U.S. NAVAL
RESEARCH
LABORATORY

Progress Towards High-gain Inertial Confinement Fusion with Lasers

A 1.3 MJ yield shot on the National Ignition Facility using 1.9 MJ of laser light demonstrated basic viability of inertial fusion. The NRL program is advancing a laser technology and approach that is projected to enable the higher gains (100+) needed for inertial fusion energy.

Presentation to APS Middle Atlantic Physicist Group

Work supported by DoE NNSA, ARPA-E, DOE FES, and NRL 6.1

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November 17 , 2021

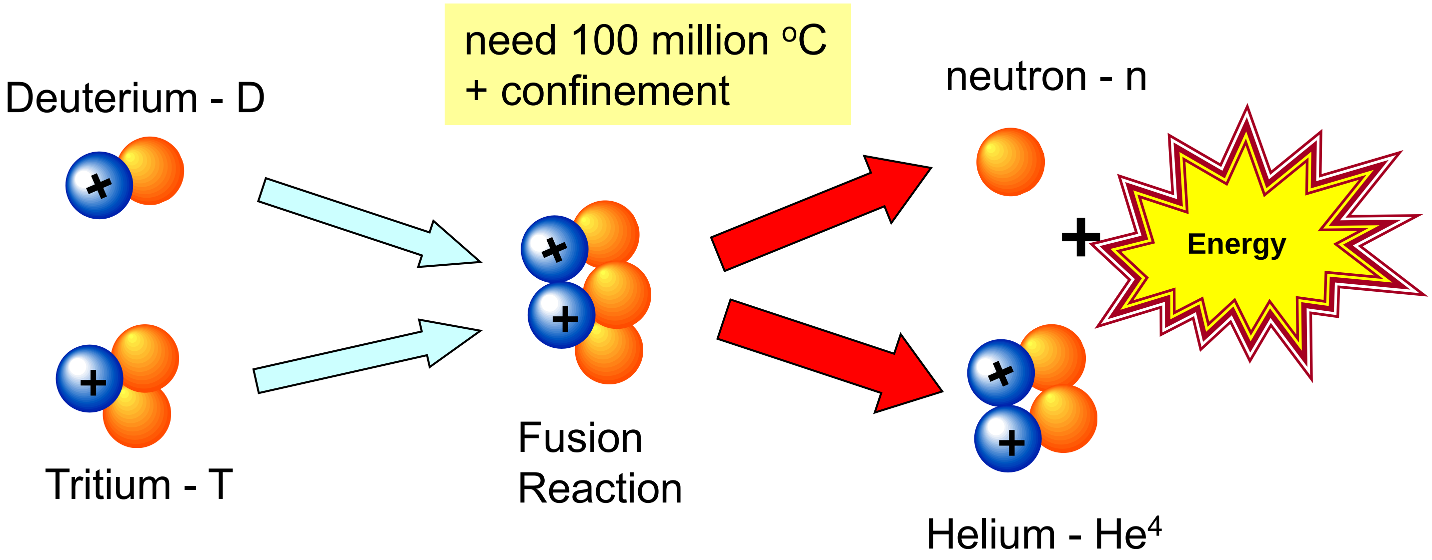
Fusion powers the visible Universe

Can it provide clean plentiful energy on earth?

The basics of nuclear fusion: at a very high temperature atoms fuse together with the release of energy

NRL PPD

The fusion reaction with deuterium-tritium is the “easiest” to achieve – others require higher temperature



need 100 million °C
+ confinement

Deuterium - D

Tritium - T

Fusion
Reaction

neutron - n

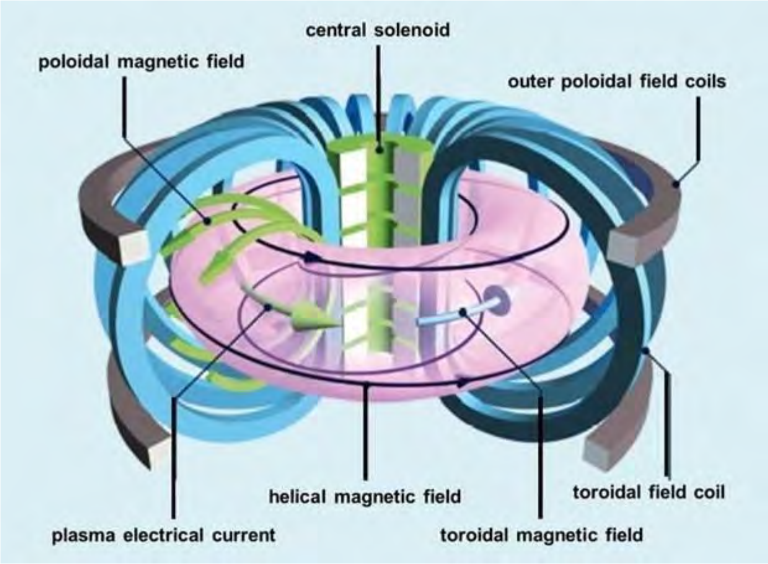
Helium - He^4

$$\mathbf{D + T \Rightarrow He^4\,(3.45\ MeV) + neutron\ (14.1\ MeV)}$$

1 MeV = 1 million electron volts – typical chemical reactions release a few electron volts of energy

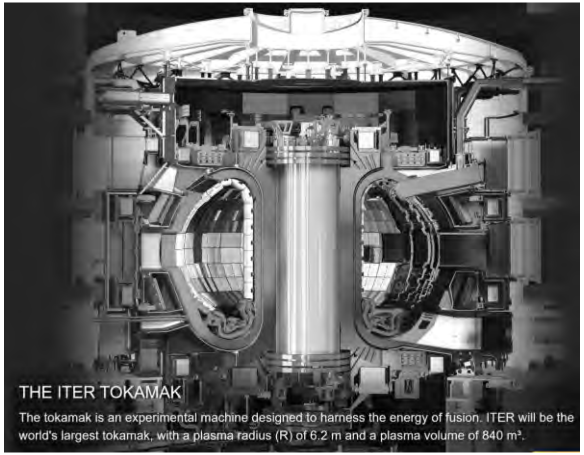
Paths to fusion on Earth: Magnetic Confinement

A strong magnetic field confines the hot burning plasma.



(from energy.gov)

Magnetic fusion ITER facility - under construction



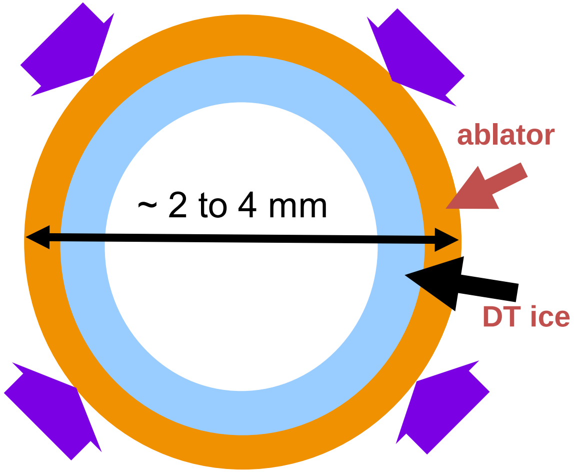
THE ITER TOKAMAK

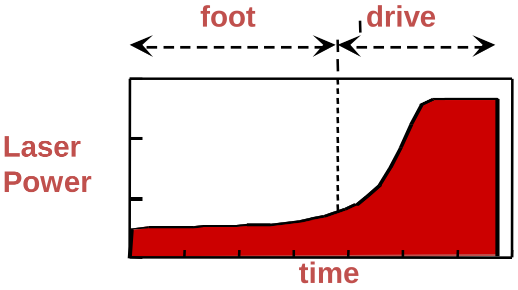
The tokamak is an experimental machine designed to harness the energy of fusion. ITER will be the world's largest tokamak, with a plasma radius (R) of 6.2 m and a plasma volume of 840 m^3.

https://www.iter.org/mach

Inertial Fusion (via central ignition)

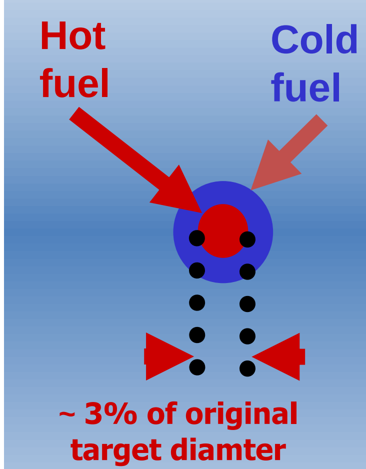
Lasers or x-rays heat outside of pellet, **~100 Mbar pressure** implodes fuel to velocities of ~300 km/sec





Central portion of DT (spark plug) is heated to ignition.

(~100 Gbar, ~10^8 °C)

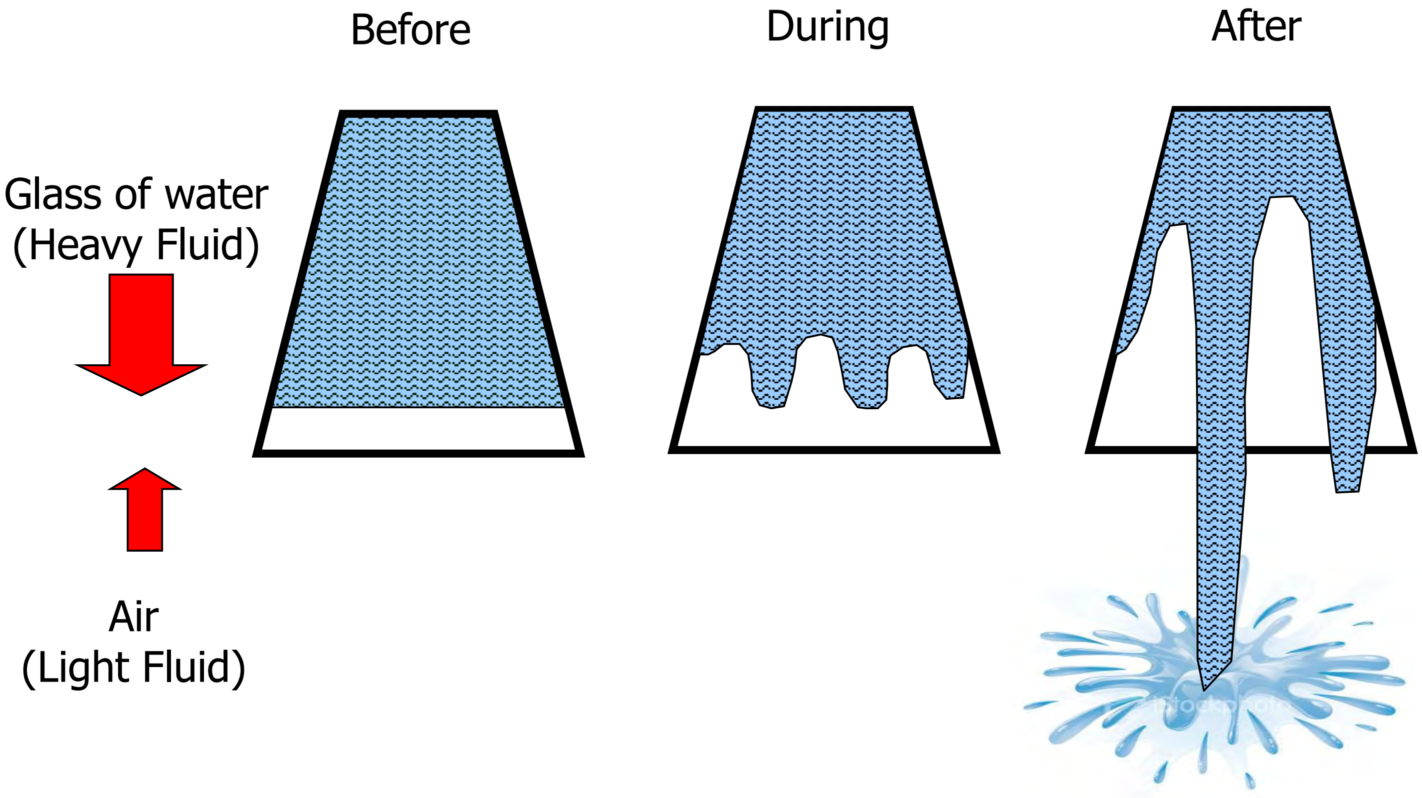


Thermonuclear burn then propagates outward to the compressed DT fuel.

- Simple concept
- Potential for very high energy gains (>100)
- Requires high precision in physics & systems
- Need to understand & mitigate instabilities

A heavy fluid supported by a lighter fluid is subject to Rayleigh-Taylor Instability

Example: A glass of water turned upside down..



Before

During

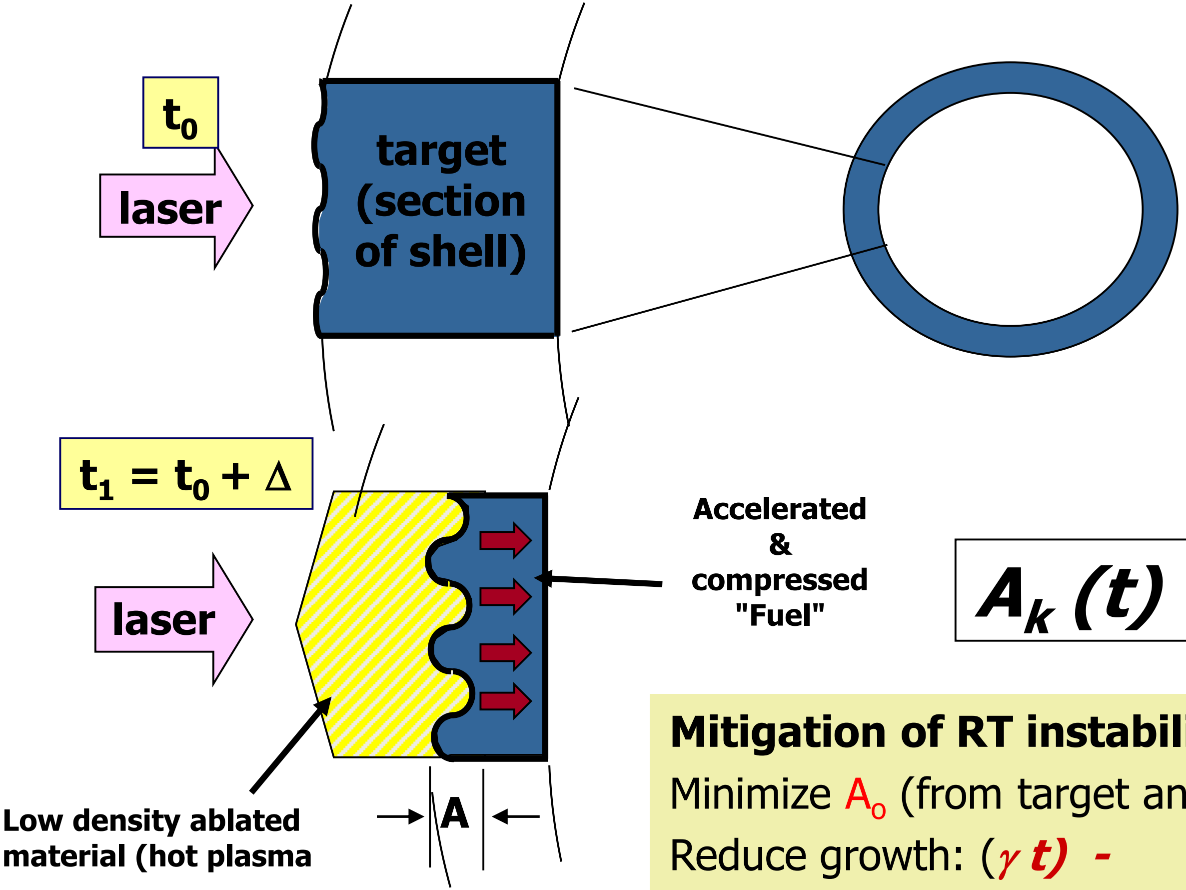
After

Glass of water
(Heavy Fluid)

Air
(Light Fluid)

An ICF pellet has a Rayleigh Taylor (RT) Instability:

Pressure from the low density ablated material accelerates the high density shell.



t_0

laser

target (section of shell)

$t_1 = t_0 + \Delta$

laser

Accelerated & compressed "Fuel"

Low density ablated material (hot plasma

A

$$A_k(t) = A_{ko}\, e^{\gamma_k t}$$

Mitigation of RT instability.

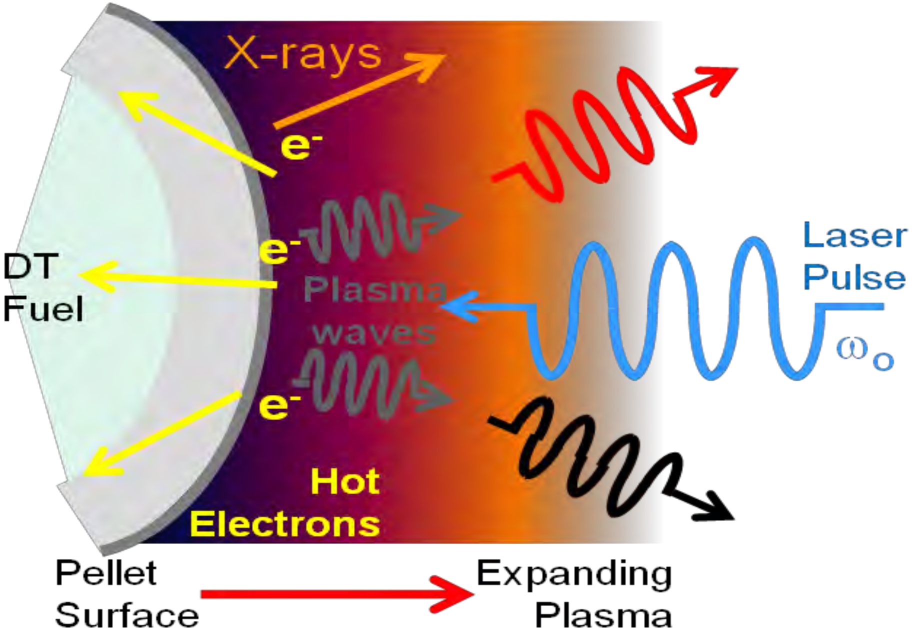
Minimize A_o (from target and drive imperfections)

Reduce growth: ($\gamma\, t$) -

Laser plasma instabilities (LPI) are a challenge to laser fusion

NRL PPD

- LPI produced high energy electrons can preheat target impeding its compression.
- LPI induced laser scattering reduces laser drive and can spoil symmetry.
- LPI limits the maximum usable laser intensity and ablation pressure

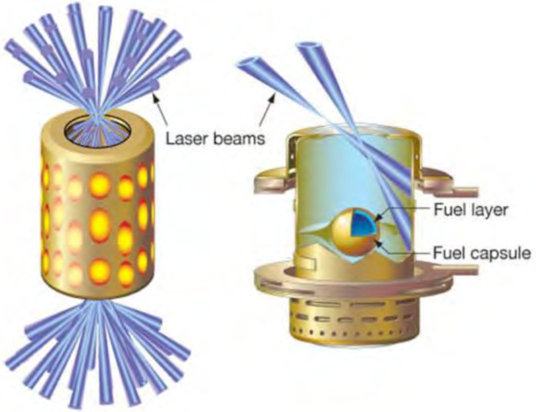


Mitigation of laser plasma instabilities

- ➢ **Broad laser bandwidth** can disrupt the coherent wave-wave interactions that produce LPI
- ➢ **Short laser wavelength** increases the instability intensity thresholds of most instabilities

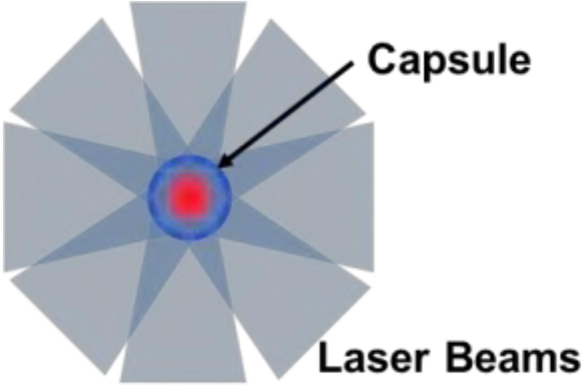
Two approaches to laser ICF

Indirect Drive (ID)– laser light converted to x-rays that drive the implosion – approach chosen for NIF.



- Mainline effort on NIF
- ID reduces laser uniformity requirements
- But is not efficient, only a small fraction of laser energy reaches target as x-rays

Direct Laser Drive – laser light directly illuminates the capsule



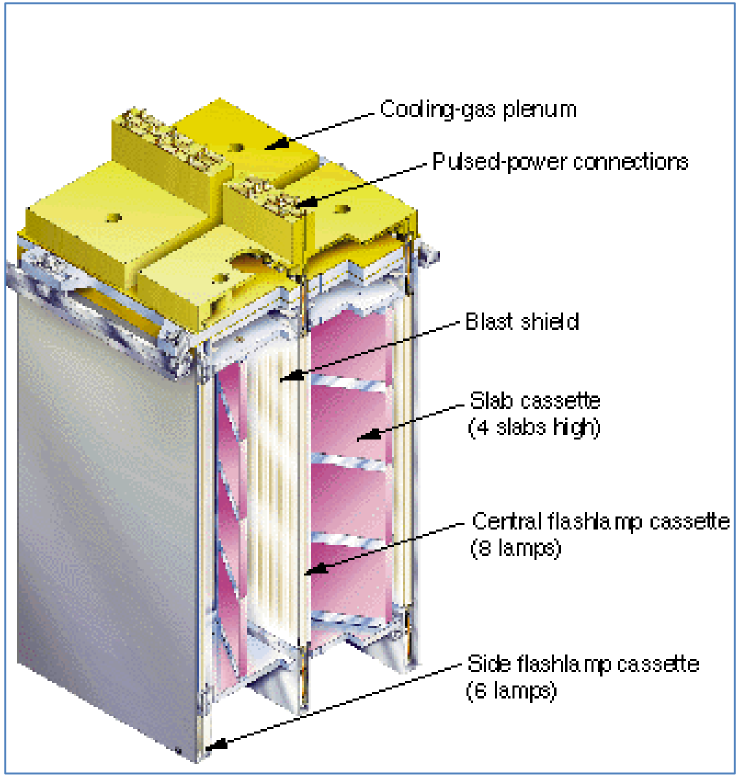
- Much more efficient than indirect drive
- But requires very uniform laser illumination of the target
- Potential for much higher gain and fusion yield

Illustration from https://lasers.llnl.gov/programs/nic/icf/

The National Ignition Facility (NIF) concentrates the energy from 192 laser beams energy in a football stadium-sized facility onto few-mm-size targets.

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

NIF utilizes flashlamp-pumped Nd:glass amplifiers, the 1054 nm light is frequency tripled to 351 nm



Nd:glass amplifier
Accommodates 8 30-cm aperture beams

Near infrared λ = 1054 nm light from Nd:glass is frequency tripled to UV and directed to target

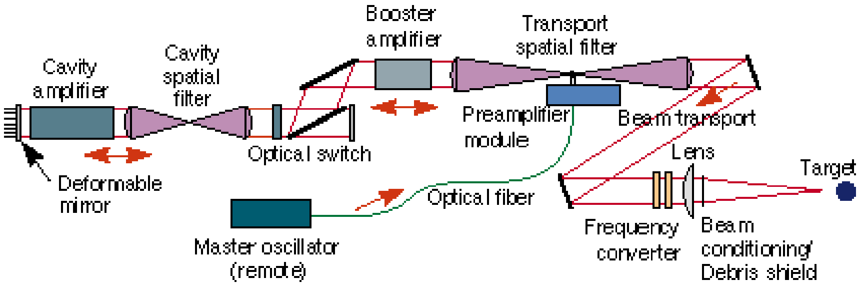
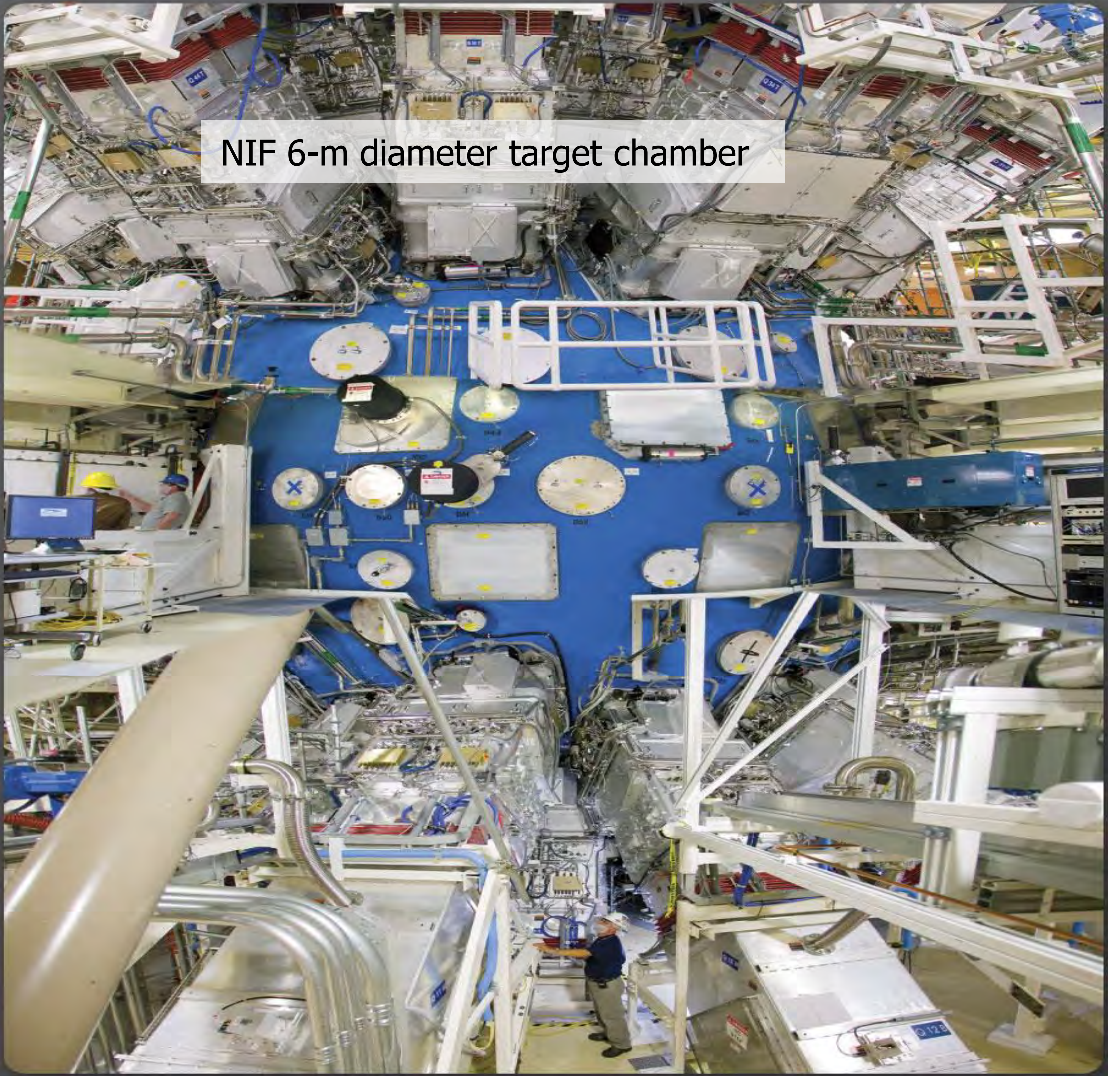


Figure 1. The layout of NIF's major components through which a pulse of laser light travels from injection to final focus on the target.

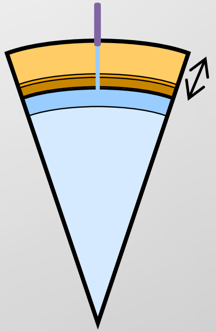
1 of 192 beams

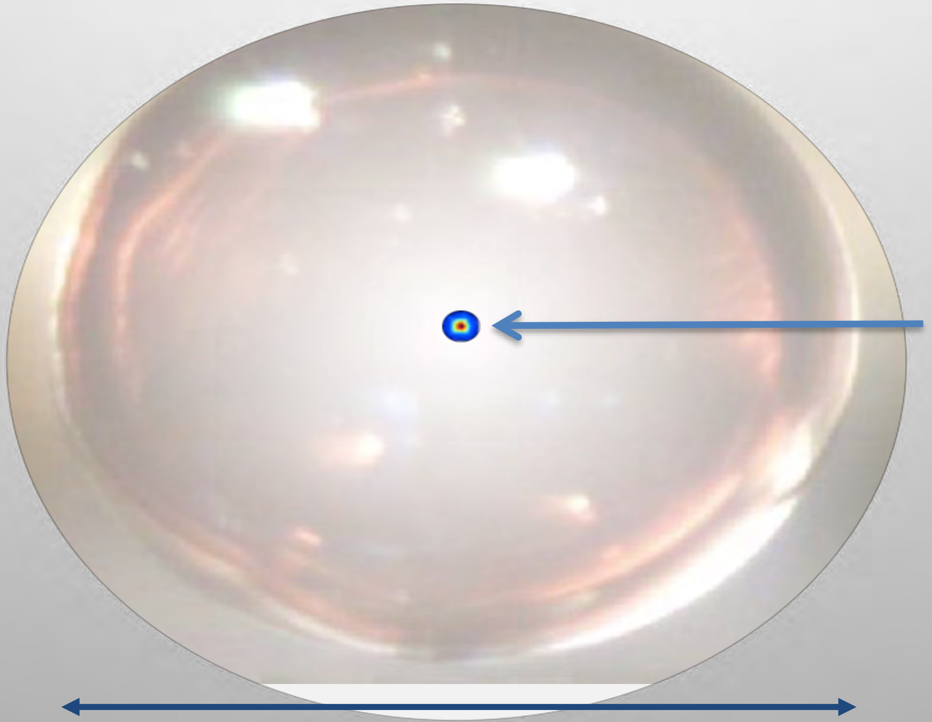
https://str.llnl.gov/str/Powell.html



NIF 6-m diameter target chamber

The challenge — near spherical implosion by ~35X



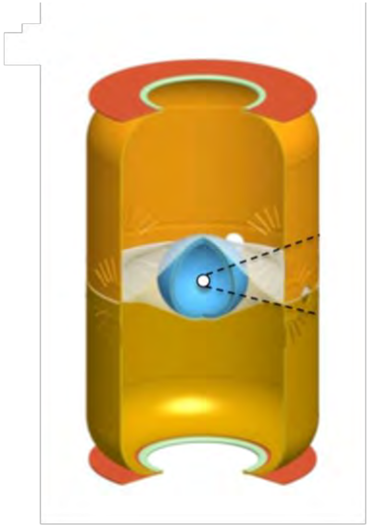


DT shot N120716
Bang Time
(less than diameter of human hair)

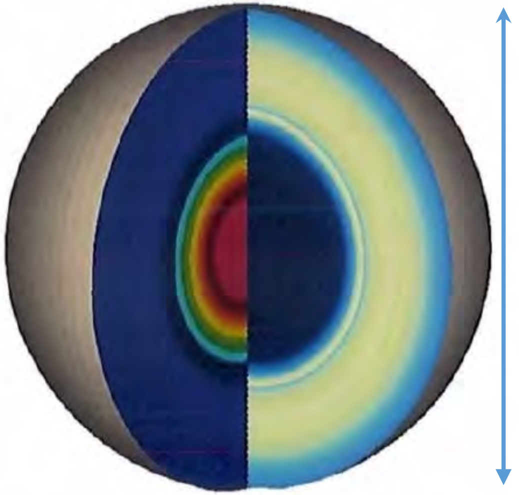
~2 mm initial diameter

Round, symmetric implosion → critical challenge for ICF

Hydrodynamic challenges to indirect drive ICF

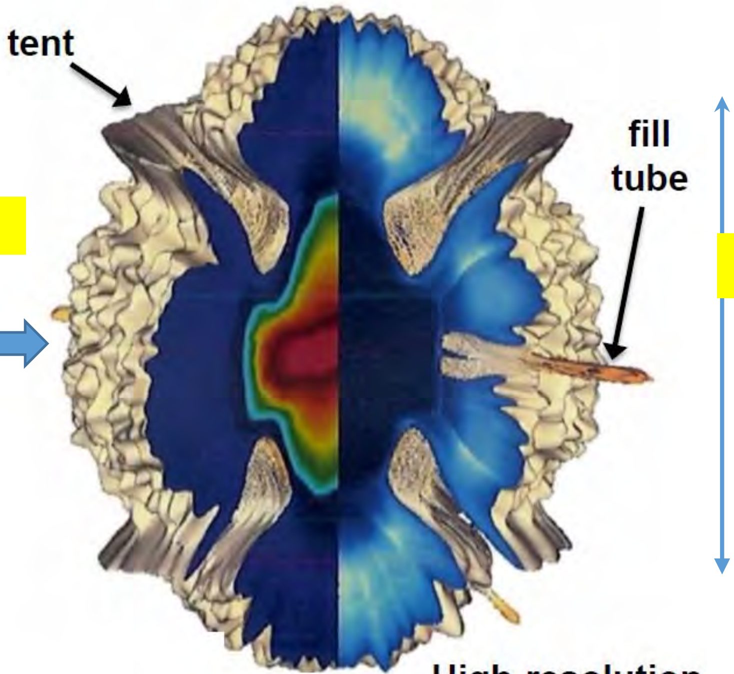


Hohlraum, capsule and tent



Highly efficient, highly symmetric simulated implosion

1D
500 zones
1 CPU
5 minutes runtime



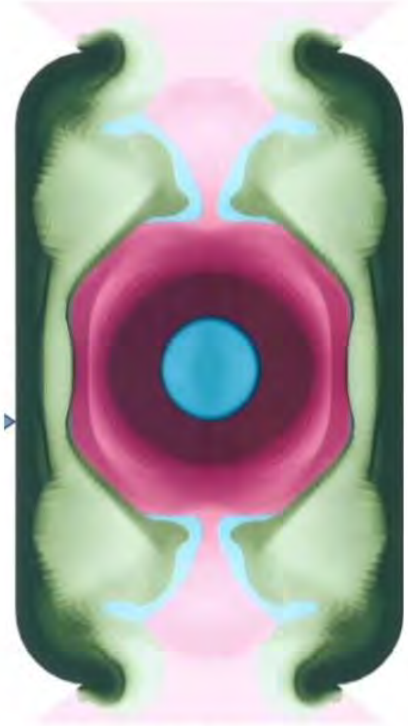
High-resolution postshot simulation of NIC experiment

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

Simulations by C. Weber

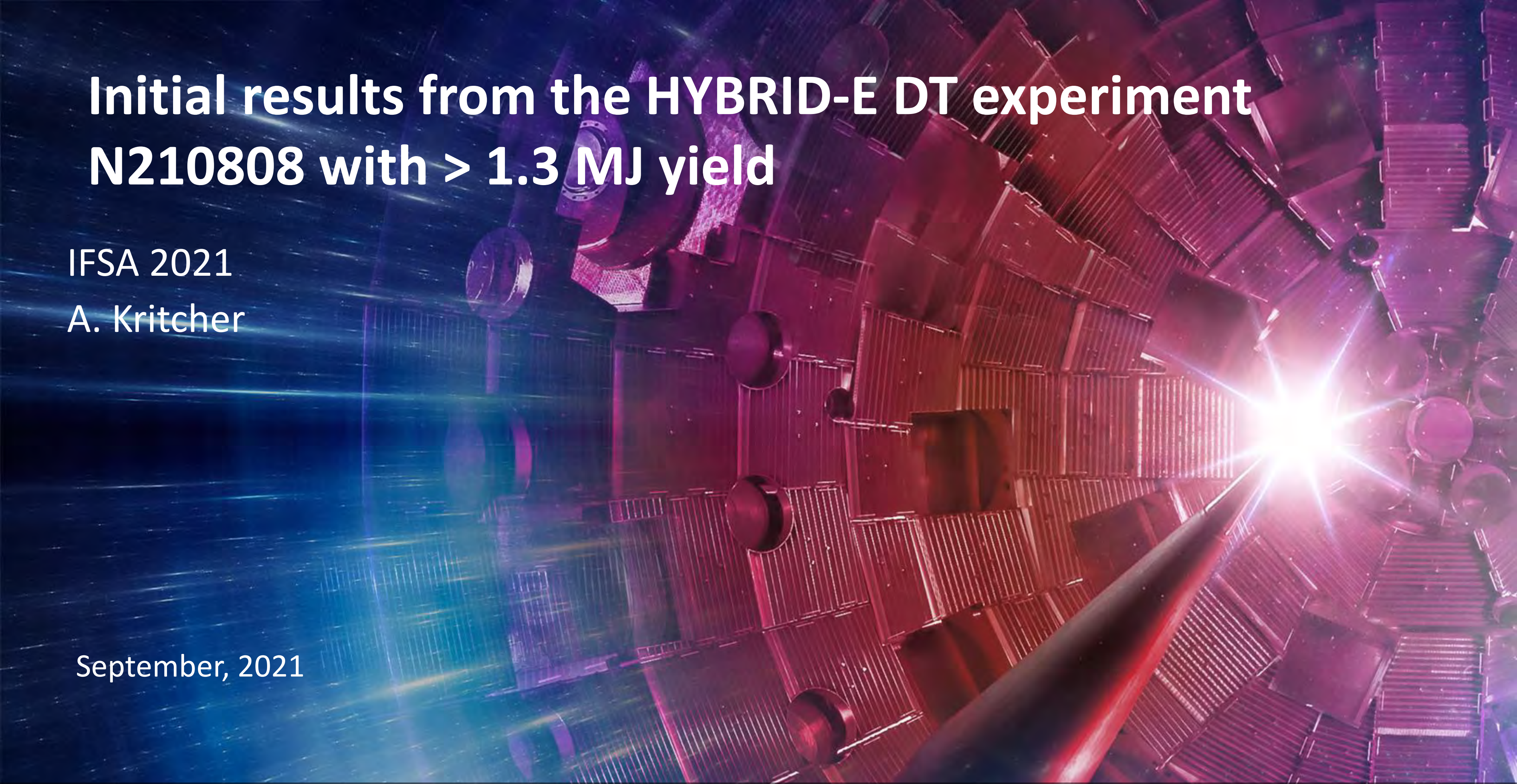
Near-vacuum and low-fill hohlraums offer a path to controllable, low-LPI environment

Helium ρ≥0.96 mg/cm^3



Helium ρ= 0.03 – 0.3 mg/cm^3

- **30-50% more efficient**
- **Minimal cross-beam energy transfer**
- **Symmetry control limited by filling→ need shorter laser pulses**



Initial results from the HYBRID-E DT experiment N210808 with > 1.3 MJ yield

IFSA 2021

A. Kritcher

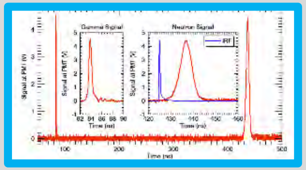
September, 2021

LLNL-PRES-826367

NIF diagnostics have provided key insight into our experiments and built understanding, here are some examples

DT Ion temperature, hot spot velocity, fuel density, yield

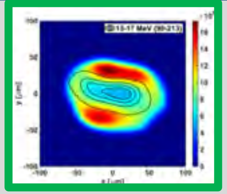
- Five Neutron Time of Flight (nToF)'s and the Magnetic Recoil Spectrometer (MRS)



DT Neutron yield

- Zirconium/Copper Nuclear activation

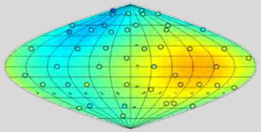
Hot spot and Fuel Shape from Neutron Imagers



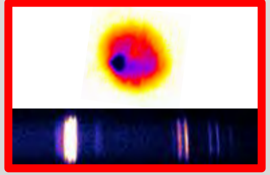
- 3 Neutron Imaging (NIS) Lines of sight for 3D reconstruction of neutron hot-spot
- 2 NIS down-scatter lines of sight for fuel shape

DT Yield Map /Fuel uniformity

- 48 Real-Time Nuclear Activation (NAD)'s read out in real-time 24/7



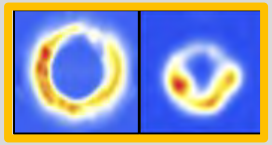
X-ray Imaging & Spectroscopy



- 3 x-ray imaging lines of sight
- X-ray spectroscopy to characterize material mixed into the hotspot

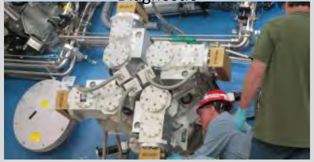
DT Fuel uniformity: Compton Radiography

- ~100keV x-rays produced by Advanced Radiography Source provide radiographs of DT fuel



Gamma Spectroscopy

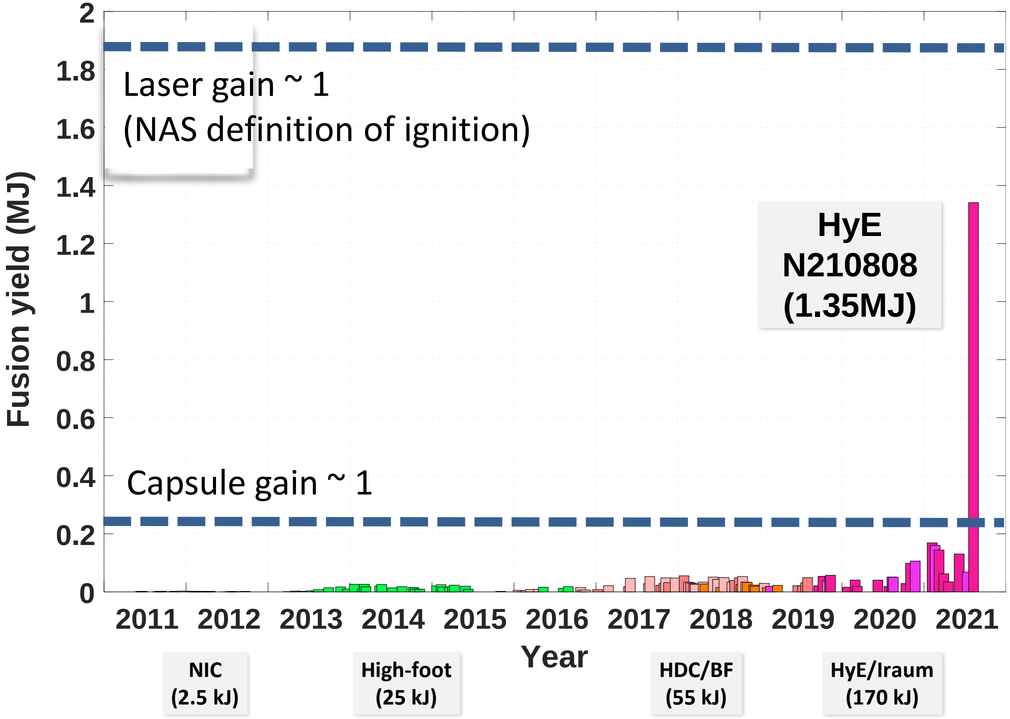
Gamma Reaction History Diagnostic



- Neutron Burn-width, time of peak emission (Bang-time) and DT neutron yield

This is the best diagnosed HED plasma on the planet! -> developed over decades by the whole HED community

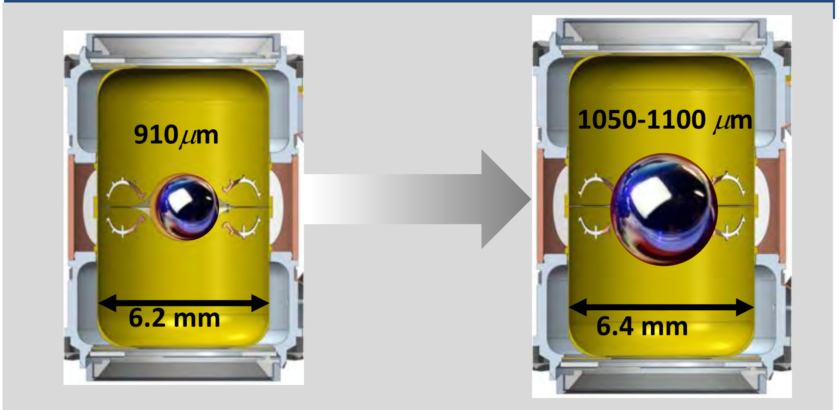
The August 8th shot (N210808) on NIF yielded more than 1.3 MJ and marks a significant advance in ICF research



Capsule gain	> 5
Laser gain	~ 0.7

The Hybrid-E target design that enabled the 1.3 MJ yield, involved increasing the diameter of the capsule which increased the % of x-rays driving the implosion

Much bigger capsule in to slightly larger hohlraum



HDC **(BigFoot)**

Lead designer: L. Berzak Hopkins, C. Thomas
Lead expt: S.Le Pape, D. Casey

HYBRID-E^{2}

Lead designer: A. Kritcher
Lead expt: A. Zylstra

High Yield Big Radius Implosion Design (HYBRID) strategy[1]

- With fixed laser energy higher efficiency hohlraums to maintain velocity
  - Much more difficult for symmetry (long pulse, smaller case to capsule ratio (CCR))
  - Use data-driven models[3] to guide design choices

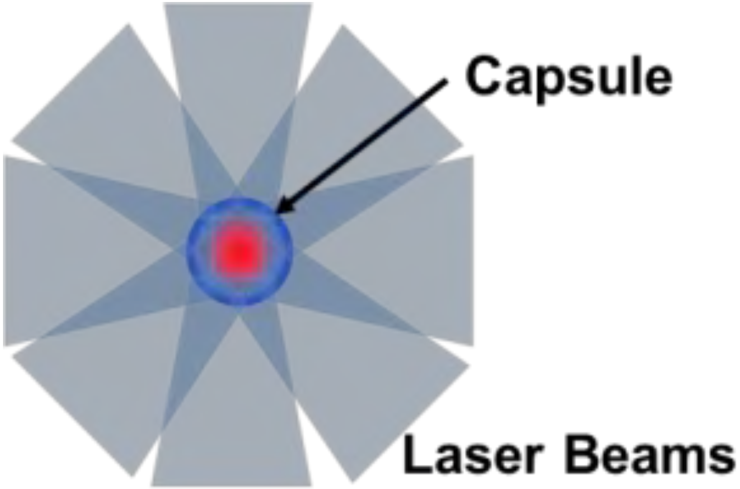
The 1.3 MJ shot shows the basic viability of laser inertial fusion

But even with HYBRID-E only about 12% of the laser energy available to drive the target implosion via x-rays.

1: O. Hurricane et al, APS-DPP, PO7.00001 (2017); PPCF 61, 014033 (2019); PoP 26, 052704 (2019)
2: A.B. Zylstra et al., PRL 126, 025001 (2021); A.L. Kritcher et al., PoP 28, 072706 (2021)
3: D.A. Callahan et al., PoP 25, 056305 (2018); J. Ralph, et al., PoP, 25, 082701 (2018)
4: A. L. Kritcher, et al *Phys. Rev. E* **98**, 053206 (2018) , L. Pickworth, et al, PoP (2020)

Direct laser drive is a much more efficient approach

Direct Laser Drive – laser light directly illuminates the capsule

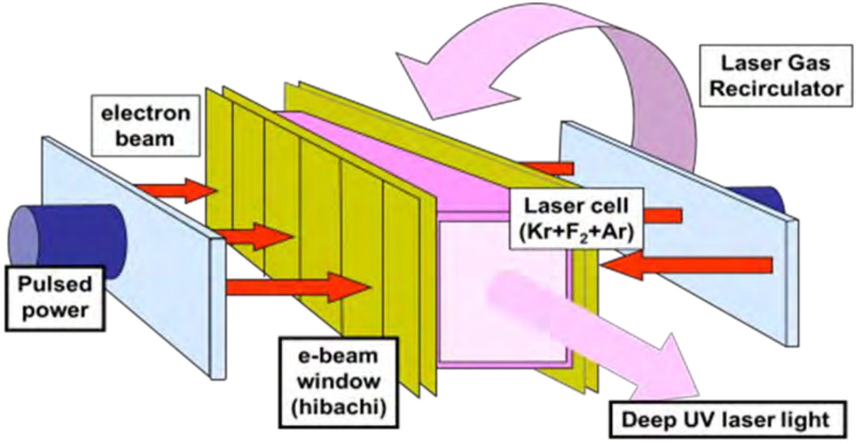


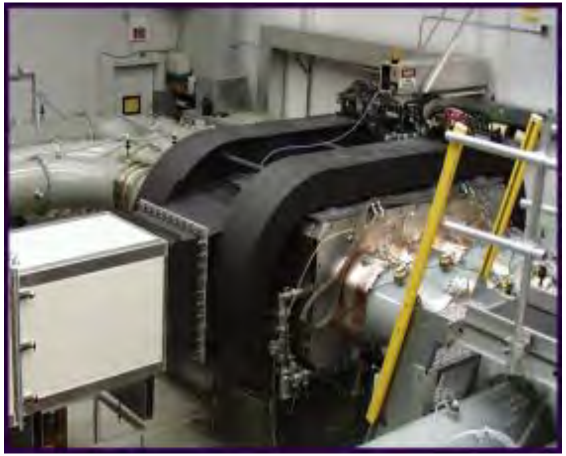
- Much more efficient than indirect drive (>5x)
- Potential to reach the high gains (100) required for the fusion energy application.

- **The election-beam-pumped argon fluoride (ArF) laser provides this best light for this approach**
- Deeper UV light than other ICF lasers provides more efficient drive for implosions
- Multi-THz bandwidth to suppress LPI
- Good wallplug efficiency (10% predicted) for laser fusion energy application

NRL is the world leader in high-energy electron-beam pumped krypton fluoride (KrF) and argon fluoride (ArF) deep UV lasers

NRL PPD

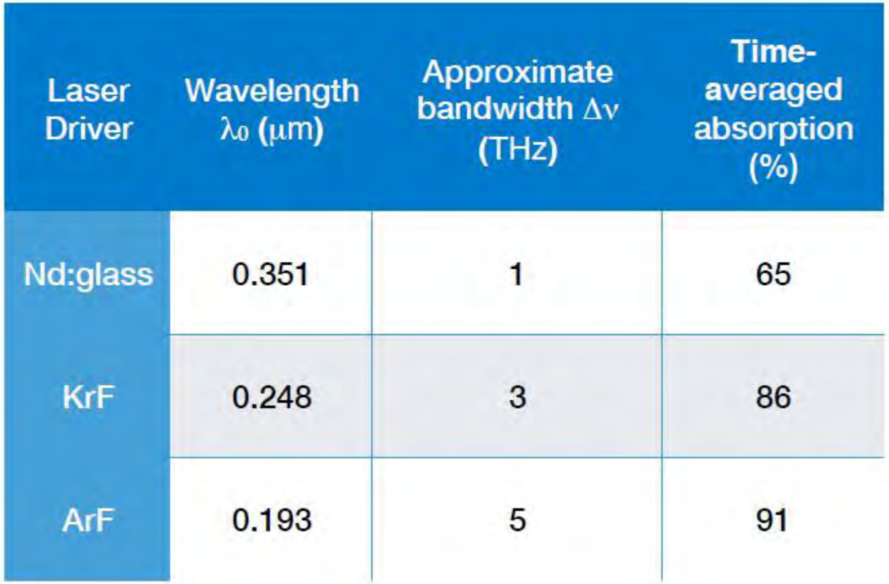




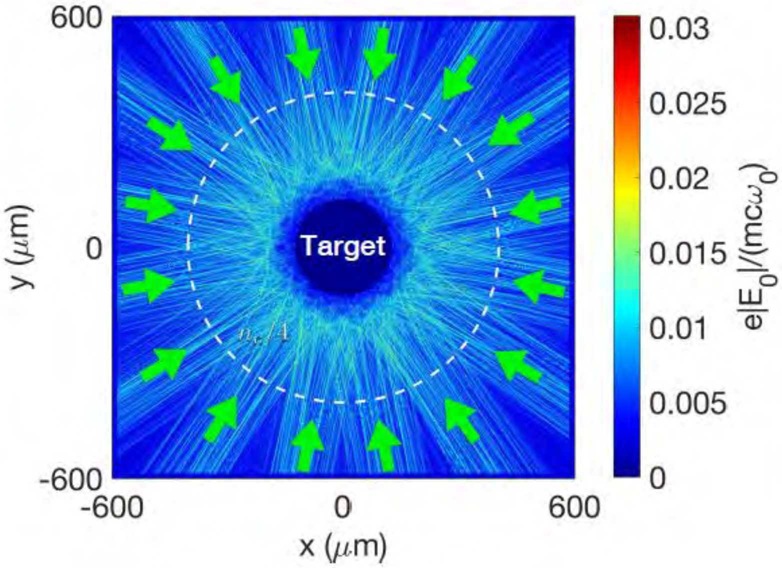
Nike 60-cm aperture KrF amplifier

- Shorter wavelength enables higher drive pressure and more efficient implosions
- Capable of more uniform target illumination than other laser drivers
- Capable of zooming down the focal diameter to follow an imploding target, which further improves the drive efficiency

2D LPSE simulations laser plasma Omega-size target show large increase in absorption with a broad bandwidth ArF driver



Laser Driver	Wavelength λ_0 (μm)	Approximate bandwidth Δν (THz)	Time-averaged absorption (%)
Nd:glass	0.351	1	65
KrF	0.248	3	86
ArF	0.193	5	91

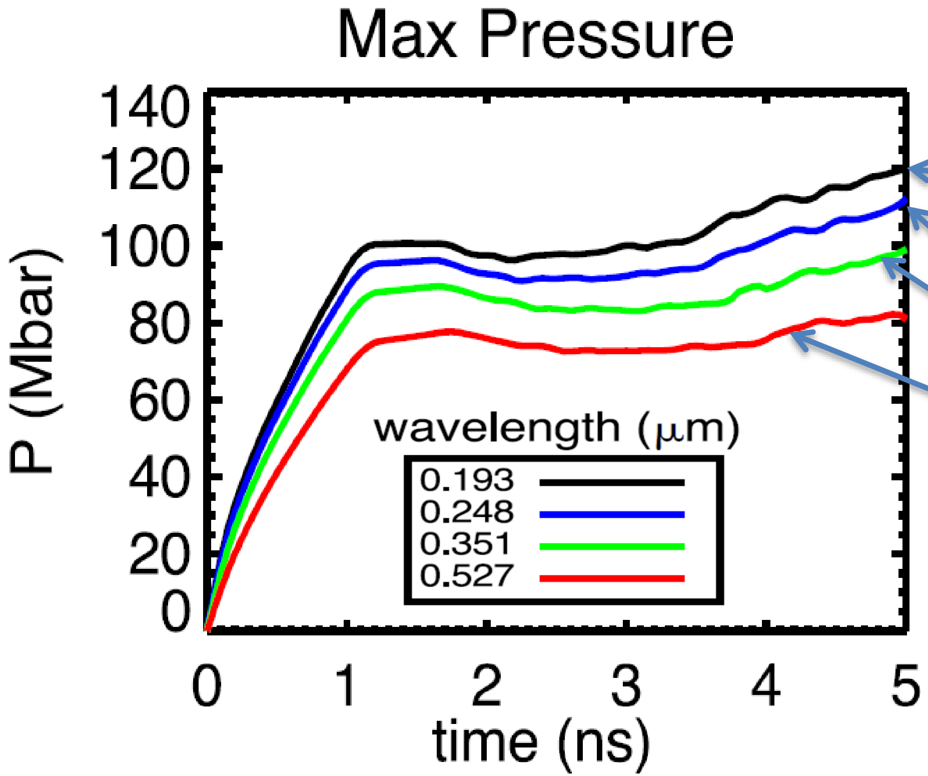


For the CH plasma corona in this example, Te = 3 keV, Ti = 1 keV and Ln = 200 μm
Increased absorption with ArF in this example is primarily due to suppress of CBET

NRL's FASTRAD3D hydrocode simulations shows the expected increase in ablation pressure with decrease in laser wavelength

NRL PPD

5 ns square wave laser pulse incident on 2.6 mm diameter plastic sphere @ 10^{15} W/cm^2 (vacuum intensity)



ArF (193 nm)

KrF (248 nm)

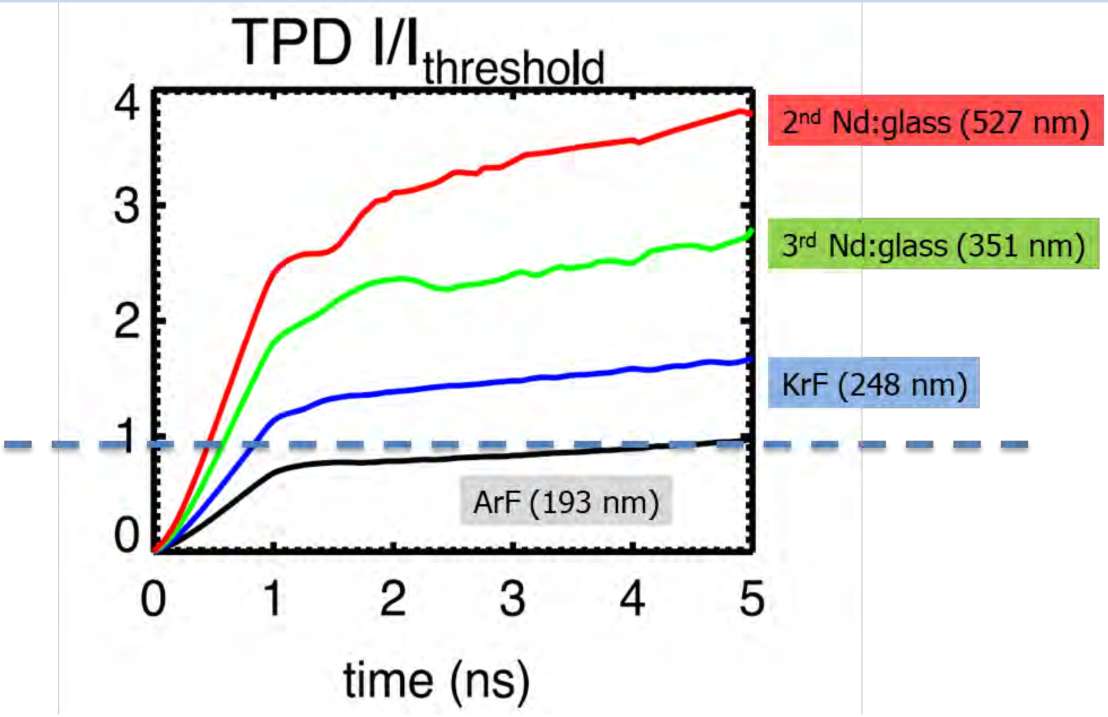
3rd Nd:glass (351 nm)

2nd Nd:glass (527 nm)

Hydrocode simulations show advantages of utilizing short wavelength light towards avoiding two-plasmon decay instability.

NRL PPD

5 ns square wave laser pulse incident on 2.6 mm diameter plastic sphere
@ 10^{15} W/cm^2 (vacuum intensity)

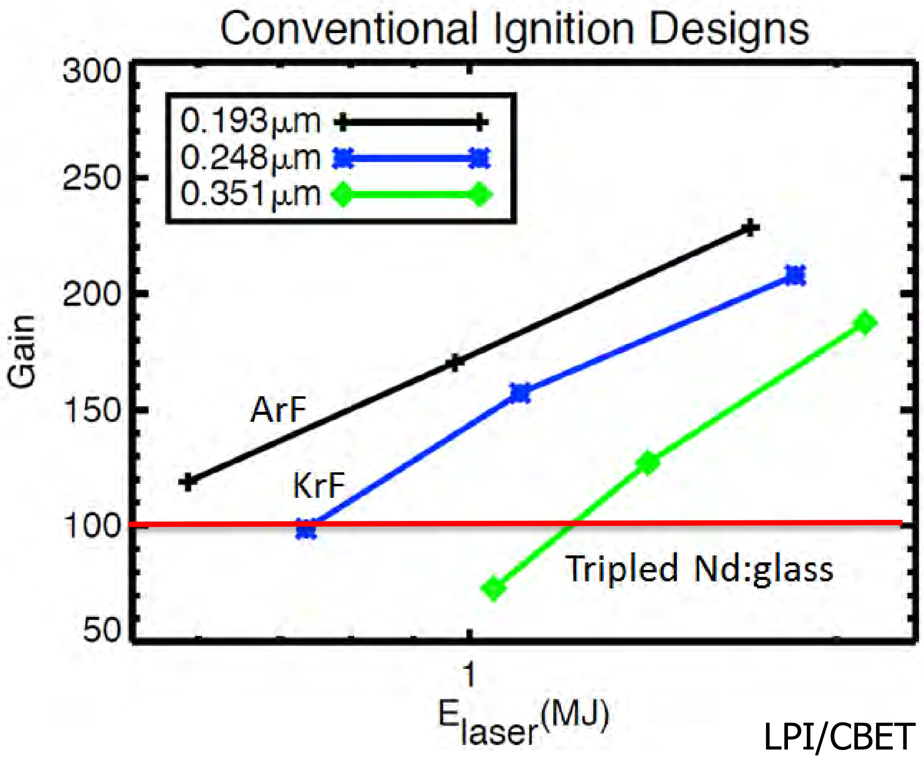


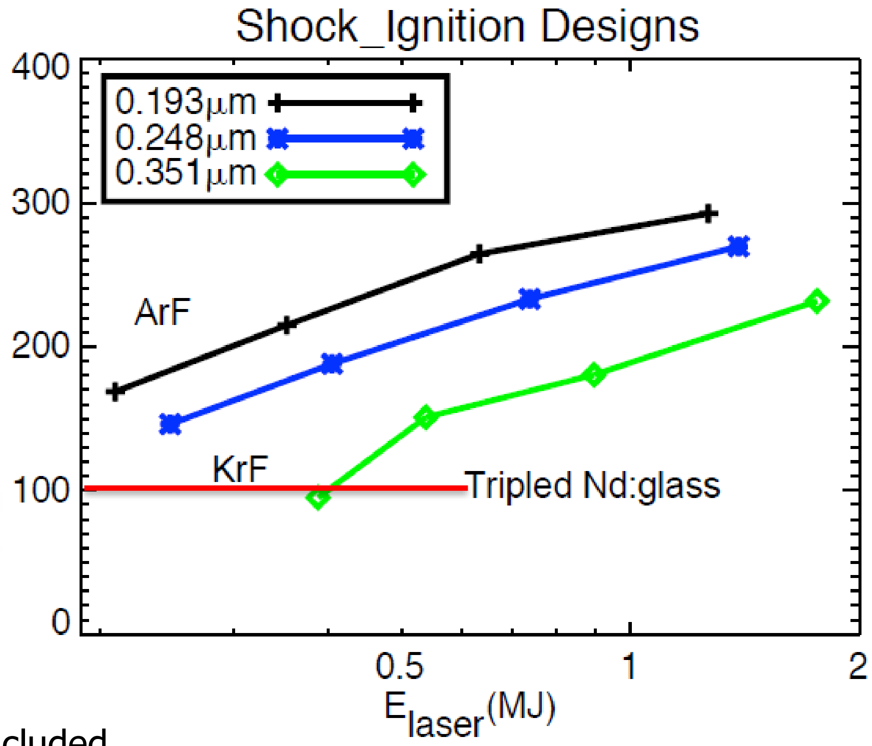
TPD is a laser plasma instability at quarter critical density that produces hot electrons.

I_threshold [10^{15} W/cm^2] = 8.06 * Te[keV] * 1/(laser_wavelength[um]) * 1/Ln [um]
(Simon et al., Phys. Fluids 26, 3107 (1983).)

NRL radiation hydrocode 1-dimensional simulations show that short wavelength enables the high gains required for the energy application (>100) at reduced laser energy

NRL PPD





LPI/CBET not included

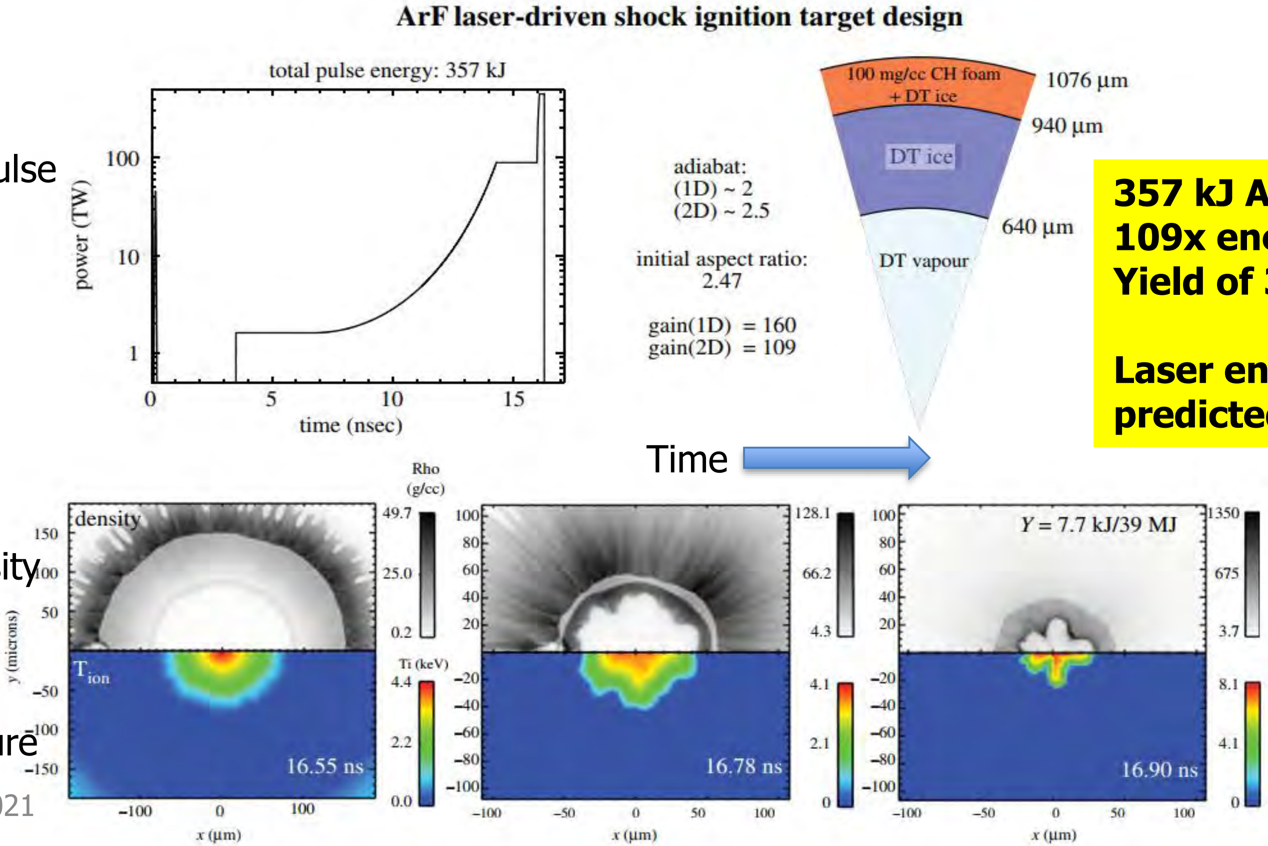
1.R. Betti, C.D. Zhou, K.S. Anderson, L.J. Perkins, W. Theobold, A.A. Solodov, Phys. Rev. Lett. 98 (2007) 155001.
4 *Simulations of high-gain shock-ignited inertial-confinement-fusion implosions using less than 1 MJ of direct KrF-laser energy*, Jason W. Bates, Andrew J. Schmitt , David E. Fyfe , Steve P. Obenschain , Steve T. Zalesak, High Energy Density Physics 6 (2010) 128–134

High-resolution implosion simulations indicate ArF light can enable high gain and yield with laser energy less than that achieved on NIF

NRL PPD

ArF laser-driven shock ignition target design

Laser pulse shape



Time

Mass density

Temperature

357 kJ ArF laser energy
109x energy gain
Yield of 39 MJ

Laser energies near 1MJ are predicted to give >100 MJ yields

Implosion simulation

Shows effects of target and laser illumination defects

See reference #1

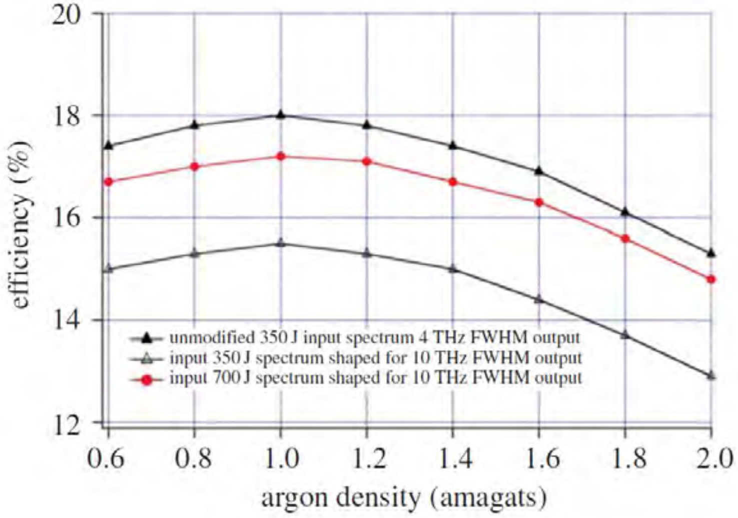
kinetic simulations of a 30 kJ ArF amplifier show high intrinsic efficiency (>16%) over a broad operating regime with bandwidths of 4 and 10 THz

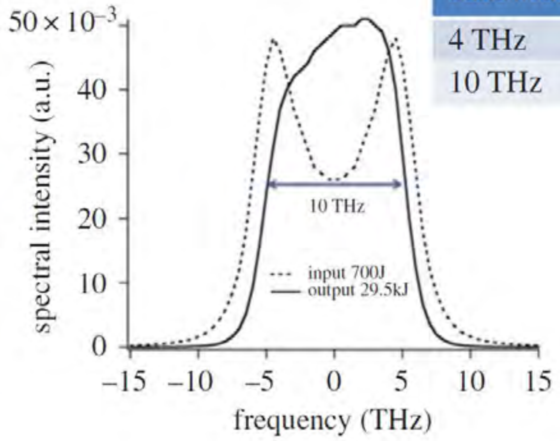
Intrinsic efficiency = laser power out/ E-beam pump power
With 16% intrinsic efficiency we project 10% wallplug efficiency

ArF laser kinetic simulations

- 60 cm × 60 cm aperture
- 200 cm gain length
- e-beam pumped at 1 MW cm^{-3}

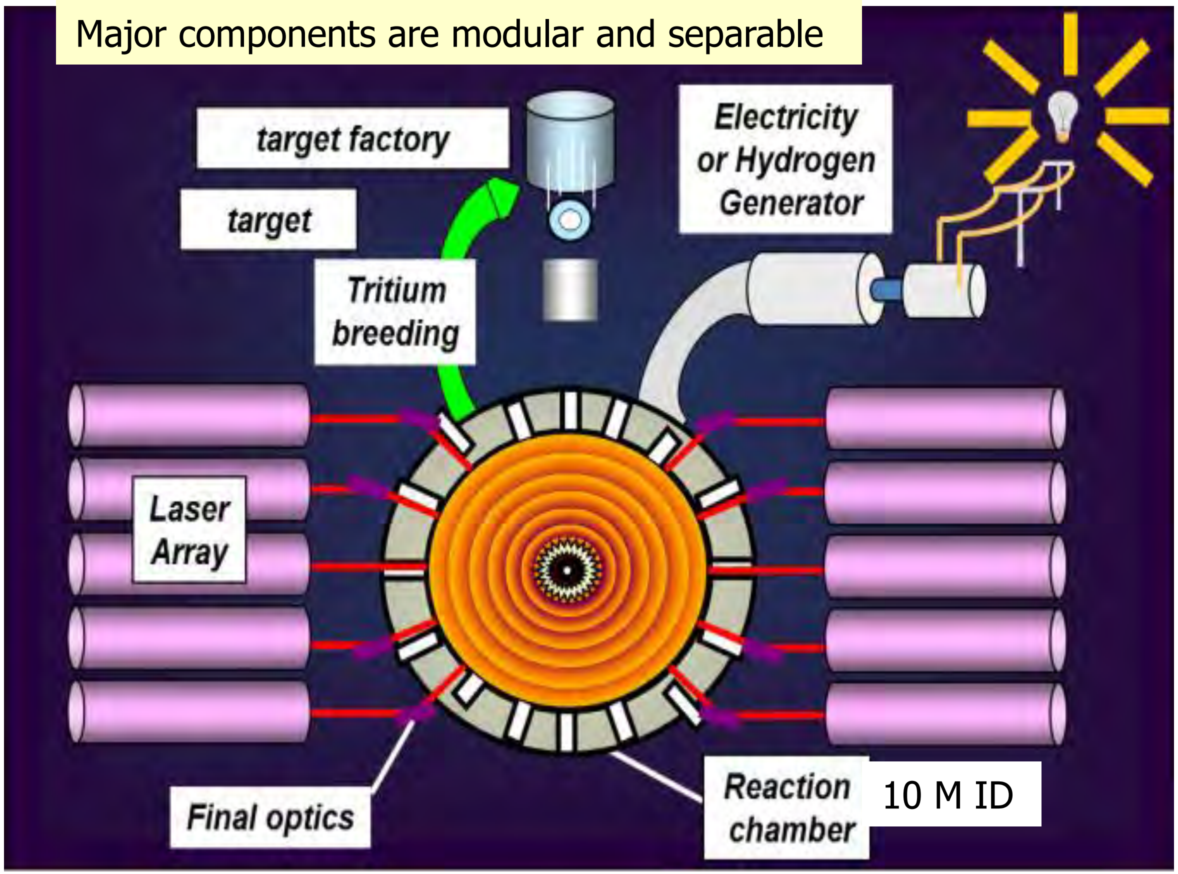
bandwidth	input	output
4 THz	350-J	31-kJ
10 THz	700-J	29.5-kJ





We expect 10% net electrical efficiency with a large ArF laser system

Energy application requires high target performance and operation at 5 to 10 pulses per second vs few shots per day on NIF



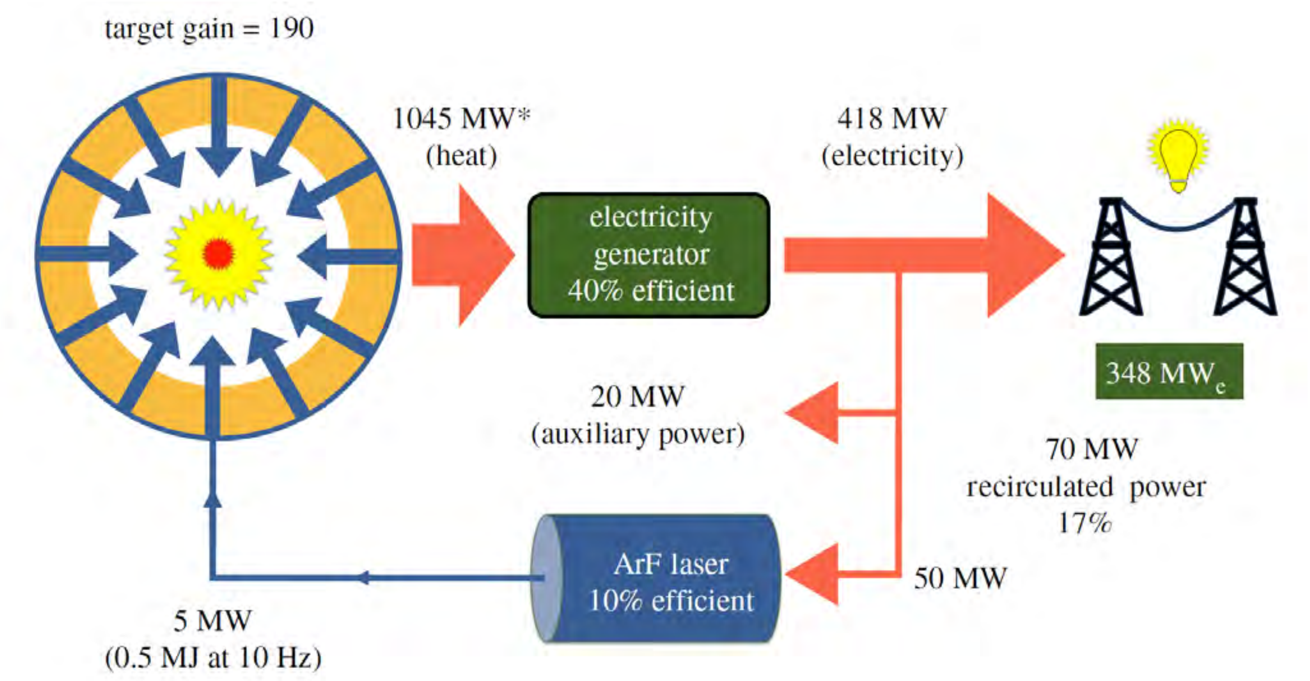
Major components are modular and separable

- Pellets containing frozen or liquid DT fuel are injected and engaged by multiple laser beams.
- Neutrons heat a fluid containing lithium in the walls
- Heat is used for conventional electric power generation.
- Neutrons produce more tritium from the lithium.

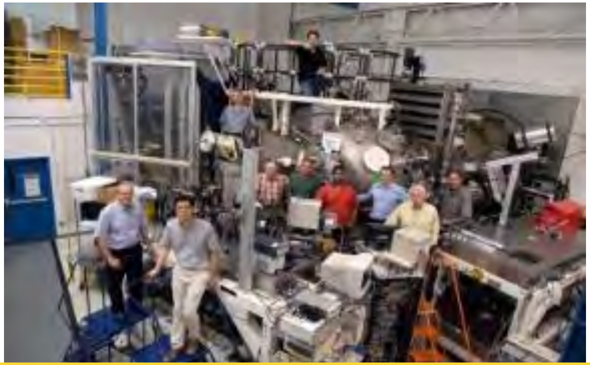
See reference #7

Use of ArF's broad bandwidth 193 nm light could enable construction of smaller lower cost IFE power plants with laser energy well below 1 MJ

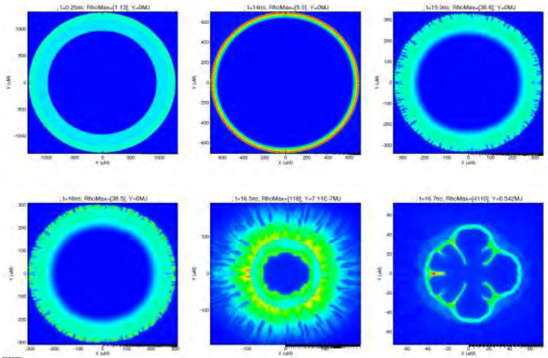
Power flow with 500 kJ 10% efficient ArF driver and 190 gain shock ignited target



The NRL laser fusion program has a broad portfolio of experimental, laser development & simulation research efforts.

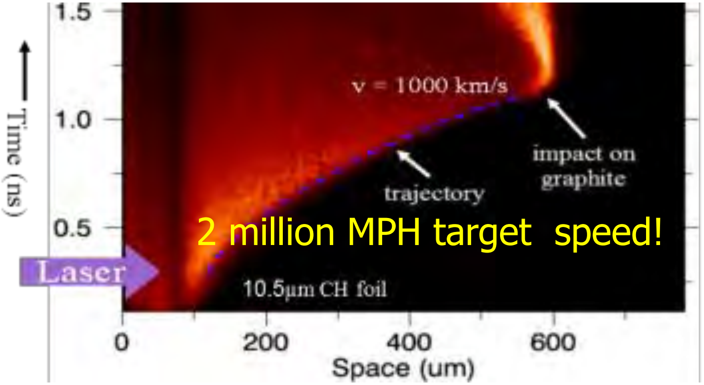


Laser target interaction experiments Nike KrF laser facility

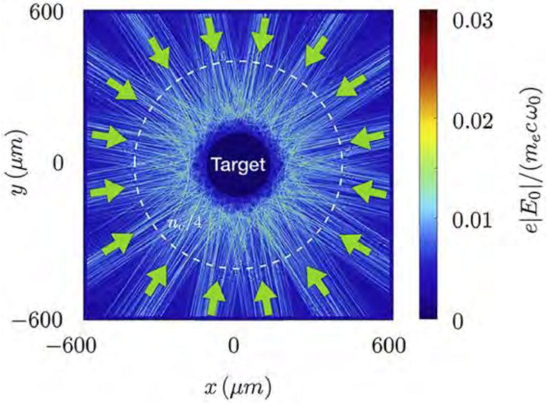


Simulation of a pellet implosion and of a laser-plasma instability

Nike 56 laser beam optics



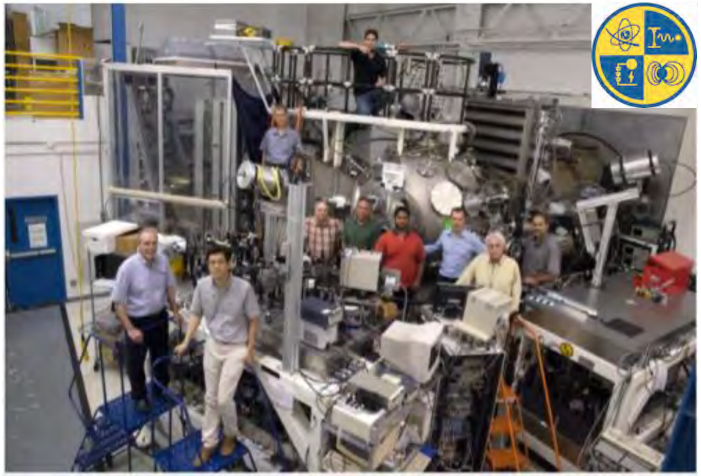
2 million MPH target speed!



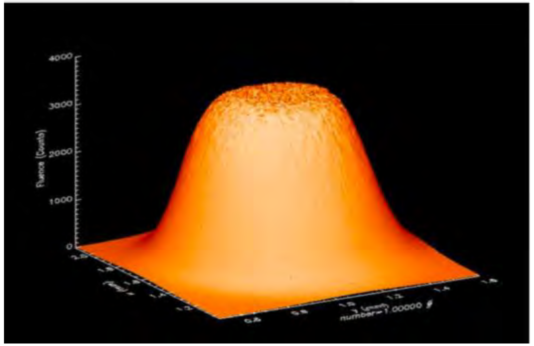
Electra Argon Fluoride laser

The NRL Nike KrF laser facility is used for basic hydrodynamic and laser-plasma interaction experiments in planar geometry

U.S. NAVAL RESEARCH LABORATORY

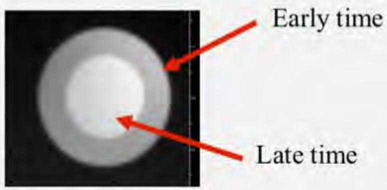


Nike parameters:
- Deep UV wavelength (248nm)
- 44 main beams for laser target interaction
- 12 "backlighter" beams
- 2-3 kJ on target long pulse (4ns)
- 1 kJ on target short pulse (300ps)
- ISI beam smoothing with up to 3 THz bandwidth



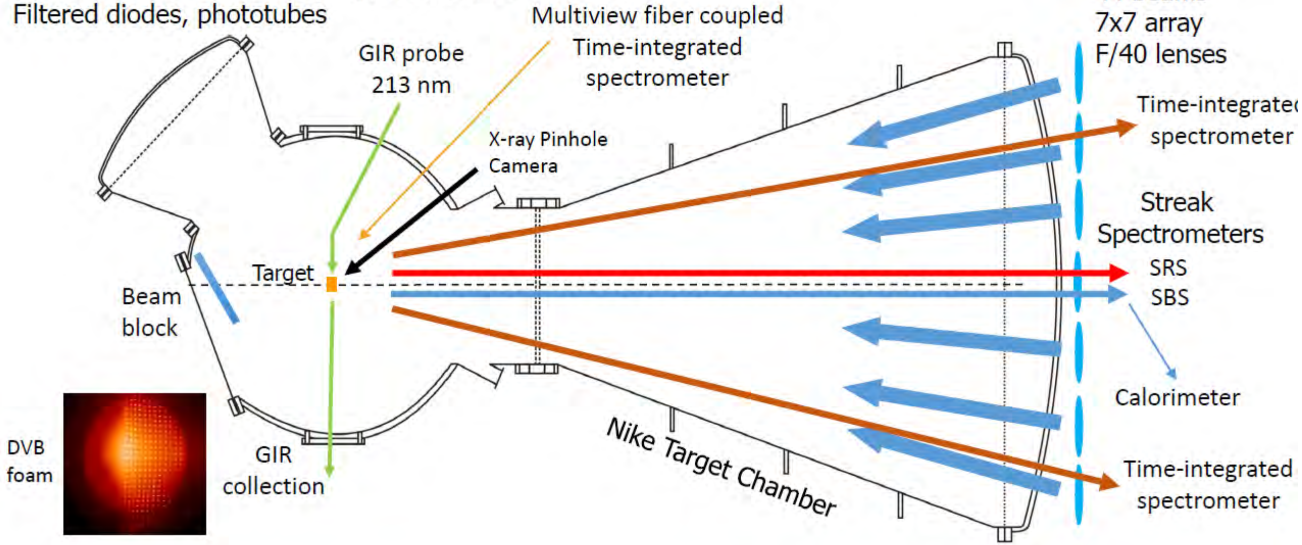
Focal diameter can be changed during the pulse

Nike zoomed focus:



Nike target chamber

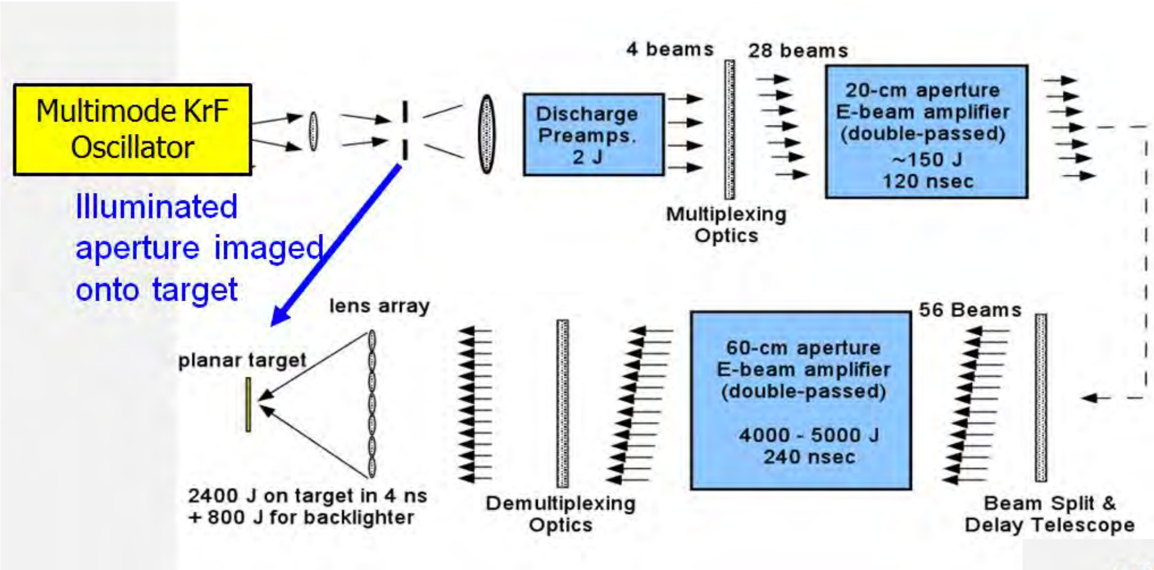
- Front end and beam 38 prop. bay spectrometer
- Beam 4 and beam 38 profile diagnostics
- 248 nm & broad half-omega spectrometers
- Filtered diodes, phototubes



GIR is a key diagnostic –information on target conditions are essential

7

Excimer angularly multiplexed laser optical systems provide high target illumination uniformity and easy implementation of focal zooming



Multimode KrF Oscillator

4 beams

Discharge Preamps. 2 J

28 beams

Multiplexing Optics

20-cm aperture E-beam amplifier (double-passed) ~150 J 120 nsec

Illuminated aperture imaged onto target

lens array

planar target

2400 J on target in 4 ns + 800 J for backlighter

Demultiplexing Optics

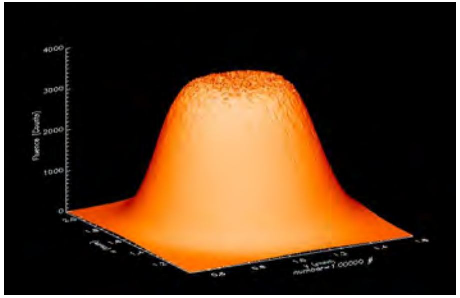
60-cm aperture E-beam amplifier (double-passed) 4000 - 5000 J 240 nsec

56 Beams

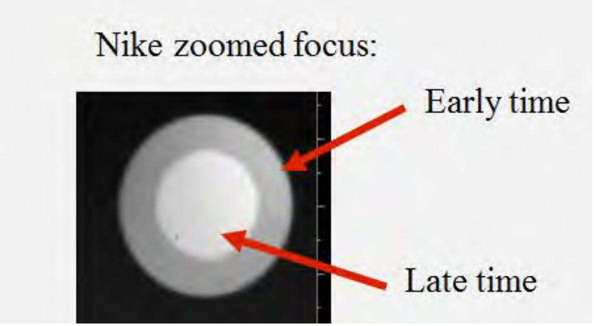
Beam Split & Delay Telescope

Nike KrF optical system with ISI smoothing

An ArF system would be similar

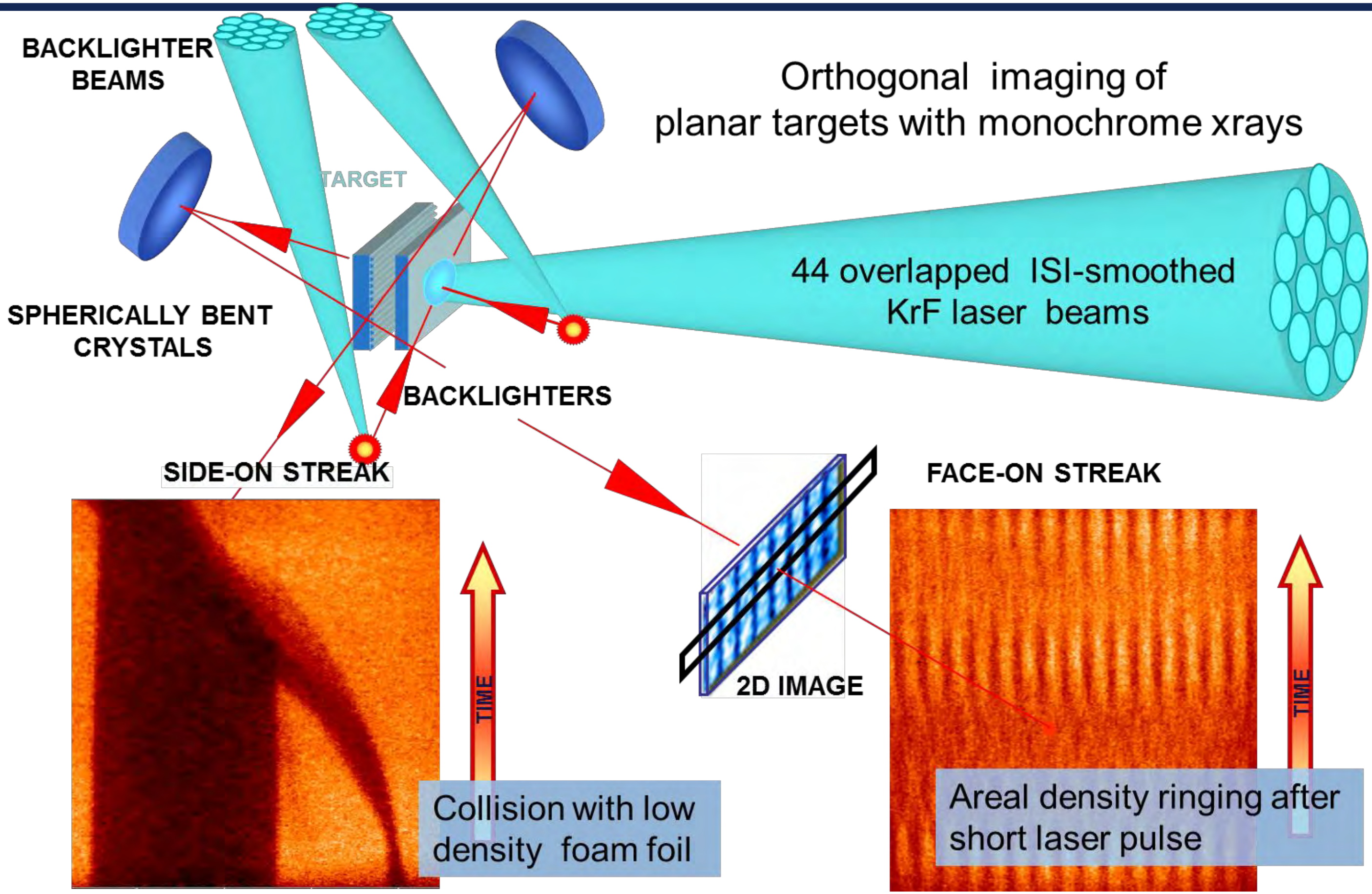


Time averaged laser spatial profile in target chamber



Nike zoomed focus:

X-ray backlighting and sidelighting are employed to measure the motion and growth of hydrodynamic instability for laser accelerated targets



Orthogonal imaging of planar targets with monochrome xrays

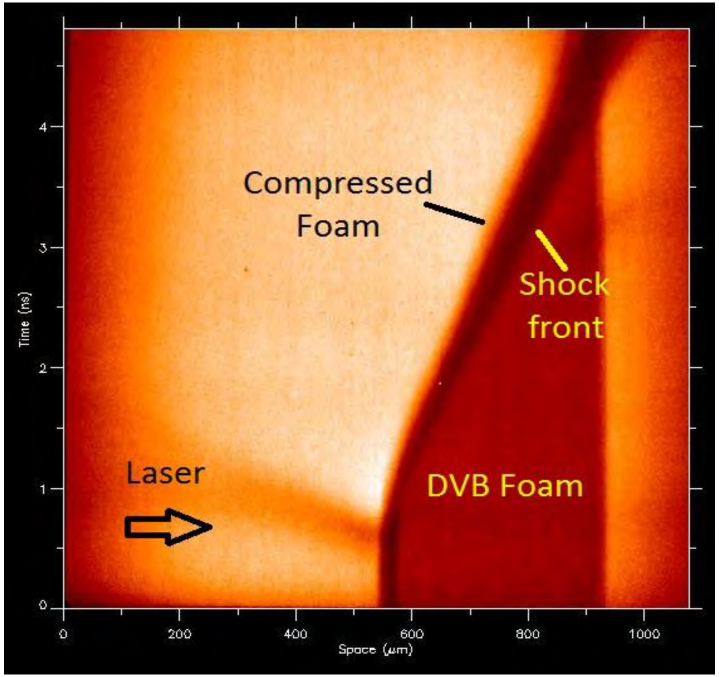
44 overlapped ISI-smoothed KrF laser beams

Collision with low density foam foil

Areal density ringing after short laser pulse

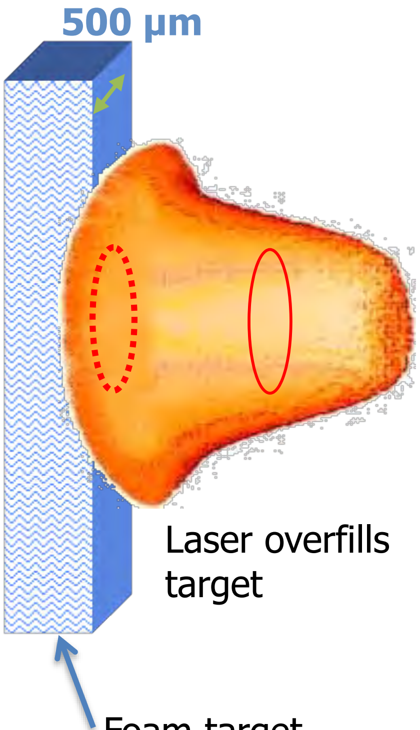
Advancing the basic physics of multi-megabar shock propagation in low density foam targets on Nike

Foams are complex materials that will not behave exactly as uniformly distributed matter



Near monochrome x-ray side-lighting @ 1.8 KeV

Yefim Aglitskiy



500 µm

Laser overfills target

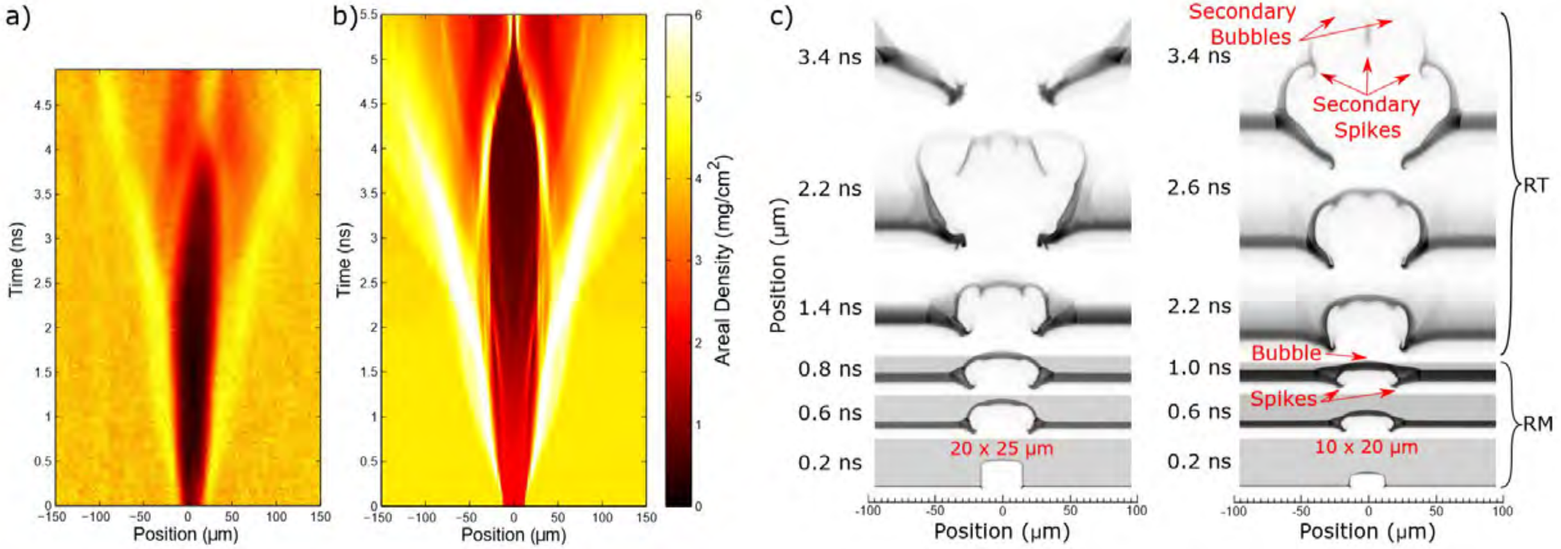
Foam target

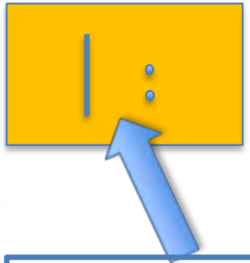
Nike experiment studding the hydrodynamics effects of isolated defects on laser accelerated targets which are compared with simulations

NRL PPD

(a) Experiment from x-ray streak and (b) simulation of growth of areal density perturbations seeded by 20 μm x 25 μm groove

NRL FASTRAD 2D simulation of growth of two groove perturbations through RM and RT phases



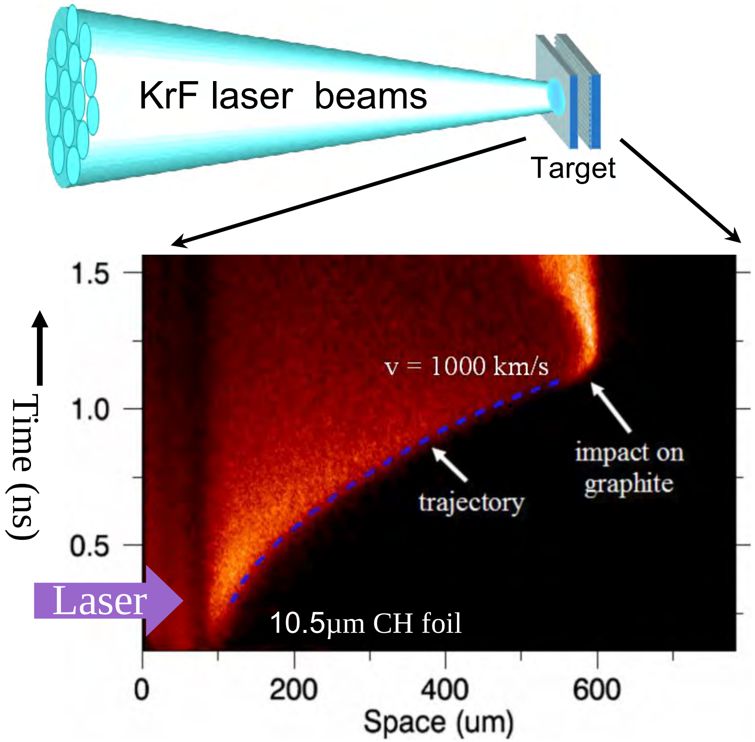


Laser incident on plastic targets with machined holes and grooves

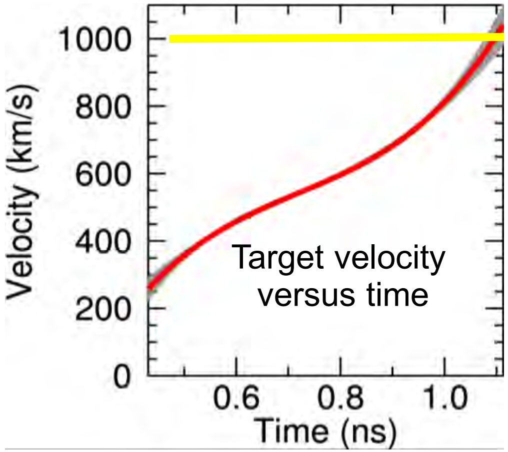
From Fig. 1 of "Multi-mode hydrodynamic instability growth of pre-imposed isolated defects in ablatively driven foils," C. Zulick et al., Phys. Rev. Lett. **125**, 055001 – Published 28 July 2020

Nike KrF laser accelerates targets to greater than 1000 km/sec

(0 to 2.2 million miles per hour in a billionth of a second!)



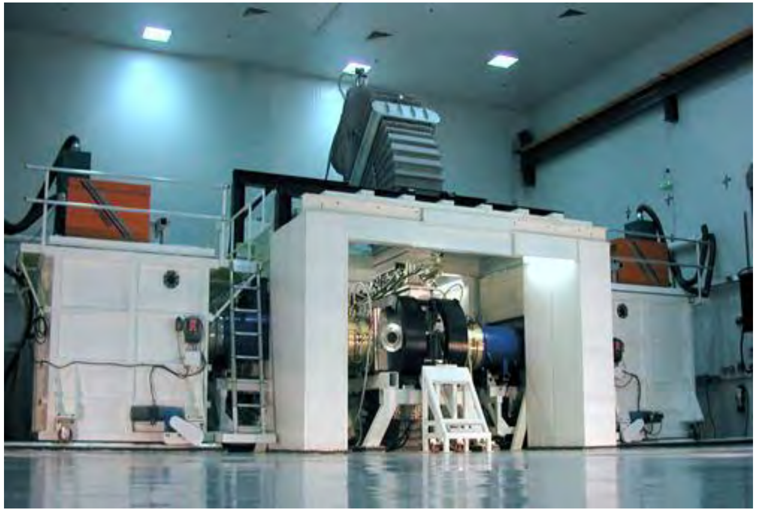
Joint experiment with Institute of Laser Engineering, Osaka University



- Previous record of 700 km/s achieved on Gekko XII/HIPER glass (351nm) laser at Osaka
- Made possible by the high uniformity and high ablation pressure generated by the KrF laser

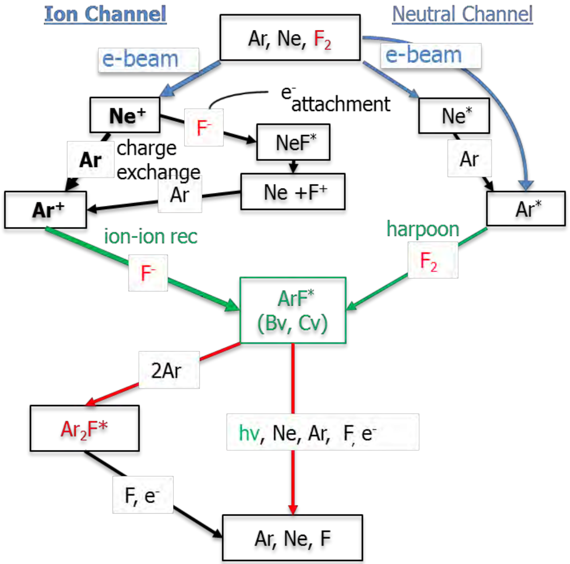
NRL 6.1 and DoE ARPA-E and Office of Fusion Energy Science support advancing high-energy ArF development

Parametric experimental studies on Electra



Modify & validate NRL Orestes laser kinetics model for ArF

ArF theory and simulations



Ion Channel

Neutral Channel

Ar, Ne, F_2

e-beam

e-beam

e^- attachment

Ne^+

F^-

NeF^*

Ne^*

Ar

charge exchange

Ar

Ar

$Ne + F^+$

Ar^+

Ar^*

ion-ion rec

harpoon

F^-

F_2

ArF^* (Bv, Cv)

2Ar

Ar_2F^*

hv, Ne, Ar, F, e^-

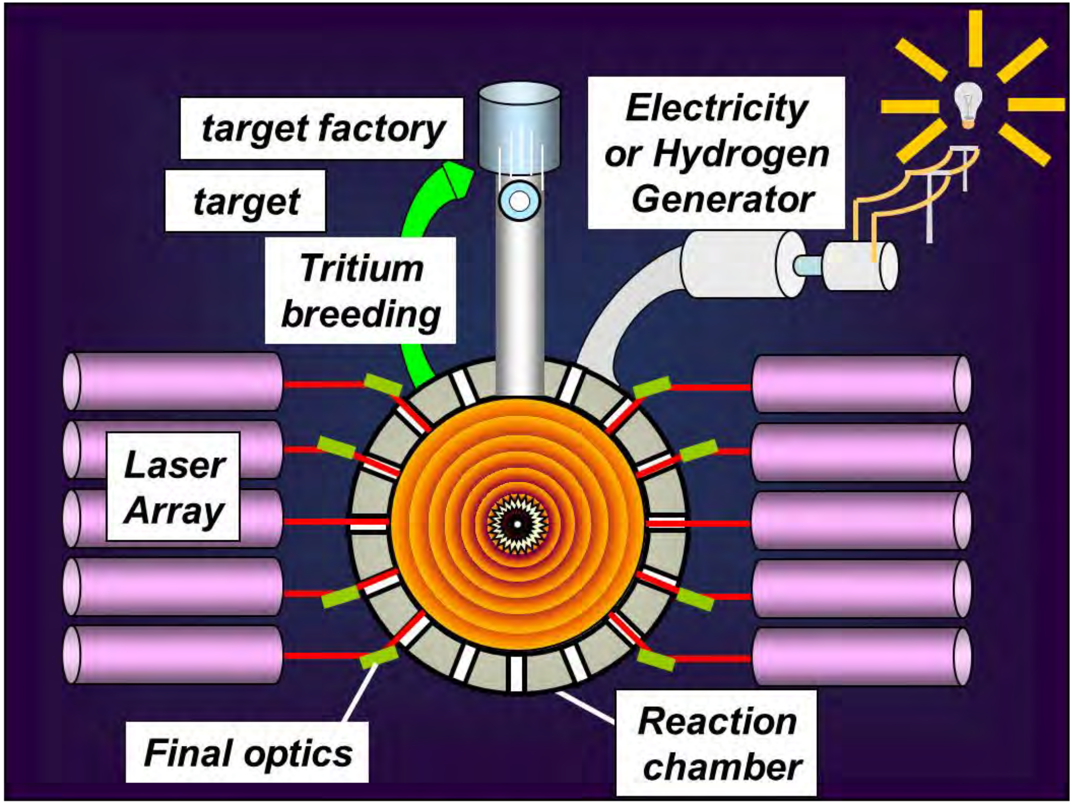
F, e^-

Ar, Ne, F

Notes

- 200 J obtained in oscillator mode (vs 96 J previous ArF record)
- Measuring gain, saturation flux and intrinsic efficiency & compare with simulations
- ArF lithographic industry has developed durable 193 nm optics – need to be scaled up in size for ICF

The high average power laser (HAPL) program managed by NRL advanced the broad range of technologies needed for a power plant.



John Sethian,
Naval Research Laboratory

EPRI Fusion Assessment Workshop
Palo Alto, CA, July 20, 2011

The High Average Power Laser (HAPL) Program:
Integrated program to develop the science and technologies for Fusion Energy with Laser Direct Drive (1999-2008)

16th HAPL meeting
Dec 4 & 5, 2006
Princeton Plasma Physics Lab

Government Labs
1. NRL
2. LLNL
3. SNL
4. LANL
5. ORNL
6. PPPL
7. SRNL
8. INEL

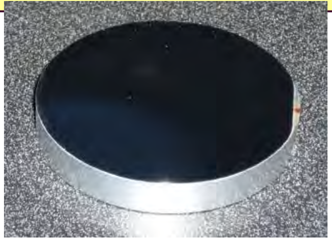
Universities
1. UCSD
2. Wisconsin
3. Georgia Tech
4. UCLA
5. U Rochester, LLE
6. UC Santa Barbara
7. UC Berkeley
8. UNC
9. Penn State Electro-optics

Industry
1. General Atomics
2. L3/PSD
3. Schafer Corp
4. SAIC
5. Commonwealth Tech
6. Coherent
7. Onyx
8. DEI
9. Voss Scientific
10. Northrup
11. Ultramet, Inc
12. Plasma Processes, Inc
13. PLEX Corporation
14. FTF Corporation
15. Research Scientific Inst
16. Optiswitch Technology
17. ESLI

HAPL generated, and in many cases, "bench tested" solutions for most key components (see http://qedfusion.org/HAPL/MEETINGS/0804HAPL/program.html)

Neutron resistant final optics:

High Laser Damage Threshold
Grazing Incidence Metal Mirror



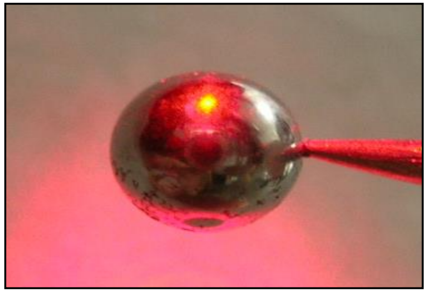
10 M shots at
3.5 J/cm^2
(not a limit!)

Low cost target fabrication:

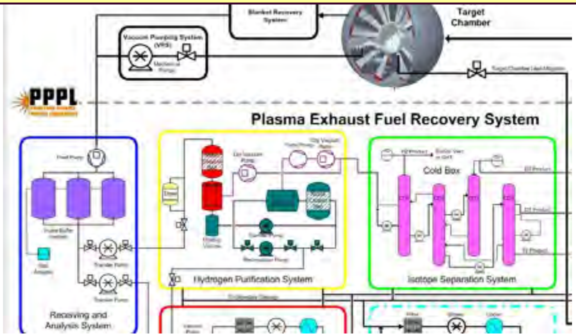
Estimated target cost $0.16 each

Injected target engagement:

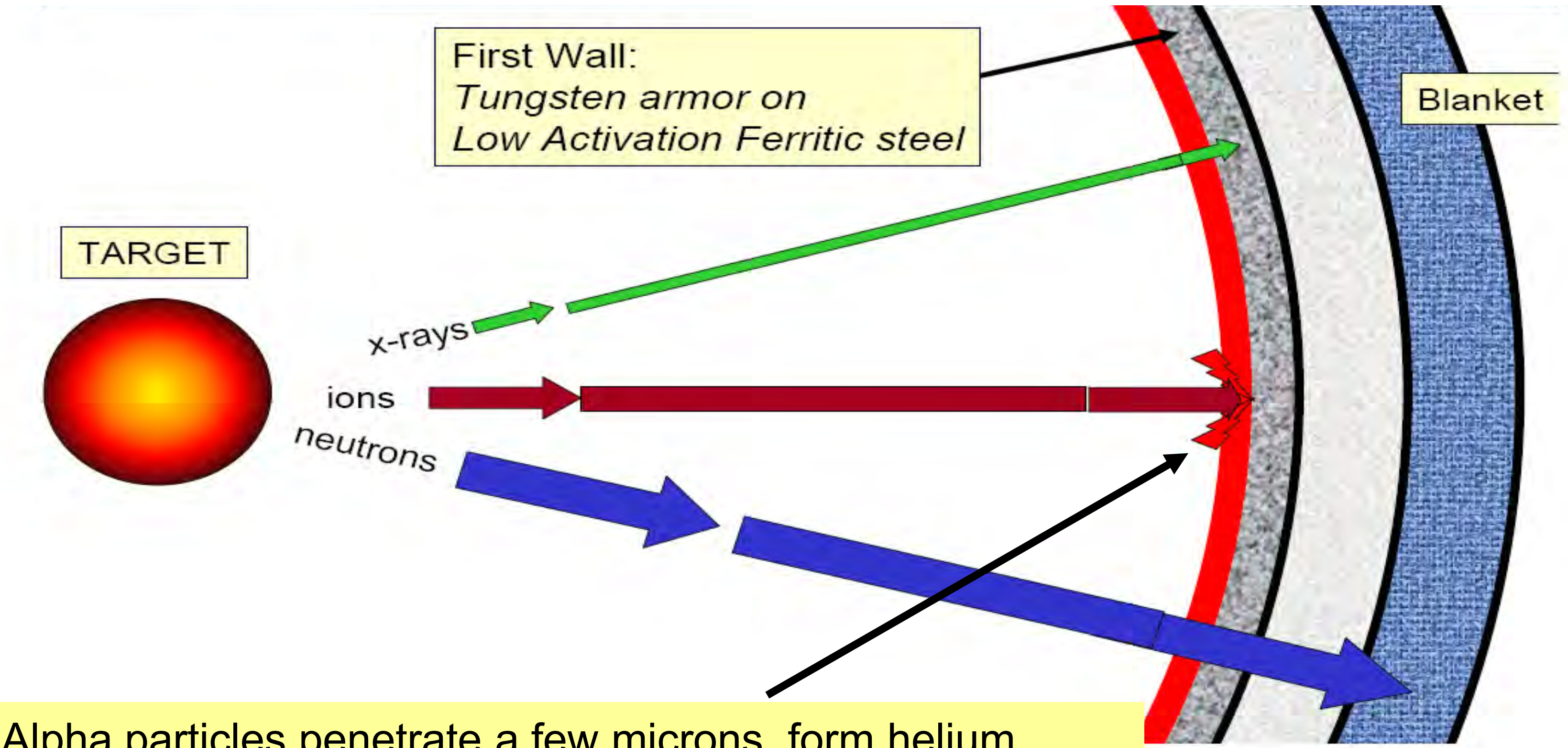
Glint system: accuracy 28 microns



Tritium handling and recovery



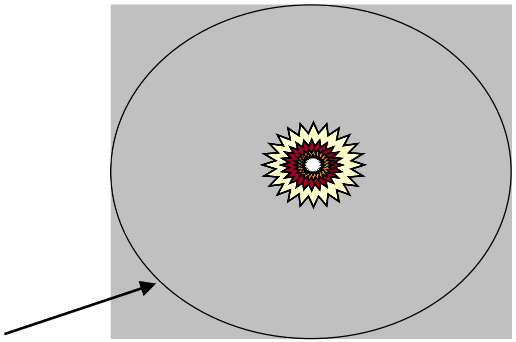
The first wall of an IFE reactor must survive the "threat" spectrum from a the target

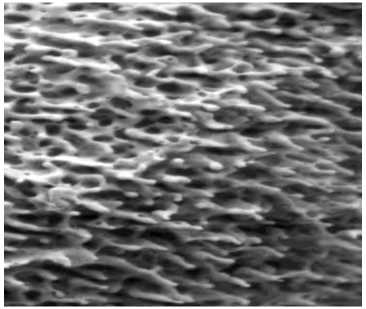


Alpha particles penetrate a few microns, form helium bubbles, and can cause the first wall surface to exfoliate

Chamber concepts to prevent damage from alphas (pressure from helium bubbles exfoliates surface)

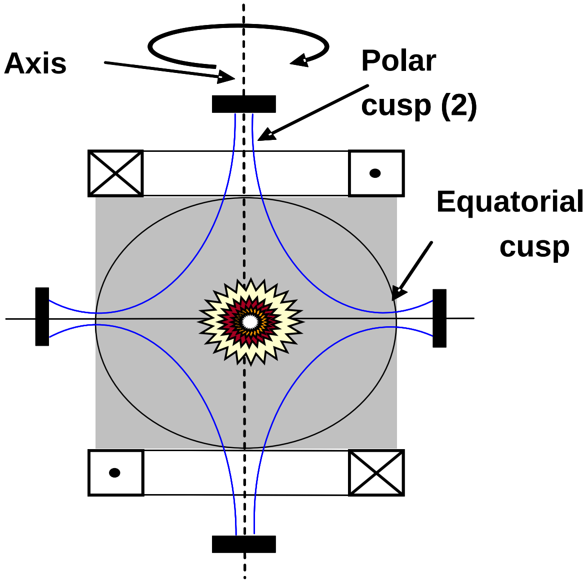
Engineered first Wall





Tungsten “foam” with cell size small enough for helium to escape

Magnetic Intervention



Magnetic cusp field directs alphas away from the 1st wall and out of the reaction chamber

The Vision…A plentiful, safe, low-carbon energy source

Fig. by John Sethian

A 100 ton (4200 Cu ft) ***COAL*** hopper runs a 1 GWe Power Plant for ***10 min***

Same hopper filled with ***IFE targets***: runs a 1 GWe Power Plant for ***7 years***

References

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