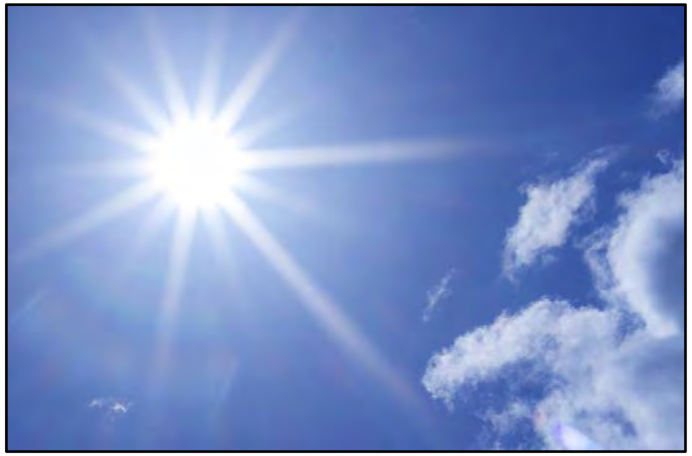
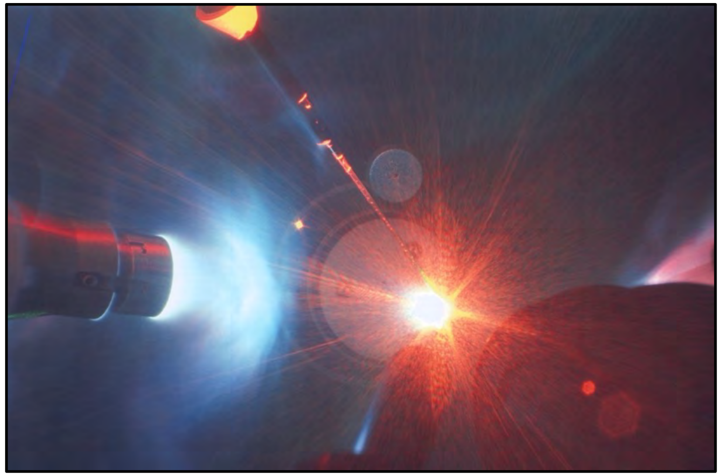
Inertial Fusion Energy (IFE): Opportunities and Challenges





Dr. E. M. Campbell
Director
University of Rochester
Laboratory for Laser Energetics

Fusion Energy Council of Canada AGM
September 15, 2021

Power must be generated near population centers!
By 2050, ~60% of world population will be urbanized*

Energy 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

Desirable features of central power production

- Abundant fuel supply
  - globally dispersed
- Environmentally acceptable
- Passively safe
  - Zero emergency planning zone possible

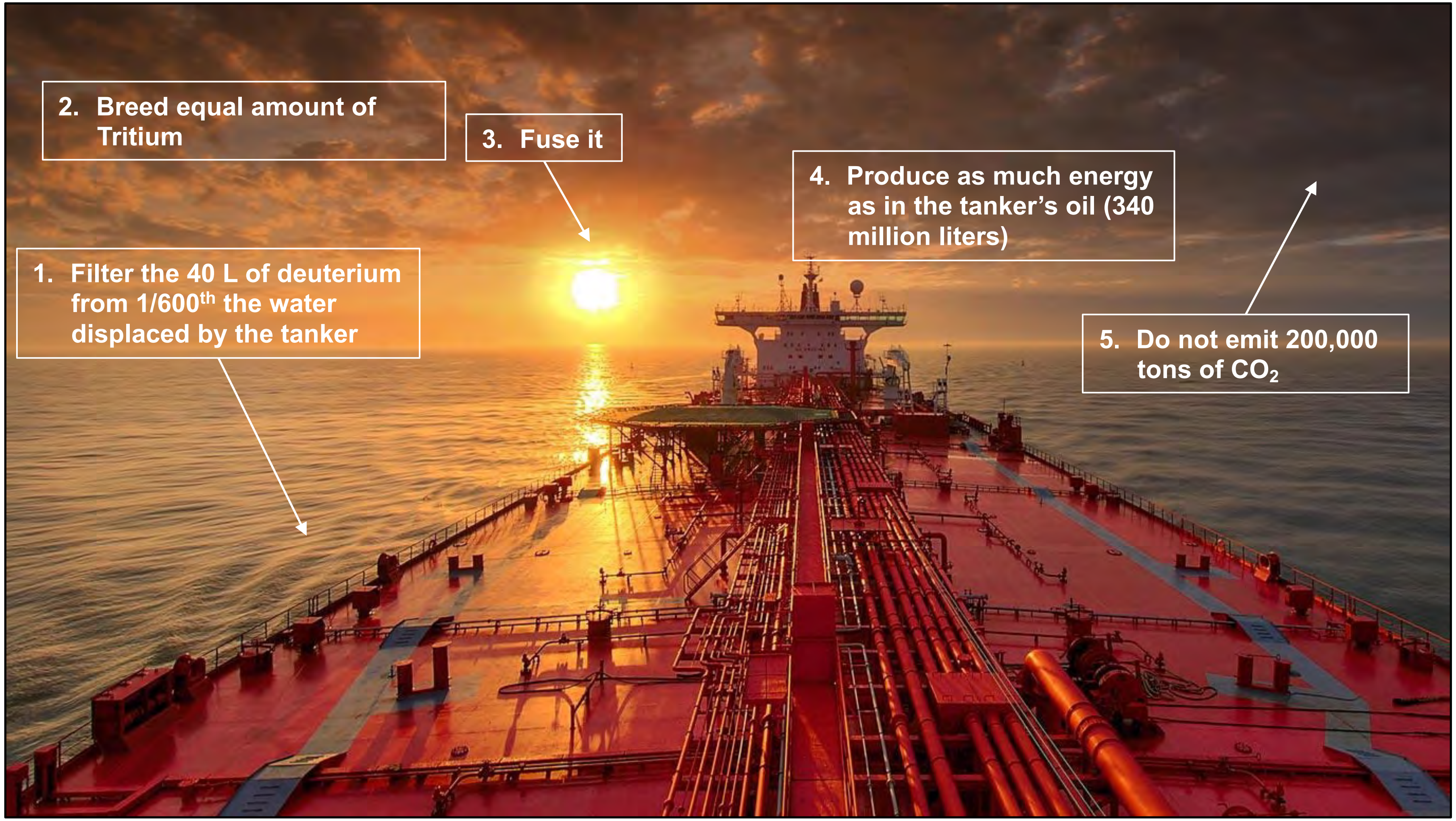
Fukushima, 2011

Chernobyl (35 years later)

- Minimal proliferation concerns

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

The promise of fusion (Deuterium, Tritium fuel)



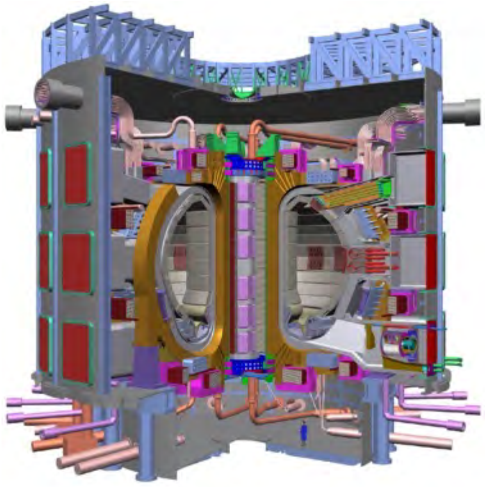
1. Filter the 40 L of deuterium from 1/600th the water displaced by the tanker
2. Breed equal amount of Tritium
3. Fuse it
4. Produce as much energy as in the tanker's oil (340 million liters)
5. Do not emit 200,000 tons of CO_2

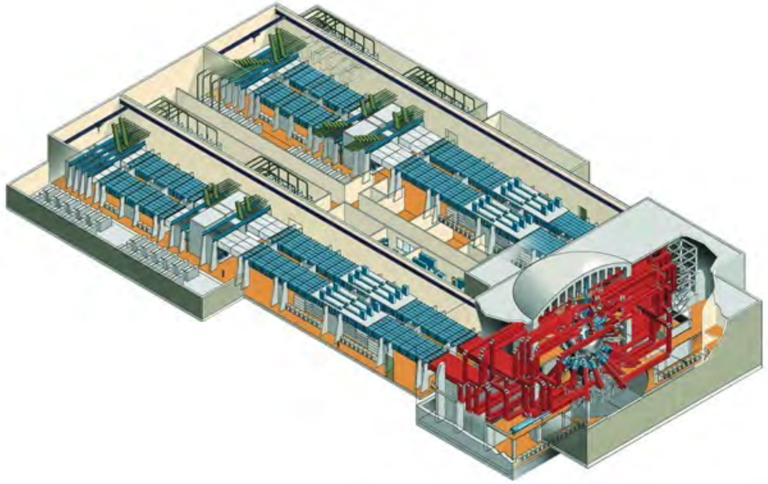
The challenge of fusion: Both temperature (~10^8 K) and *confinement* are required for the net release of energy by fusion

ITER

$P\tau^* > 10$ atm-s

National Ignition Facility (NIF)





- Magnetic fusion
  - plasma confined by magnetic fields
  - $n_i \sim 10^{14}$ cm^{-3}
  - $\tau \sim 1$ s

- Inertial confinement fusion (ICF)
  - plasma confined by inertia
  - $n_i \sim 10^{25}$ cm^{-3}
  - $\tau \sim 10^{-10}$ s

ICF requires "matter at extreme conditions."

National Security has motivated many scientific and technical advances that have benefited society

- 94 reactors at 58 plants

There are 94 nuclear reactors in the U.S.: ~20% of electricity and 55% of the carbon-free electricity generation.

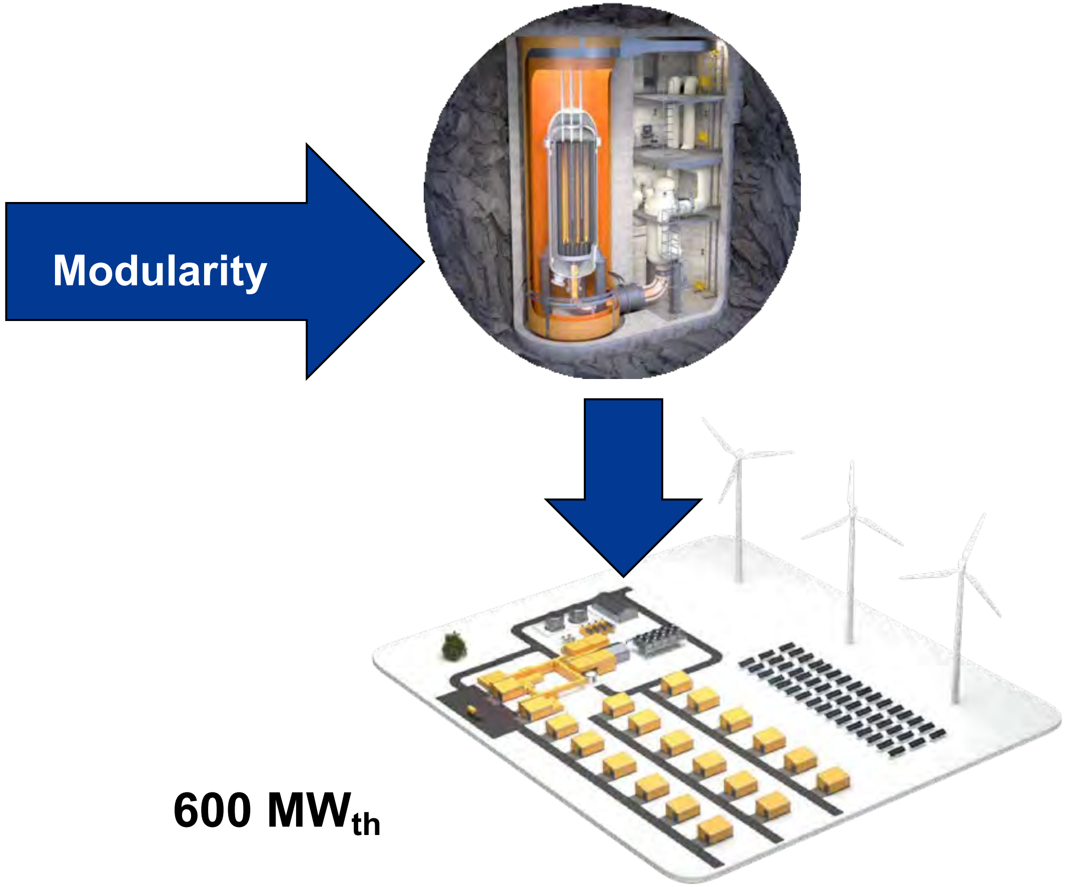
Science the Endless Frontier
Vannevar Bush, July 1945

High-Performance Computing

Space (i.e., GPS, weather)

Radar

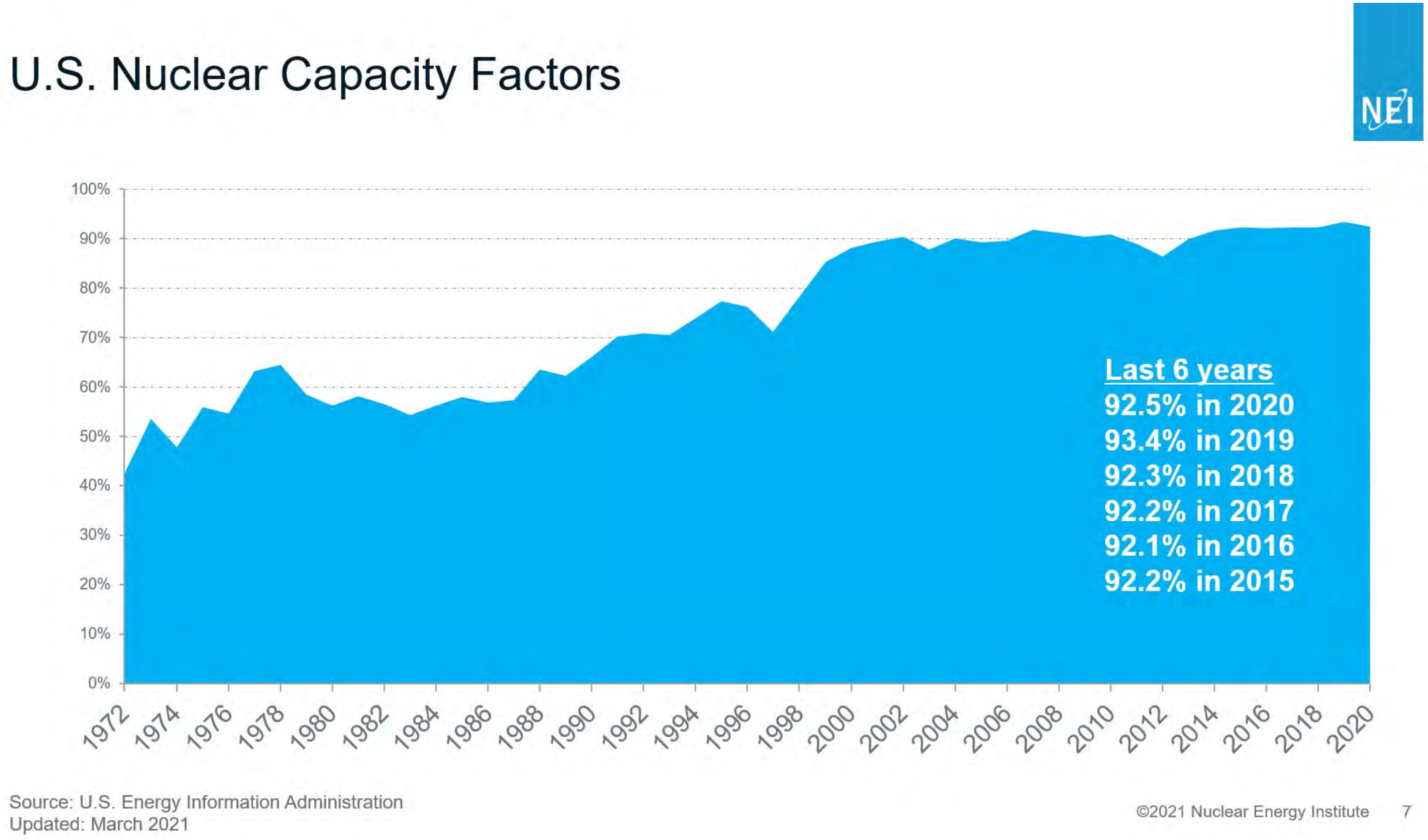
IFE and Fusion must learn from the "Fission Experience": The good, bad, and ugly!



- 94 reactors at 58 plants
- Plant output ~1 GW$_e$
  - construction cost
    - \$5/watt$_e$ to \$8/watt$_e$
  - construction time
    - 84 to 117 months

And………

Capacity factor for nuclear plants has grown from ~50% in the 1970s to over 90% today

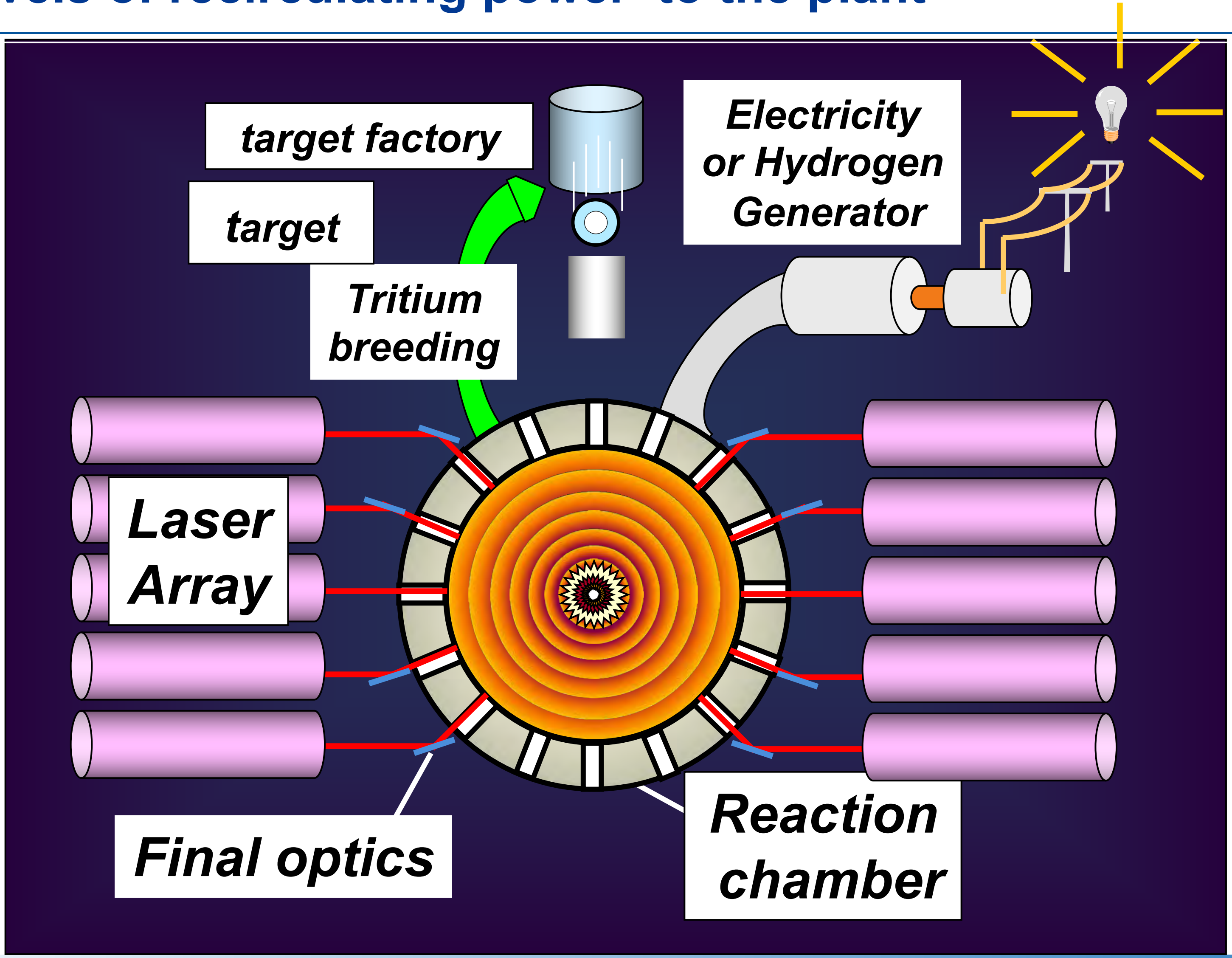


U.S. Nuclear Capacity Factors

Last 6 years
92.5% in 2020
93.4% in 2019
92.3% in 2018
92.2% in 2017
92.1% in 2016
92.2% in 2015

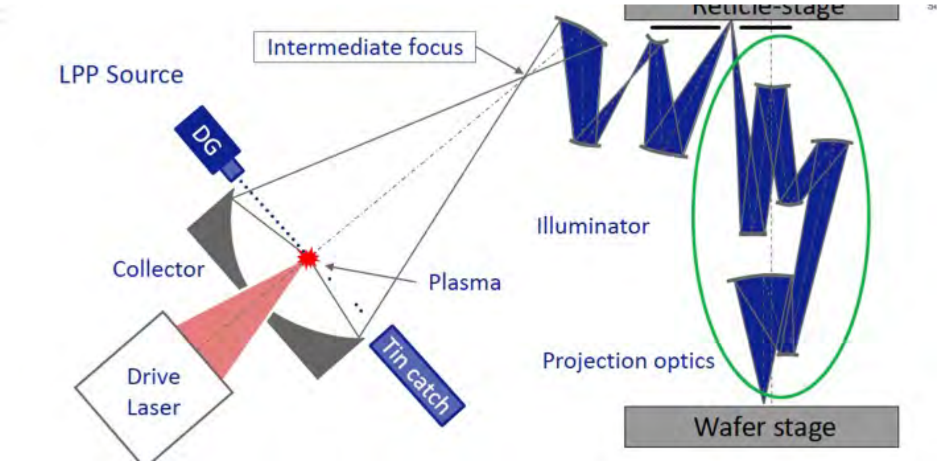
Source: U.S. Energy Information Administration
Updated: March 2021

Fusion energy with lasers or pulsed power requires ηG^{1}>~10 for acceptable levels of recirculating power to the plant



[1] Driver efficiency, η; Target gain, G

EUV Lithography (invented by ICF scientists[1]) for IC production @ ~13.5 nm is similar to an IFE plant



- **50 KW laser (CO$_2$)**
  - rep-rate: 50 kHz
- **~50 micron Sn micron target**
  - Injected & irradiated by laser @ ~10^{12} w/cm^2
  - Pulse shaping (~nsec duration)
- **"First wall protection"** (expensive EUV condensing optic and focusing lens)
- **$>10^9$ shots**
- **Capacity factor as high as ~90%**

EUV prototype
(LLNL, SNL, LBNL)

TWINSCAN NXE EUV lithography systems

- **7 nm node (Logic and DRAM markets)**
  - **Development underway for 5 nm and 3 nm node**
- **Shipments (units) 30 (2019) @ $120M/system**
  - **ASML has shipped 100 EUV steppers at end of CY2020**
- ***New Apple iPhone has 8 Billion transistors produced by EUV lithography!!****

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[1] **"Soft x-ray Projection Lithography," N Ceglio, A.M. Hawryluk, *et al.*, Journal of Vacuum Science and Technology 8,1935 (1990)**

Laser based Inertial fusion energy will leverage technologies developed for inertial confinement fusion

- Inertial confinement fusion (ICF) programs developed many technologies that naturally extend to Inertial fusion energy (IFE)
  - High-bandwidth/high-contrast pulse shaping
  - Beam shaping
  - High-performance optical coatings
  - Laser glass and optical technologies
  - Target fabrication
- Spin-off IFE technologies can also expect to be applied to other fields
  - Extreme Ultraviolet (EUV) laser sources
  - Laser peening and other materials-processing techniques (large scale additive manufacturing, surface processing)
  - Laser accelerators
  - Radiation sources

Rep-rated facilities developed for HEDP, radiation sources and ultrahigh-intensity laser-matter research will also benefit IFE.

IFE features, advantages, challenges

IFE Features:

- Rep rates from 0.1 Hz to 10 Hz
  - 3.16×10^6 -3.16×10^8 /yr (@ 100% capacity factor)
- Driver
  - Energy/pulse
    - 0.5-20 MJ
  - Peak power
    - >~500 TW
  - Average power
    - 3 to 10 MW
- Targets
  - ~9,000 to 900,000/day
  - Target cost <$1

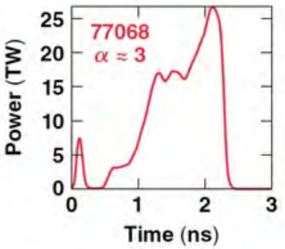
IFE advantages

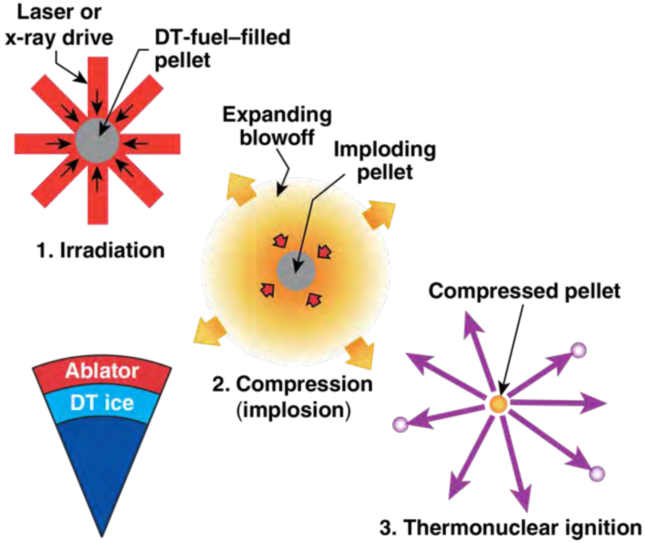
- Separable components
- Highly modular
- Attractive development path
  - "Non-nuclear" demo plant
  - Low rep-rate "nuclear" facility for target development
  - Driver modularity
- Fueling and ash removal
- Load following
- Flexible "first wall"
- Technology and science spin-offs
- Multiple target concepts with same driver
- Multiple sponsors for technology and science
  - Technologies (i.e., laser diodes, optics)
  - Target physics and supporting technologies
  - Scientists and engineers

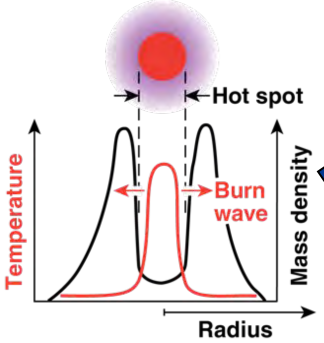
Target Physics

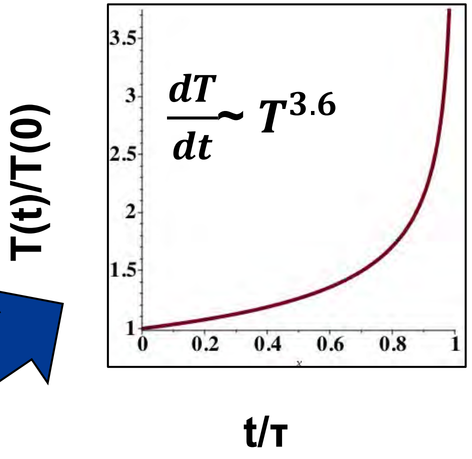
ICF is enabled by drivers (lasers and pulsed power) that compress energy in space and time; laser-induced ablation generates ultrahigh pressures that compress a fusion capsule to ignition conditions (compression amplifies pressure!)

Ignition$_{DT}$ ➡ Thermal instability (P_α> all loses)









- Fusion energy out (E_F)
  - $E_F = \varepsilon_f \phi m_{DT}$
    - specific DT fusion energy (4×10^8 J/mg)
    - burnup fraction $\phi = \rho R/[\rho R + f(T)]$
    - equimolar DT mass (m_{DT}) mg

100-MJ fusion yield

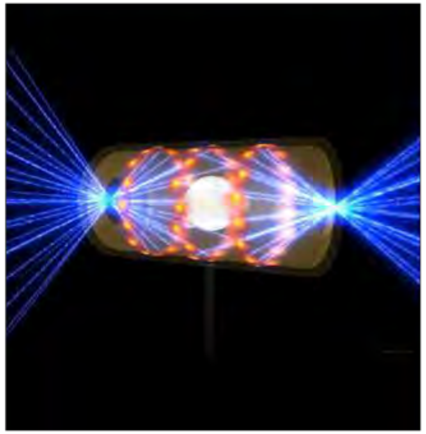
- $\phi = 1/3$; $m_{DT} = 0.75$ mg

Gain, $G = \frac{\text{Fusion energy out}}{\text{Driver energy in}}$

"Hot-spot" ignition requires the core temperature to be at least 5 keV and the core fuel areal density to exceed ~300 mg/cm^2.

An advantage of ICF: There are three credible approaches to MJ and greater fusion yields in the laboratory

Laser indirect drive

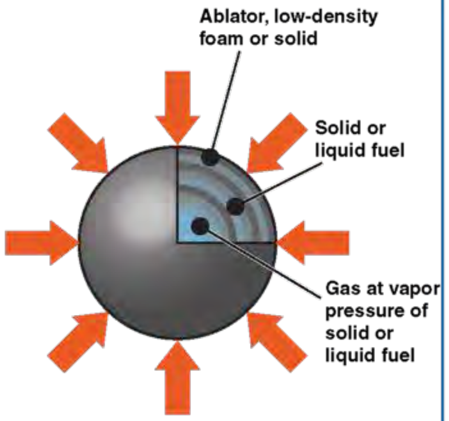


LLNL lead laboratory (LANL)

Facility

- NIF
  - OMEGA

Laser direct drive

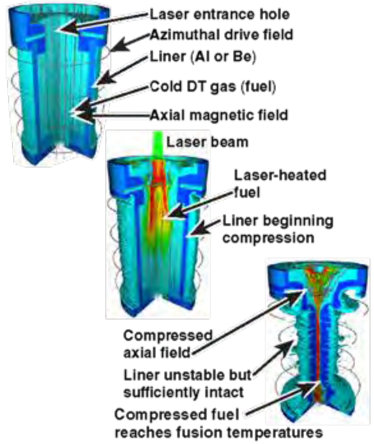


LLE lead laboratory (NRL,LLNL, LANL)

Facility

- Omega
  - NIF
  - NIKE

Pulsed-power magnetized fusion



SNL lead laboratory (LLNL, LANL, LLE)

Facility

- Z
  - Omega
  - NIF

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Innovative variations exist within each approach (e.g., shock ignition, fast Ignition, hybrid targets, B fields).

Each ICF/IFE approach has advantages and challenges

Indirect (x-ray) Drive

- *Advantages*
  - Multiple drivers
    - Lasers, pulsed power, ions
  - Favorable hydrodynamics
    - High ablation rates, reduced Attwood Number (shallow density gradients)
    - No high frequency noise sources (imprint)
- *Challenges*
  - Lower gain
  - Reduced energy to capsule $(P_{ig})^{th} \sim (E_{hs})^{-1/2}$
  - Laser-plasma Instabilities (long scale length plasmas)
  - Complex Hohlraum physics
  - Radiation preheat
  - Reduced diagnostic access

Laser Direct Drive

- *Advantages*
  - Efficient coupling of laser energy to target
    - Lower pressure for ignition
      - $(P_{ig})^{th} \sim (E_{hs})^{-1/2}$
      - Lower convergence (~20 to 25)
      - Higher adiabat
    - Higher potential gain
    - Innovative approaches
      - Shock ignition
      - Fast ignition
    - Diagnostic access (3-D)
- *Challenges*
  - Hydrodynamic instabilities
  - Laser imprinting
  - Electron driven ablation
    - Higher RT growth rates
    - Thin shells
  - Laser plasma instabilities
    - Cross beam energy transport (CBET)
    - 2 ω_{pe} , stimulated Raman scattering (SRS)

Pulsed Power

- *Advantages*
  - Large energy coupled to fuel
  - No/minimal LPI
  - High driver efficiency
- *Challenges*
  - No stand-off
  - Diagnostic challenges

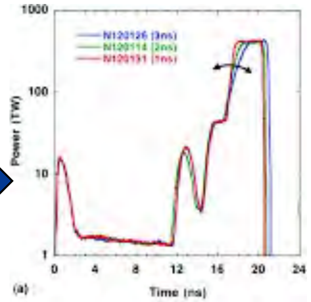
Energy flow in an x-ray–driven (LID) and direct drive (LDD) target today

Capacitor banks (~400 MJ)

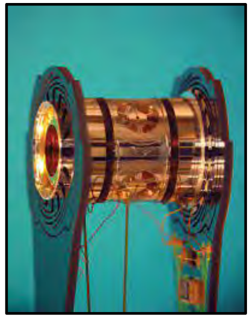
Flash lamps

4 to 5 MJ at 1052-nm laser

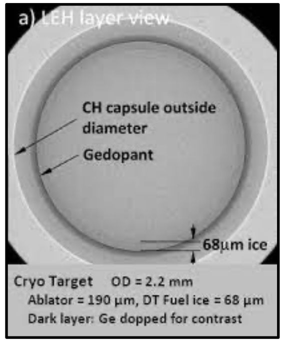
Frequency
conversion



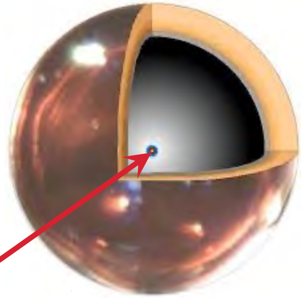
~2 MJ at 350 nm
(~0.5% EO
Efficiency)



~1.8 MJ at 300 eV
blackbody Hohlraum

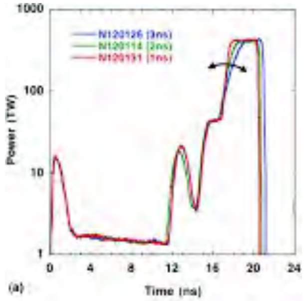


~0.2- to 0.3-MJ
capsule

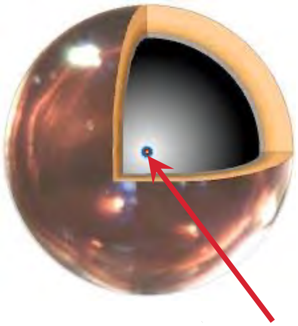


~0.02 MJ
imploded target

or



~2 MJ at 350 nm



~0.1 MJ
imploded target

LDD requires better "beam conditioning" than LID.

Several metrics can be used to see fusion progress in ICF. Assertion: capsules that absorb <~ MJ will achieve adequate gain for IFE

- Fusion output equal to energy in the central hot spot of the compressed target
  - status: Achieved on the NIF (LID)
- Alpha heating dominates energetics in the central hot spot (alpha amplification)
  - status: Preliminary analysis indicates this has been achieved on the NIF (LID)
- Capsule gain
  - for laser indirect drive (LID) this would require fusion output >200 to 300 kJ
  - for laser direct drive (LDD) this would require fusion output >1 MJ
  - Status: Capsule gain for LID demonstrated ($\text{Gain}_{\text{capsule}}$ ~4-5)
- Target gain
  - For LID this requires capsule gain of 5 to 10
  - For LDD this requires capsule gain of 1
  - Status: Target gain of ~0.7 with LID

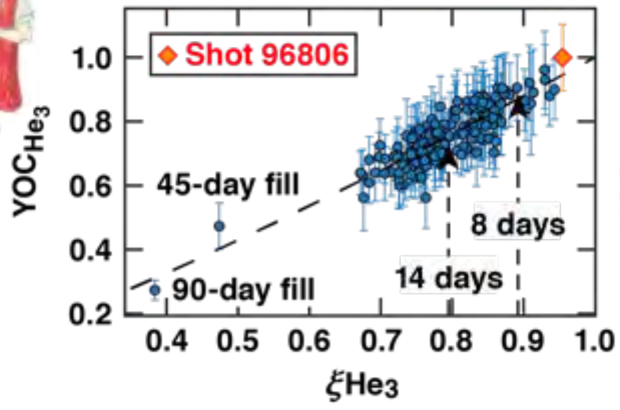
- Ignition [A. Christopherson et al (PRE 2019), J. Lindl et al (POP 2018)]
  - alpha amplification >25 to 30
  - Status: Analysis to date has estimated amplification of ~25-with ~250kJ absorbed and alpha power dominating over energy loss mechanisms (radiation, conduction, explosion) for finite time duration

Challenge: Program is "data starved" with too few implosions/year (NIF and OMEGA).

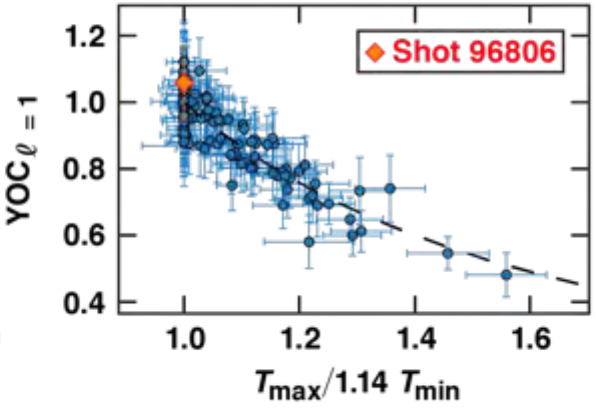
What about LDD?...........

Statistical modeling of *systematic* OMEGA experiments, 3-D diagnostics and simulations have successfully improved performance and developed an understanding of implosion degradation mechanisms

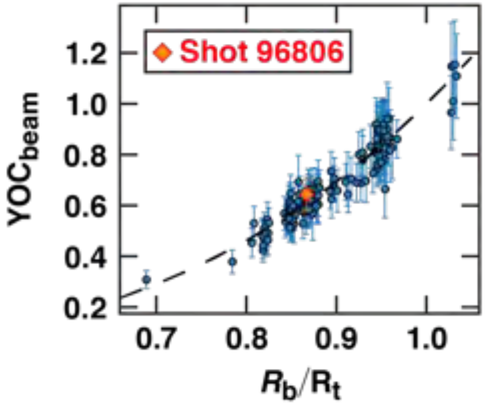
Dependence on He_3 and fill age



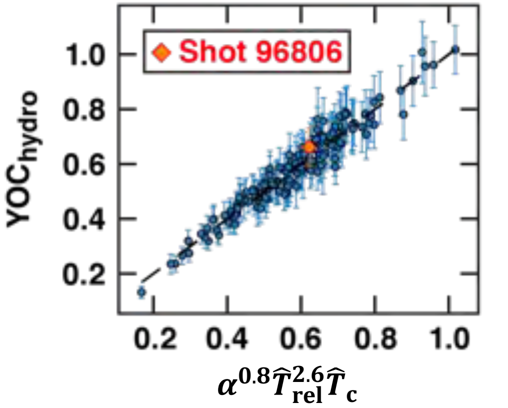
Dependence on the $\ell = 1$ mode

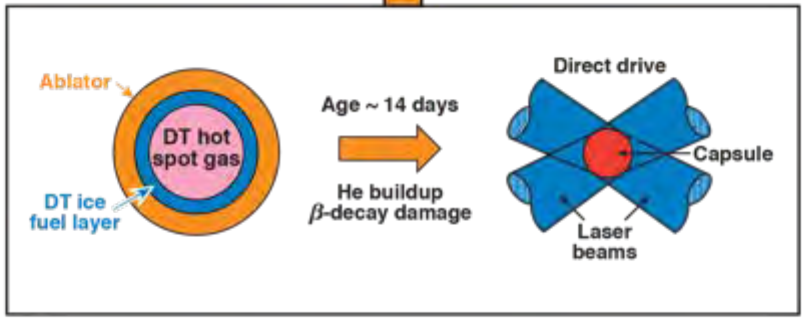


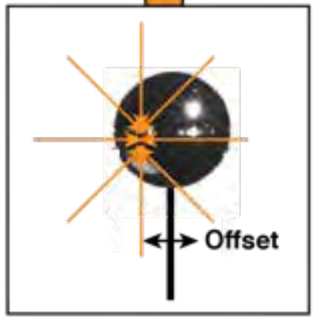
Dependence on laser beam to target size

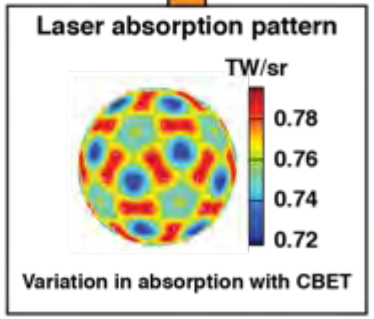


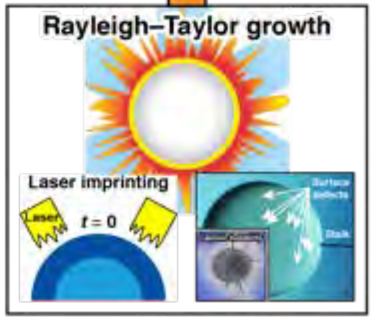
Dependence on hydrodynamic stability parameters











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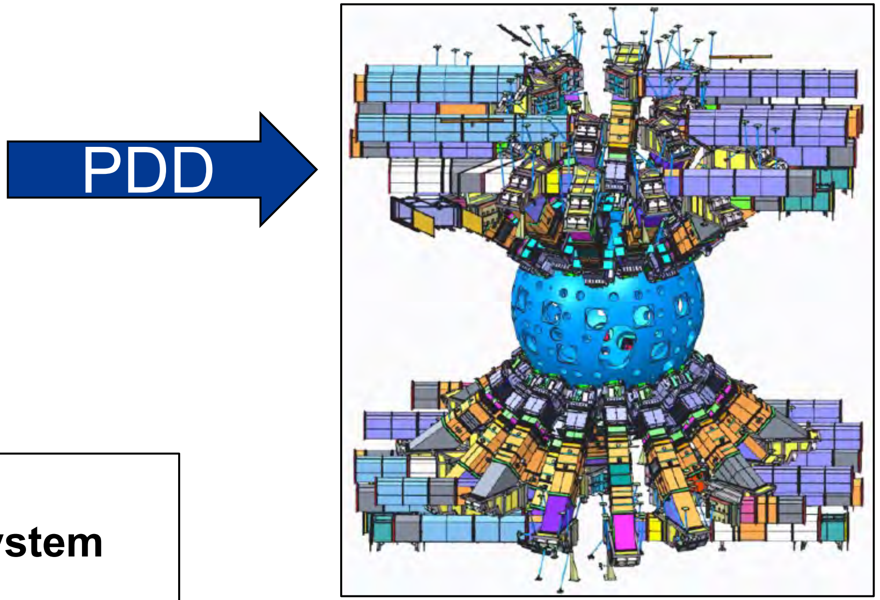
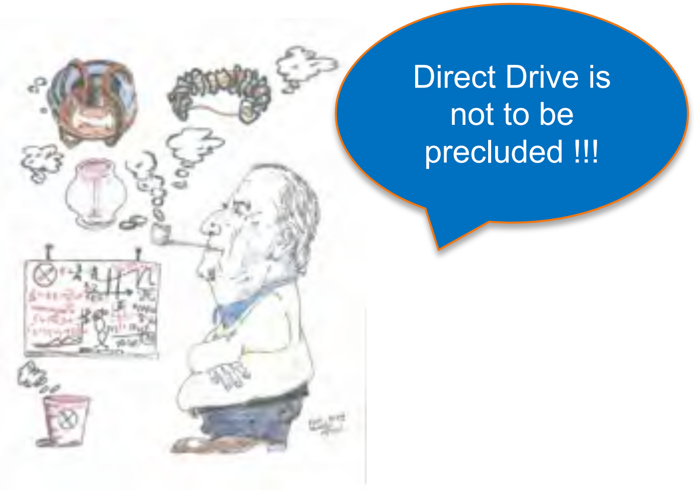
Experiments on "Present day" NIF to study laser–plasma coupling in ignition scale plasmas to date have been encouraging, increase understanding, and exercise modeling/simulation tools.

The original vision of NIF was that all credible approaches to ignition and gain would be explored over the lifetime of the facility; LLE, LLNL, LANL, and GA will work together to develop cost, schedule for modifications for Polar Direct Drive (PDD)

J. Lindl Book, page 157

“ Although indirect drive is the primary approach to ignition on the NIF, developments in direct drive have reached the point where this approach also looks quite promising. With the implementation of additional beam smoothing and more beam ports NIF can be capable of both indirect and direct drive.”





PDD Requirements

- **Cryogenic Target System**
- **Phase plates**
- **Wavelength detuning (CBET reduction)**
- **Beam smoothing**
    - **laser/target solutions**

Advantages of Polar Drive

- **Innovative targets (e.g. B fields)**
- **Reactor flexibility (IFE)**
- **Reduced impact on present NIF**

IFE

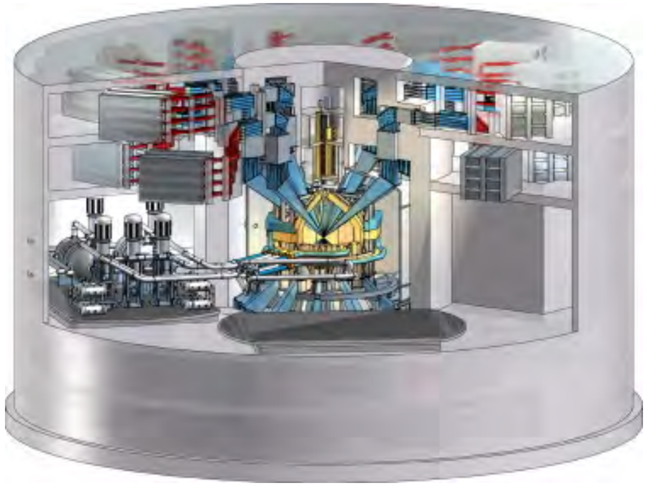
The advantages of IFE

- Separability and modularity
  - driver
  - target
  - flexibility in target chamber concepts (first wall can be “liquid”)
  - fueling and “ash removal”
- Multiple concepts
  - numerous target concepts can be explored with the same driver (lasers and pulsed power)
- National security sponsorship
- Attractive development plan
  - single-shot facility for target performance and optimization
  - two step “reactor demonstration” possibility
  - multiple sponsorships for key technology
    - i.e., laser diodes are key for directed energy systems and industrial applications
      - DOD roadmap has 500 kW, >30% efficient lasers in several years
    - i.e., additive manufacturing (targets)


Printed target

Magnetic and Inertial fusion energy plants based on DT fuel cycle share common challenges[1,2,3,4]

- Radiation flux and first wall survivability
    - Similar average neutron wall loads (~MW/m^2) but IFE is pulsed (~10 HZ) with higher 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
        - Economic recovery
        - Safety



[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)—Laser Indirect Drive
[3] M. Dunne et al "Timely Delivery of of Inertial Fusion Energy (LIFE)" Fusion Science and Technology," 60 (2014) — Laser Indirect Drive
[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)—Laser Direct Drive

Recommendation: Joint workshop with MFE and IFE scientists and Engineering and develop concepts for an IFE chamber Dynamics Experimental Facility[5]

[5] UCB program in 2003 explored jet stability and chamber clearing issues with H_2O

Laser Drivers for IFE

That stimulated emission idea has sure paid off!

LLNL and NRL (with Congressional help) initiated the HAPL (High Average Laser Program) in the 1990s to develop krF and diode-pumped SSL

A conversation at LLNL in 1960

Edward, I think we can do fusion with this new invention, lasers!

John Nuckolls
(“father of ICF”)

Not if plasma physics gets in the way!

Edward Teller

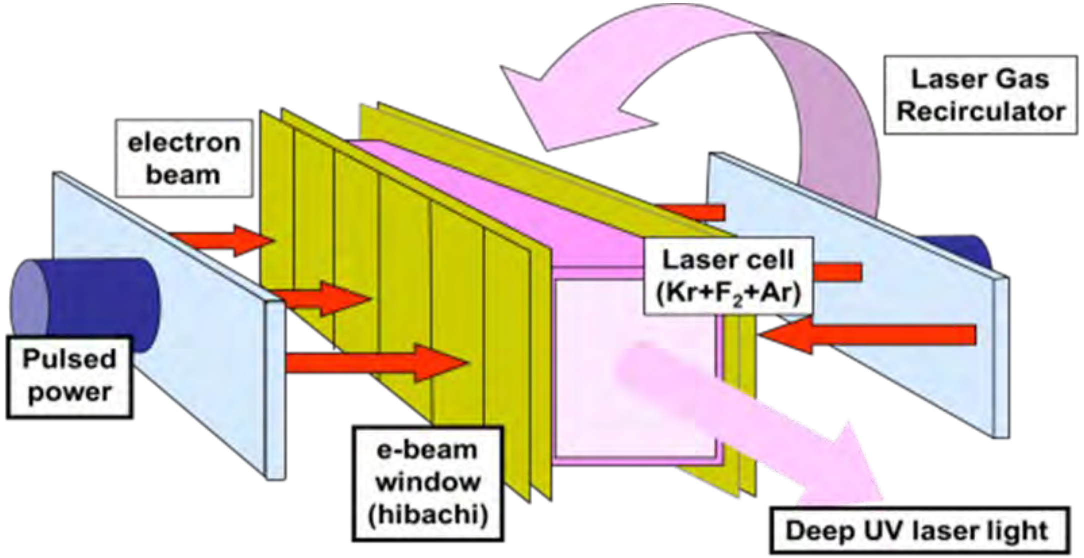
You should be worried!

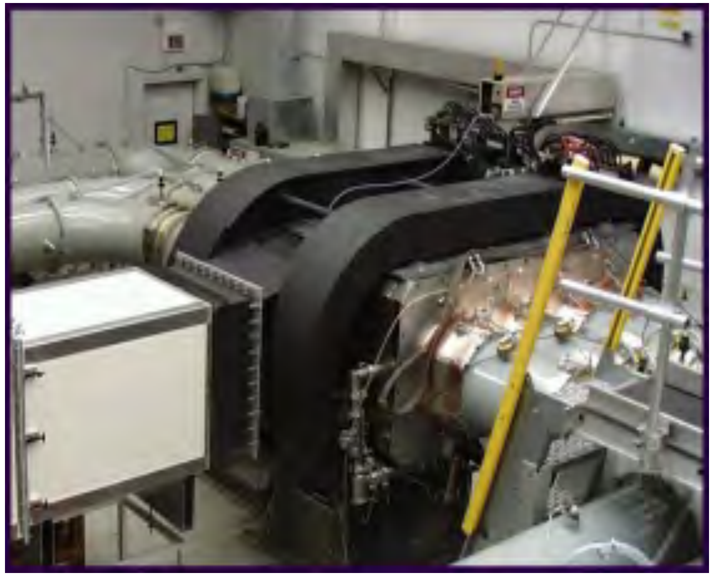
Marshall Rosenbluth

John Hunt
(Inventor of all modern SSL architectures)

Short wavelength, incoherence (Spatial, Temporal), stud pulses are solutions.

The electron-beam-pumped fluoride (KrF) and argon fluoride (ArF) lasers offer deeper UV and broader bandwidth than current ICF laser drivers[1]





Nike 60-cm aperture KrF amplifier

- Shorter wavelength enables higher drive pressure and more efficient implosions
- Broad bandwidth (>3 THZ for KrF and >8 THz for ArF) helps suppress LPI and reduces laser imprint from beam smoothing
- The combination of very short wavelength (193 nm) and projected good wall-plug efficiency (10%) make the ArF driver very attractive for inertial fusion energy

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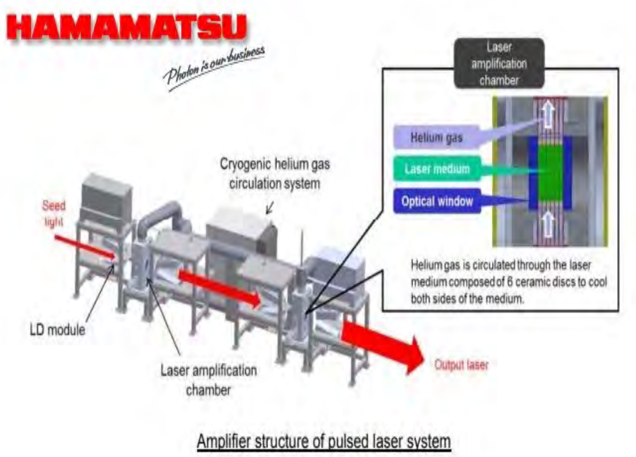
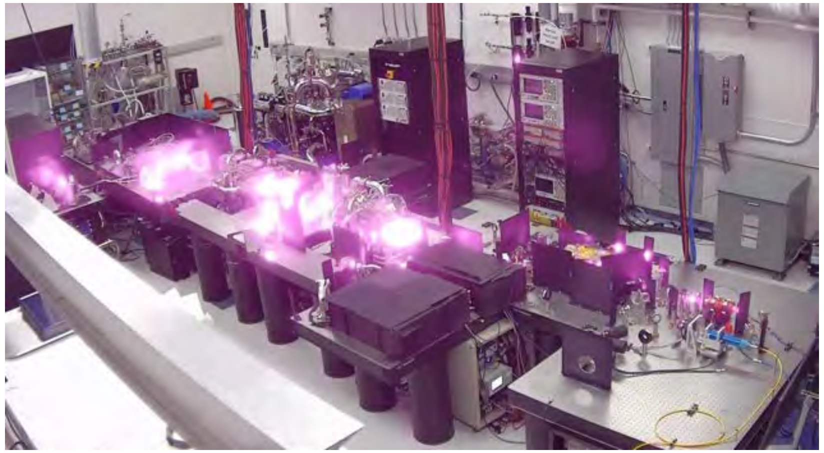
[1] VG provided by NRL

Solid-state lasers for IFE[1] leverage ongoing developments in national security, industry, and high-intensity laser research



Laser Peening
(>100 Joules, Hz rep rates, nsec pulse)

LLNL pump laser for HAPS for ELI
(10 Hz, ~200 joules, ~5-10 nsec pulse)



GA Directed Energy Program
(100s of KW and high E-O Efficiency)

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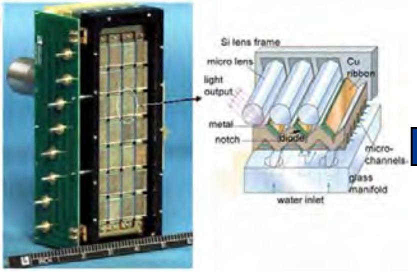
[1] W. Krupke "Diode Pumped Solid state lasers for IFE," SPIE Proceedings Vol 3047 (1997)

Energy flow in an x-ray–driven (LID) and DPSSL direct drive (LDD) target tomorrow

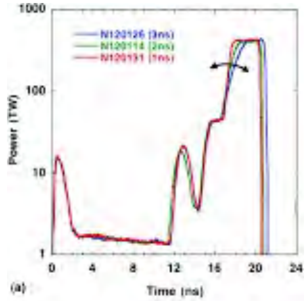
Electricity from the "grid" (10.3MJ)



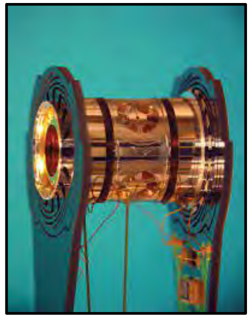
Laser diodes (6.7 MJ)

4 MJ at 1052-nm laser

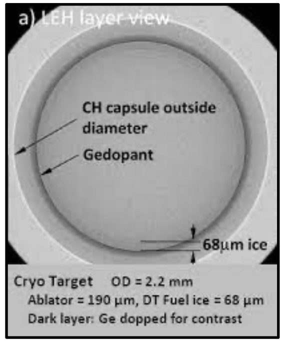
Frequency conversion



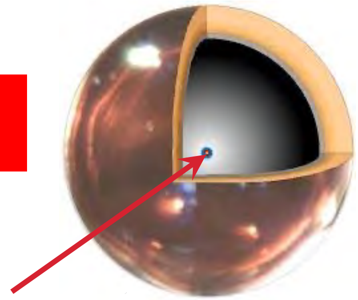
~2 MJ at 350 nm (19.4% E-O efficiency)



~1.8 MJ at 300 eV blackbody Hohlraum

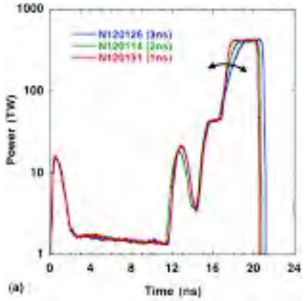


~0.2- to 0.3-MJ capsule

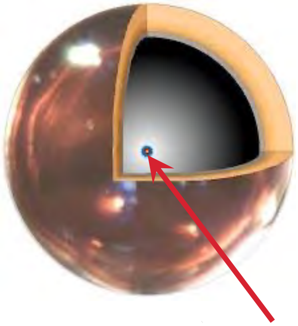


~0.02 MJ imploded target

or

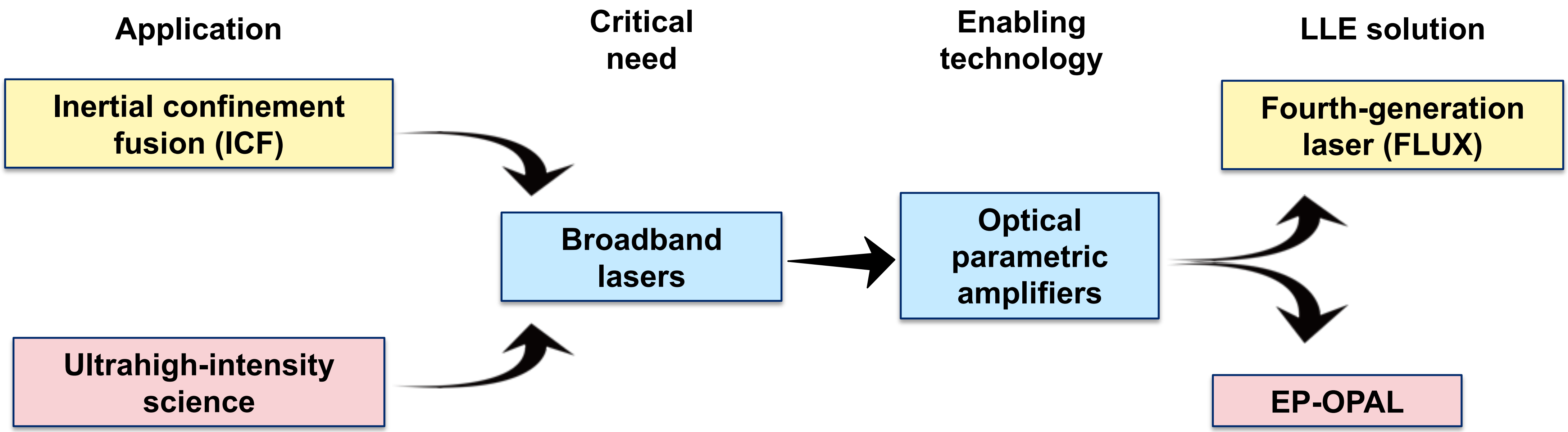


~2 MJ at 350 nm



~0.1 MJ imploded target

Laser technology developed for short-pulse, high-intensity lasers that require significant bandwidth and applications for ICF/HEDP and high-field science



Application

Inertial confinement fusion (ICF)

Ultrahigh-intensity science

Critical need

Broadband lasers

Enabling technology

Optical parametric amplifiers

LLE solution

Fourth-generation laser (FLUX)

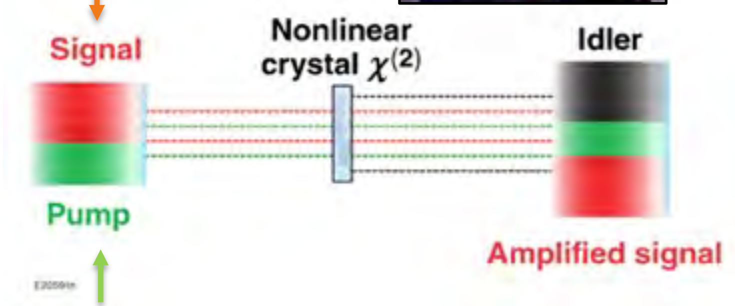
EP-OPAL

- 20-fs pulses
- >25-PW beams

Broadband (>10 THz) UV lasers (FLUX) with flexible temporal formats to suppress LPI and laser imprint to expand parameter space for ICF and HEDP

DKDP

Broadband input

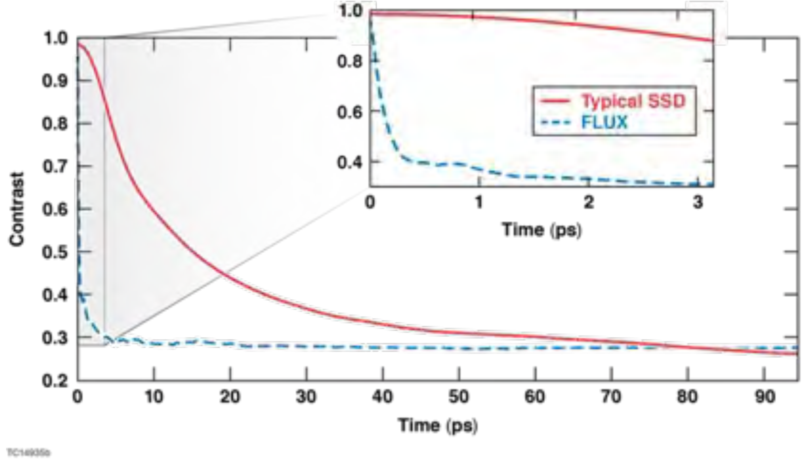


Narrowband, temporally shaped 530-nm pump

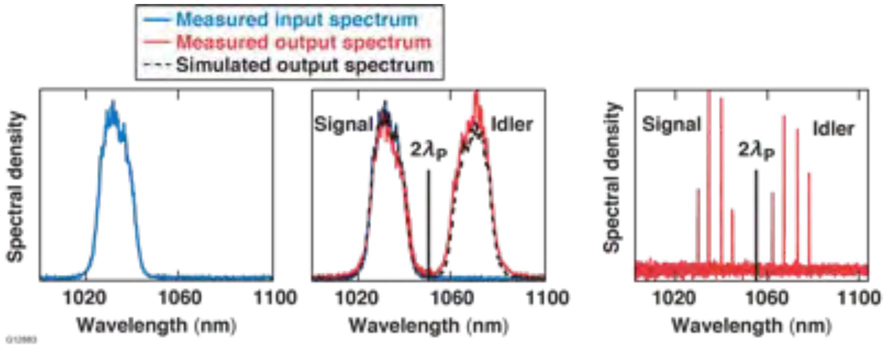
- Compensation gratings
- Frequency conversion

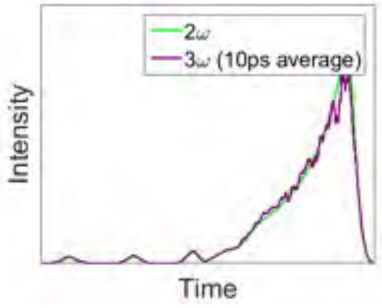
Physics

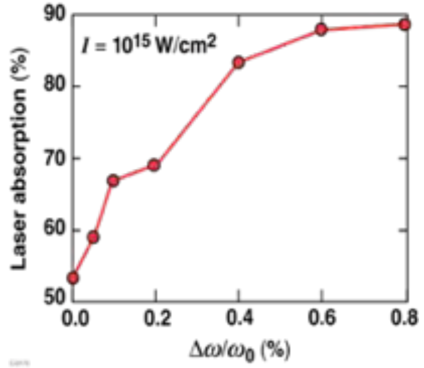
Imprint reduction: ~picosecond beam smoothing



Increased absorption (reduced CBET)





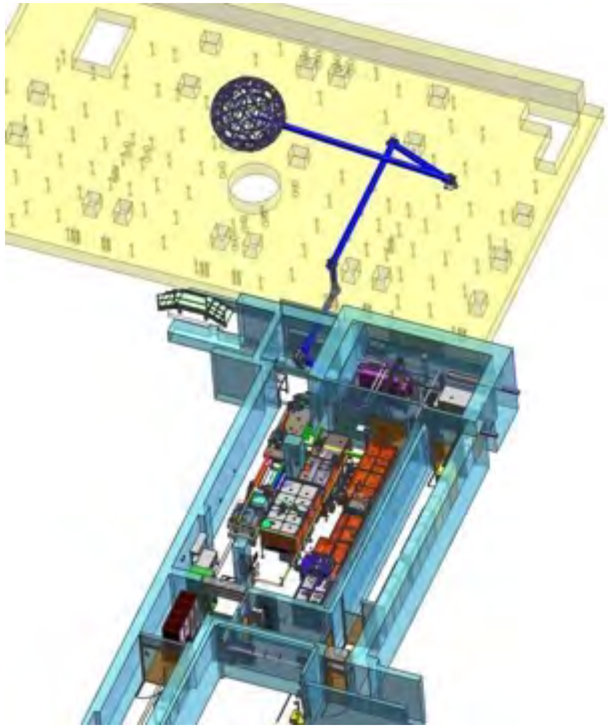


Bandwidth and spectral shaping

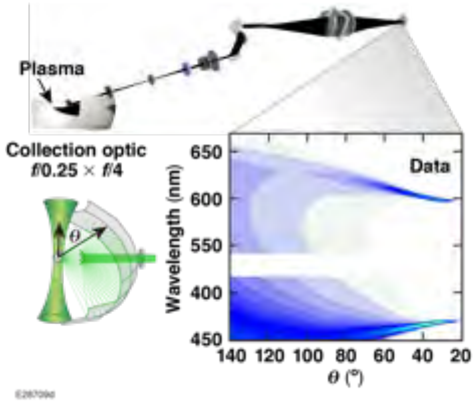
Temporal pulse shaping

Similar to TOP9 CBET platform, FLUX will be transported to OMEGA to provide independent plasma control, “coupling” beams, and extensive diagnostics

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

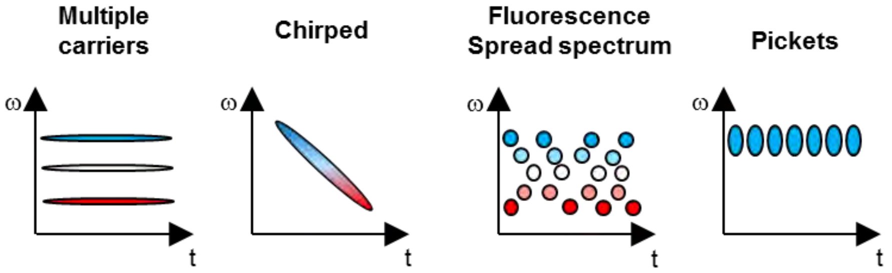


Multi-angle (120°) Thomson scattering



And……

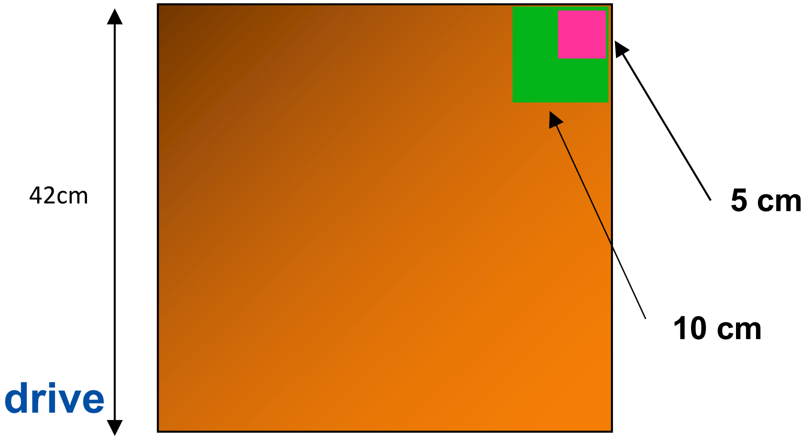
Bandwidth formats



Stud-like

Some “out of the box thinking”—StarDriver™—a highly flexible architecture for laser-driven inertial fusion

- **A laser constructed from 10^4 to 10^5 individual beamlines using cm-scale apertures provides more flexibility to optimize the laser drive**
  - compatible with high-volume manufacturing that can significantly reduce costs
  - a wider range of gain material options are possible
  - beamlines can operate differently to enable complex pulse, shapes, wavelengths, and focal spot zooming to optimize laser drive

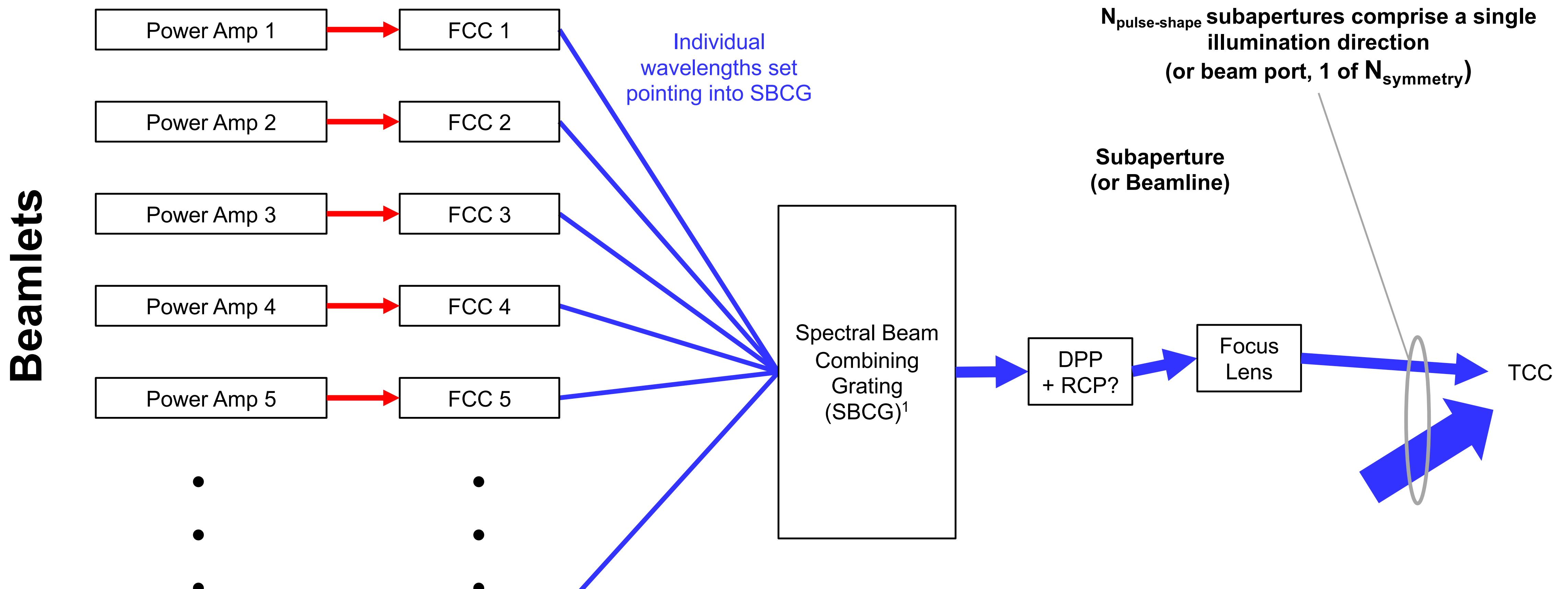


- **A large number of independent beams effectively produces an “incoherent source” to irradiate the target**
  - reduces (or even eliminates) laser−plasma instabilities
  - reduces laser nonuniformity that drives hydrodynamic instabilities

DCS Laser @ANL
(100 Joules, 350nm, 5 nsec)

StarDriver™ leverages many technologies developed for ICF and other high-power laser applications.

StarDriver™ subaperture composed by spectral beam combination



$N_{\text{pulse-shape}}$ subapertures comprise a single illumination direction (or beam port, 1 of N_{symmetry})

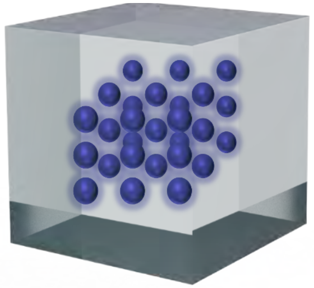
[1] SBCG developed for DEW (multi-color fibers) applications

Targets


That stimulated emission idea has sure paid off!
Evan
Get Relative

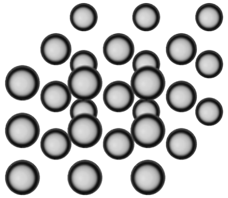
Mass Production of Targets for Sustainable Fusion Energy

- Holographic 3-D printing



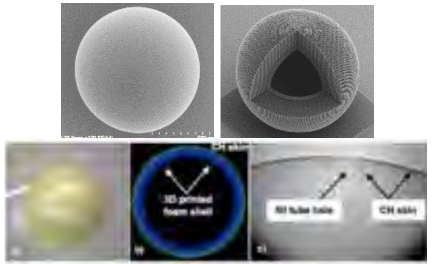
Holographic 3-D Exposure

Development in solvent



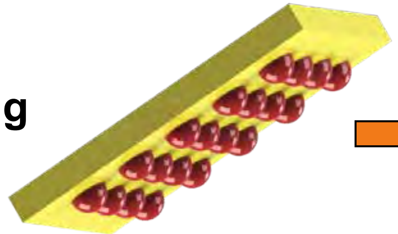
Batch targets produced in seconds to minutes

Targets for use



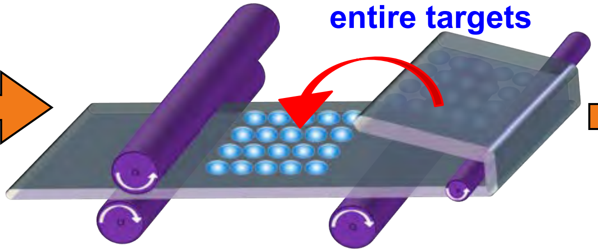
Printed solid capsule and foam targets (GA, UNL)

- Nanoimprint and Origami Folding

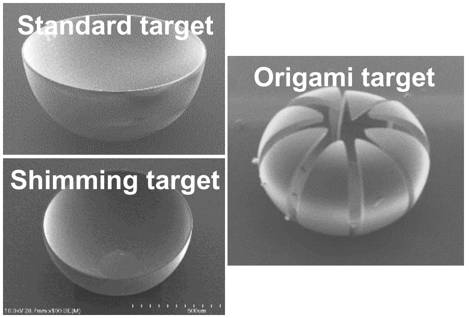


Laser manufactured mold

Origami folding to form entire targets

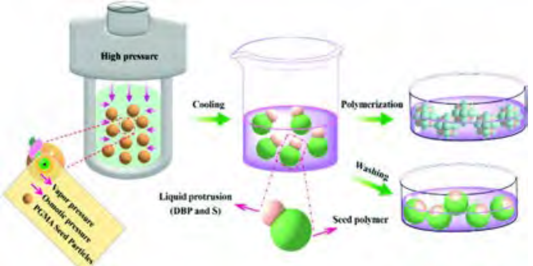


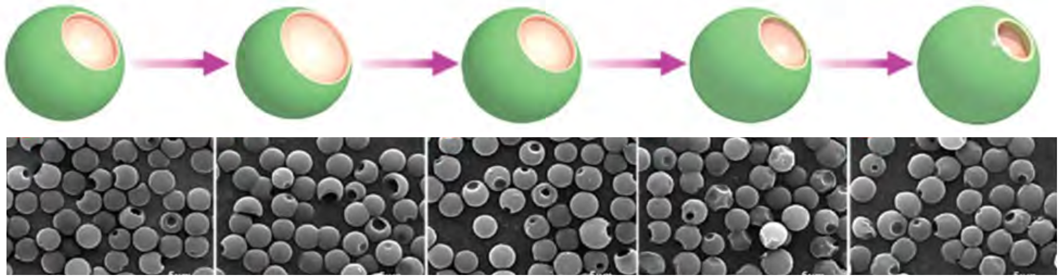
Roll-to-roll nanoimprinting of mass hemispherical targets



Standard, Shimming, Origami capsule targets (UNL)

- Emulsion polymerization

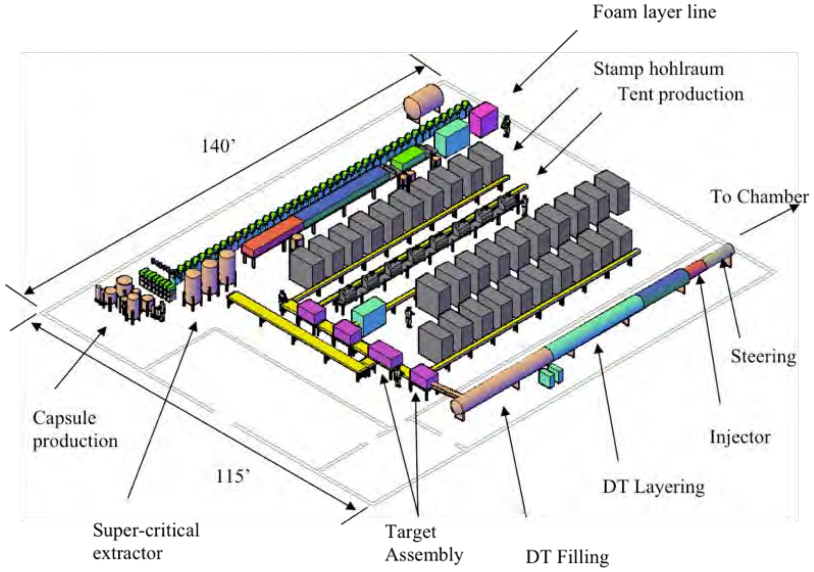




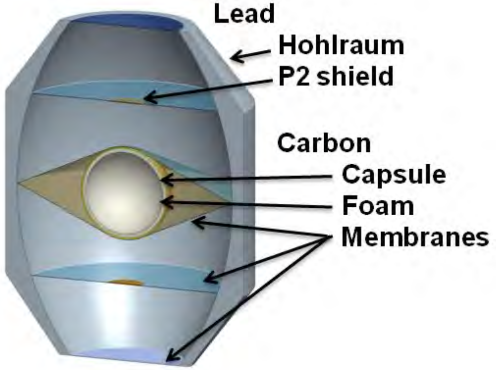
Mass target production via wet chemical processes

Polym. Chem., 2016, 7, 7078

Concepts for mass production of LID targets have also been developed[1]



- Use known high-throughput, low-cost manufacture techniques such as injection molding, plating
- Use large batch size for chemical processes
- Completely automated production line
- Statistical process control
- Approach based on consultation with relevant industrial suppliers



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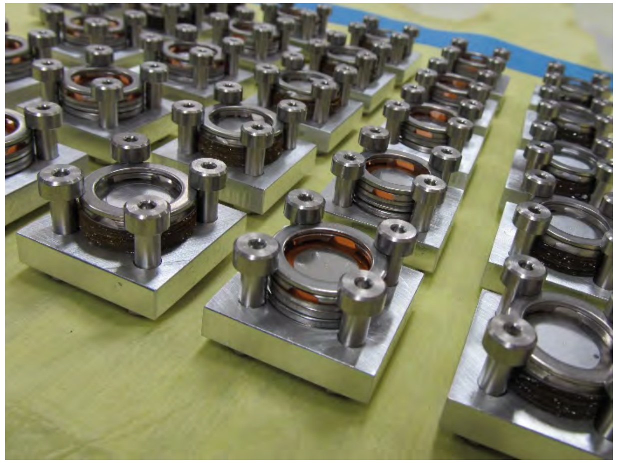
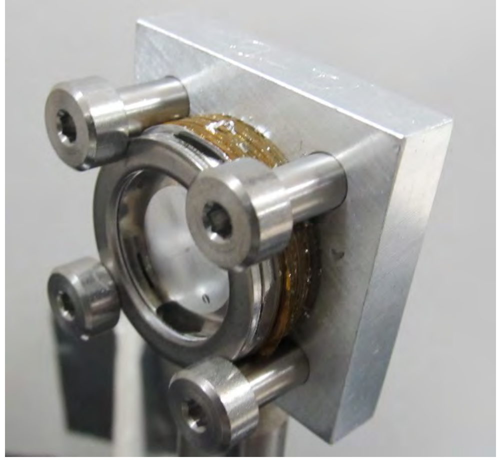
[1] VG supplied by Mike Dunne (LIFE Project)

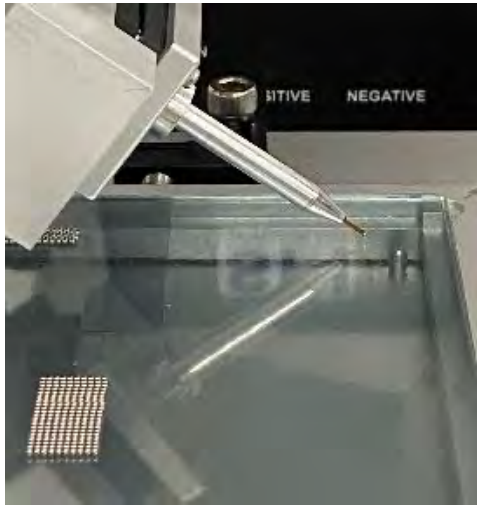
Investments in Automation & Robotics Systems are required for IFE[1]

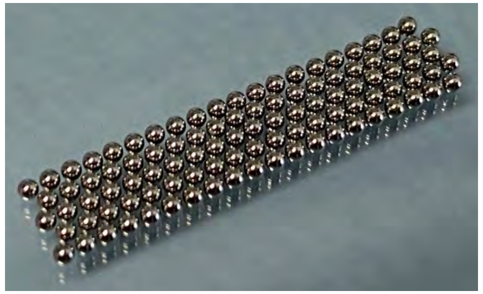




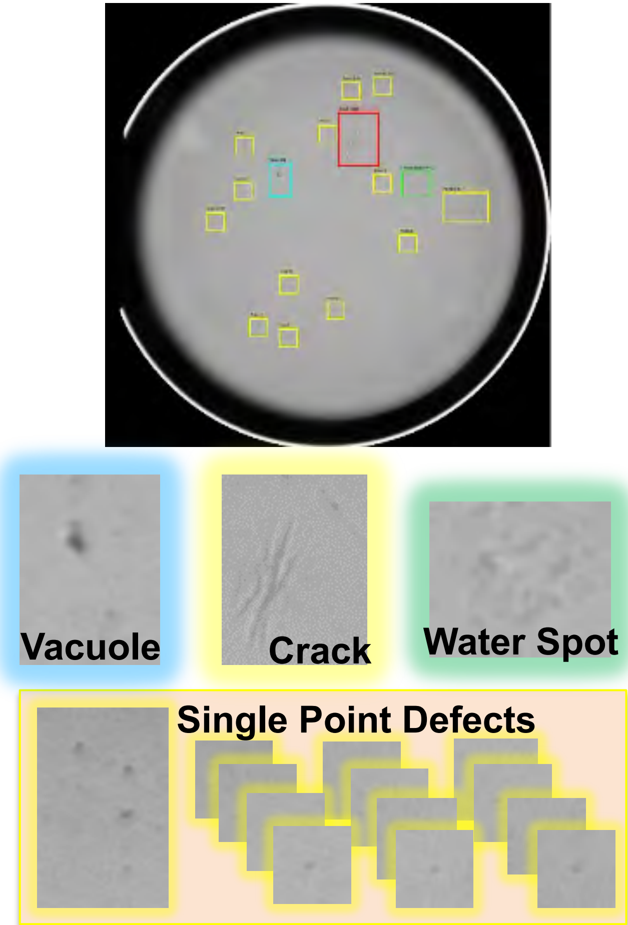
multi-layer spacer - foil stack compression assembly

Cone-in-shell FI target





Vision Assisted, Robotically picked and manipulation of spherical beads



Automated visual inspection and defect identification

Rep-Rated facilities (i.e., MEC-U) will motivate needed advances!

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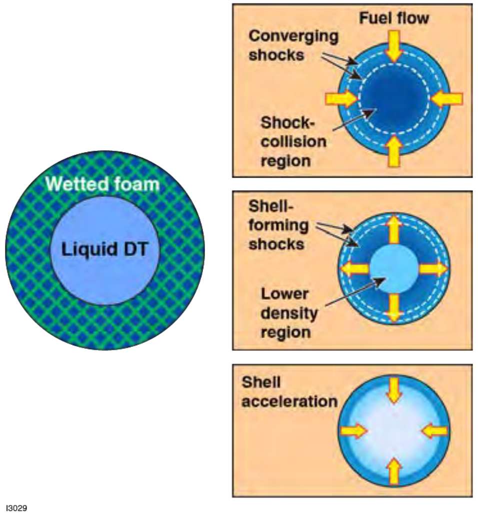
[1] VG provided by GA

LDD designs are being developed that exploit advances in target fabrication (foams)

Dynamic Shell Design (LLE)



Wetted Liquid foam targets (LANL)

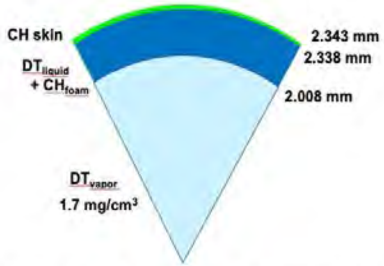
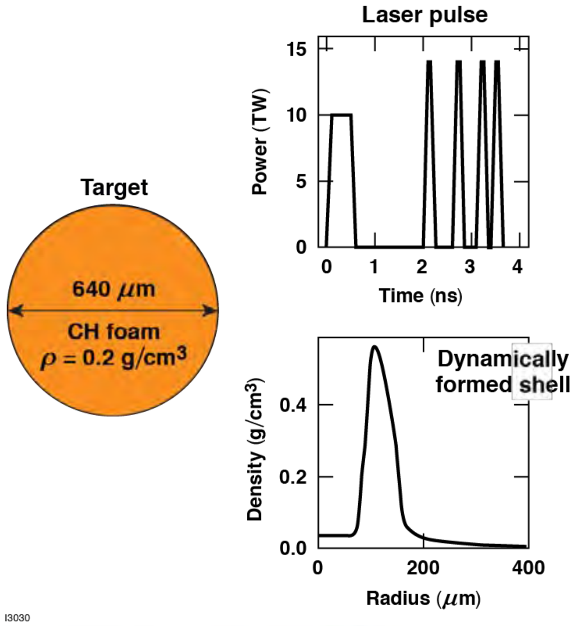


Figure 1: The PDD-WF target concept with dimensions used in the 2D simulations.

Proof-of-principle experiment on OMEGA (FY22)



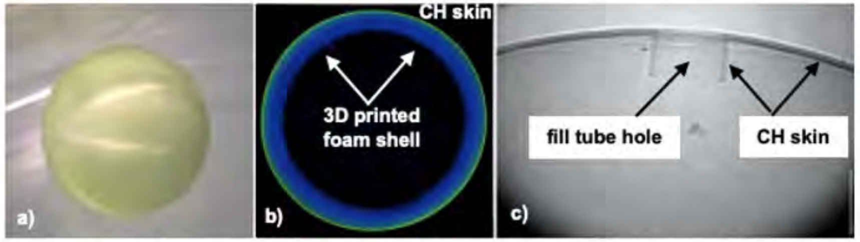


Figure 4: a) PDD-WF capsule 3D printed with the dimensions specified in Figure 1; b) full diameter tomograpic image of the capsule; c) detail of the fill tube region (Alex Haid, GA).

Printed Foam targets (GA)

Fusion ignition is analogous to the Wright Flyer.
Could the Wright Brothers have imagined the 787?

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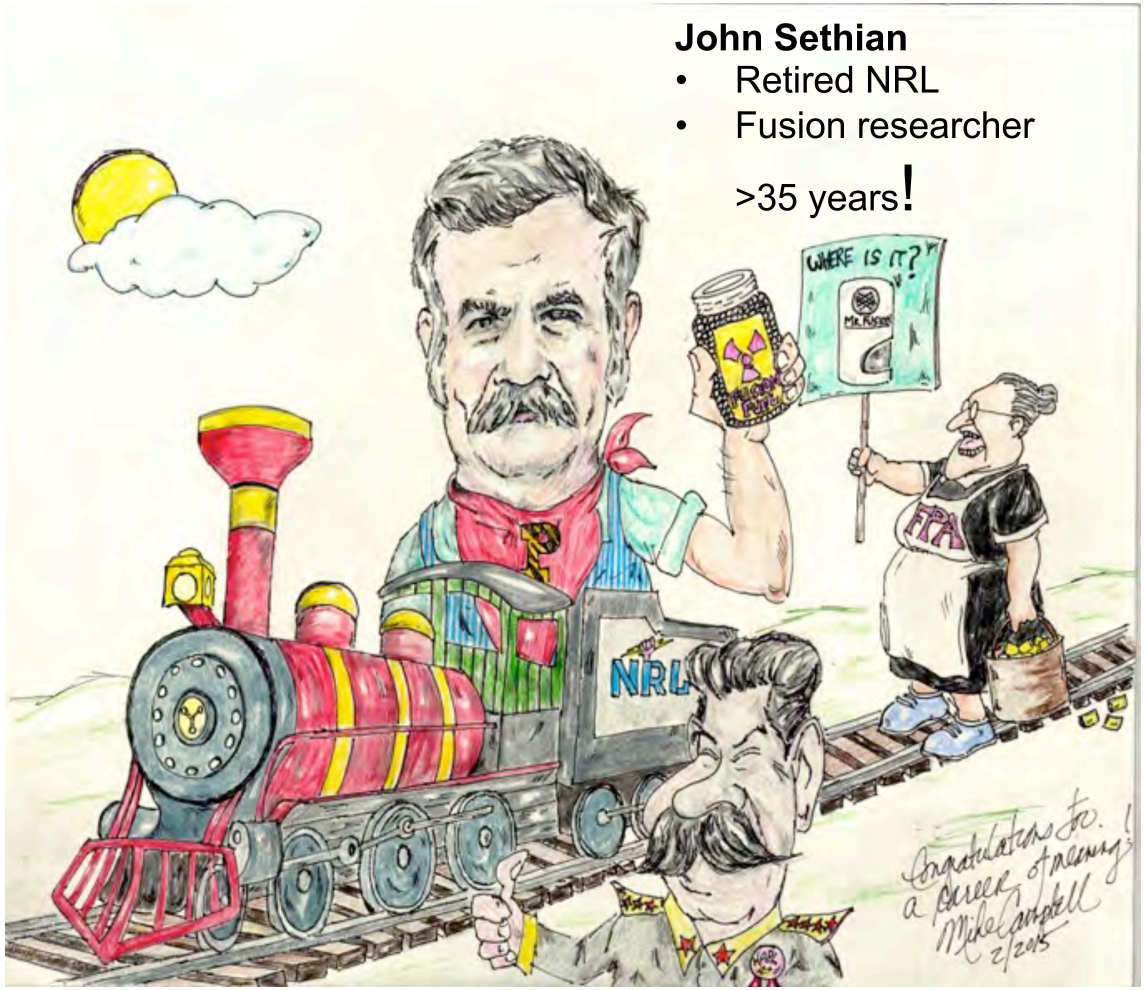
Fusion energy will require careers and dedication

My son, now 27!



John Sethian

- Retired NRL
- Fusion researcher

>35 years!

AN IFE program should actively engage the private sector

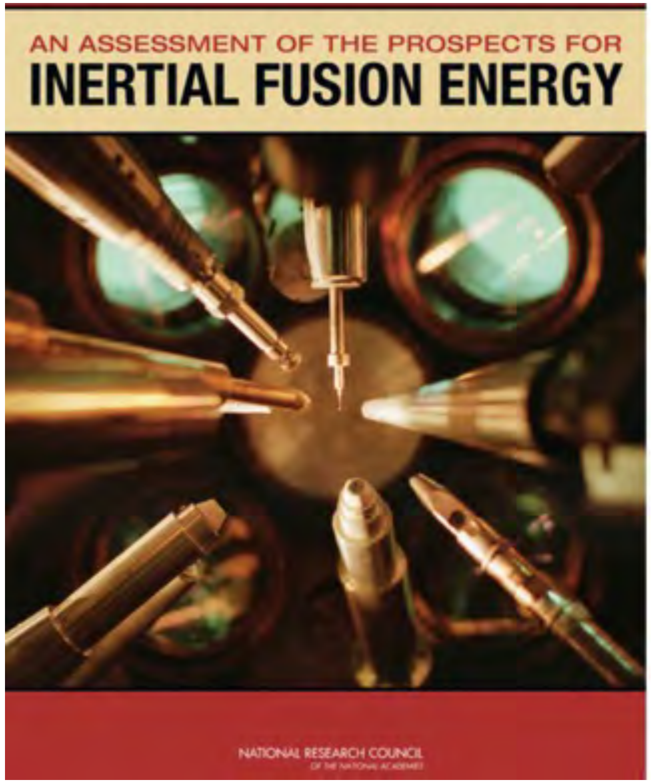
NASA Last shuttle Launch (2011)

SPACEX Falcon Heavy Launch (2018)

An IFE program would provide major benefits to the nation, both in advancing U.S. leadership in HED science and as a potential path to energy in the future

The NAS 2013 Study “An Assessment of the Prospects for Inertial Fusion Energy”* had a number of conclusions and recommendations including:

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



AN ASSESSMENT OF THE PROSPECTS FOR
INERTIAL FUSION ENERGY

NATIONAL RESEARCH COUNCIL

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*_An Assessment of the Prospects for Inertial Fusion Energy_, Committee on the Prospects for Inertial Confinement Fusion Energy Systems, NRC (National Academies Press, Washington, D.C., 2013).

As Teddy Roosevelt[1] would say

"Far better is it to dare mighty things, to win glorious triumphs, even though checkered by failure…..than to rank with those poor spirits who neither enjoy nor suffer much, because they live in a gray twilight that knows not victory or defeat."

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[1] U.S. President (1901-1908)