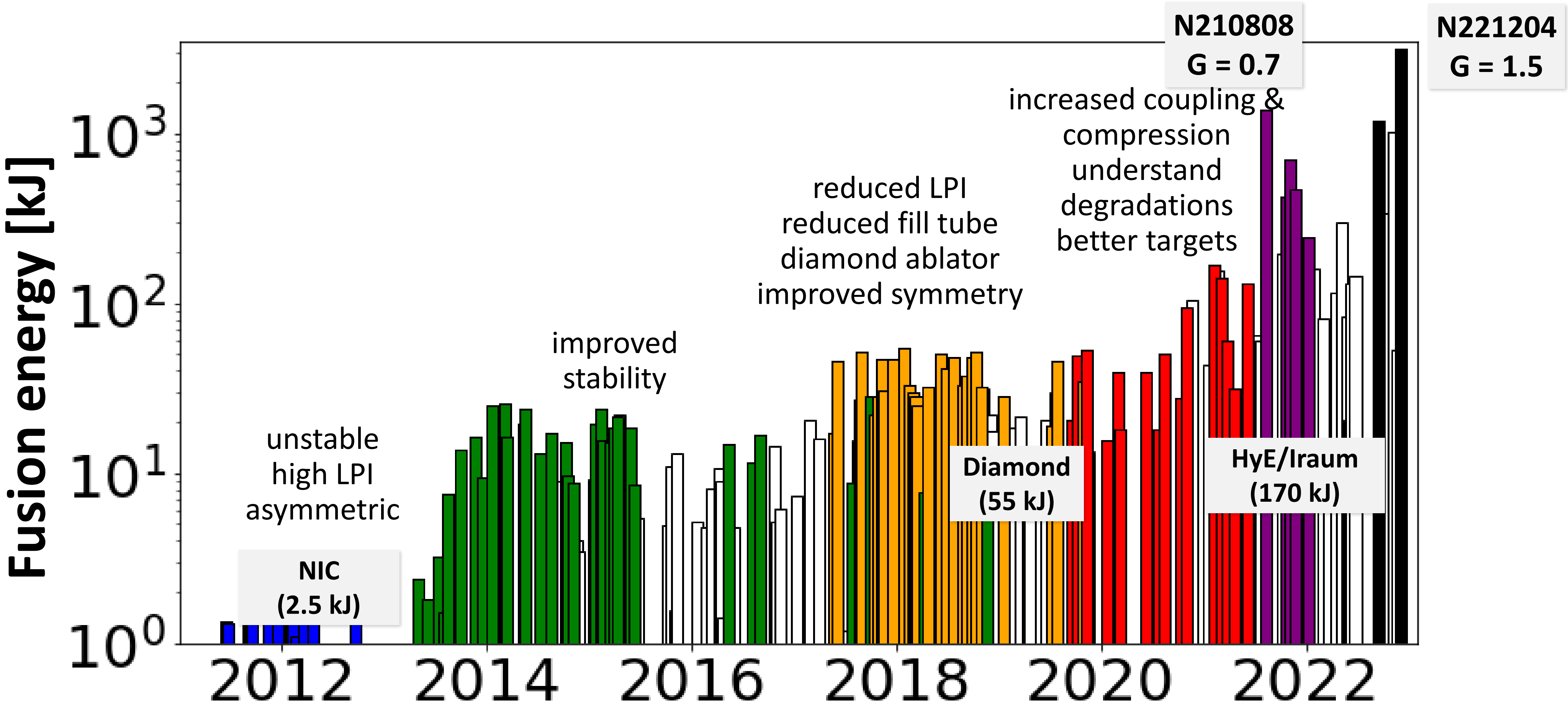
Extrapolated fusion yield vs. GLC ($\chi_{\text{no-}\alpha}$)

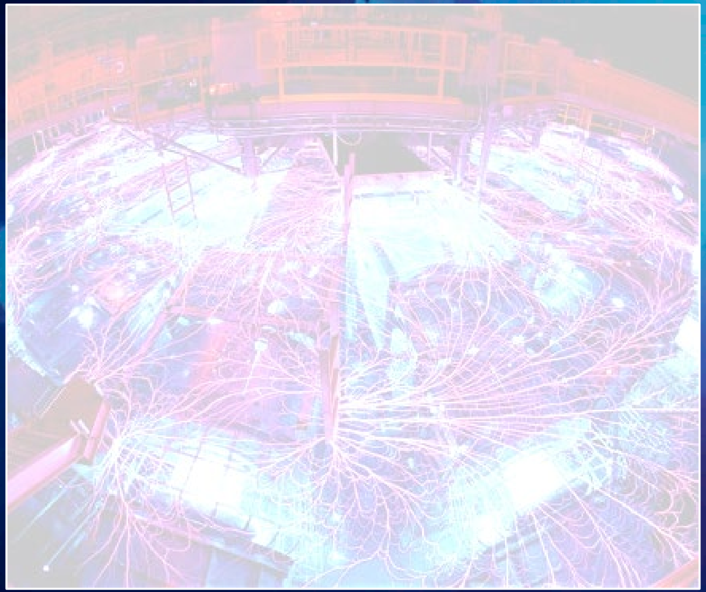
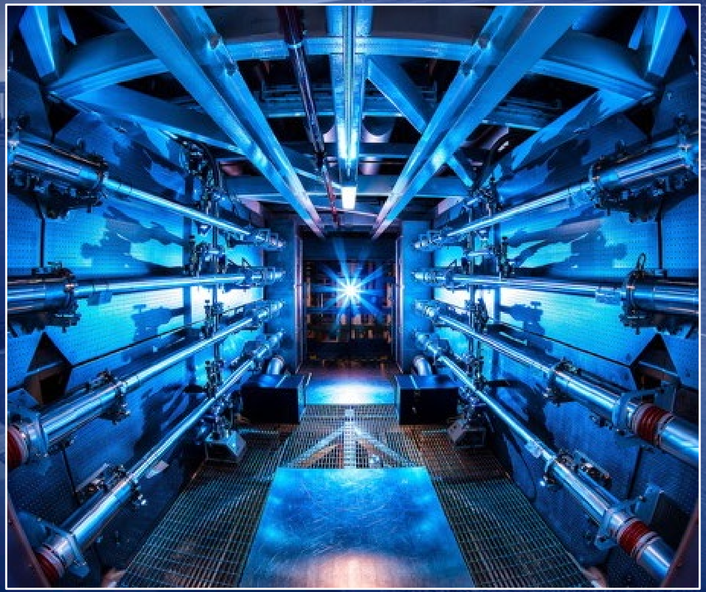


*V. Gopalaswamy *et al.*, "Tripled Yield in Direct–Drive Laser Fusion Through Statistical Modelling," *Nature* 565 (7741), 581–586 (2019).
**A. Lees *et al.*, "Experimentally Inferred Fusion Yield Dependencies of OMEGA Inertial Confinement Fusion Implosions," Phys. Rev Lett. 127, 105001 (2021).

Steady advances in physics understanding and technological improvements culminated in target gain G>1 on December 5, 2022

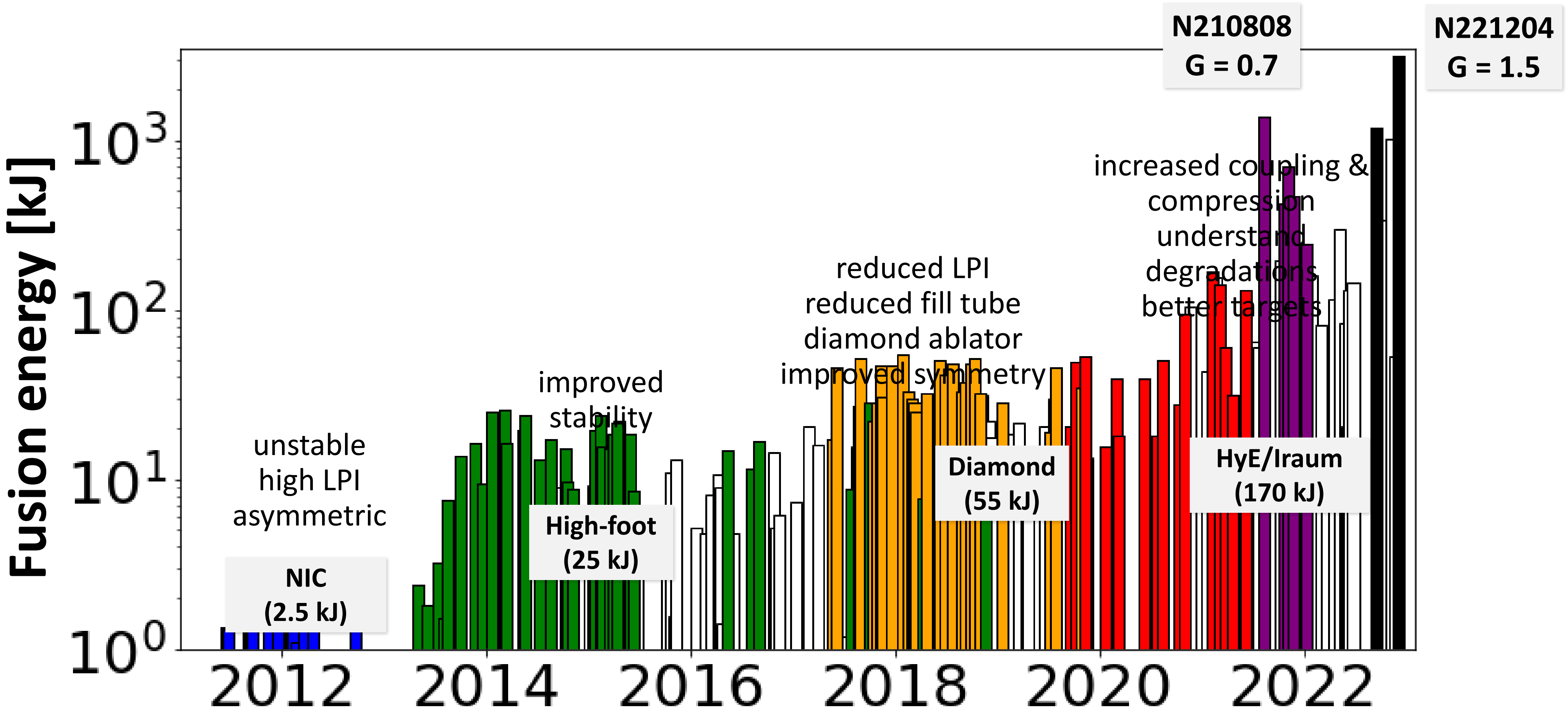




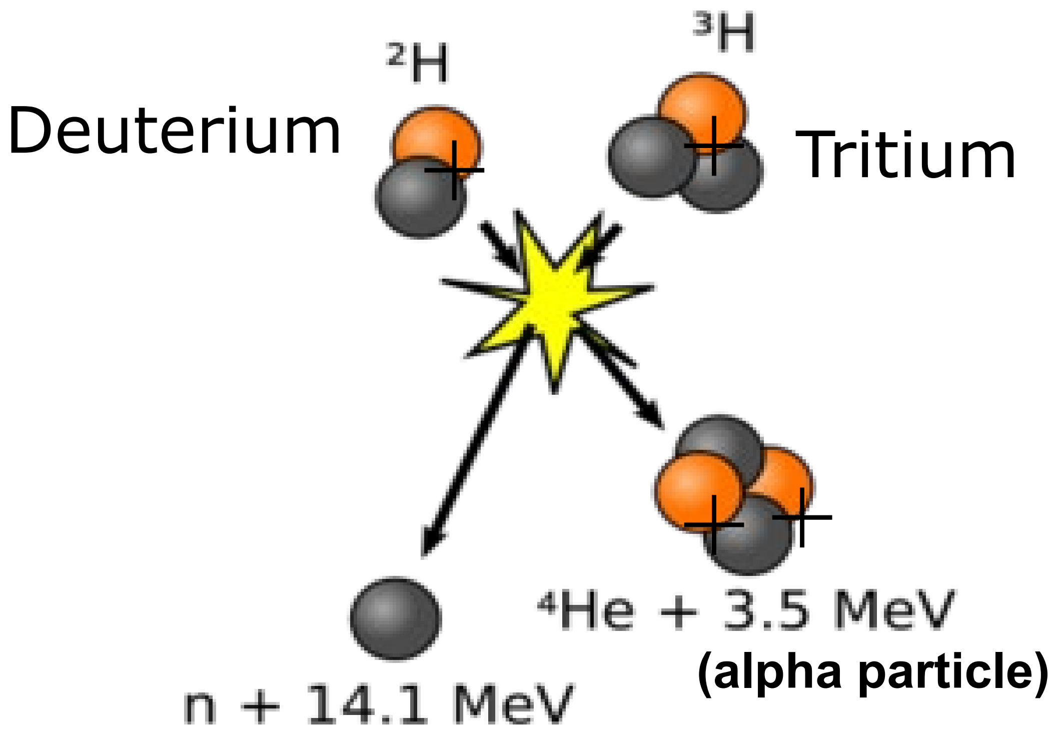
From Inertial Confinement Fusion to Inertial Fusion Energy

Steady advances in physics understanding and technological achievements culminated in G >1 on December 5, 2022



National Academy of Sciences 2013: "The appropriate time for the establishment of a national, coordinated, broad-based inertial fusion energy program <u>within Department of Energy would be when ignition is achieved"</u>

Fusion reactions have the highest energy density among all energy sources



1kg of	Energy, kwh
Coal	8
3	
Uranium fission (current nuclear power plants)	24 Million
Deuterium-Tritium fusion	95 Million

3 MillionX

4X

Fusion energy can be clean, carbon-free, on-demand, and placed close to population enters

Fission - Fukishima, 2011
Meltdown, Proliferation fears

Solar/Wind – Intermittent,
Need better battery technology & robust grid

By 2050, ~ 70% of the global population will be urbanized*. Currently, energy is produced far from population centers
- **Fires caused by transmission lines**
- **Cost of power includes generation and transmission**
- **Grids are sensitive to cyber attack and disruptions**

Fusion Energy

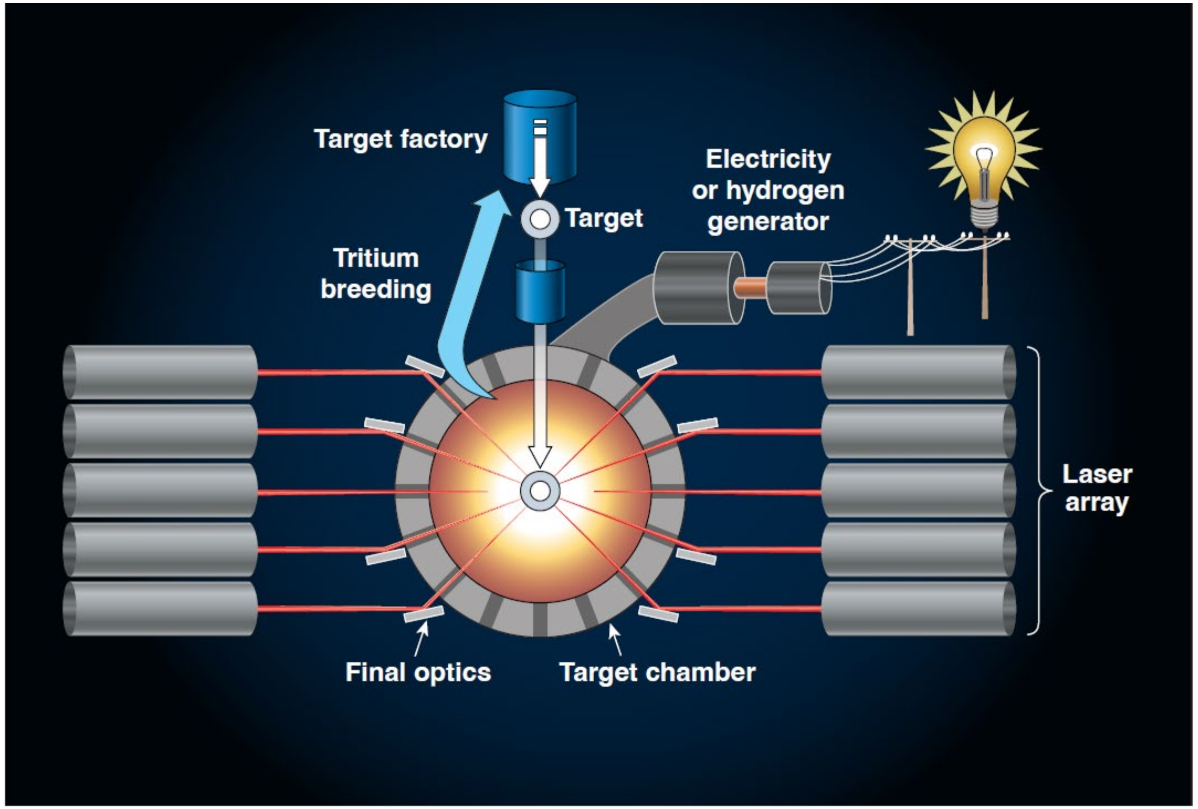
- **Available 24/7**
- **Environmentally acceptable**
- **Passively safe (can be placed close to urban centers)**
- **Abundant deuterium supply —globally dispersed**
- **Minimal proliferation concerns**

Energy products : electricity, transportation fuels (H_2, Biofuels), heat, H_2O production, industrial needs

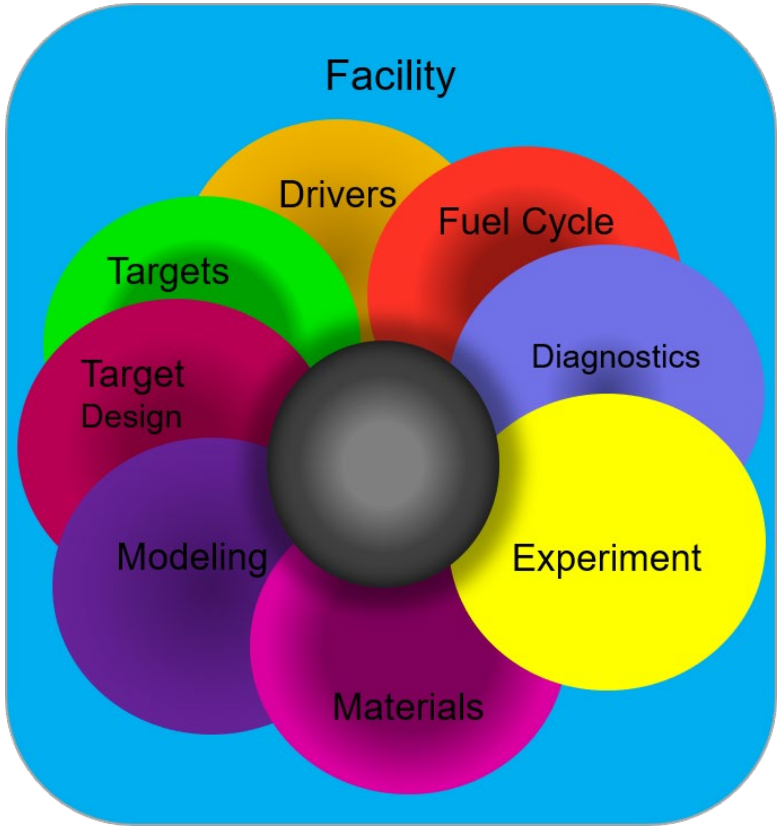
*** UN: 2018 Revision of World Population Prospects**

An IFE power plant has many aspects that need development

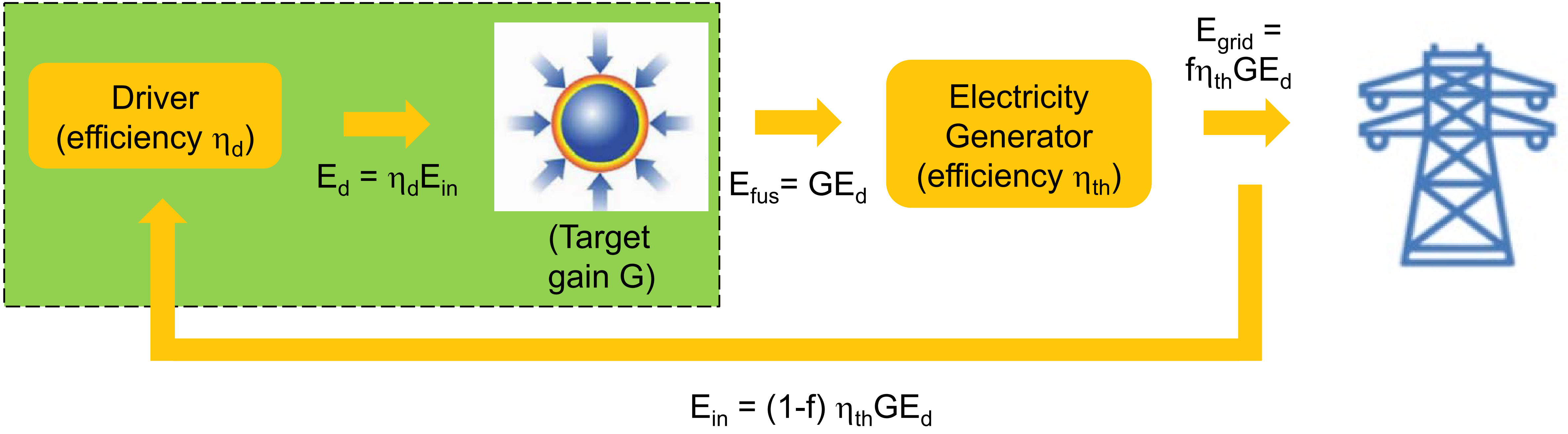
Schematic of an IFE plant



Modularity



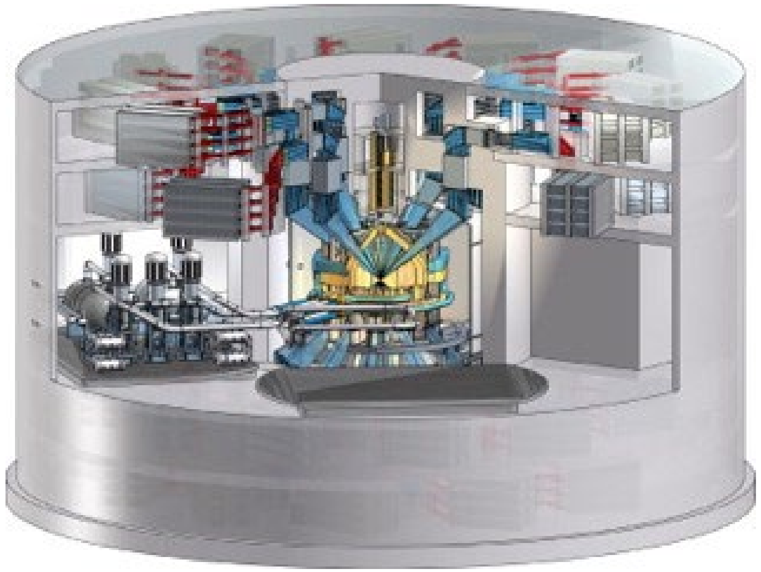
Efficiencies at every step of power generation require $\eta_d G$>~10 with implosions performed at the rate of approximately 10/s



- **Increase Gain by controlling various sources of nonuniformity and better physics modeling**
- **Increase driver efficiency through new drivers – solid-state lasers, excimer lasers, heavy-ions.**

Many engineering challenges need to be addressed for Inertial Fusion Energy

- **Radiation flux and first wall survivability**
  - High average neutron wall loads (~MW/m^2) and pulsed (~10 HZ) with high peak power loading
  - Several chamber concepts have been developed
    - Thick liquid wall
    - Wetted wall
    - Protective gas
    - Vacuum



- **Tritium engineering/science**
  - High-gain IFE targets will burn up ~30% of the fuel
  - Tritium breeding, recovery
  - blanket, chamber
  - Economics [breeding, recovery (blanket and chamber)]

[1] J. Alvarez et al "Potential common radiation problems for components and diagnostics in future MFE and ICF devices," Fusion Engineering and Design 86 (2011)
[2] W.R. Meier, A.M. Dunne, et al "Fusion Technology Aspects of IFE (LIFE)," Fusion Engineering and Design 89 (2014)
[3] M. Dunne et al "Timely Delivery of of Inertial Fusion Energy (LIFE)" Fusion Science and Technology," 60 (2014)
[4] J.D. Sethian et al "The Science and Technologies for Fusion Energy with Lasers and Direct Drive Targets," IEEE Trans on Plasma Science 38 (2010)

Significant progress in policy and legislation is already reducing the uncertainty in the fusion energy landscape and lowering barriers to entry by private entities

described in this report. **The Administration then prioritized five areas[1] to launch the Net-Zero Game Changers Initiative**:

- **Efficient Building Heating and Cooling**, including refrigerants with low global warming potential;
- **Net-Zero Aviation**, cost-competitive with conventional aviation, including electric and hybrid aircraft and sustainable aviation fuels production;
- **Net-Zero Power Grid and Electrification**, including advanced transmission and distribution systems;
- **Fusion Energy at Scale**, cost-competitive with conventional energy; and
- **Industrial Products and Fuels for a Net-Zero, Circular Economy**, including secure supply chains and alternative pathways for producing low-carbon steel, aluminum, cement, chemicals, industrial heat, clean water, and electrofuels.

US Innovation to Meet 2050 Climate Goals; Five priorities outlined by The White House (Nov 2022)

APRIL 19, 2022

Readout of the White House Summit on Developing a Bold Decadal Vision for Commercial Fusion Energy

- **Community Engagement**: The Biden-Harris Administration will lead the development of a decadal strategy to accelerate the realization of commercial fusion energy that benefits all stakeholders. Future workshops will build on this momentum to further define a clear path to success.
- **Department of Energy Agency-Wide Fusion Initiative**: DOE launched an agency-wide initiative to accelerate the viability of commercial fusion energy in coordination with the private sector. **Dr. Scott Hsu**, head of the fusion program at ARPA-E, the Advanced Research Projects Agency – Energy, was announced as the new DOE Lead Fusion Energy Coordinator and joins the Office of the Under Secretary for Science and Innovation.
- **Funding to Advance the Science for a Fusion Pilot Plant:** DOE announced two funding opportunities totaling $50 million that will support foundational science and technology research connected to high-priority issues for a future fusion pilot plant, including plasma modeling, interactions, and control.

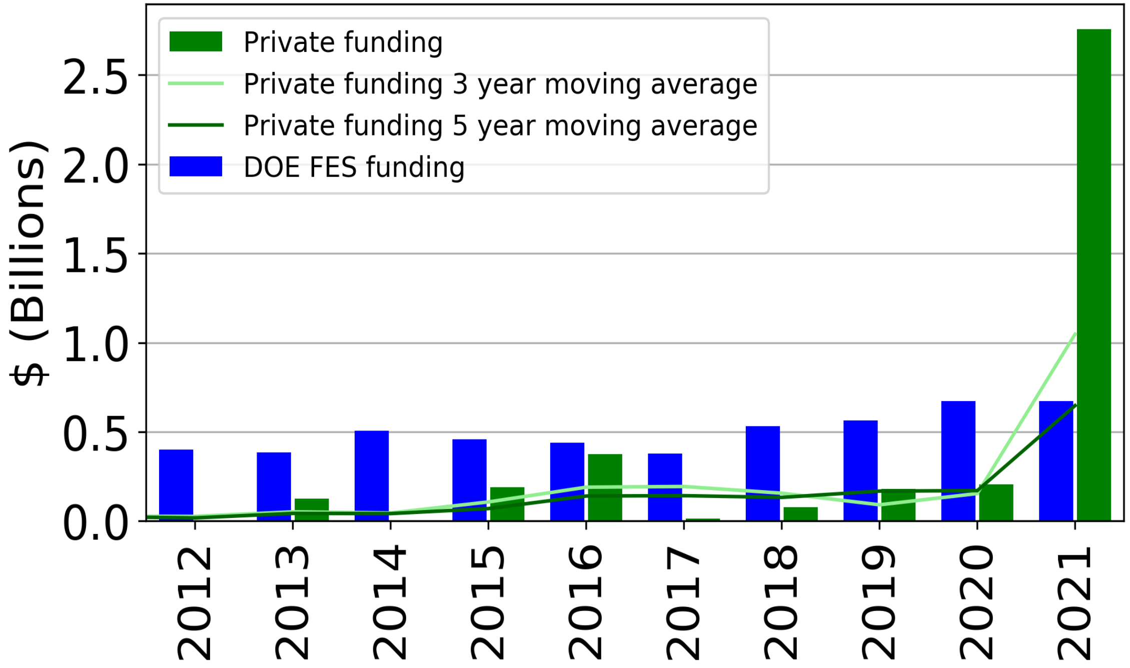
Reducing regulatory Uncertainty (April 14, 2023)

NRC to Regulate Fusion Energy Systems Based on Existing Nuclear Materials Licensing

The Nuclear Regulatory Commission has directed the staff to create a regulatory framework for fusion energy systems, building on the agency's existing process for licensing the use of byproduct materials.

Private-public partnerships will be critical to explore the many paths towards fusion energy and identify the optimal concept

- **Nearly 20+ private companies are exploring fusion energy globally (6 are pursuing Inertial Fusion Energy)**
- **Each company is pursuing a different approach**

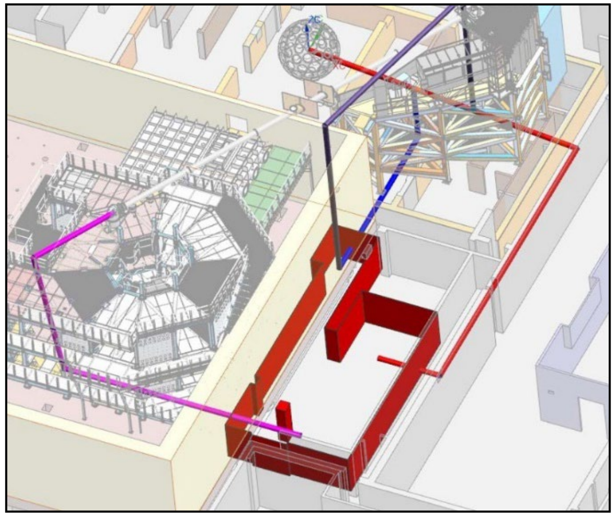


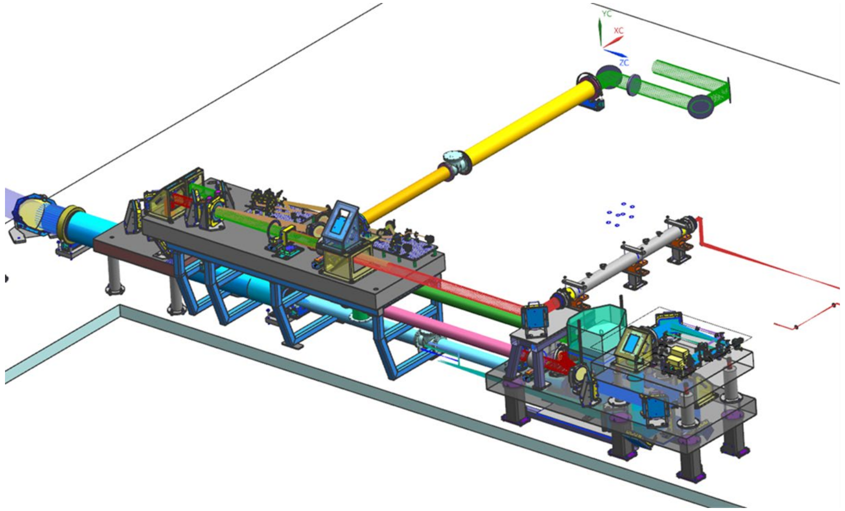
- Commonwealth Fusion Systems (Cambridge, MA)
- Focused Energy Inc. (Austin, TX)
- Princeton Stellarators Inc. (Branchburg, NJ)
- Realta Fusion Inc. (Madison, WI)
- Tokamak Energy Inc. (Bruceton Mills, WV)
- Type One Energy Group (Madison, WI)
- Xcimer Energy Inc. (Redwood City, CA)
- Zap Energy Inc. (Everett, WA)

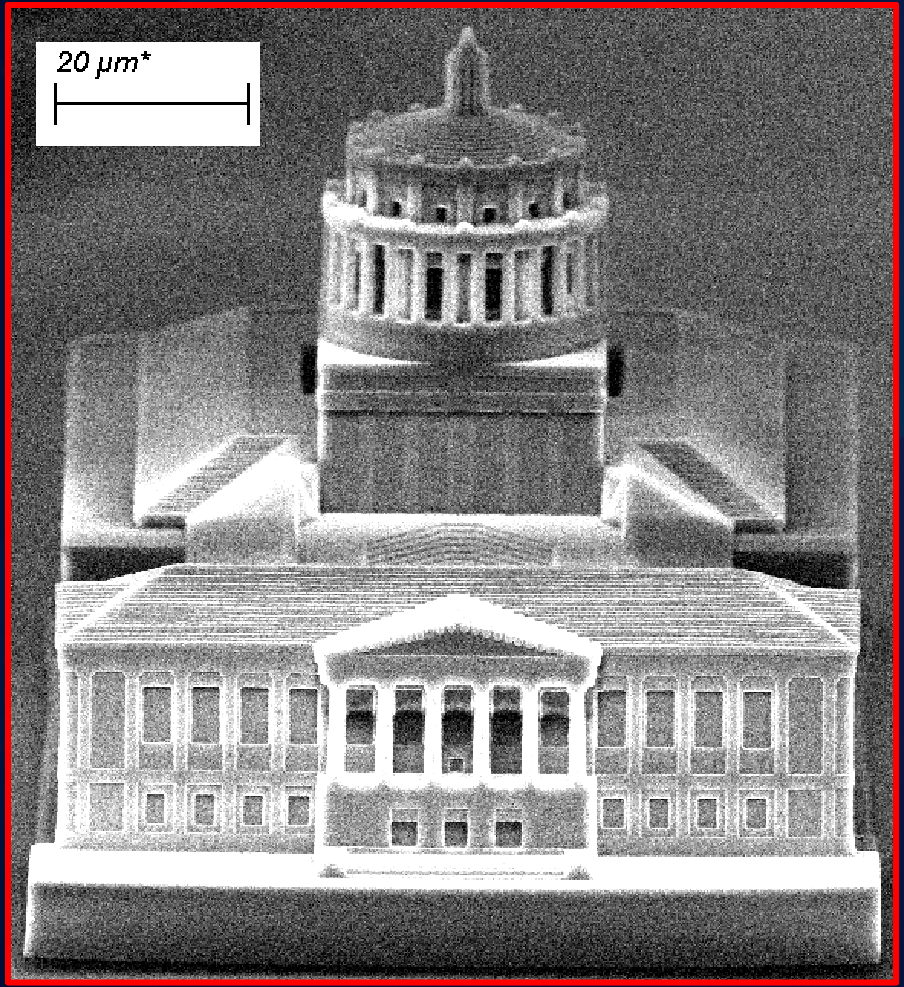
Figure by Sam Wurzel (ARPA-E) [via Scott Hsu (Office of the Undersecretary of Science, DoE)]

Direct Drive is the most efficient approach but new lasers are needed – LLE is on the verge of demonstrating a break through in performance

FLUX (Fourth-generation Laser for Ultrabroadband eXperiments)	
Physics requirement	**Specification**
Central wavelength	351 nm (3ω)
Fractional bandwidth $\Delta\omega/\omega_0$	1.5%
Pulse duration/shape	1.5 ns/flat in time
Energy	150 J
On-target power	0.1 TW
Far-field size	Focusable to 100 μm (with distributed phase plates)
On-target intensity	10^{15} W/cm^2







Meliora

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Questions?