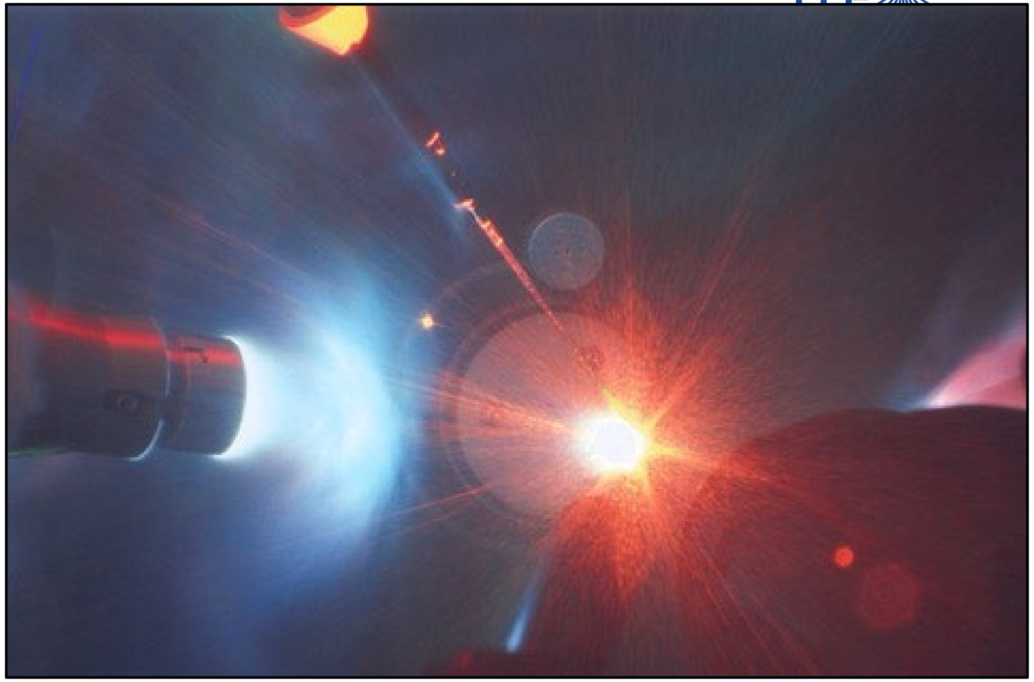
High Energy Lasers-opportunities and challenges for fusion energy and national security

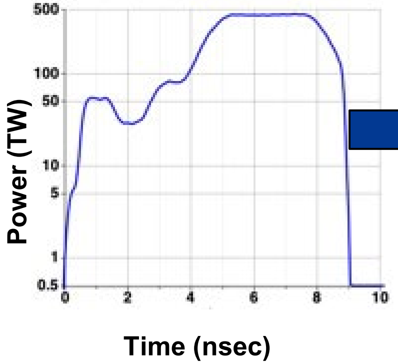


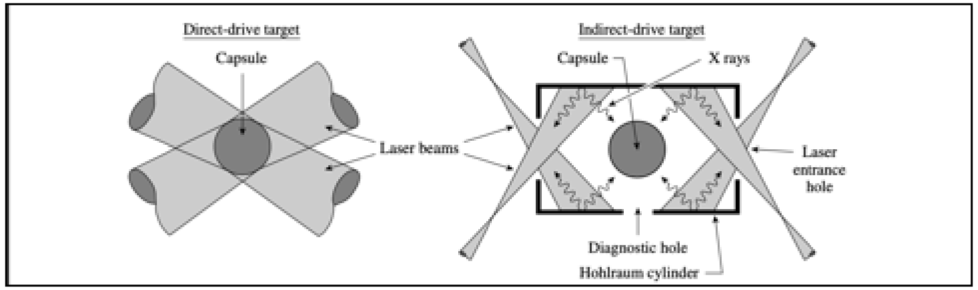
Dr. Mike Campbell
Professor of Practice UCSD
Retired (Director LLE)
University of Rochester
Laboratory for Laser Energetics
Former Senior VP for Energy (GA)
Former Associate Director Lasers (LLNL)

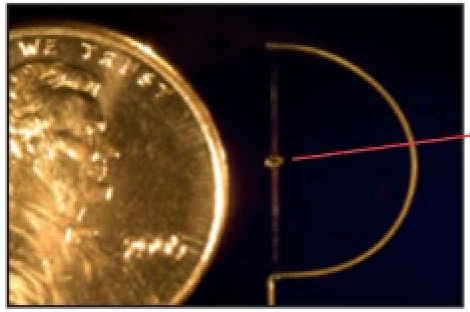
National Academy of Sciences
November, 2025

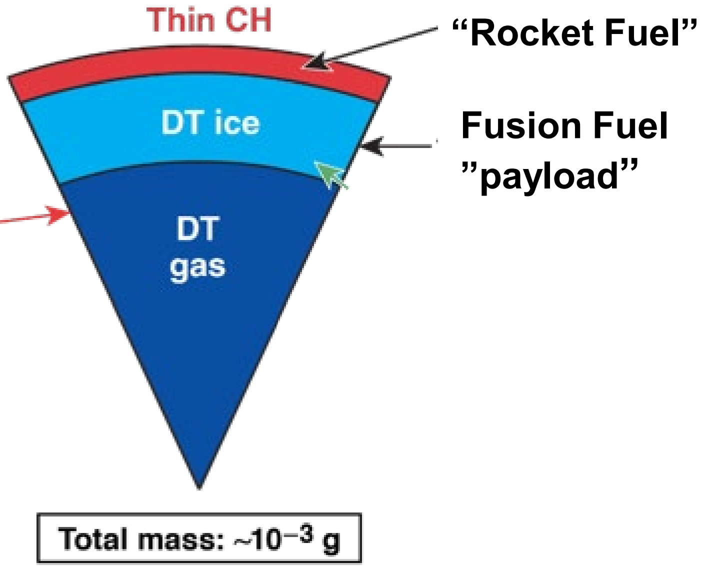
Laser Driven ICF 101

A laser driven ICF target (mass~1 mg) can be thought of as an "imploding rocket" with a DT payload whose "rocket" fuel (the ablator) is energized by the laser with a final velocity of 10^{-3} of the speed of light (200 miles/sec)! Compression amplifies pressure creating fuel at pressures >100 billion atmospheres!







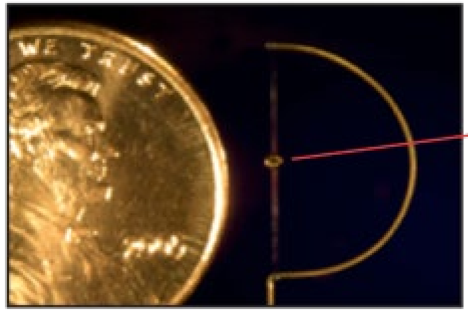


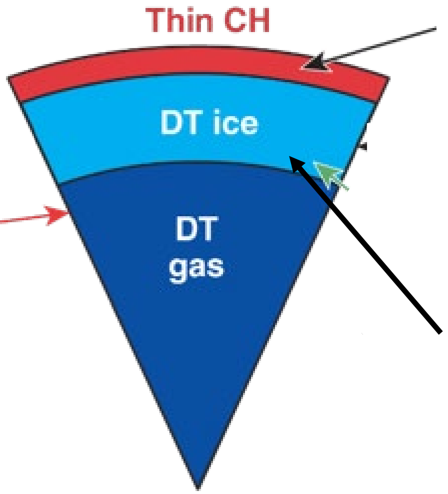
Implosion Physics

- Energy in compressed fuel (E_{fuel})
  - $E_{fuel} = \eta\gamma E_{laser}$
    - η = capsule absorption fraction
    - γ = "rocket efficiency"
  - Indirect drive
    - η ~10-15%
    - γ~ 10-15%
  - Direct Drive
    - η ~70-90%
    - γ~ 5-8%
- Convergence, C_{fuel} $(R_{inital}/R_{final})^{fuel}$
  - C_{fuel} ~20-40

The compressed fuel contains only ~1% to 7% of the incident laser Energy

To achieve high gain (Fusion energy/driver energy) required for IFE with a credible driver (~<10 MJ), with a **temporally shaped pulse**, the fuel must be ignited and generate a fusion burn wave that propagates into "cold" fuel (at stagnation the fuel is isobaric)





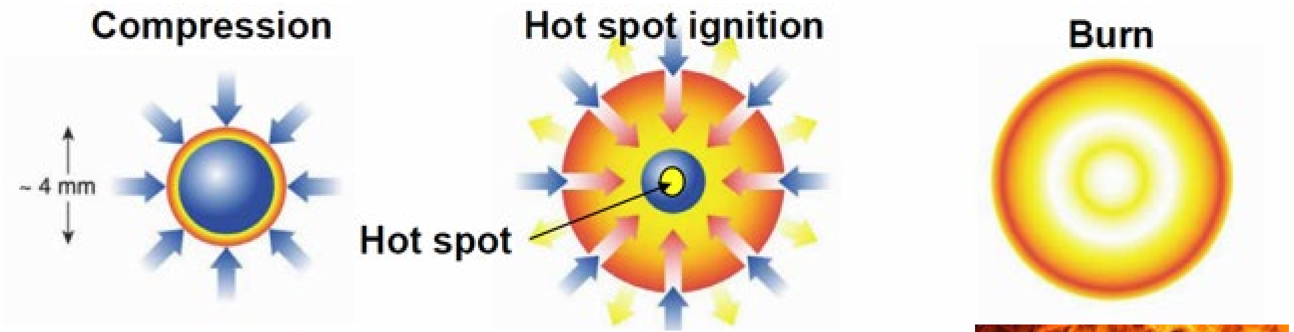
Total mass: ~10^{-3} g

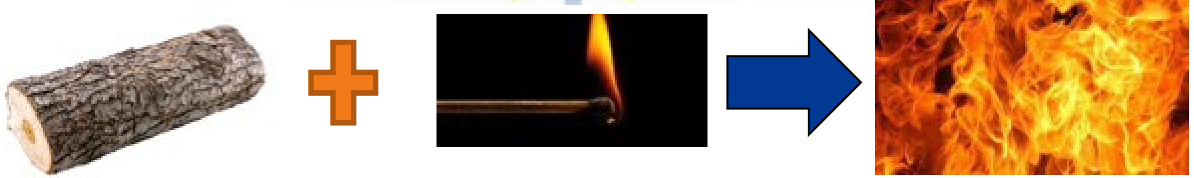
Ablator ("rocket Fuel")
- CH
- HDC (diamond)
- Be

Fuel ("payload")

Fusion = $Mass_{DT}\,\varphi E_{fusion}$

- $\varphi =< \rho R/(\rho R+6)$
- E_{fusion}~340 MJ/ mg_{DT}





$P_{ignition} \sim (E_{fuel})^{-1/2}$

- **Motivation**
  - Specific heat of DT is ~100MJ/KeV-gram
    - **$1mg_{DT}$ @ 5 KeV= 500 kJ**
  - Minimum energy (no entropy addition) to compress DT is ε_{Fermi} (j/g)~ 3 x$10^5\rho^{2/3}$
    - **1 mg @ 500 g/cm^2 =23 kJ**
      - **Entropy addition (shocks, electron preheat, radiative preheat)**
    - Adiabat :P_{shell}/P_{fermi}

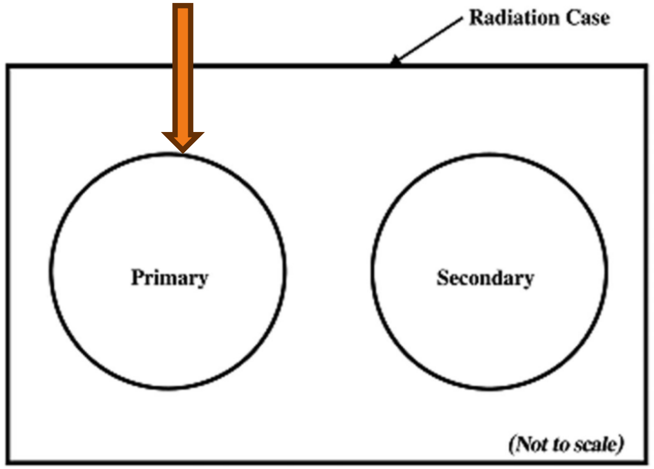
A little history of ICF
From the 1950s to mid 1980s

“And some things that should not have been forgotten were lost. History became legend. Legend became myth.” Quote from Lord of the Rings!

Indirect drive ICF hohlraums pre-dated the laser![1]

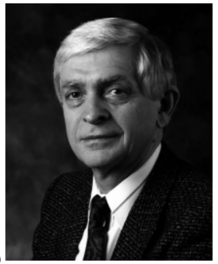
~ 1950: Teller-Ulam

1 kT ~4 x10^{12} joules[2]

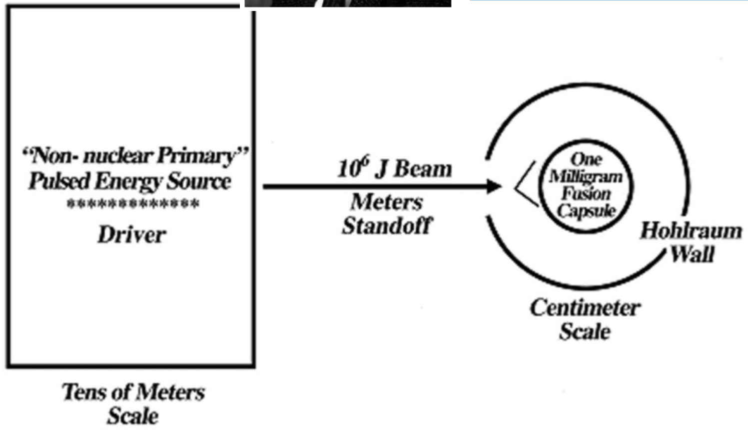


Sedan Crator
"Plowshare"

~ 1960 Nuckolls



note: - 1 MJ Energy
- 1 cm scale
-DT (~340 MJ/mg)



Non- Nuclear "primary"

- Plasma jet (PJMIF- LANL today)
- Hyper-velocity pellet (FLF today)
- Charged particle beam (HIF today)

[1]J. Nuckolls, "Contributions to the genesis & development of ICF" in "Inertial Confinement Nuclear Fusion: A historical approach by its pioneers", G. Velarde & N. Santamaria, eds. Foxwell & Davies, UK (2007)

[2] Discussed in "Oppenheimer"

Laser Driven ICF Activities began in the early 1960’s following the demonstration of the laser by Maiman; Programs expanded rapidly after Nuckoll’s et al Nature paper and high-power laser development in the 1970’s

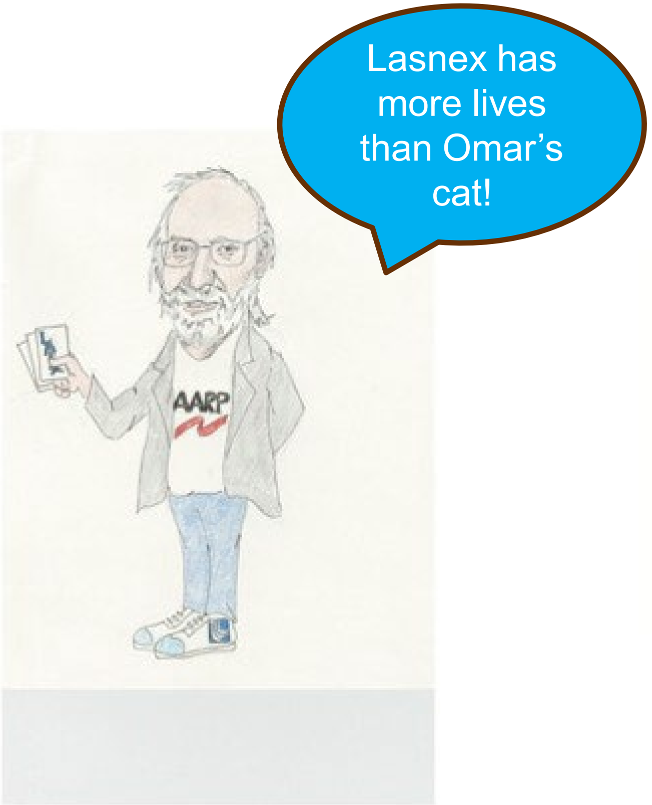
2025 E Fermi Award

1

Laser Compression of Matter to Super-High Densities: Thermonuclear (CTR) Applications *

JOHN NUCKOLLS, LOWELL WOOD, ALBERT THIESSEN & GEORGE ZIMMERMAN

University of California Lawrence Livermore Laboratory



Other events: Arab oil Embargo; ”détente” with the USSR

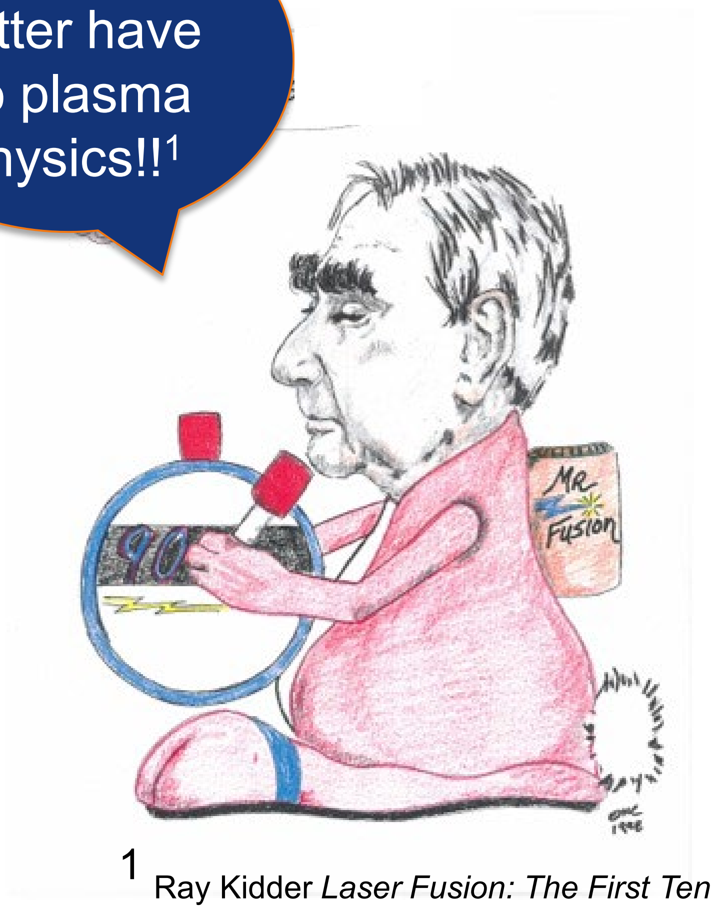
- **[*]A. Ron Thiessen passed away on Dec 27,2022**

Teller's thoughts on ICF

UR LLE

I have this idea for laboratory fusion!

John, It better have no plasma physics!![1]



1 Ray Kidder *Laser Fusion: The First Ten Years 1962-197*

8

There were limited laser options for the high peak powers required for ICF in the early 1970's; LLNL recruited John Emmett from NRL to develop solid state lasers; LANL choose CO_2

William Krupke

Y-program forms experimental division

Continued growth of the laser fusion program here has led to some reorganization and personnel changes in Y-Program to become effective July 10, according to Carl Haussmann, Associate Director for Plans and Lasers.

The experimental laser efforts now spread over several organizations will be consolidated into one division. It has been designated Y-Division and will be headed by two people joining the Laboratory from other well known laser research and development facilities. The two are John Emmett, who will be Y-Division leader, and William Krupke, who will be associate division leader.

John Emmett, 33, has been head of the laser branch of the Naval Research Laboratory in Washington, D.C. He received his PhD from Stanford University in 1967. William Krupke, 35, has been associate manager of the laser technology department of Hughes Aircraft Co., Culver City, Ca. He received his PhD from UCLA in 1966.

In commenting on the consolidation plan Carl Haussmann noted that "several divisions have participated in the growth of laser work here over the years."

"This has been helpful during our period of expansion," Carl said, "but it was concluded that it would be best for the program's future if laser experimental efforts were consolidated into one division. That's what we're doing now and John Emmett will be heading that consolidated effort. Bill Krupke will be assisting him with portions of the ongoing program and with the detailed changes associated with the creation of a new division.

"The Physics Department's Q-Division – under Ray Kidder, a pioneer in laser fusion work here and in the world – will continue to provide theoretical and other support to the laser program. Ray will also continue to lead the laser plasma physics experimental effort for the coming year. This will help strengthen that effort and will assure effective completion of experiments now in progress."

In 1969 the laser effort at this Laboratory was running at about \$2 million. By this last fiscal year the research budget for lasers had expanded to \$9 million and will grow to an expected \$12 million in fiscal year 1973. Also, Lab officials anticipate the approval in the near future for the construction of a large laser research and development facility. The facility will have specialized laser laboratories and space for 200 people. ■

The 1970's and early 1980's was a decade of laser building at LLNL and LANL culminating in the planned construction of NOVA that was predicted to achieve ignition and gain with 240 KJ of 1 μm light!

LLNL

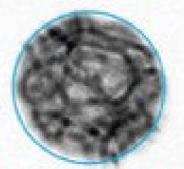
Janus (2 beams@<100 Joules/beam)
- **Goal**: plasmas heated to Multi-KeV temperatures achieve DT fusion[1]

Argus(2 beams ~ 1000 joules/beam)
- **Goal**: first modern laser architecture and explore physics of laser produced hohlraums

Shiva (20 beams @500 joules/beam)
- **Goal**:radiation driven ablative implosions to high DTdensity (20 g/cc)

NOVA (20 beams@12 kJ/beam = 240 kJ
- **Goal: Ignition and gain**

~1µm Laser wavelength (n_{crit} ~10^{21} electrons/cc) and Unconditioned beams



LANL

Gemini (2 beams, ~2 kJ)
- **Goal:** Laser-plasma interaction research

Helios (8 beams, ~10 kJ)
- **Goal:** ICF research

Antares (24 beams, ~20-40 kJ)
- **Goal**: ICF and HEDP research
- Energy>100 kJ was also considered

~10.6 µm Laser wavelength (n_{crit} ~10^{19} electrons/cc)

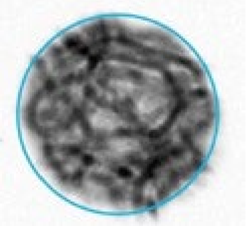
[1]KMS fusion was first!

The 100X (ρ_{DT}=20 g/cc) Campaign was the major X-ray Drive Experimental Program (Shiva laser[1]) at LLNL and the first attempt at ablatively driven implosions

- **Experiment Method:**
  - **1.064 µm irradiation of Au hohlraums**
  - ~150-200 ev radiation drive
  - High pressure DT capsule (SiO_2 pusher and CH ablator)
  - *Neutron activation of the pusher to diagnose fuel compression (ρR)*

"First Shovel" for Shiva, 1974

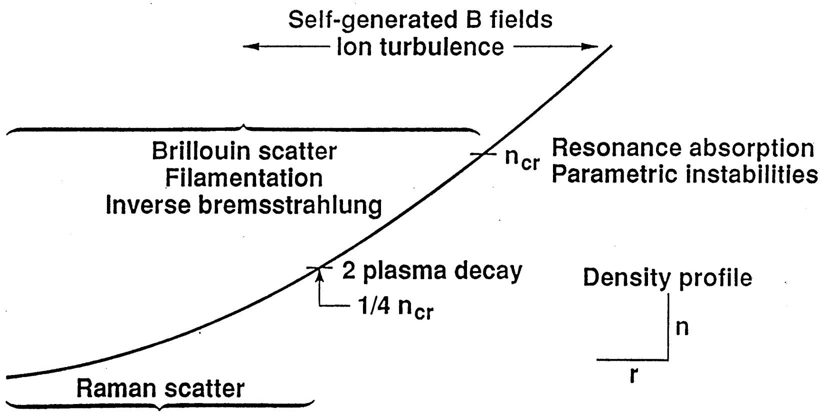
- **Preliminary experiments on Argus to explore laser driven Hohlraums**
  - 1.064 µm, 2 kJ laser (~1 kJ/nsec per beam)
  - 2 "unconditioned beams"



"on target laser"

[1]John Lindl book on ICF

Argus experiments discovered the "infra-red catastrophe" - *Laser-Plasma Interaction Physics above threshold in the long scale length hohlraum plasma: evidence of ~100 keV electrons from neutron TOF detectors*



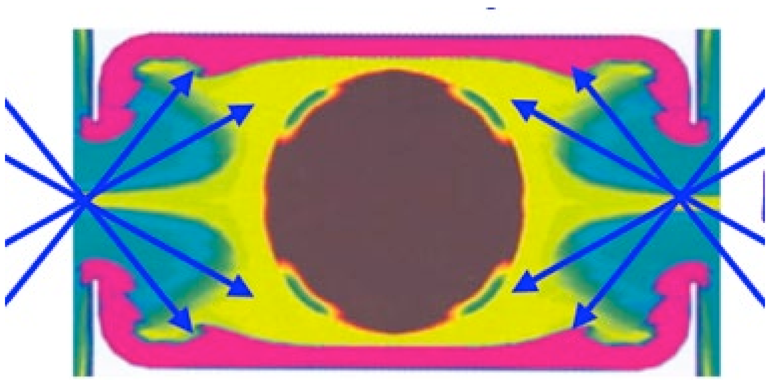
Many processes compete to determine the coupling.
The mix of these processes depends on the plasma conditions.
The plasma conditions depends on the mix of the processes.

$N_{cr}(cm^{-3}) \sim 10^{21}/(\lambda_{\mu m})^2$

SRS threshold:

$$I(W/cm^2) > \frac{4x10^{17}}{L_{\mu m}\lambda_{\mu m}}$$

Single laser beam



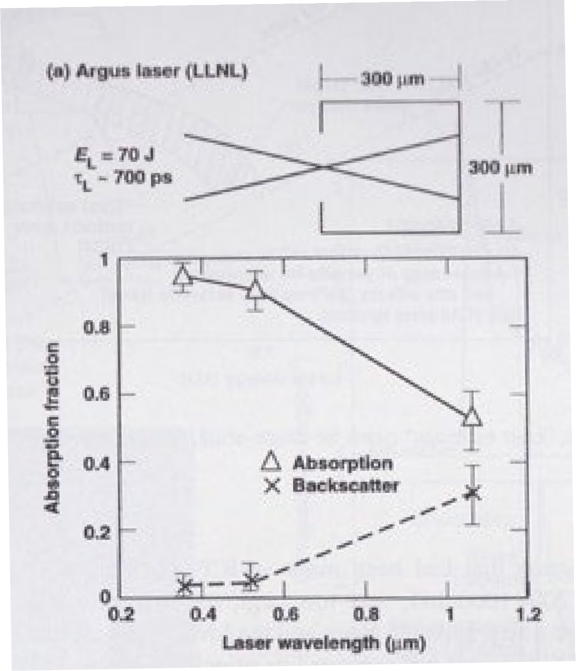
- ***$L_{\mu m}$ ~ length/2$_{hohlraum}$~1000 µm***
- ***I_{laser} > 10^{15} Watts/cm^2***
  - ***I_{SRS}~4 x10^{14} W/cm^2***

Solution: UV lasers and "clean up the beam"

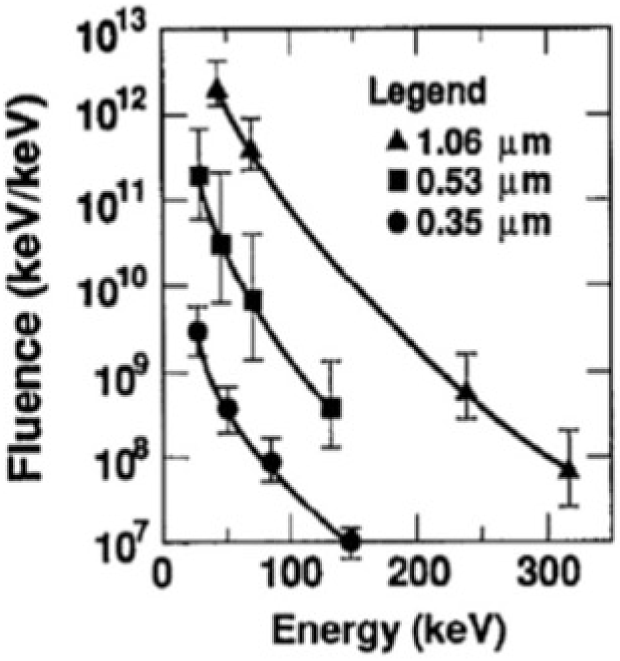
Argus experiments (<100 Joules) demonstrated benefits of short wavelength and despite LPI dominated Hohlraums and low fusion yields, "high density", ablative implosions were demonstrated at Shiva[1]

Argus Experiments

Hohlraum Coupling

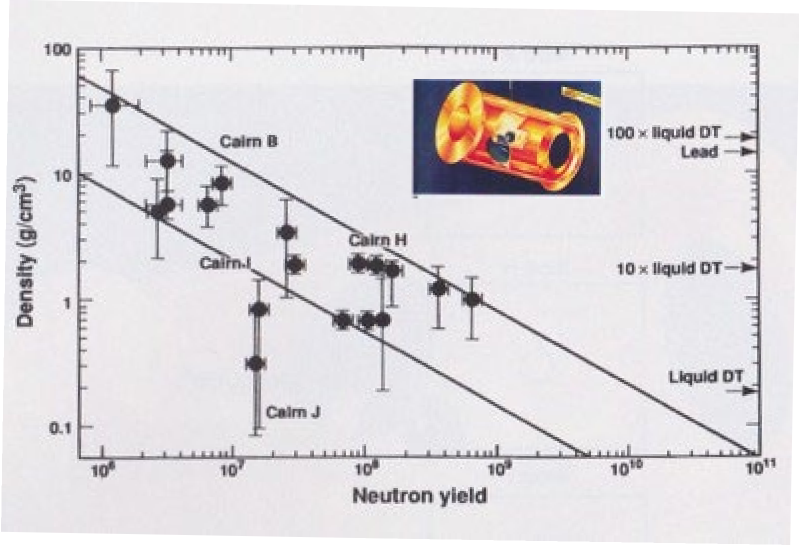


Hot electron generation significantly reduced



Results were classified until 1992

Shiva Experiments



DT fuel density inferred by pusher areal density with different hohlraums

[1] Edwards, Campbell submitted to Review of Modern Plasma Physics

The results from Argus (sub-micron laser wavelength) and Shiva (implosion performance in LPI dominated Hohlraum) motivated changes in the Performance and Mission Of NOVA with funding restored by Congress

UR LLE

Performance

240 kJ (20 beams) @1 μm

30 kJ-40 kJ (10 beams) @ 0.35 μm at the same project cost (~$180M)
Largest 0.35 μm at time was Argus (~30 Joules!)

Mission

- **Explore physics of Indirect Drive ICF**
- **Develop "physics case" for a "High Gain" 10 MJ Laser Facility**

The Novette laser (2 beams of Nova) was funded as a bridge between Shiva and NOVA

Novette was a “short lived” but productive facility

- Positive lessons
  - Short λ Physics (0.53μm,0.25 μm) continue to be positive at mult-kJ laser energies
  - First “Weapons” research (”Star Wars era”)
    - First (along with PPPL) laboratory demonstration of x-ray laser
      - Collisionally excited Se laser
    - First Dawson award for HEDS/ICF
    - First weapons supported Program
  - Laser Physics
    - Large aperture (~20 cm) KDP crystals for frequency conversion
    - Demonstration of NOVA laser chain performance and component supply chain

Novette Laser

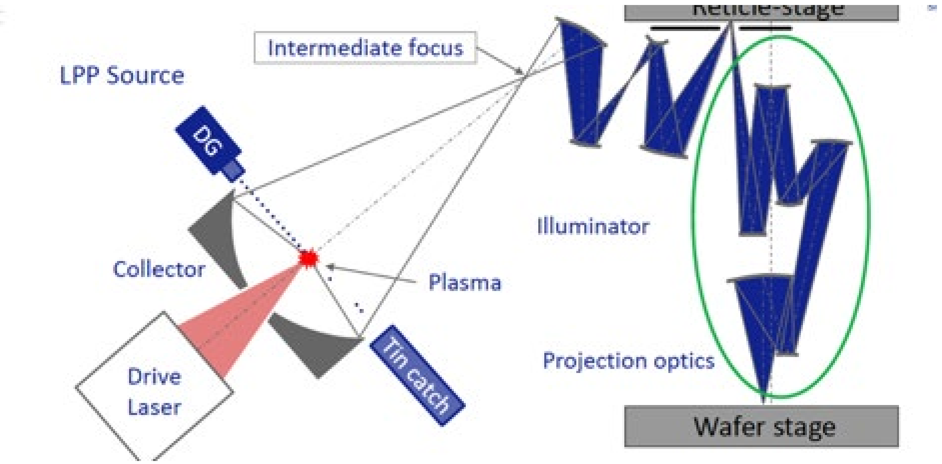
“Soft” x-ray laser

25 year x-ray laser celebration

X-ray laser target design used LPI target (exploding foil) designed to show large SRS in “open geometry”(Hohlraum research was classified until early 1990’s!)

15

EUV Lithography (invented by ICF scientists[1]) for IC production @ ~13.5 nm has features similar to an IFE reactor and was motivated by advances in diagnostics (optics at ~10 nm) developed for the x-ray laser program



- **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)

[1]The first publication on "EUV": Andy Hawryluk and Lynn Seppala at the Electron Ion and Photon Beam Technology conference, May 1988, published in JVST in Jan/Feb 1989. This paper resulted in the first patent, 5003567 issued in March 1991

BUT…………………

- Laser glass manufacturing was flawed and resulted in Pt damage that significantly limited laser energy/power
  - Discovered when Novette was dismantled to be placed at NOVA
    - Novette beams were LAST to be installed at NOVA
    - Laser Diagnostic system was flawed
      - Modified Diagnostic package did NOT include Near field image of the laser beam

- LESSON LEARNED:
  - Experimental Program focused on Novette and not in bringing NOVA up as an Experimental Facility
  - Created need for "Precision NOVA " Program
    - Full 1.05 µm performance (120 kJ @~1 nsec)
    - Enhanced 0.35 µm performance (30-40 kJ @~1 nsec)
    - Power and energy balance to +/- 5%
    - Pulse shaping (first ever for ICF!)
    - Pointing accuracy (~10 µr)

Joe Kilkenny joined LLNL in 1983

- First of "international " staffing of LLNL ICF Program

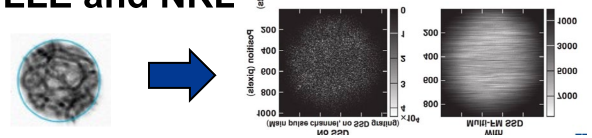
Lesson not to be forgotten (fusion community): Pay attention to the "supply Chain" for critical components!

The Journey to NIF

The Journey to NIF-the 1980’s and early 1990’s

- With reality of data, LLNL long term strategy developed in the 1980’s focused on the Laboratory Microfusion Facility
  - 10 MJ, 0.35 µm (estimated facility cost ~<$ 10^9)
  - Target gain ~100; radiation drive @ ~200 ev-250 ev (LPI concern)

- Nova developed into a Physics and User facility
  - Pt glass problem was fixed and glass replaced
    - full 1.06 µm performance (120kJ @3 nsec)
    - 3 ω frequency conversion “fixed”
  - Second target chamber added (Shiva Target chamber)
- Progress in Direct drive at LLE and NRL



  - “beam smoothing”
    - ISI and SSD
    - Beam Smoothing valuable to ALL laser community
      - NOVA was LAST large laser to adopt!
  - KrF (0.26 µm) at NRL and tripled Nd:Glass (0.35 µm) at LLE
- LANL abandons CO_2 (Antares laser closed) and initiates KrF (Aurora)laser
  - Aurora designed as a KrF laser @ ~ NOVA scale energy

19

Halite/Centurion and the NAS review

- **Innovative use of nuclear explosives to explore implosion physics relevant to ICF**
  - **Conducted by LANL/LLNL**
  - **Remains classified**
  - **DOE statement at Princeton:**
    - **Sheldon Kahalas, director of the nation's microfusion effort, run by the Federal Department of Energy, told a Princeton University conference that a top-secret effort code-named Centurion-Halite had achieved results that marked a "historical turning point" for the fusion program.**
    - **He and other scientists at the Princeton conference said the nation was ready to start planning a full-scale laboratory microfusion facility, <u>which they estimated would cost between $500 million and $1 billion.</u>**

- **Success resulted in Congressional demand for NAS review of Program**
  - **Chaired by Steve Koonin**
  - **Dates: 1989-1990**

The New York Times

A Step Toward Harnessing Fusion Energy

AN ISRAELI SOLDIER IS SHOT TO DEATH IN THE WEST BANK

PRESIDENT'S PARTY IS BADLY DEFEATED IN SALVADOR VOTE

Secret Advance in Nuclear Fusion Spurs a Dispute Among Scientists

Industry Acts to Save Ozone

Unyielding Panamanian

Changing Times Turn Tables On a 'Saint' of the Stalin Era

Man Fatally Beaten By East Harlem Mob Angry at $20 Theft

Final Bow for Many Theater Area Businesses

March 21,1988 (Bill Broad)

Koonin NAS review was pivotal in establishing the strategy for the ICF Program

- LLNL proposed LMF as next step
  - LMF: 10 MJ laser with target yield of 1 Gjoule (gain 100)
  - NAS rejected as too ambitious!
- Report recommended increased focus on laboratory experiments (Nova)
  - NOVA became primary laboratory facility for the ICF program[1]
- Excimer laser activity at LANL was cancelled
  - P. Leonardo Mascheroni and Claude R. Phipps had proposed ~100MJ HF laser !

Marshall Rosenbluth "the Pope of Plasma Physics" and key member of Koonin NAS

[1] Committee report:"Because of these success, the committee now believes that uncertainties in ignition arise only from considerations of **mix, symmetry and laser plasma-interactions** that can be best studied in laboratory experiments" –> NOVA technical contract

Early encounters with the NAS committee and its Preliminary Report altered LLNL Strategy : Ignition and modest gain with ~MJ class laser

- NOVA Upgrade Became focus with Indirect (x-ray) ~MJ class laser @0.35μm in NOVA/Shiva building (renamed NIF by DOE since new building required)
    - Required Hohlraum peak T_{rad} ~300 eV-demonstrated on NOVA
    - Ignition and modest gain (~10)
- Need to better inform Committee and stakeholders of technical progress (and history)
  - NAS recommended standing independent review committee (ICFAC)
  - Recognition of the Need for a "Technical Contract"
    - Program Plan that guided ICF research on NOVA and would be accepted/endorsed by Community
    - Established milestones
      - ICFAC and other stakeholders could follow Progress/setbacks
  - Need to Improve NOVA performance
    - Precision NOVA
- Direct Drive was too immature as baseline and NO Pulsed Power Approaches showed promise
  - LLNL was only ICF laboratory to support SNL conversion to Z
- Develop NOVA into user facility with emphasis on Weapons Program
  - Limited basic science programs also initiated for outside users
    - 20th Anniversary of laboratory astrophysics in 2016

NOVA flourished in the 1990's and played a major role in establishing Mission Need and Physics basis for NIF

- **Precision NOVA was successful**
  - First to emphasize power balance, temporally shaped pulses and develop needed diagnostics
  - Exceeded power/energy and pointing specifications
  - Added Beam smoothing (LLE Help!)
- NOVA became an effective user facility
  - ~1400 experiments per year
    - 2 target chambers were essential
  - Weapons Program conducted over 50% of experiments with ~50% by primary Division (Charlie McMillian Helped!!)
  - ICF Program completed "technical Contract"
    - LANL,SNL ,LLE played significant role
    - SSD was added to NOVA (LLE critical role)
  - Extensive Diagnostic development
    - Framing cameras, neutron spectroscopy, etc.
  - Limited but innovative Science Campaigns
    - Laboratory Astrophysics (Thx to Bruce Remington)
    - EOS (thx to Rip Collins)
    - Opacity and radiation physics (thx to Dick Lee)
    - High field Physics
      - First PW demonstrated (thx to Mike Perry and Donna and Gerard)
  - Numerous Awards
    - Three Dawson Awards
    - 5 excellence in Weapons Physics Awards
    - Two Best of the Best Popular Science Award
    - >20 R&D 100 awards

Flexible X-ray imager
Budil et RSI, Feb1996

Marshall Sluyter was Key ICF leader at DOE

Dave Crandall Became head of the ICF Program at DOE (moved from OFES)

UR LLE

UNIVERSITY of ROCHESTER

23

In addition to physics challenges, cost effective MJ class Fusion lasers required several "miracles"

- **Laser glass manufacturing**
  - **"Batch" to continuous processing (Jack Campbell)**
- **Major reduction in number of amplifier stages**
  - **NOVA :all amplifiers were used in a single pass**
  - **NIF :all amplifiers were multi-pass (John Trenholme)**
    - **Regenerative amplifier (regen)**
    - **4 pass angular multiplexed main amplifier**
      - **Large aperture Plasma electrode Pockels cell (Mark Rhodes)**
      - **"multi-nanosecond " Spatial filter**
- **Precision and flexible pulse shaping**
  - **Programmable pulse shaping (Russ Wilcox)**
    - **Adapted from telecom industry**
    - **Fiber optic oscillator and transport to pre-amp (regen)**
- **Large Aperture KDP crystals for harmonic conversion and "plasma" Pockels Cell**
  - **Adapted from Russian research (LLNL hire)**
- **Beam Conditioning**
  - **Adaptive optics (deformable mirrors)**

Jack Campbell

The Beamlet laser was developed to demonstrate the NIF architecture and to initiate the supply chain

24

Beamlet success was needed to move NIF forward

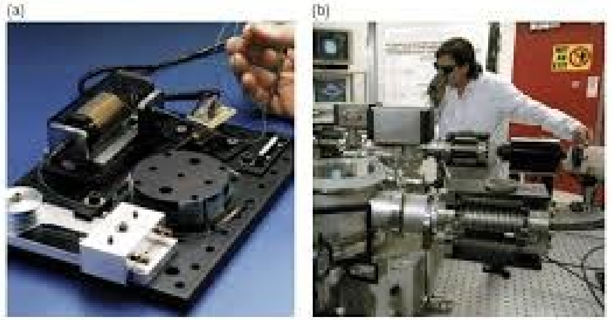
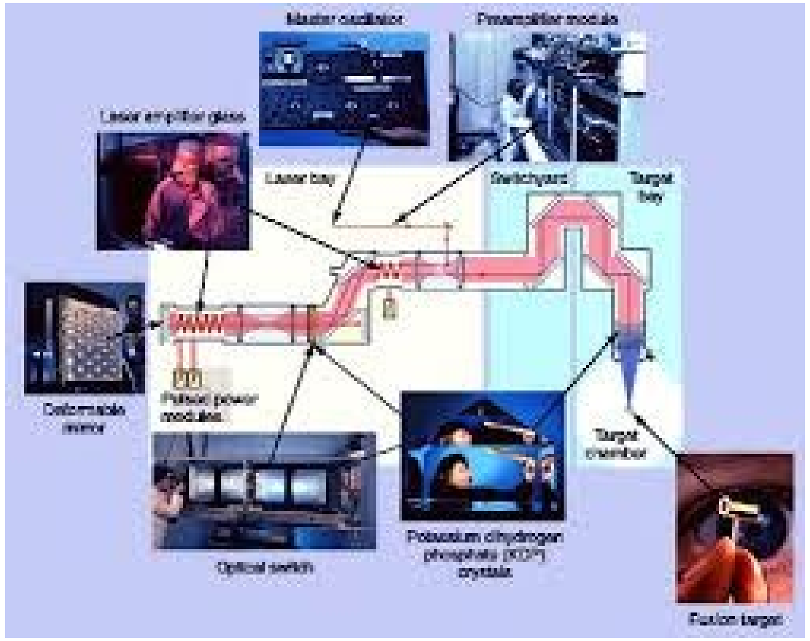


Figure 2. (a) NIF's low-power pulse is first amplified by these ytterbium-doped optical fibers (seen glowing blue at lower left). (b) The pulse is then amplified to 22 joules by four-pass amplifiers (here tested in the laboratory by technician Mike Martinez), which are part of the preamplifier module (PAM).



Beamlet energy output (1 beam) @ 1.05µm exceeded the 20 beam Shiva laser

Beamlet is now at Sandia !

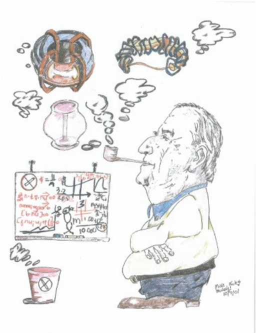
Jack (Beamlet Project leader)

Bruno (Beamlet Scientist)

Neal Frank (Beamlet Engineer)

A scientific, Mission, and political strategy was required to secure NIF

- **Scientific**
  - Halite-Centurion Success
  - Successful Nova technical contract
    - Inclusive (LLNL, LANL, SNL,LLE)
    - Transparent
      - **Standing external committee (ICFAC)**
        - **Monitored and endorsed research**
  - Successful Beamlet project
  - AWE and CEA Support
- **Mission**
  - Stockpile Stewardship Program (Vic Reis)
    - Extensive Weapons program research on Nova
    - No alternative to lasers
      - Z at SNL was still in the future
- **Political**
  - All members of CA delegation signed support letter to DOE
  - NY delegation support (LLE Helped)
  - Strong local community support
  - Open letter of support by Hans Bethe, Henry Kendall Herb York
  - Harold Agnew (3rd LANL Director, Manhattan Project)
  - Industry Support
    - **Hoya established glass projection in Fremont, CA**
  - Standing NIF committee (DOD, Labs, Science Community)



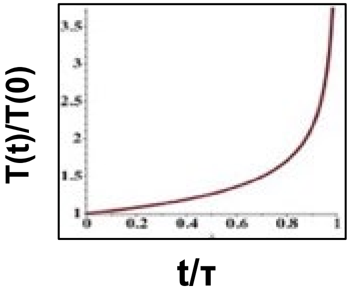
Pete Dominici (R, NM) chaired both Appropriation and Authorization Committees

National Ignition Facility

Useful categories to define fusion performance with DT fuel (~340 MJ/mg)

- **Burning plasma**
  - ICF: Self-heating energy exceeds external “pdV work” to heat and compress the DT
  - MFE: Self-heating energy exceeds external heating of the DT
- **Ignition (i.e. Lawson Criterion)**
  - Self-heating power exceeds all DT plasma power losses
    - \- Losses are radiative, electron heat conduction, negative pdV work (ICF)
  - Results in thermodynamic instability (explosive increase in T, Y, etc).

$$(P\tau)_{ignition} \sim 11\ f(T)/\Theta_\alpha\ \text{(atm-sec)}$$



Fusion rate

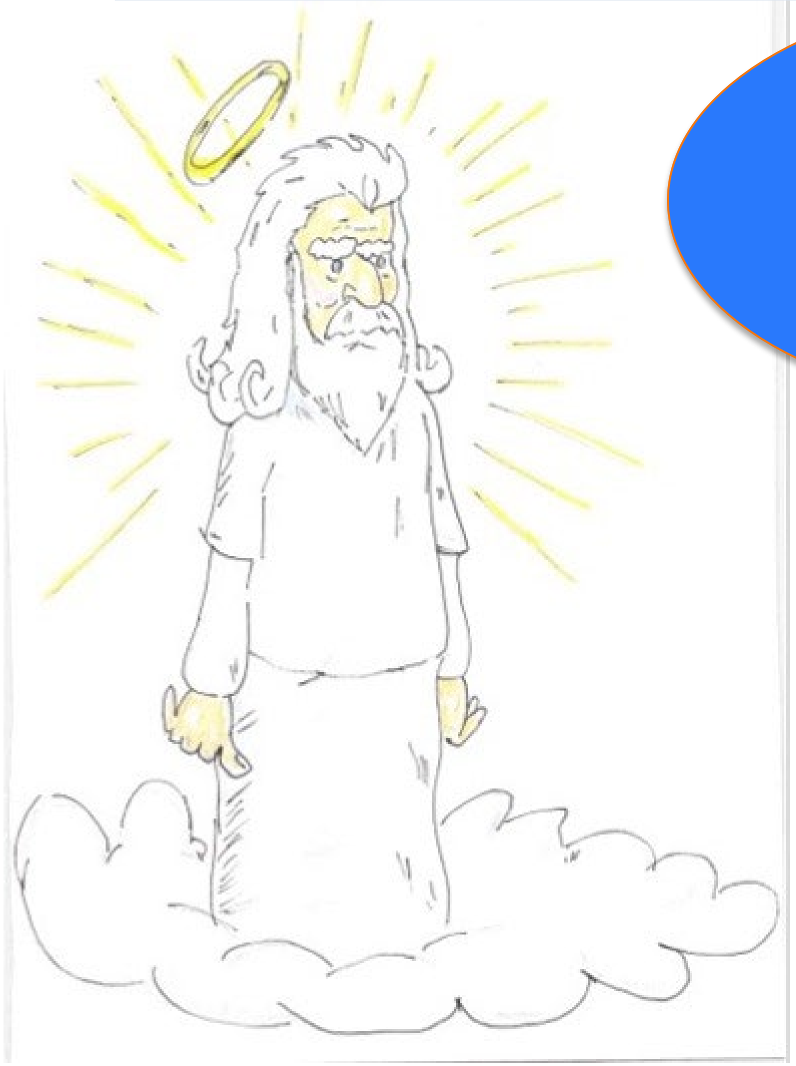
- **Required for ICF (τ~100 psec, P>10^{11} atm)**

- **Target (Scientific) Gain (Q_{sci})**
  - Fusion yield exceeds laser energy into target
  - 1997 NAS committee used this as “ignition” in a report & the U.S. DOE adopted this definition
    - Target gain of 1 is the metric of success for the NIF Facility/fusion program

- **Engineering Gain**
  - Fusion energy >than input energy from the Grid

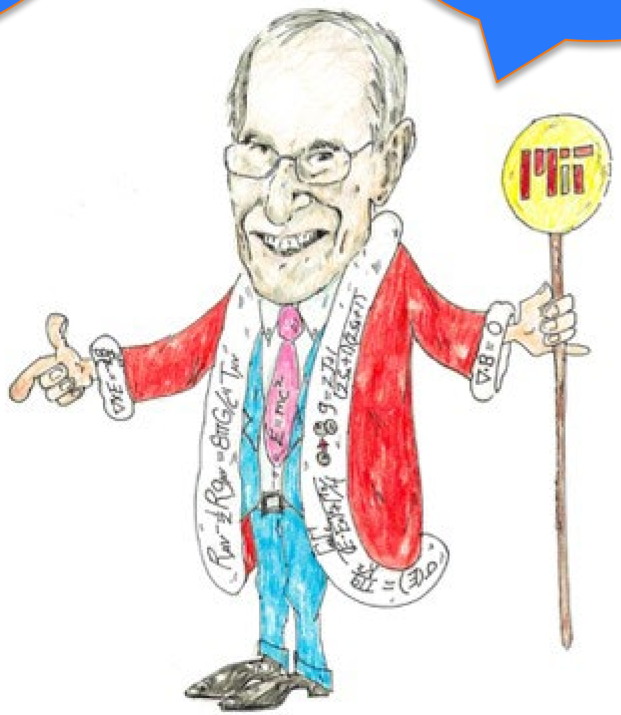
Θ_α=fraction of alpha particles deposited in the plasma

The National Ignition Campaign (NIC) was the first attempt to achieve ignition but with an LPI dominated hohlraum and very demanding capsule design



Tell then to raise the adiabat and lower the gas in the hohlraum to reduce LPI!

I supported NIF but no ignition! What should they do!?



Arthur Kerman

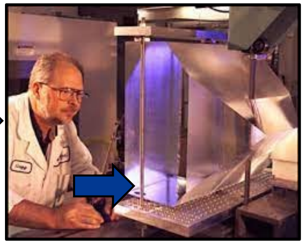
ICF is the most scientifically advanced fusion concept: NIF has achieved ignition and scientific gain>1 with only ~25 kJ in the imploded fuel[1]

UR LLE

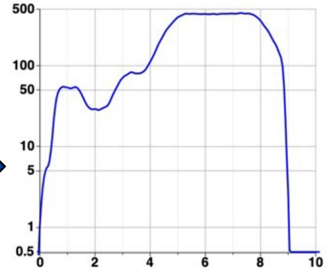
Capacitor banks (~400 MJ)

Flash lamps

4 to 5 MJ at 1052-nm laser



Frequency conversion



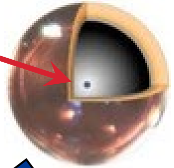
~2 MJ at 350 nm

~2 MJ at 300 eV blackbody Hohlraum[1]

~0.2- to 0.3-MJ capsule[1]

$P_{ignition} \sim (E_{fuel})^{-1/2}$

~0.02 MJ imploded target



- 8.6 MJ of fusion
  - Q_{sci} ~4.1
  - $Q_{capsule}$~33
  - 25 micrograms of DT "Burnt"
    - ~11% of the DT
  - "burn temperature" increased to ~23keV
  - Burn-up fraction~ 11%

NIF was funded as a scientific facility for national Security and is based on laser technology of the 1990's

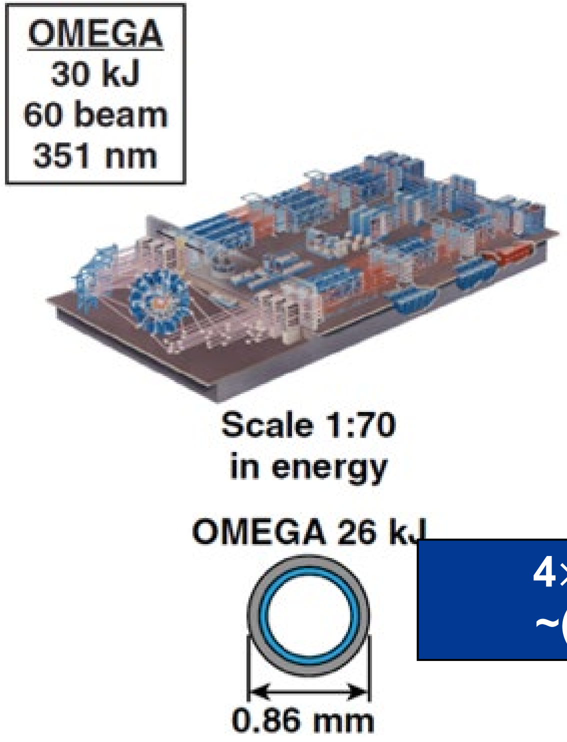
[1] 2022 American Physical Society Dawson Award for excellence in plasma physics

What about Laser Direct Drive?

Experiments addressing critical issues for laser direct drive are being conducted on laser facilities from "millijoules to MegaJoules"

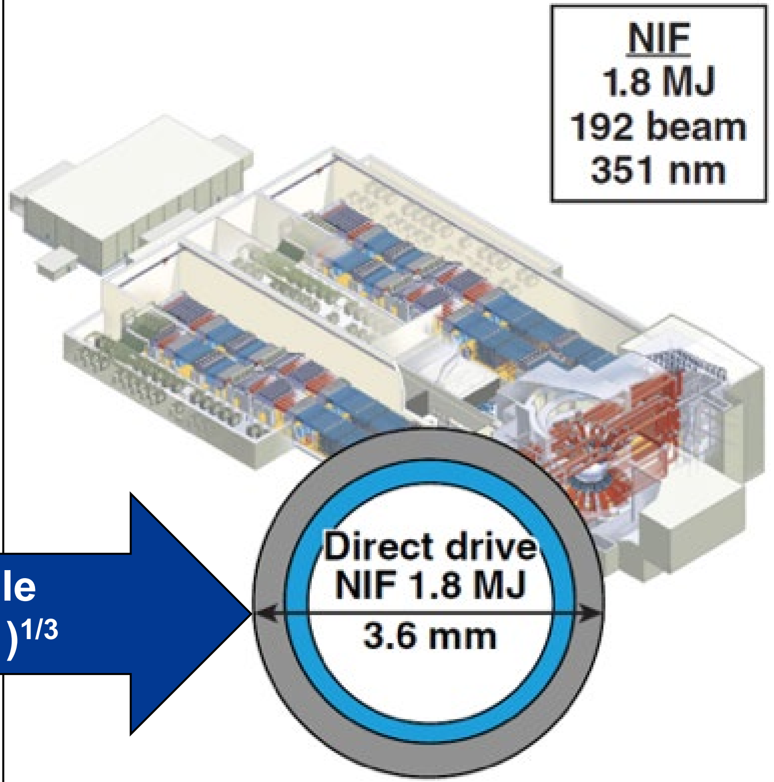
<u>Damage testing facility</u>
~2(mj (20 fsec) probe
100 mj (~100 psec)

Plasma Formation, imprint



Laser coupling, preheat, imprint, and hydrodynamically scaled implosions (SSD & PDD)

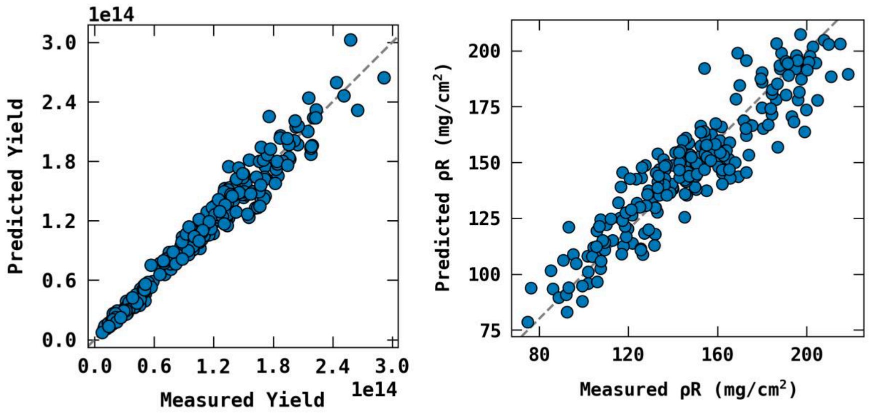
4× in scale
$\sim(E_{NIF}/E_{\Omega})^{1/3}$



Laser coupling, hydro scaling, preheat, and imprint at the MJ scale, Polar DD implosions (present NIF)

Recent OMEGA DT cryogenic implosion campaigns produced **the highest yields (3.1 E14 DT) and highest scaled Generalized Lawson Criteria (GLC) ~1.03 +- 0.05)**, a hot-spot pressure >~100 Gbar, and fusion yield/Hot spot energy >1.0[1] with absorption ~70%, Adiabat 6, and convergence ~20

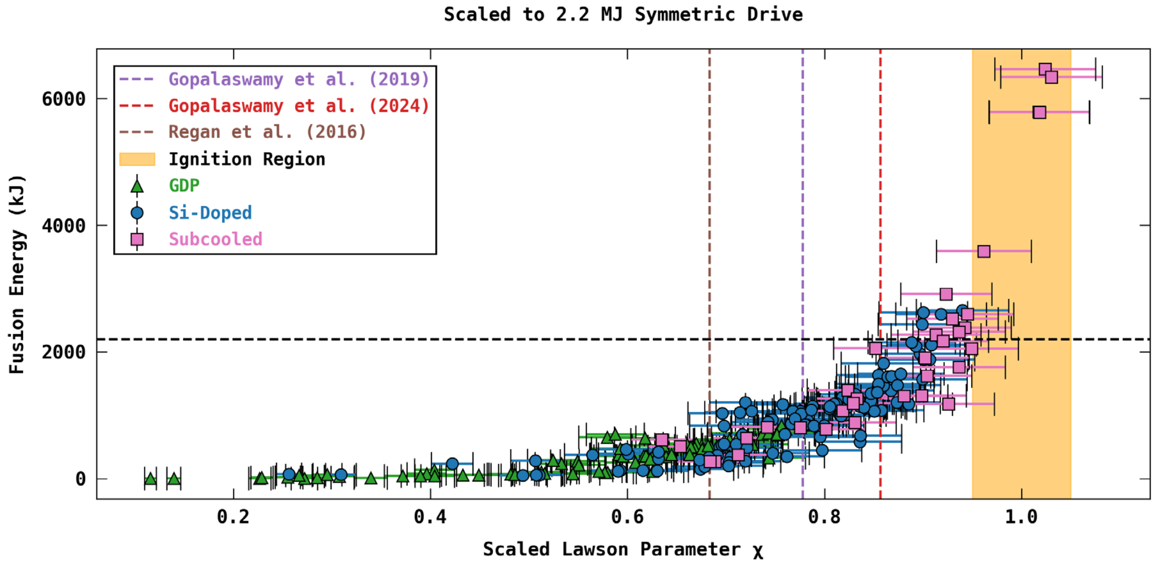
Statistical modeling (SM) predictions*
vs.
Measured neutron yield and areal density



Scale to NIF Energies

- $Mass_{fuel} \sim E_{laser}$
- $R_{fuel} \sim (E_{laser})^{1/3}$
- $t_{imp} \sim (E_{laser})^{1/3}$

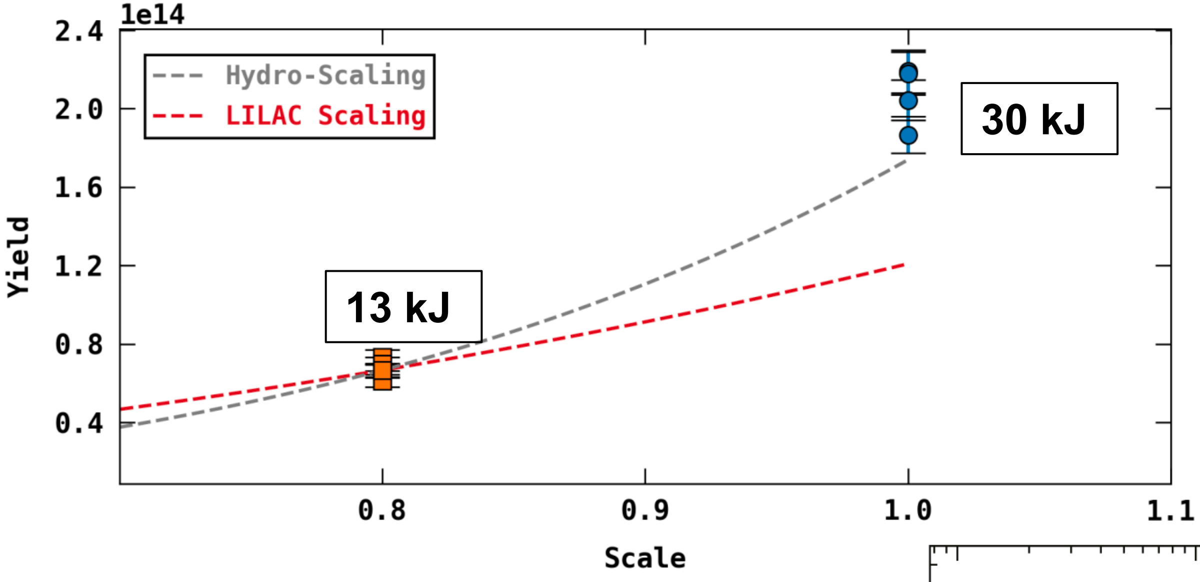
Extrapolated (Hydro scaled to NIF energy (2.2MJ)) fusion yield vs. GLC ($\chi_{no\text{-}\alpha}$)

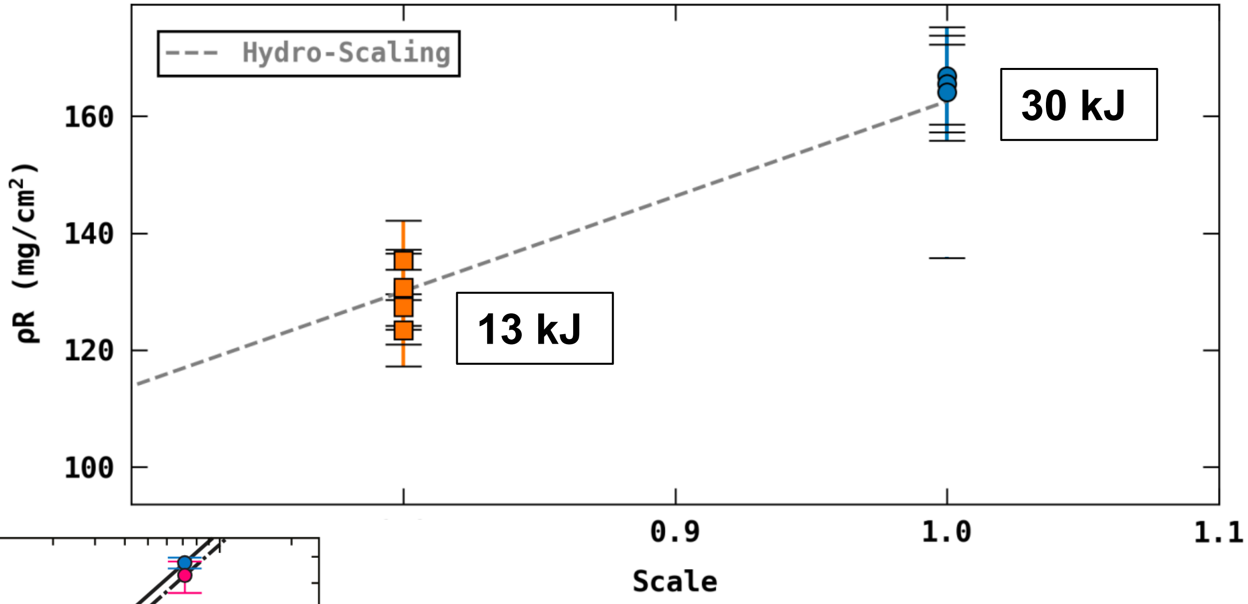


The improved performance is based on using the insights from systematic experiments/modeling/simulation to reduce the impact of degradation mechanisms (LPI, low mode drive asymmetry, hydro, beta decay) through innovative target designs and 3-D measurements.**

[1] 2024 American Physical Society Dawson Award for excellence in plasma physics

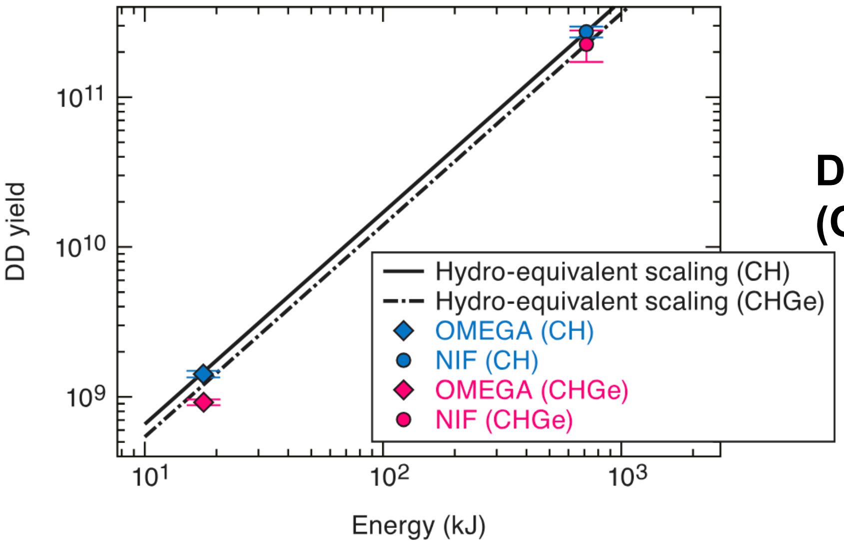
Hydro scaling experiments within the limits of OMEGA (Cryo implosions) and NIF (gas filled D_2) are encouraging





Hydro Scaling

- $Mass_{fuel} \sim E_{laser}$
- $R_{fuel} \sim (E_{laser})^{1/3}$
- $t_{imp} \sim (E_{laser})^{1/3}$



D_2 gas filled implosions (OMEGA and NIF)

IFE Perspectives

The world needs central (24/7) carbon-free power that is inherently safe, with a small ”footprint”, flexible in location, and capable of multiple energy products (electricity, process heat, Hydrogen, water)

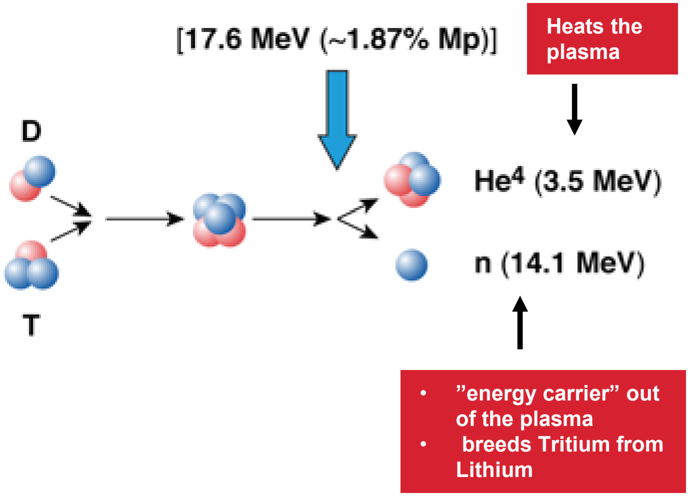
Let’s make Fusion the solution!

Be clear on the challenges!

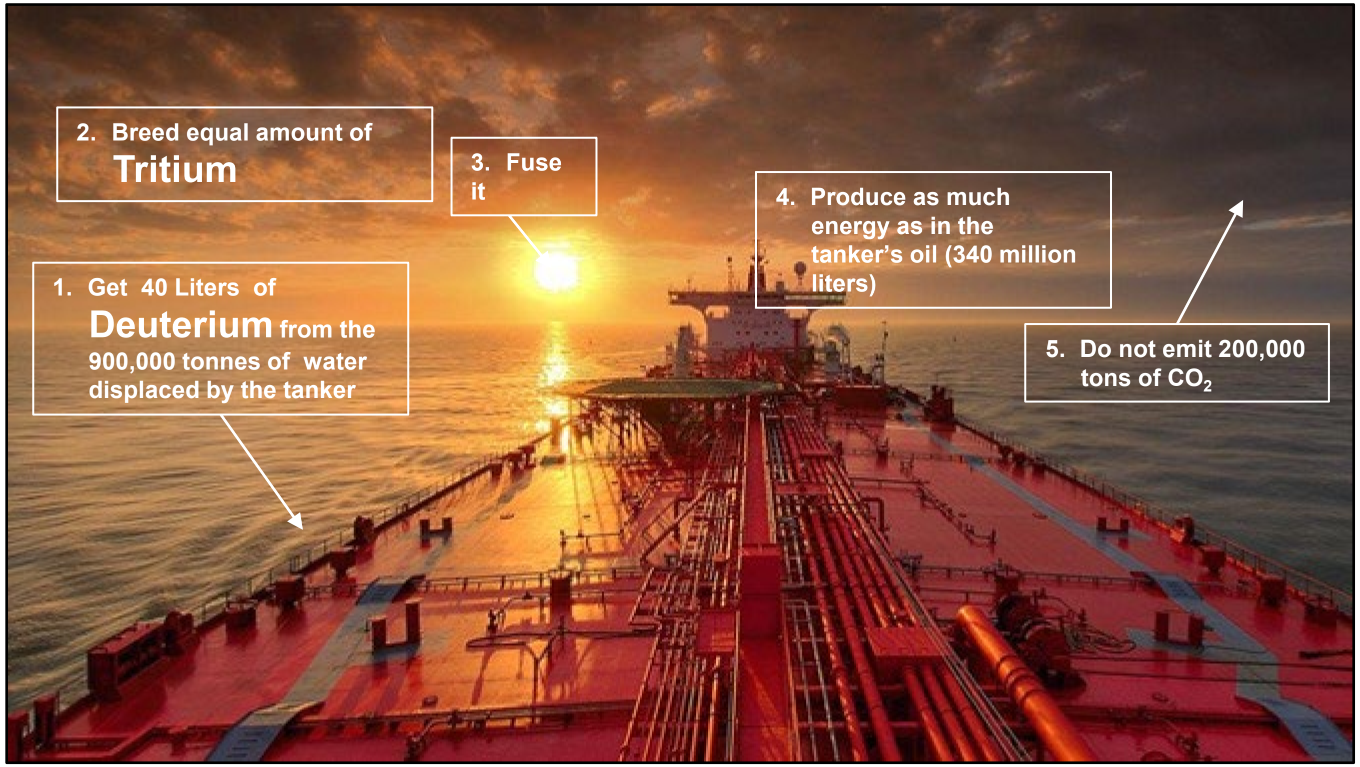
Be realistic and avoid the hype!!

Fusion, identified in the 1930s pursued in the lab since the 1950s! Why do we like it?

E_{DT} =340 MJ/mg (100 kW-hr/mg)



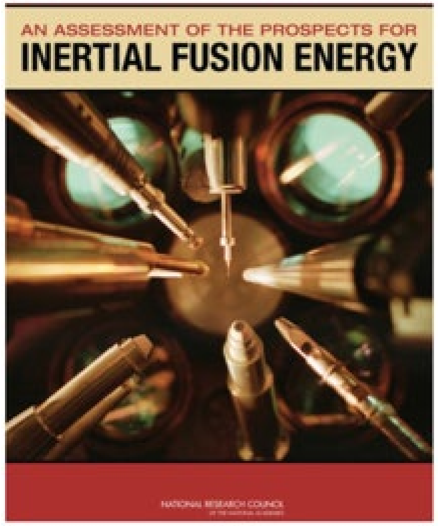
Deuterium (D), Tritium fuel[1]



[1]There are other fusion fuels (D,D) (P,^{11}B) (D ^{3}He)with advantages /challenges but DT is most advanced

National Security has motivated and enabled many scientific and technical advances that have benefited society: IFE will leverage NNSA's ICF and other national security Programs

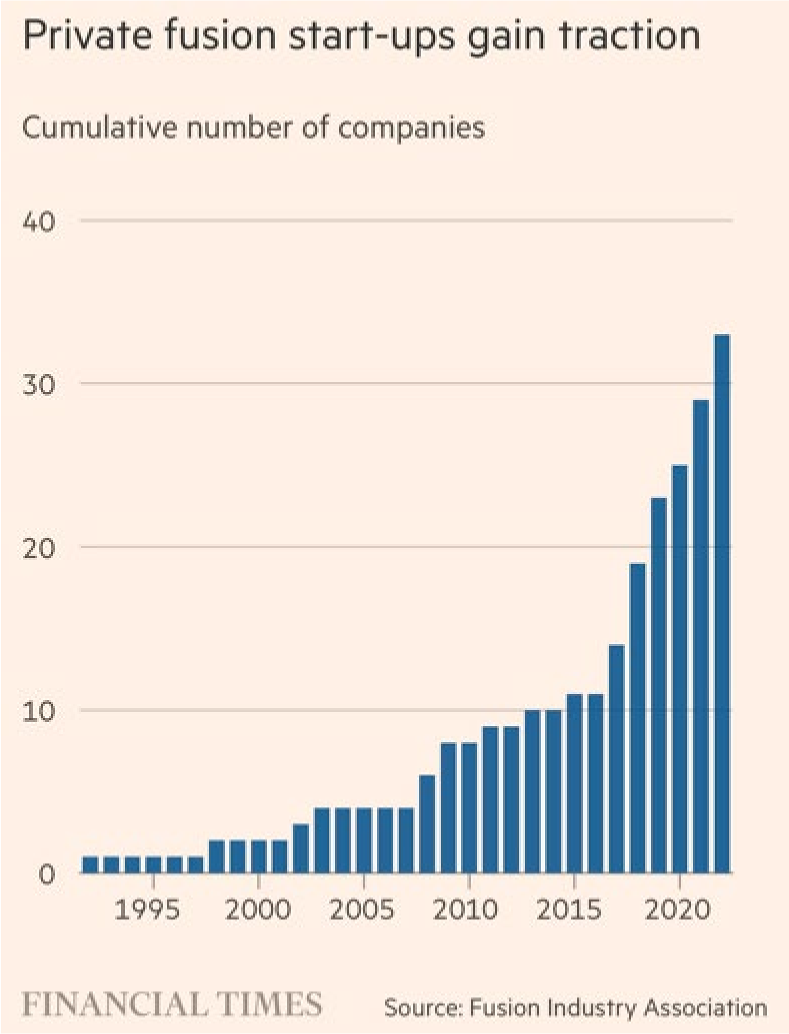
The appropriate time for the establishment of a national, coordinated, broad –based Inertial Fusion Energy program within DOE would be when ignition is achieved.



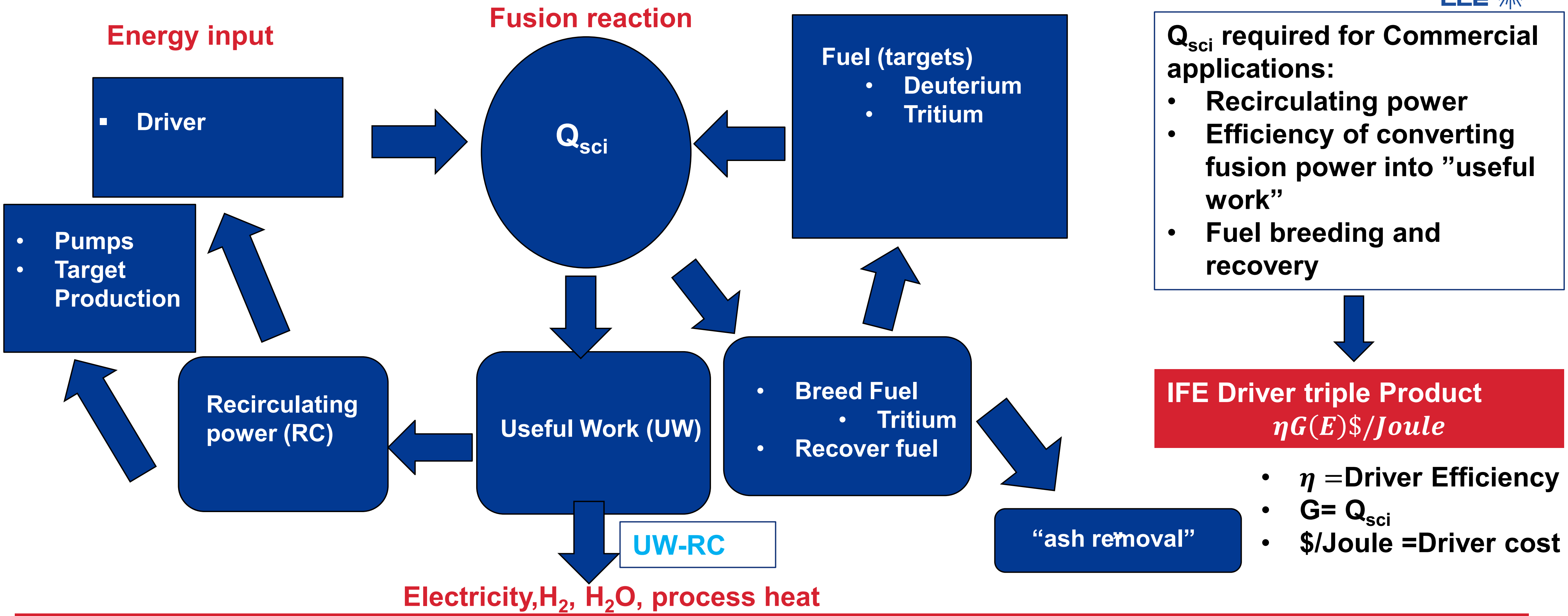
NASEM report 2013

Advances in both the technology and science have catalyzed significant private investment in fusion

- **Examples**
  - The Development of high temperature superconducting magnets
    - Commonwealth Fusion Systems is building the first DT burning tokamak in the US since 1997
  - **The demonstration of scientific gain>1 on the National Ignition Facility**
  - **Laser based companies**
    - **Xcimer (KrF)**
    - **Focused Energy (DPSSL)**
    - **Inertia (DPSSL)**
    - **Marvel (DPSSL)**
    - **BlueLight Fusion**
  - **Pulsed Power Based Companies**
    - **Pacific Fusion**
    - **Fuse**
    - **First Light Fusion**



All fusion energy plants will have similar sub-systems but the technology/details will be different and influenced by the choice of fuel (DT fuel example)



A System approach in addition to the "science " is required to evaluate fusion energy concepts-Successful science is necessary but not sufficient for commercial fusion energy (for DT : for Electricity at 5 cents/kW-hr, each GJ of fusion must cost <$5

There are several possible fuels that can be used for Fusion Energy

DD fusion (ΔE_{fusion} (7.3 MeV))

D +D ⟶ T (1.01 MeV) + p^+ (3.02 MeV)

D +D ⟶ ^{3}He (0.82 MeV) + n (2.45 MeV)

DT fusion (ΔE_{fusion} (17.6MeV))

D +T ⟶ ^{4}He (3.5 MeV) + n (14.1 MeV)

E_{fusion}~340 MJ/mg

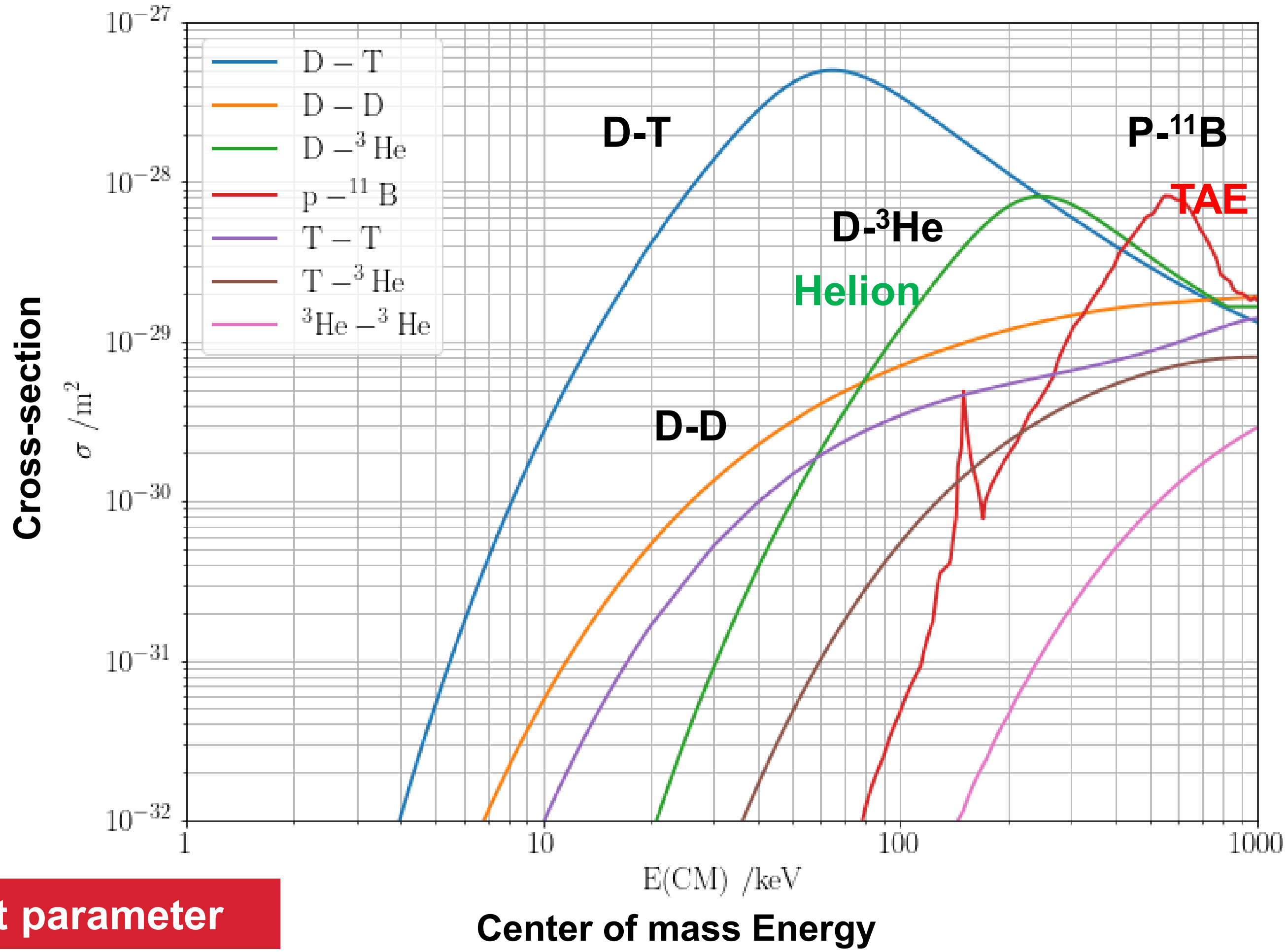
P^{11}B fusion (ΔE_{fusion} 8.7 MeV)

p +^{11}B ⟶ 3 ^{4}H (8.7 MeV)

E_{fusion}~75 MJ/mg

D^{3}He fusion (ΔE_{fusion} 18.4 MeV)

D +^{3}He ⟶ ^{4}He + p + 18.4 MeV



Fusion Gain (E_{fusion}/E_{CM}) is an important parameter

ICF has advantages for the development of Fusion Energy

- **Separable components of the plant**
- **Fusion takes place in ~cm^3 of the center of the chamber-enables flexibility in reactor design and plasma facing "first wall"**
- **Attractive development path**
  - "Low rep-rate facility for target/physics development **(DON'T NEED LOTS OF TRITIUM!)**
  - Modularity (driver, targets)
- **Fueling and ash removal (high fuel burn-up)**
  - Sufficient T breeding (~1.1) with natural Lithium
- **Technology and science spin-offs**
- **Multiple target concepts (same driver)**
  - **Direct Drive must be developed without 4 pi illumination**
    - Enables hybrid targets
    - X-ray driven targets
    - Enables capsule protection from Chamber radiation
    - Enables breeding with natural lithium
    - National Security applications
- **Multiple sponsors for technology and science (DOD, NNSA, Industry, FES**
  - Technologies (i.e., laser diodes, optics, pulsed power)
  - Target physics and supporting technologies
  - Scientists, engineers, technical staff

China and ICF (SG IV)

National Security is an "adjacent market" for IFE

IFE-Fusion takes place in cm^3 at chamber center: flexibility in chamber design

Liquid "plasma facing wall"

- *Waterfall of flibe: coolant, x-ray/debris absorber, neutron moderator, and tritium breeding material*
    - *"complete recovery of full fusion yield (~340 MJ/mg)*
- *Liquid flibe directly protects first wall from x-ray/debris and 14 MeV neutrons*
- *No "first wall problem" - structural wall can last lifetime of the plant.*
- *Significantly lower activation and waste production compared to conventional DT fusion approaches*
- *natural lithium for breeding*

Research is required with increased emphasis on tritium science (breeding, recovery), plasma facimg components (including optics for laser drivers) waste stream and for pulsed power drivers :driver, target coupling

Anything else?

Fusion energy will require IFE systems with rep rates of ~0.1 Hz (8640 shots/day) to ~10 Hz (864,000/day)

- **Driver**
  - Energy/pulse
    - 1--10 MJ
    - Metric is $/joule for laser system including thermal management
  - Peak power
    - >~500 TW
  - Intensity (~10^{15} watts/cm^2 to10^{21}watts/cm^2
  - Average power
    - 3 to 100 MWatts (NIF is ~200 Watts, EUV laser are ~50 KW)
  - Optical component survivability
    - Maximum ”damage free” optical fluence (NIF fluence is ~7 Joules/cm^2) and damages every shot
- **Targets**
  - 10^4 to 10^6 targets/day
  - Injected into chamber and properly illuminated with the laser
  - Target cost <$1
- **Chamber**
  - Plasma facing first wall survival
    - ~30% of energy in ions and x-rays
    - Tritium breeding and recovery
    - ”chamber reset time”
    - Waste stream

Economic Challenge: At 5 cents/kw-hr, marginal cost of each GJ of fusion must be <$5

IFE Program: Address the high-leverage, impactful topics

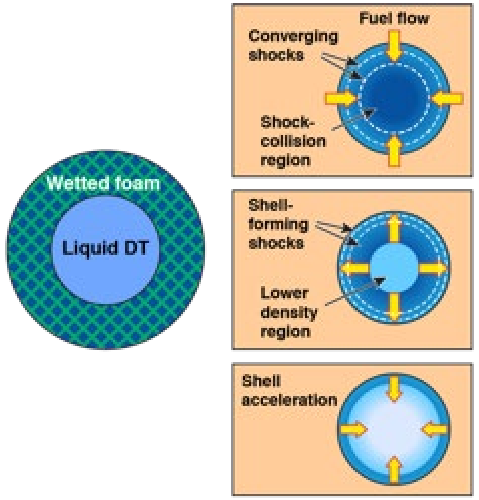
- **Research Program**
  - Targets
    - Target fabrication (affordable, mass production, placement in target chamber)
    - Model and simulations
    - Experiments on existing facilities
  - Lasers
    - Driver design and architecture
    - Demonstrate “unit cell” and optical train (average, peak power)
      - Efficiency
      - Robustness and durability
      - Supply chain and economics
  - Design for a “single shot” IFE facility (now BIG should it be?) that addresses both physics and “technical challenges” and exploits the advantages of IFE (one driver-multiple concepts) and hundreds of complex experiments (implosions) per year (“IFE SPARC”)
  - This facility could also serve a dual use mission: national Security (The LMF!)-funded by the private sector?
  - Partner with broad fusion and nuclear industry on Tritium (breeding and recovery), materials

NIF Beamlet

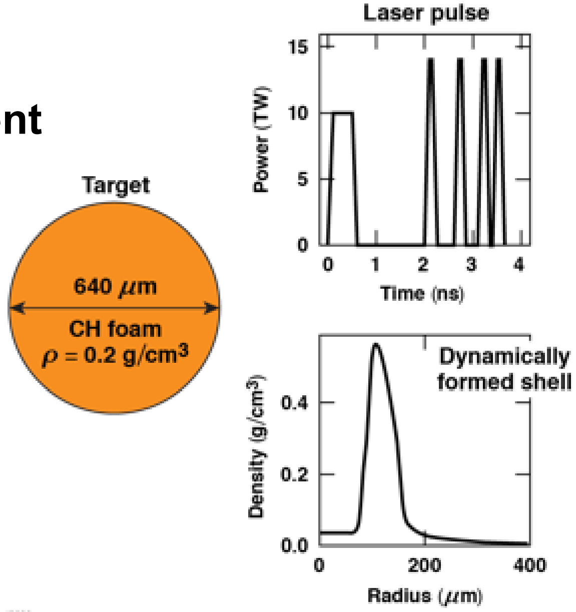
Recognize that there is NO IFE laboratory and between LLNL and LLE ~100 Cryogenic implosions/year.

IFE target designs are being developed that exploit advances in target fabrication (printed foams) that address the cost and complexity of IFE targets and reduce “plant Tritium inventory” to less than 1 kg: Research on Foam targets is critical topic!!

Dynamic Shell Design (LLE)



OMEGA Experiment



Wetted Liquid foam targets (LANL)

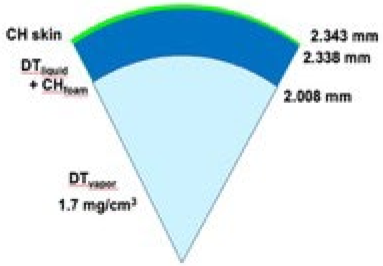


Figure 1: The PDD-WF target concept with dimensions used in the 2D simulations.

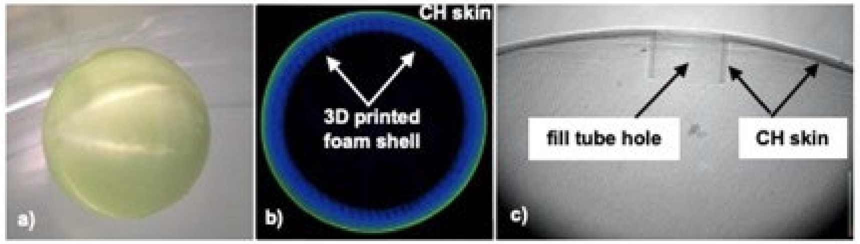
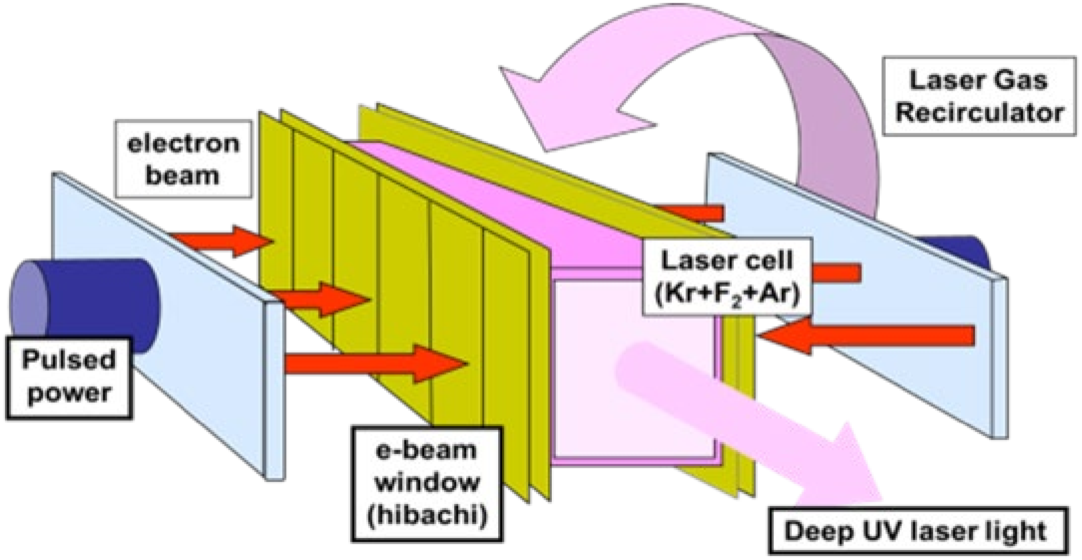
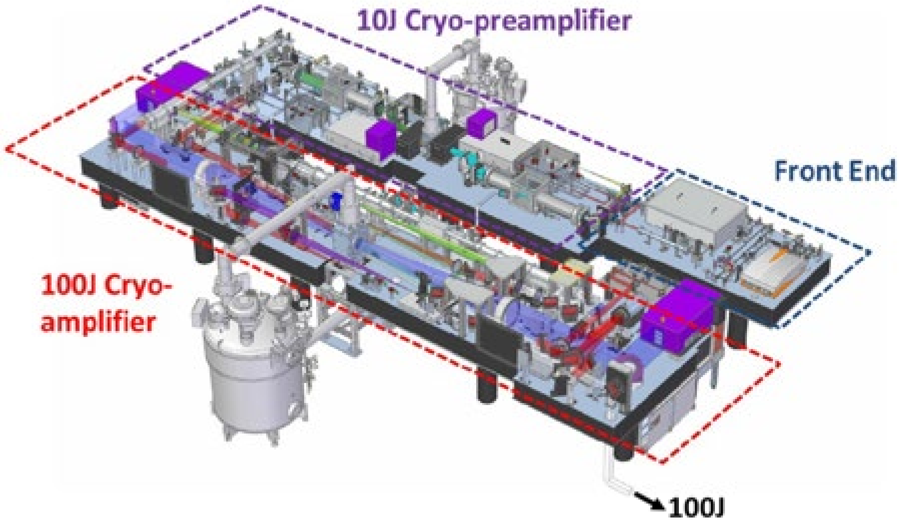


Figure 4: a) PDD-WF capsule 3D printed with the dimensions specified in Figure 1; b) full diameter tomograpic image of the capsule; c) detail of the fill tube region (Alex Haid, GA).

Printed Foam targets (GA)

IFE lasers-Two Possibilities





Pulsed Power-driven Excimer gas lasers

- Pulse Compression
  - Optical multiplexing (ICF-X: ArF (193 nm and 10 THz bandwidth)
    - ICF-X
  - Brillouin Pulse compression
    - Xcimer (248 nm)

Diode pumped Solid State lasers

- Non-linear frequency conversion
  - ~350 nm (third harmonic of ~1000 nm fundamental)
- Several approaches for Bandwidth and LPI mitigation (STUD pulses)
  - Inertia, Focused Energy, Marvel

Supply Chain must be addressed!:pulsed power, diodes, gain media, non-linear crystals,optics

Tritium research should become a major focus for DT fueled Fusion plants[1]

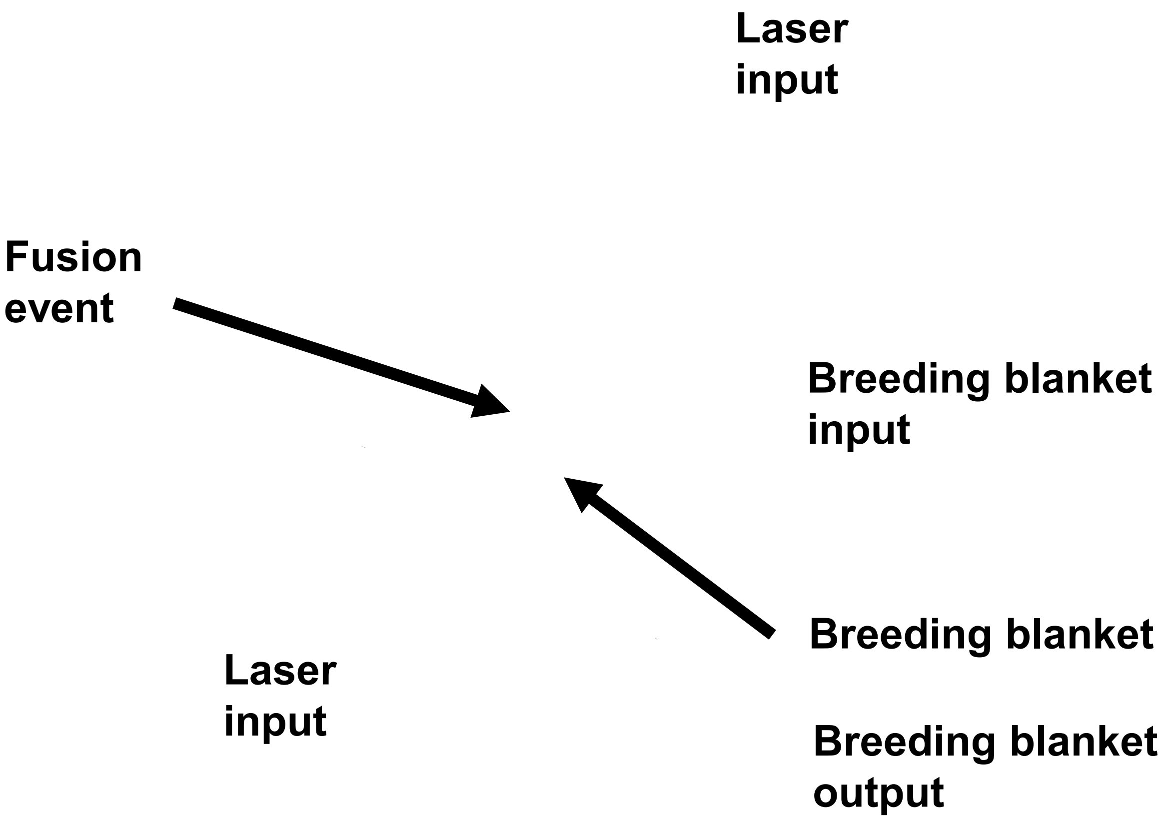
UR LLE

	ITER	MFE-DEMO	IFE-Pilot	IFE - Full
Fusion power (MW)	500	2700	1100	2200
Fueling rate (kg/hr)	1.1	1	0.03	0.06
Fueling rate (g/day)	25333	20600	735	1356
Burn fraction	0.003	0.02	0.23	0.27
T consumption (g/day)	76	412	169	366
T recovery (g/day)	25257	20188	566	990
T breeding	<0.4	450	203	439

[1]Recent developments in IFE safety and tritium research and considerations for future nuclear fusion facilities
Susana Reyesa, Tom Anklama, Wayne Meiera, Patrick Campbella,
Dave Babineaub, James Becnelb, Craig Taylorc, Jim Coonsc

While significant challenges remain, the large fuel"burn-up fraction" and fueling efficiency are attractive features of IFE. Challenge includes removal/recovery of target components

Don't forget lithium!!Schematic of an Inertial Confinement Fusion Reactor with a liquid plasma facing "first wall"



First wall Options

- **FLIBE (Li fluoride, Be fluoride)**
- **Lead lithium**
- **lithium**

Tritium Breeding from Lithium

n+ ^{7}Li → ^{4}He + T (Tritium) + n (Neutron)- 2.67 MeV

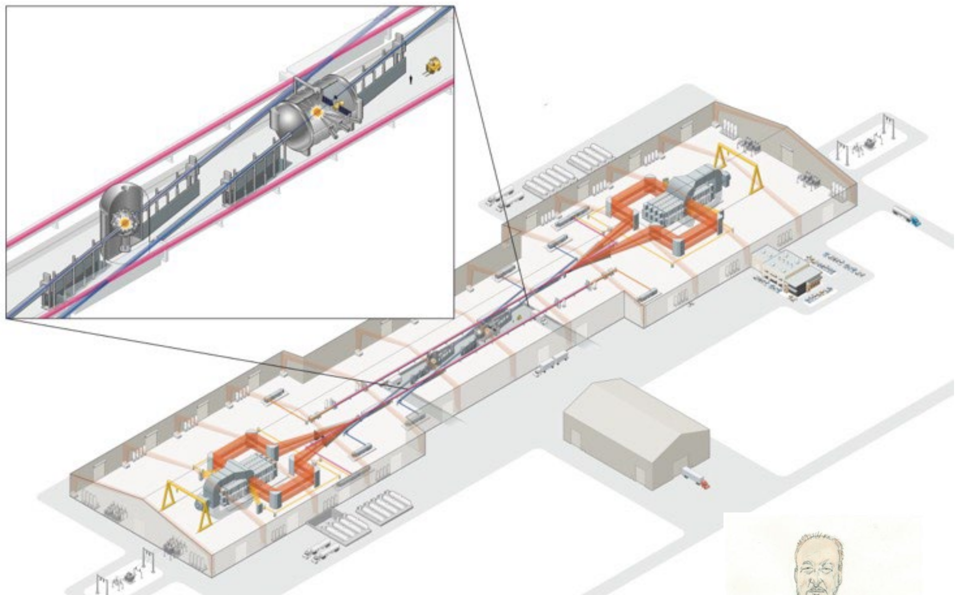
n + ^{6}Li → ^{4}He + T (Tritium) + 4.78 MeV

GW_e IFE plant

- **FLiBe Inventory – 1.6 x 10^6 kg**
- **Total Lithium inventory = 2.2 x 10^5 kg**
- **TBR = 1.17**
- **^{6}Li/^{7}Li burn-up rates: 264/34 kg/yr**

Public-Private partnership(?): Low rep rate facility to develop and demonstrate high yield (>100 MJ and Engineering Breakeven) and address other topics for fusion energy could provide significant value to Stockpile Stewardship

Two target chambers would increase facility utility and value



Xcimer 4 MJ 248 nm laser

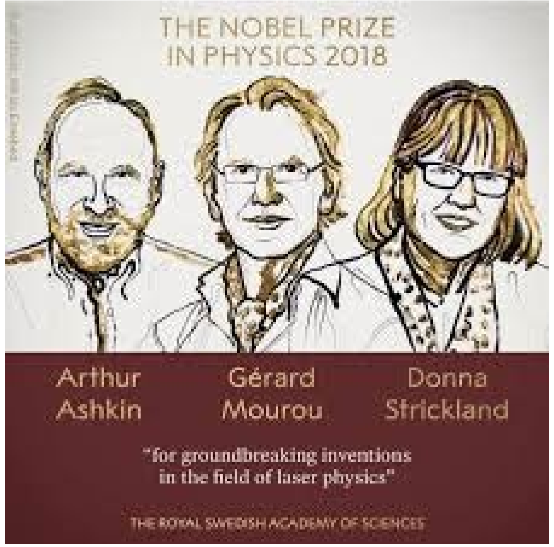
[1] LANL and Xcimer have ongoing research partnership (CRADA)

Pacific Fusion IMG driver

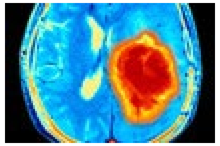
The scientific and technical challenges of Fusion have led to many spin-offs; Further development will almost certainly lead to more: Ultra-high intensity lasers

UR LLE

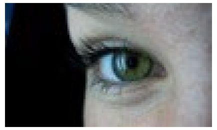
- Strickland, Donna; Mourou, Gerard (1985). "Compression of amplified chirped optical pulses". *Optics Communications*. **56** (3): 219–221



me

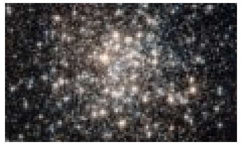


Radiation treatment for cancer



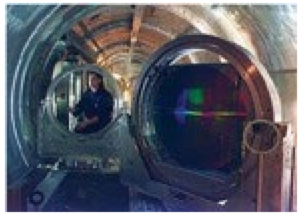
Lasik Eye surgery

Commercial Products
Fsec machining



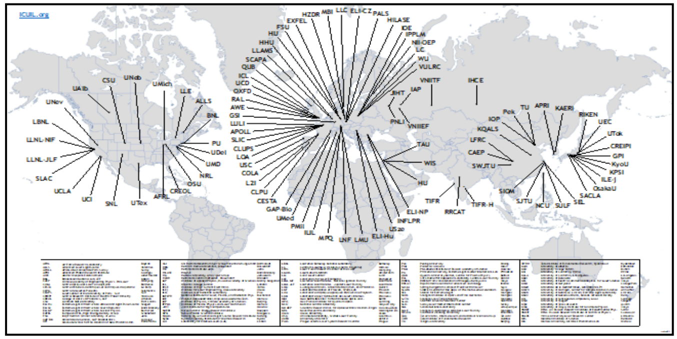
Physics of the Universe in the Laboratory

Ultra-Fast Probes/radiation sources/compact accelerators



Charlie Townes (nobel for lasers)

Petawatt (1997) @ LLNL



2022

The time for Directed Energy has come! Israel’s Iron Beam is now part of the Iron Dome!

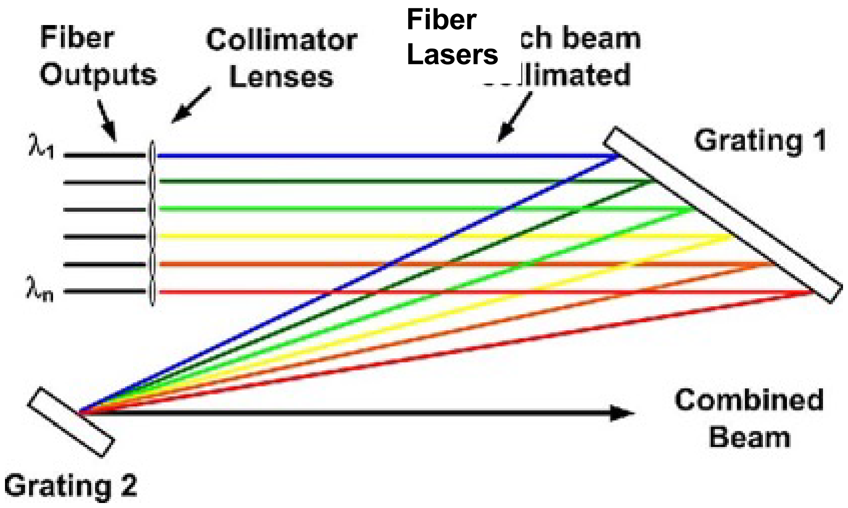
Attack by Swarms of missiles and Intercepts by kinetic weapons

Rafael’s 100 kW spectrally combined fiber laser

There is a worldwide effort ongoing in DEWs

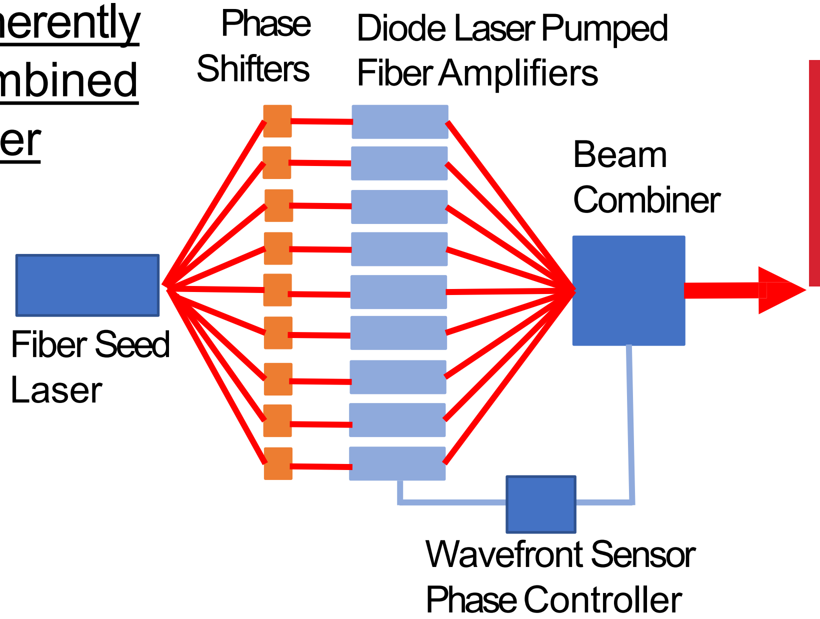
Many of the DEW laser concepts and key technologies originated in the ICF Program; 500 kW (LMC, GA) and MW (nLight) systems are in development and planned for 2026

Spectrally Combined Laser



Grating developed for NOVA PW

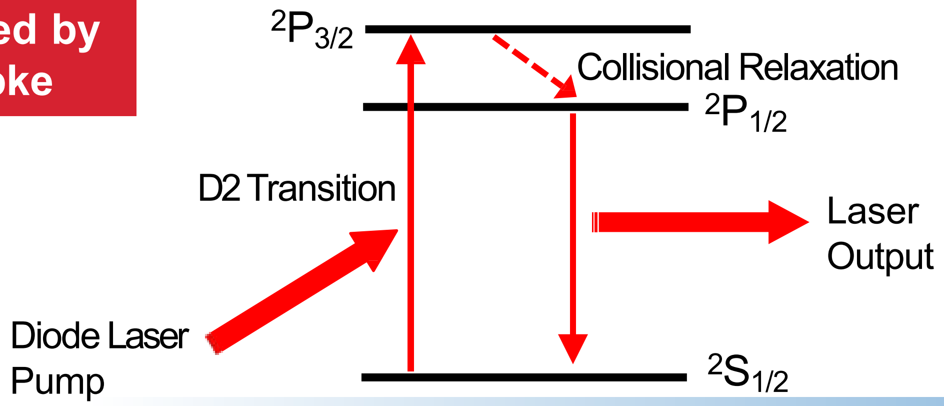
Coherently Combined Laser



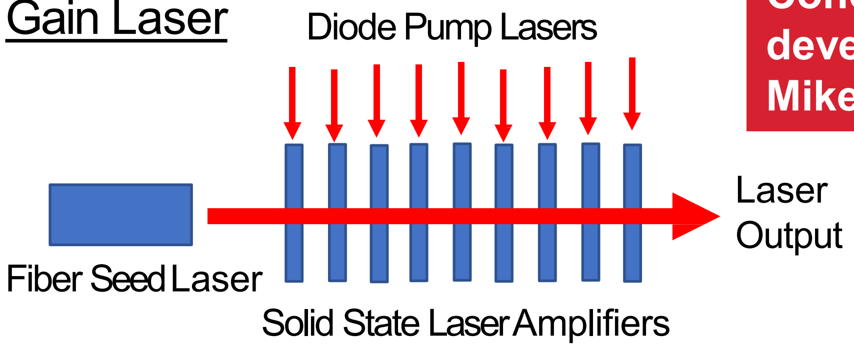
Chief Scientist (NG) Josh Rothenberg

Concept developed by Bill Krupke

Diode Pumped Alkali Laser (Gas)



Distributed Gain Laser



Concept developed by Mike Perry

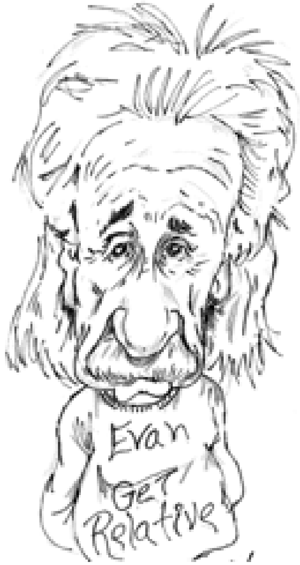
Fusion ignition is analogous to the Wright Flyer. Could the Wright Brothers have imagined the 787?

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.”

I agree!

Me too!



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