Addressing Challenges to Development of Laser Fusion Energy

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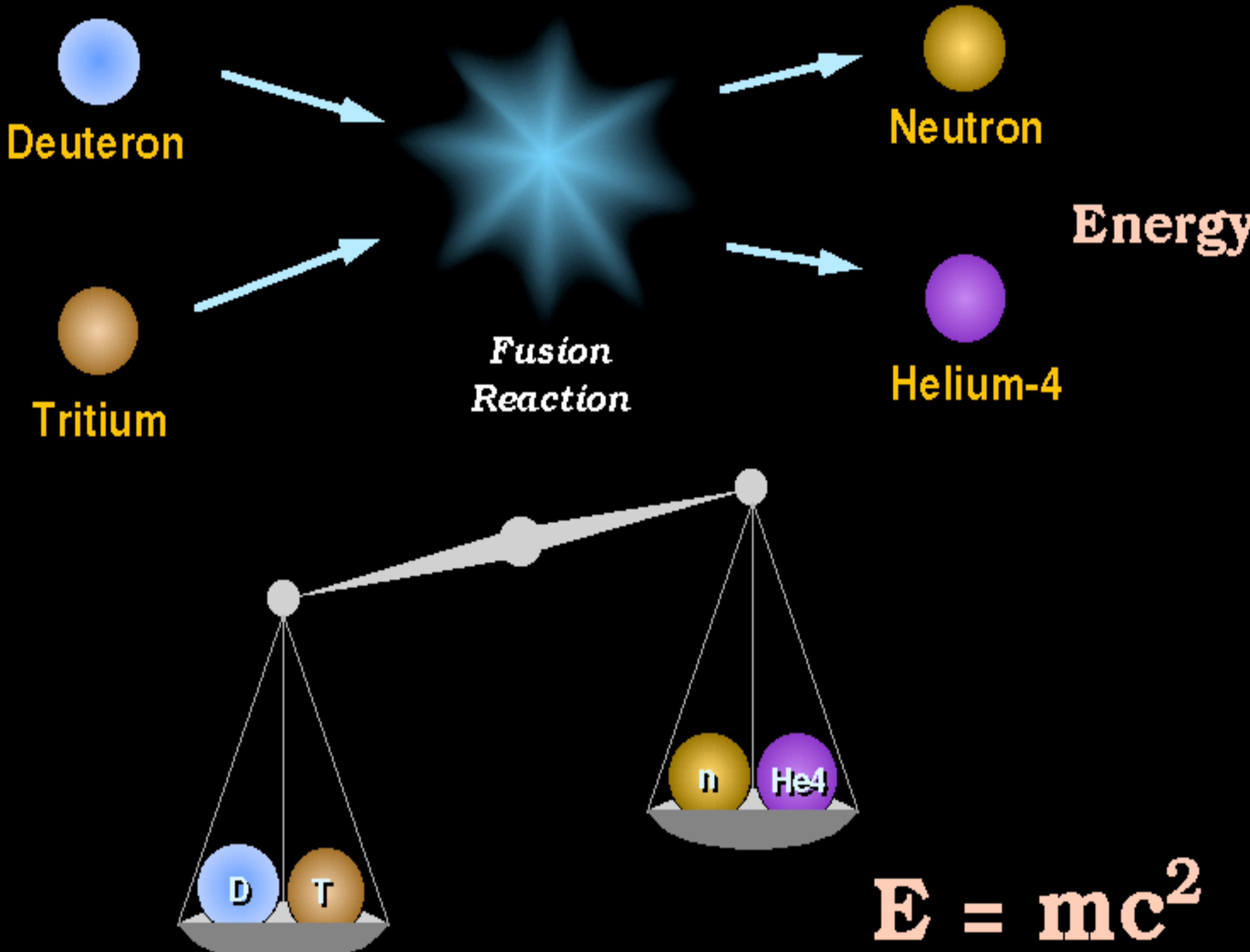
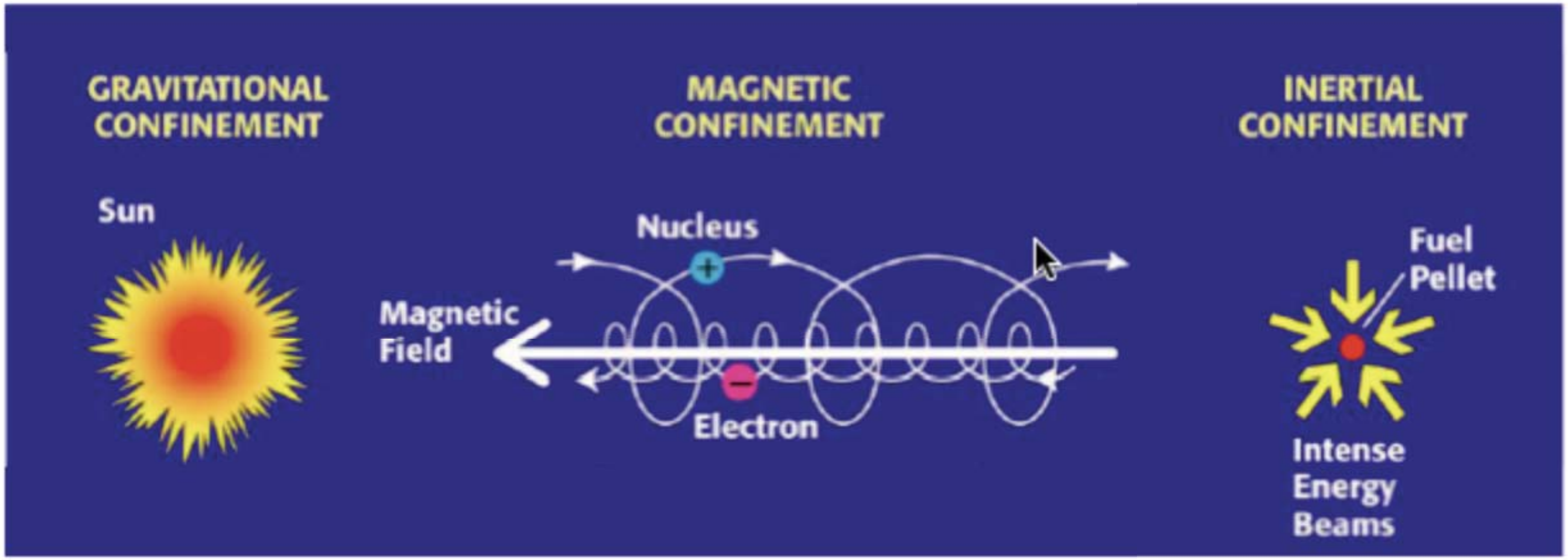

Deuteron
Tritium
Fusion
Reaction
Neutron
Energy
Helium-4
D
T
n
He4
E = mc2

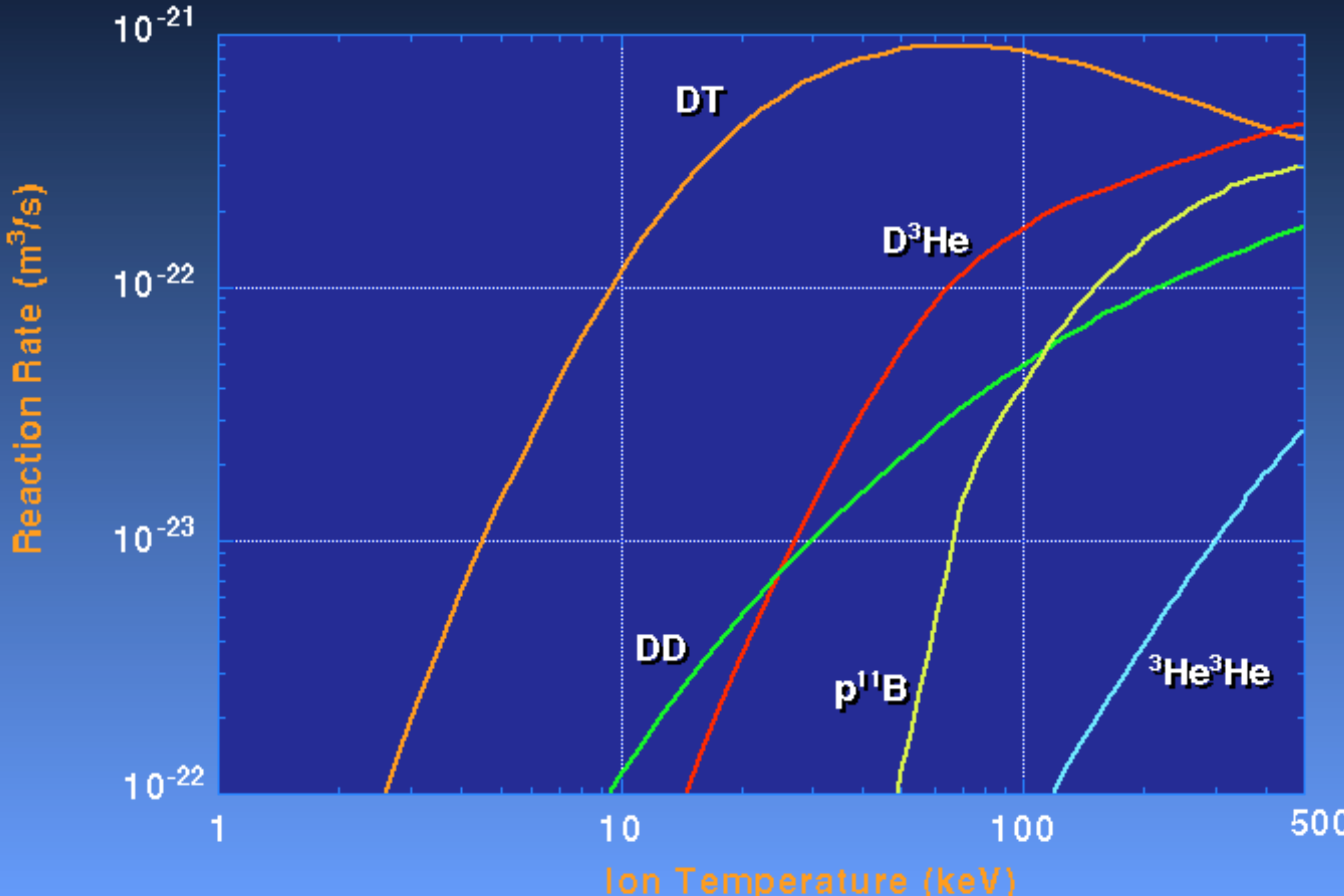
There are several ways to reach fusion conditions – all involve a plasma



High-density, high-temperature thermonuclear plasmas must be confined long enough for efficient fusion reactions to occur:

==> Net energy gain

Maxwellian Fusion Reaction Rates

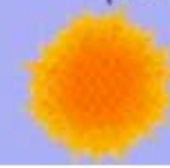


D-T Fusion Represents a Nearly Inexhaustible Energy Source

Fuels: **Deuterium**: abundant in sea water

Tritium: Half-life~12 years…must be produced?

Reaction		Ignition Temperature		Output Energy
Fuel	Product	(millions of °C)	(keV)	(keV)
D + T	^4He + n	45	4	17,600



$^6Li + n \rightarrow T + {}^4He + 4.8\ MeV$ + others

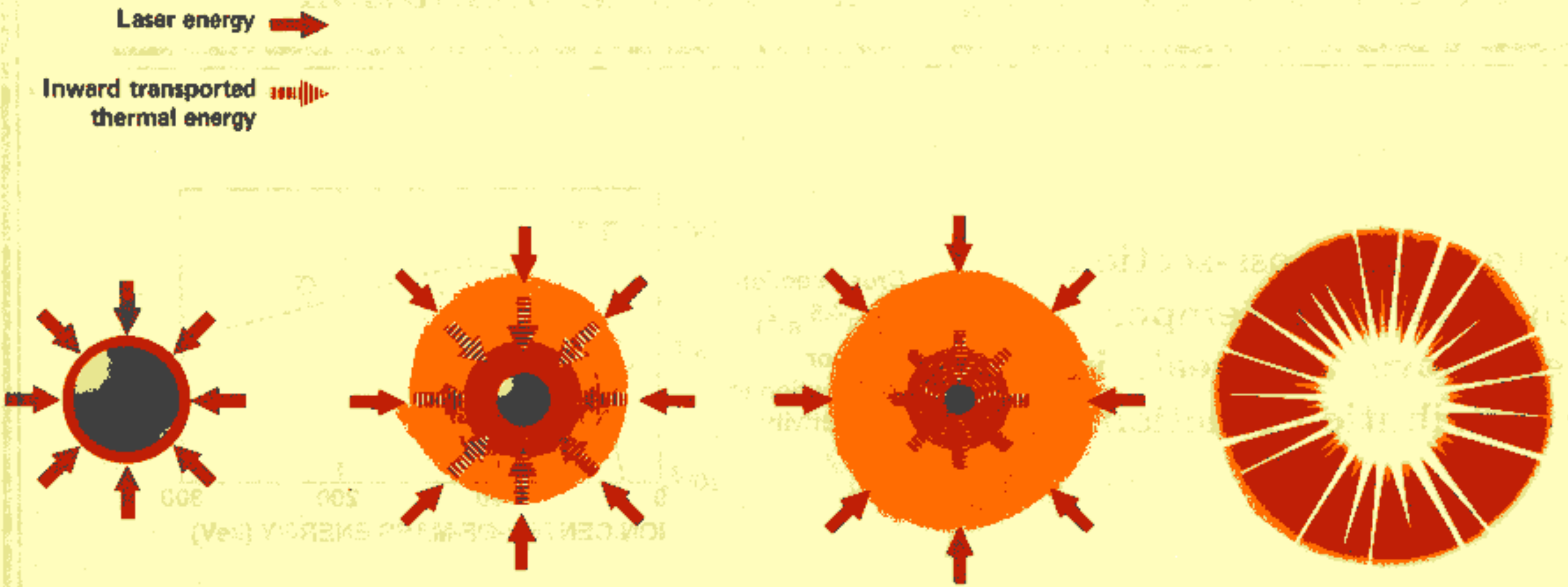
$T_{bred} / T_{burned} > 1$

"Real" fusion fuel cycle:

$^6Li + D = 2\,{}^4He + 22.4\ MeV$

No Resource Concern

INERTIAL CONFINEMENT FUSION CONCEPT



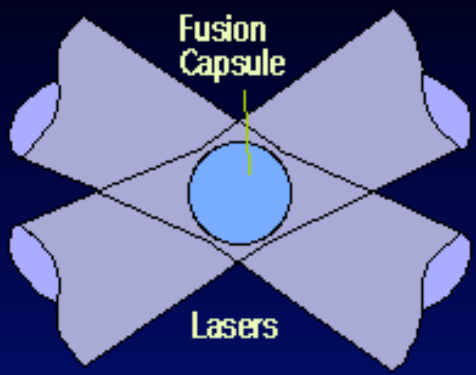
Atmosphere Formation
Laser or particle beams rapidly heat the surface of the fusion target forming a surrounding plasma envelope.

Compression
Fuel is compressed by rocket-like blowoff of the surface material.

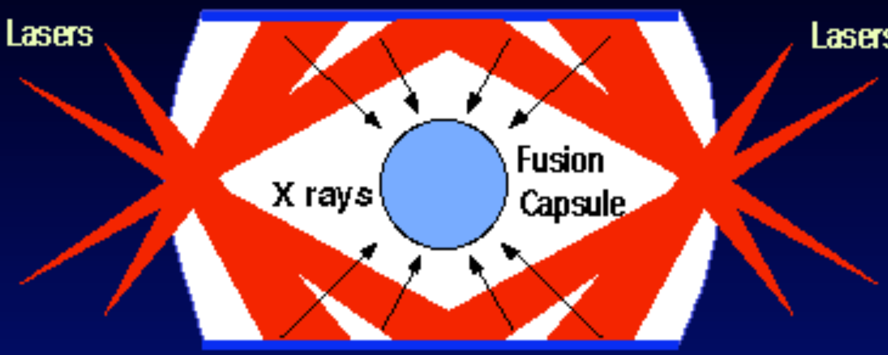
Ignition
With the final driver pulse, the fuel core reaches 1000 – 10,000 times liquid density and ignites at 100,000,000°C.

Burn
Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the driver input energy.

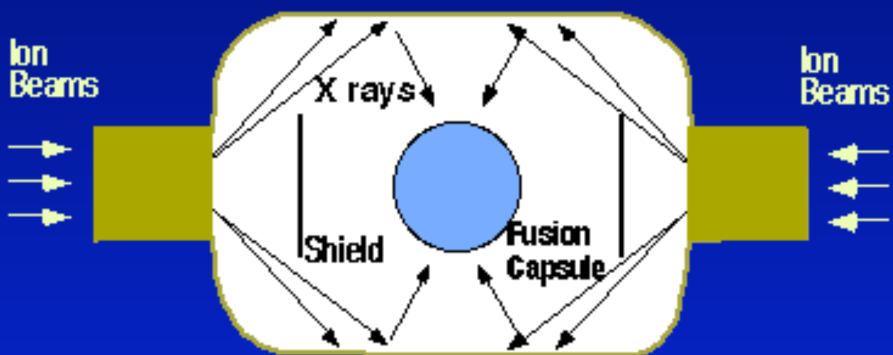
There Are Four Different ICF Target Designs



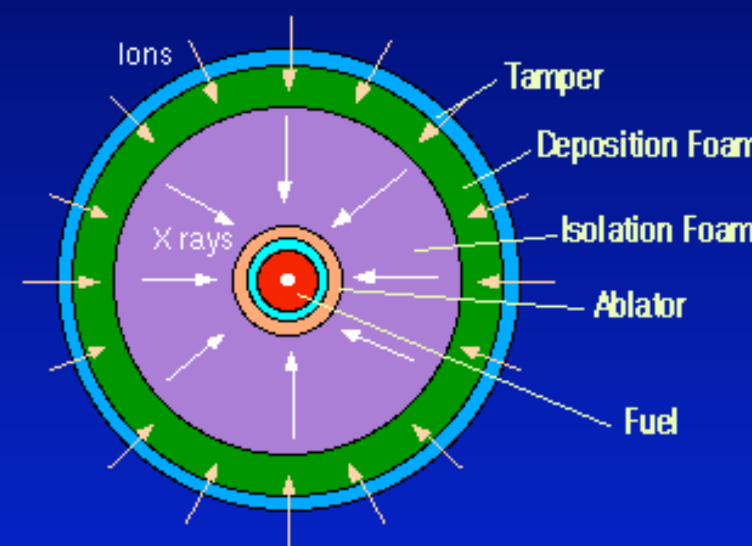
Direct Drive Lasers



Indirect Drive Lasers



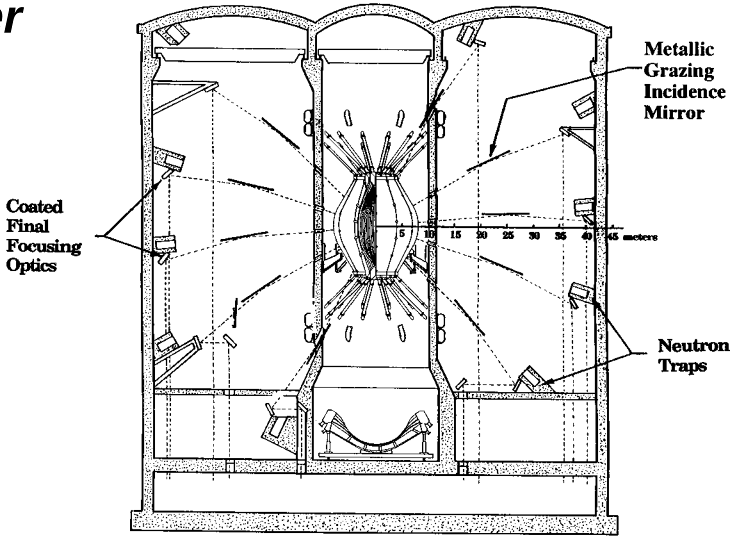
Indirect Drive Heavy Ions



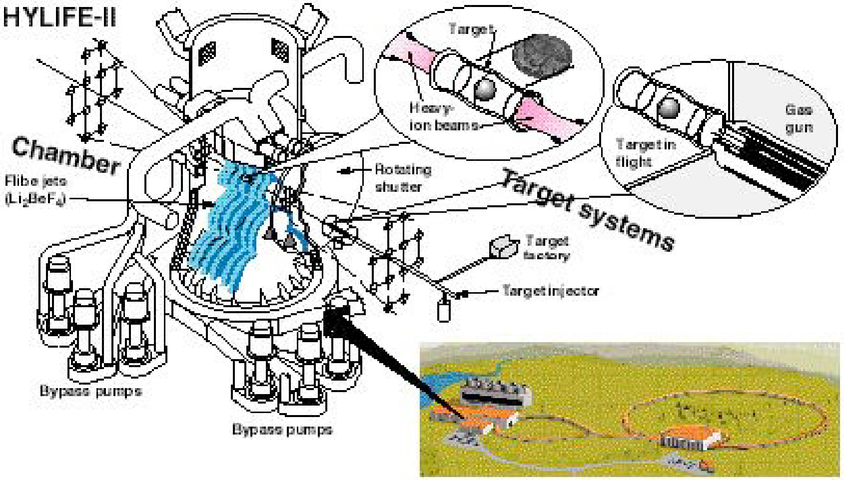
Indirect Drive Light Ions

There are 4 Current ICF Drivers

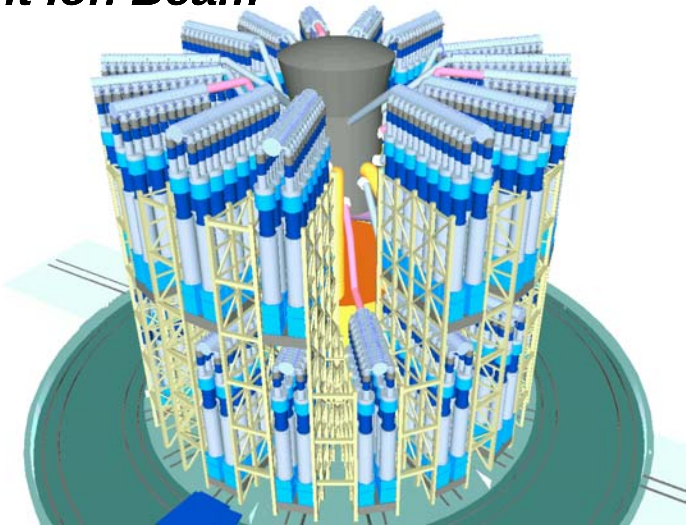
Laser



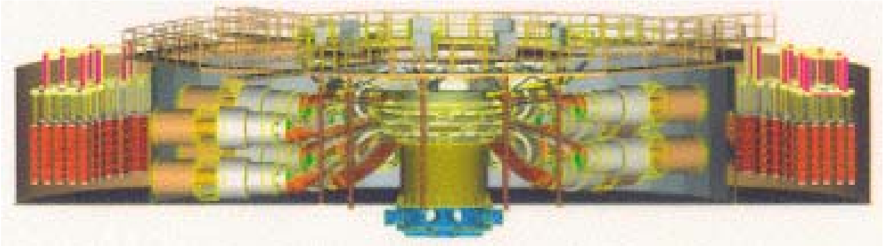
Heavy Ion Beam



Light Ion Beam



Z-Pinch – Energy application depends on finding a credible rep-rate concept



Light ion development currently on hold due to inability to focus adequately

NIF Enabled by Rapid Advance in Laser Technology

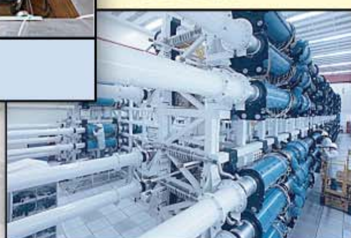
- Glass laser energy has increased 10^6
- Fusion energy will need:
  - increased efficiency
  - increased repetition rate

Janus

1972

100 J
1.05 µm

Shiva



1978

10 kJ
1.05 µm

Nova

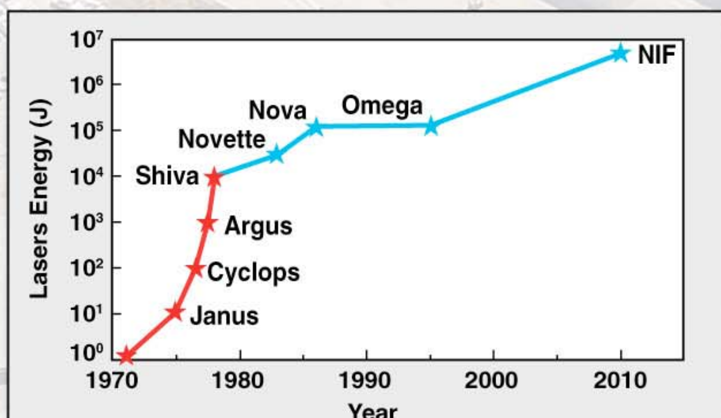
1984

30 kJ
351 nm

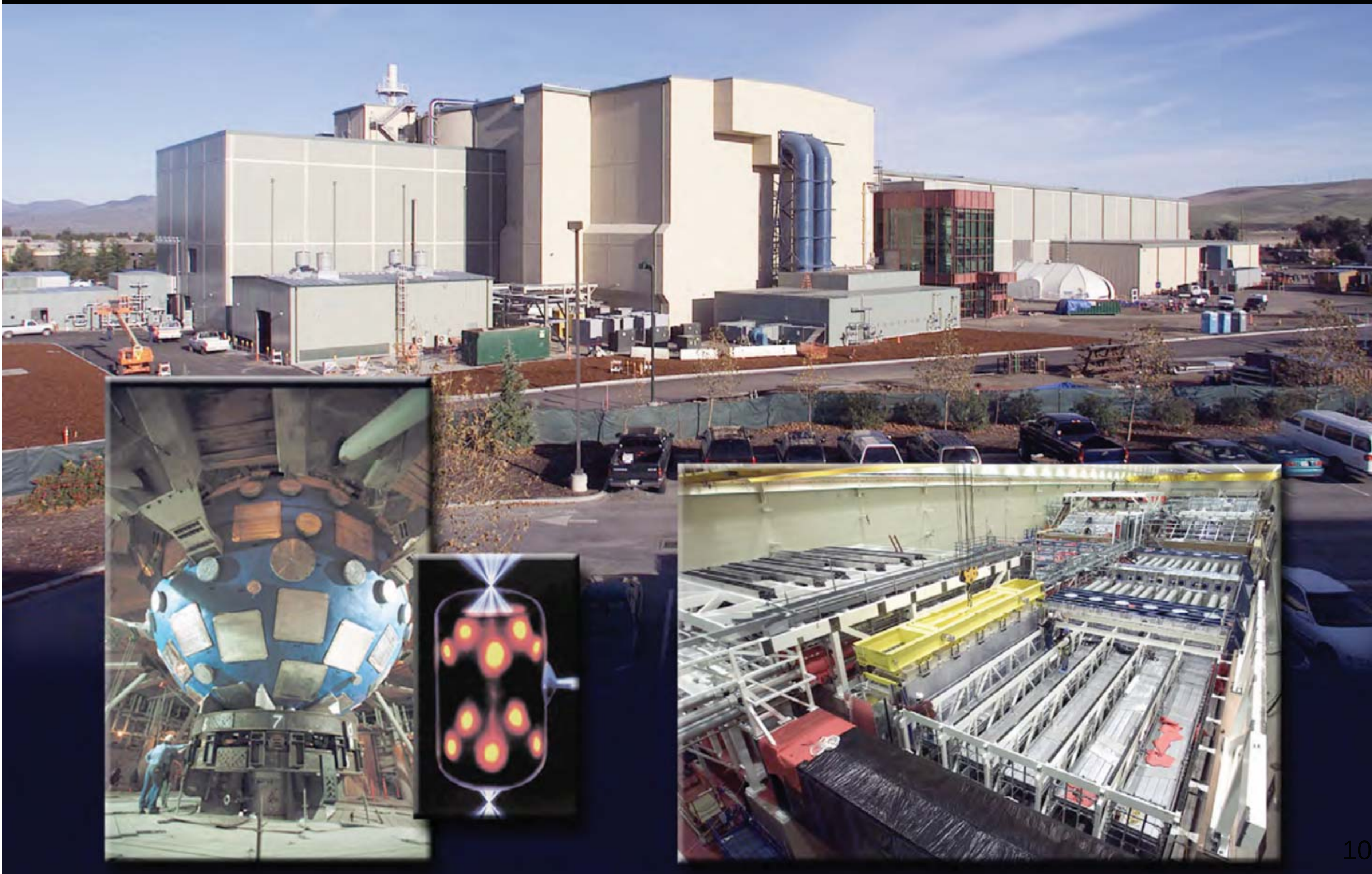
NIF

2009

1.8 MJ
351 nm



The National Ignition Facility-1.8 MJ Laser



NIF-1201-04097_MOD2.eps

The High Average Power Laser (HAPL) team is developing the science and technology for a laser fusion energy.

19th HAPL meeting, October 22-23, 2008, UW-Madison, Wisconsin

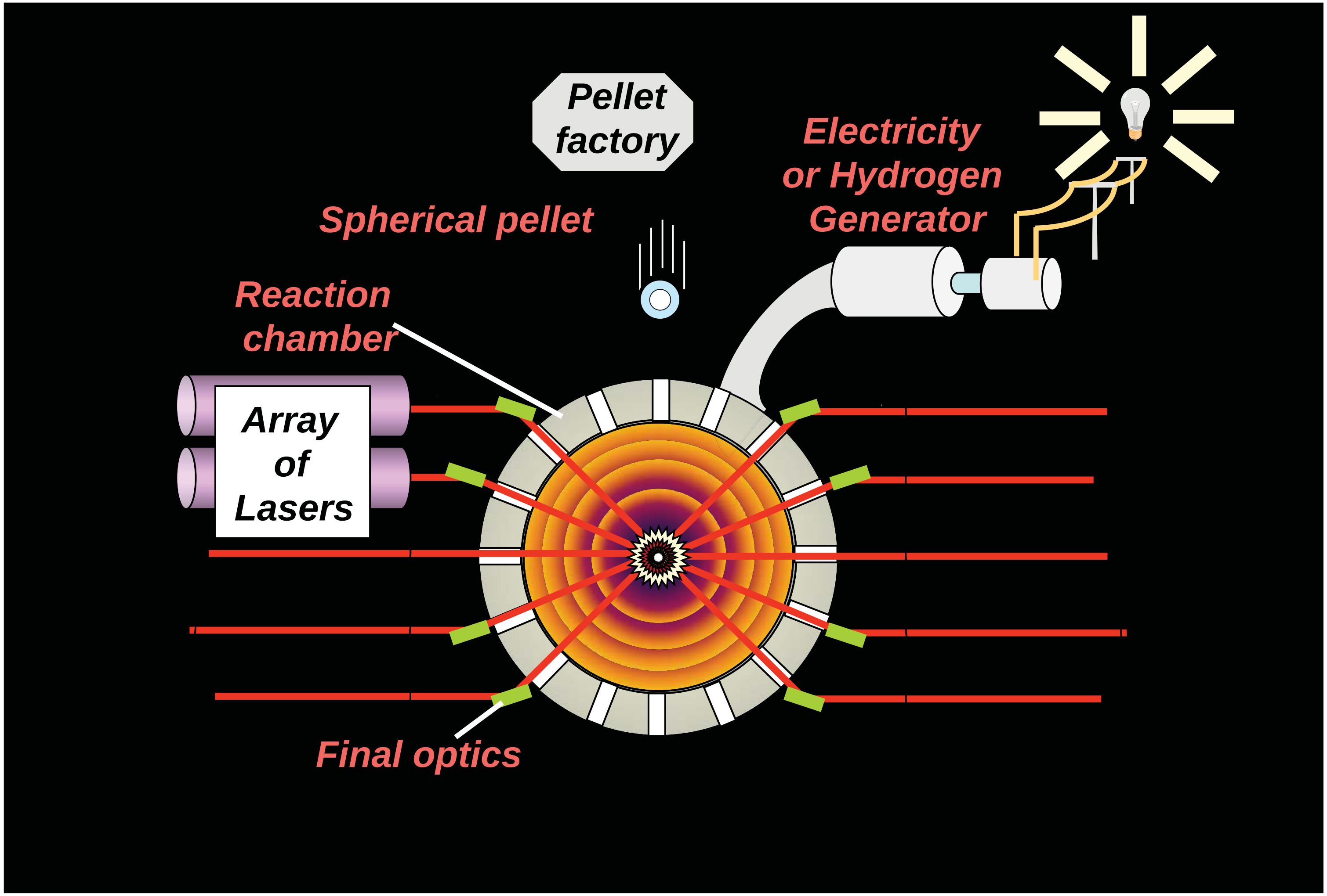
Led by J.D. Sethian Naval Research Lab

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

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

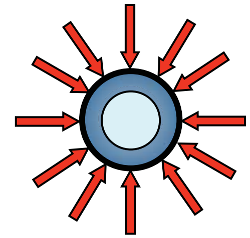
Industry
1. General Atomics
2. L3/PSD
3. Schafer Corp
4. SAIC
5. Commonwealth Tech
6. Coherent
7. Onyx
8. DEI
9. Voss Scientific
10. Northrup
11. Ultramet, Inc
12. Plasma Processes, Inc
13. PLEX Corporation
14. APP
15. Research Scientific Inst
16. Optiswitch Technology
17. ESLI

Fusion Energy with Laser Direct Drive

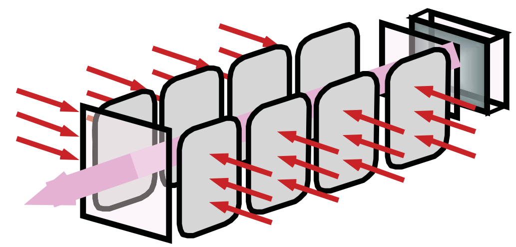


Why we believe direct drive with lasers can lead to an attractive power plant

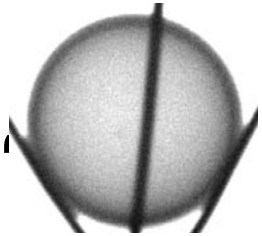
Simplest (robust) target physics:



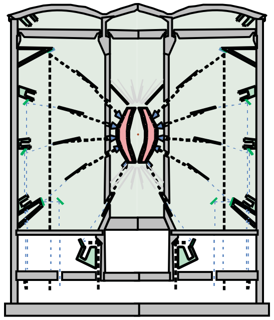
Laser (most costly component) is modular
Lowers development costs



Simple spherical targets:
facilitates mass produced “



Power plant studies show concept economically attractive

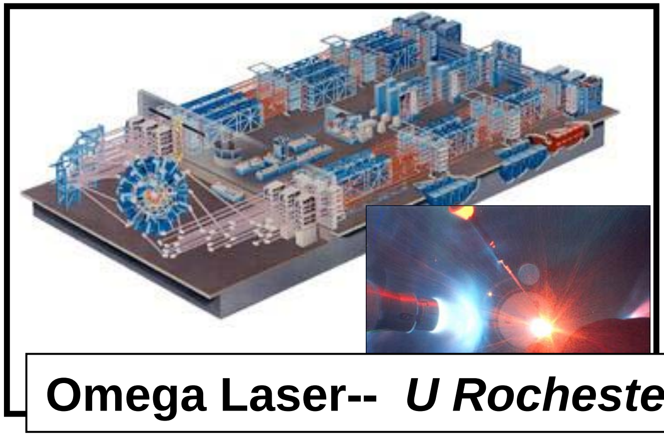


Separate components allows economical upgrades

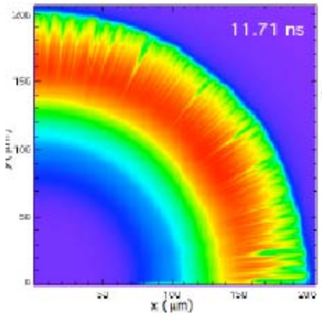
Target physics based on very large body of work in the US ICF Program

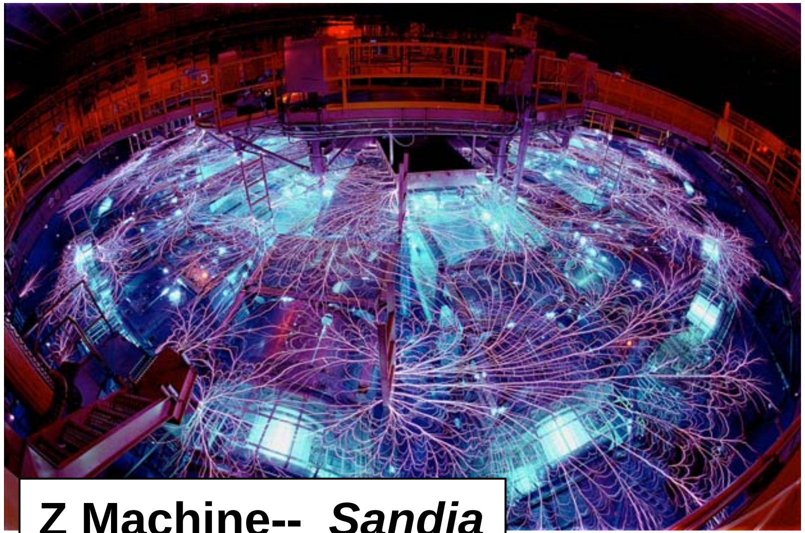
Only two main issues: Hydro stability & laser-target coupling
Can calculate with bench marked codes

Nike Laser-- *NRL*



Omega Laser-- *U Rochester*



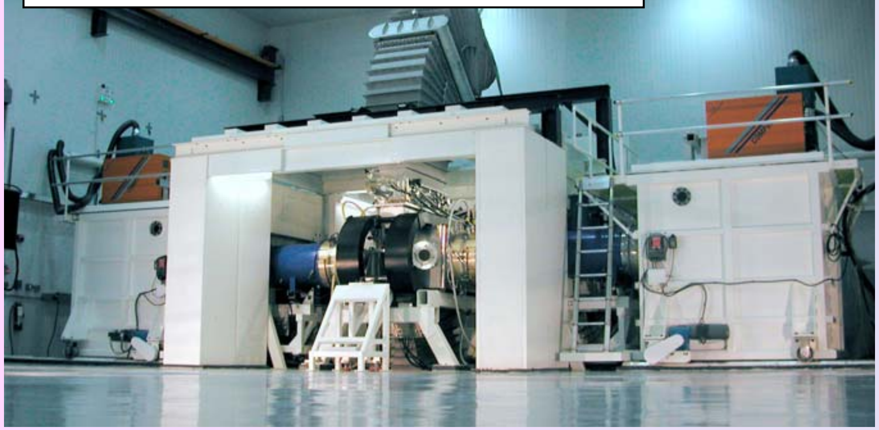


Z Machine-- *Sandia*

National Ignition Facility-- *LLNL*

Both HAPL Lasers have demonstrated high energy, rep rate, long duration, operation.

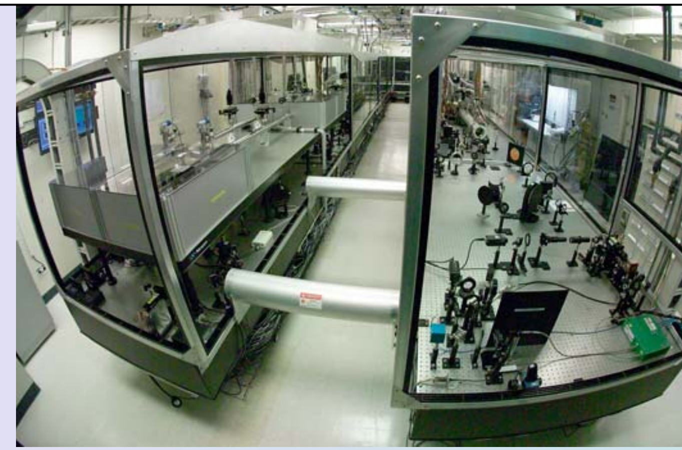
Electra KrF Laser (NRL)



- λ = 248 nm
- 700 J max, 120 ns, 2.5-5 Hz

- > 250,000 shots cumulative
- 300 J, 2.5 Hz, 110 min (16 k shots)
- Predict >7% total efficiency
  - (based on component development)

Mercury DPPSL Laser (LLNL)



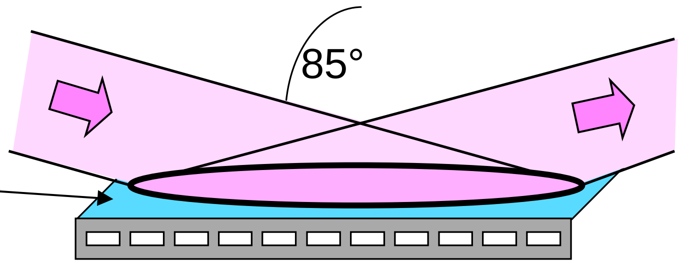
- λ = 1051 nm
- 65 J max, 15 ns, 10 Hz

- > 300,000 shots cumulative
- 55 J, 10 Hz, 30 min (18 k shots)
- 73% Conversion to 2 ω

Final Optics:

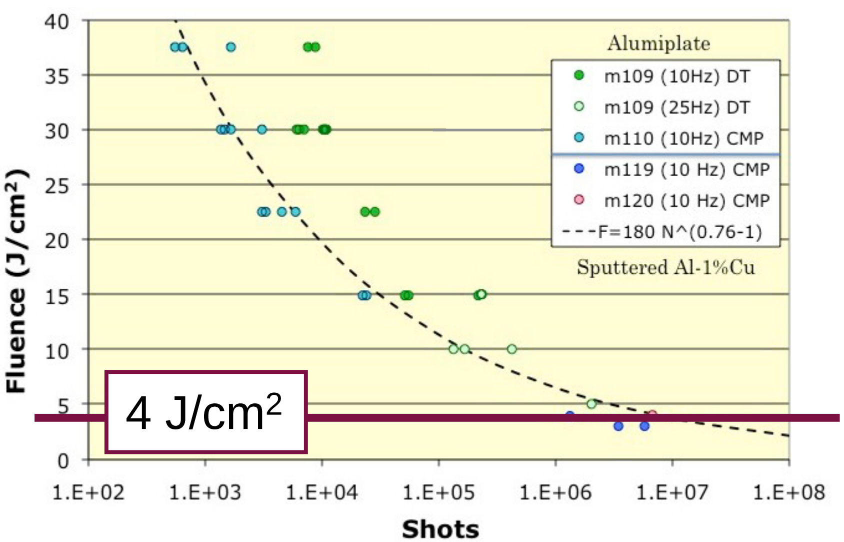
- GIMM Damage threshold now 4 J/cm² @ 7 M shots
- We are also revisiting dielectric mirrors

Grazing Incidence Metal Mirror (GIMM)



Al-1% Cu

neutron resistant base

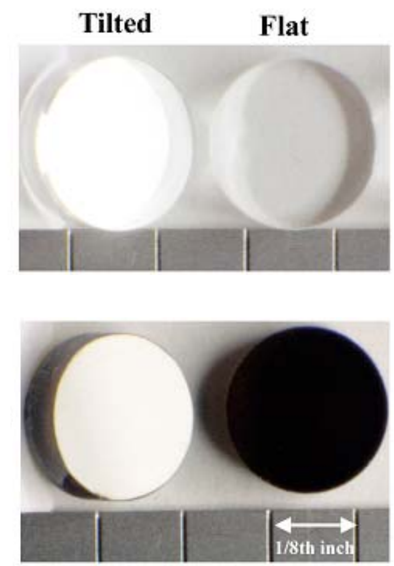


Dielectric Mirror

EXP'T: Expose mirror systems to HIFR (ORNL Fission Reactor)
Prototypical fluences and temp

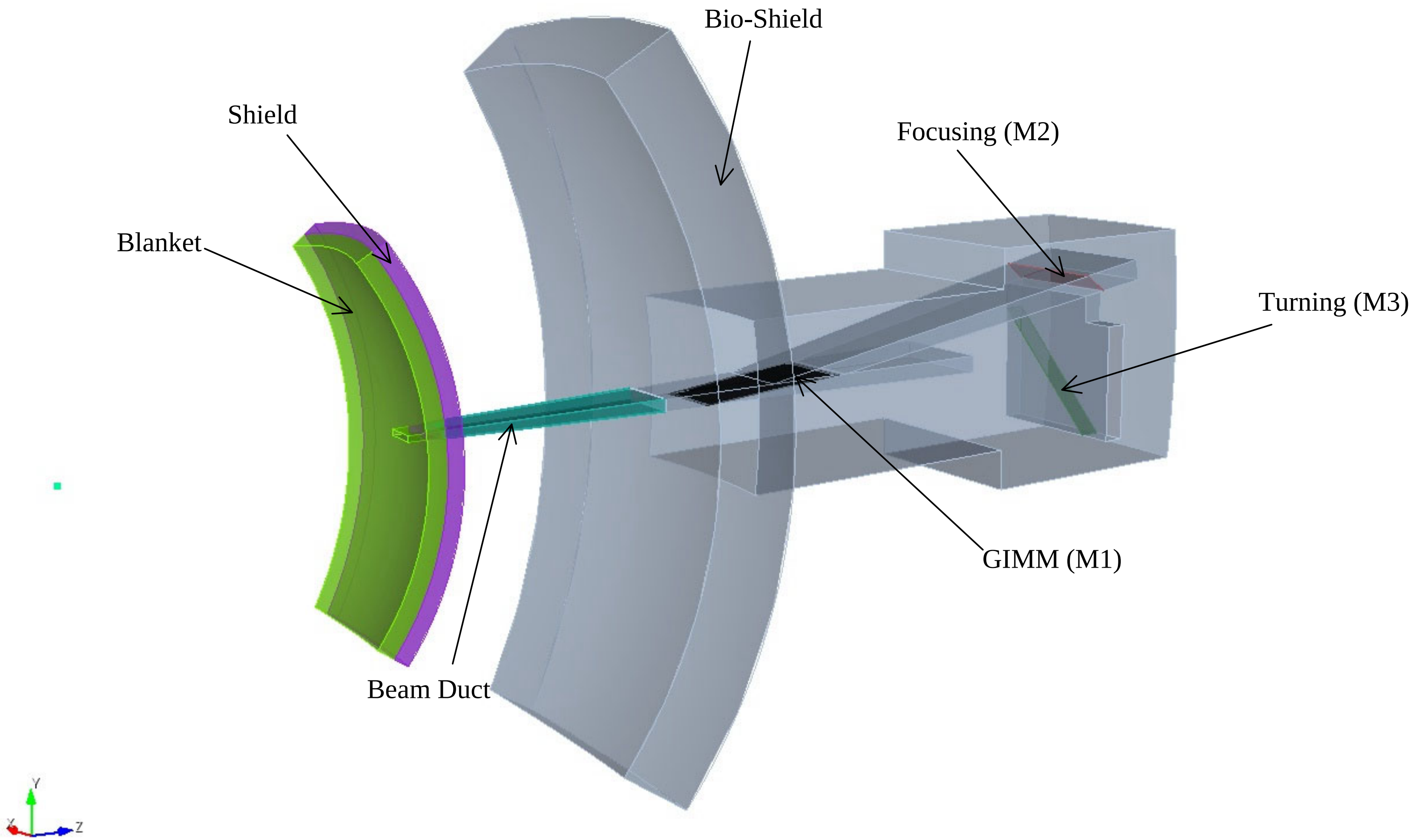
RESULTS: HfO_2 / SiO_2 layers on Sapphire

Control

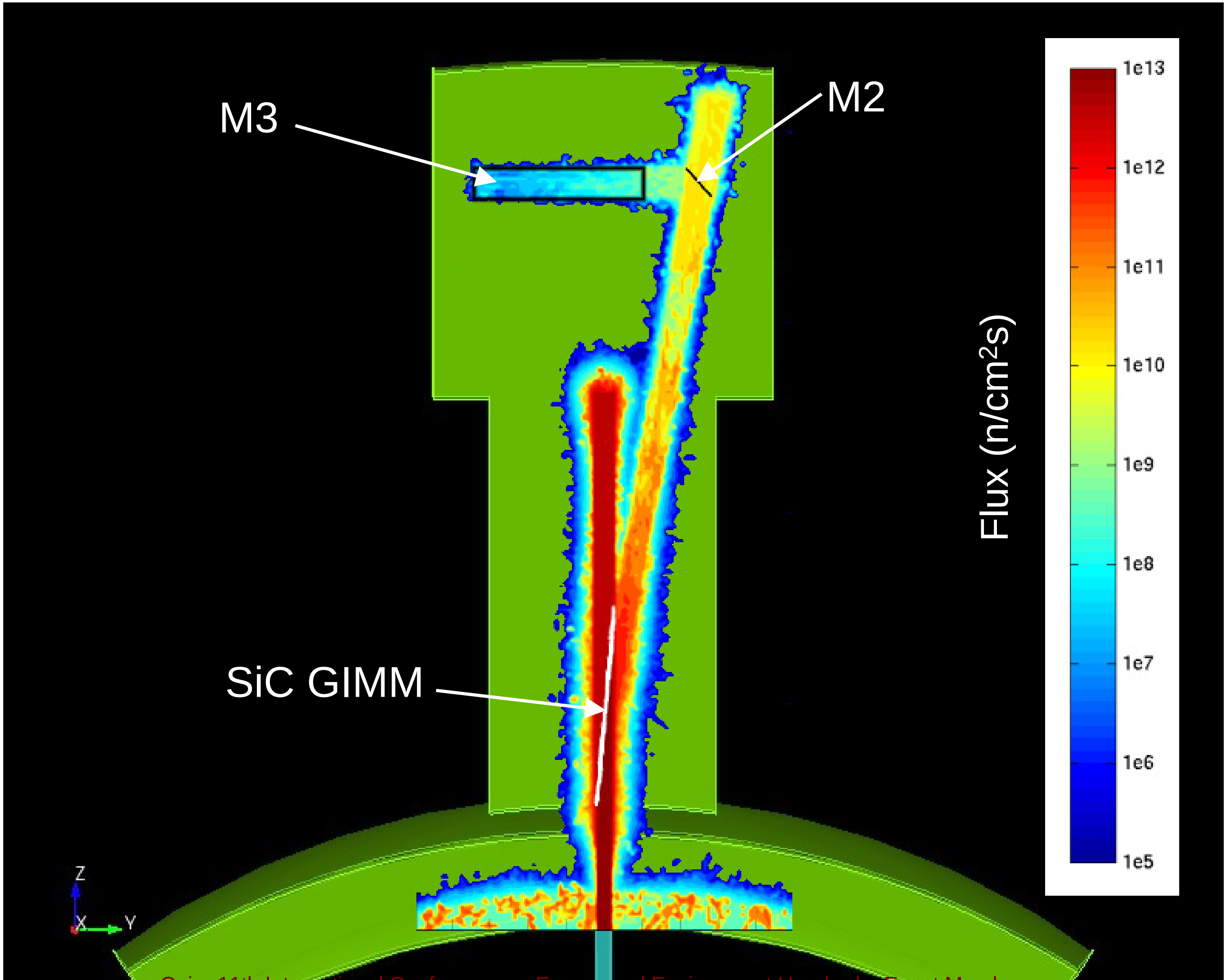


10^{20}n/cm²

Geometrical Model Used in 3-D Neutronics Analysis

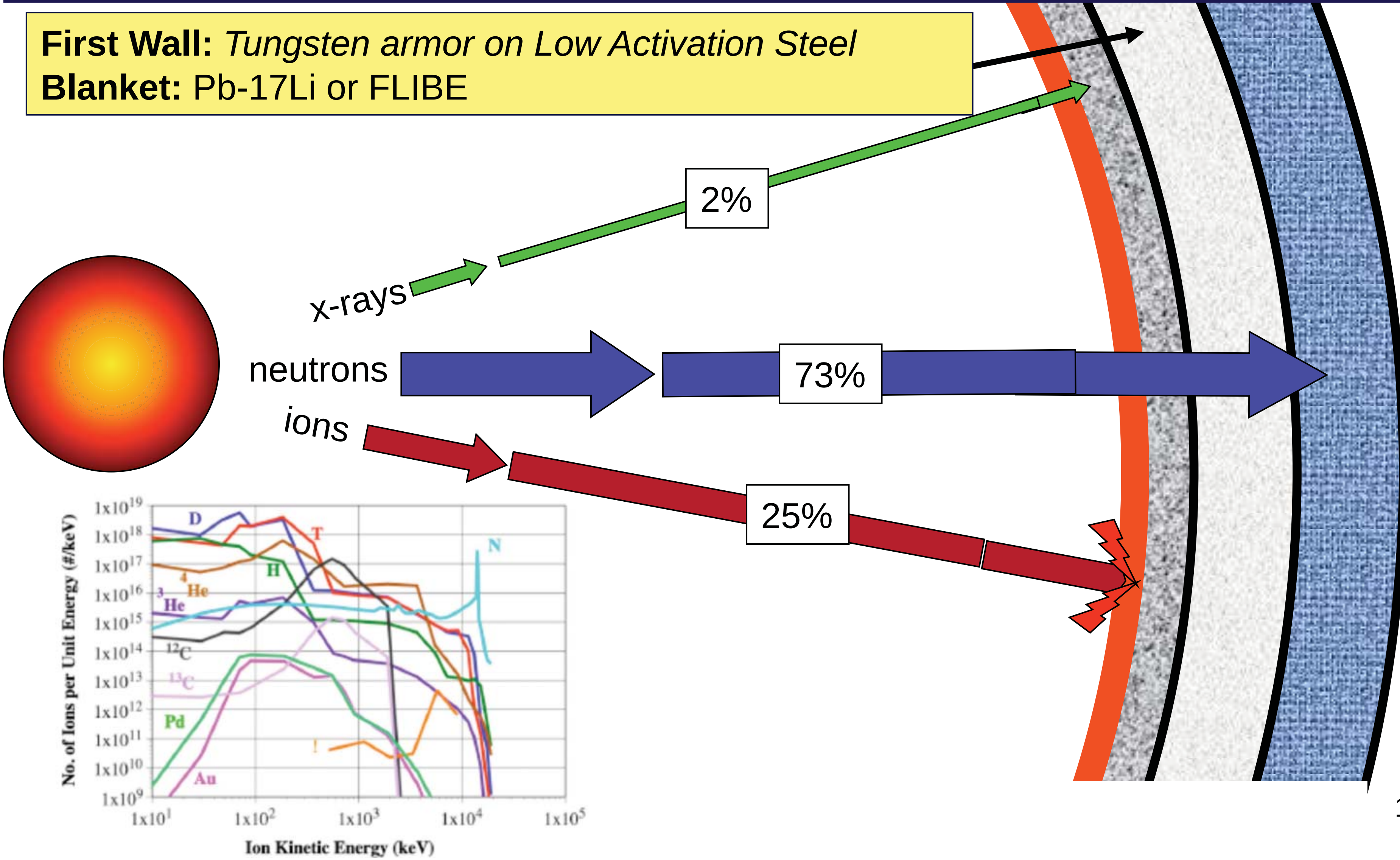


Fast Neutron Flux Distribution in Final Optics of HAPL



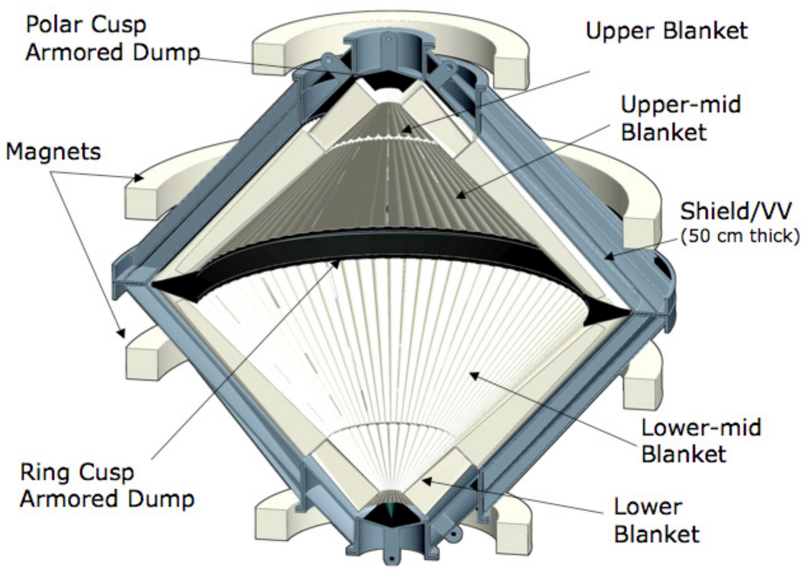
The "first wall" of the reaction chamber must withstand the steady pulses of x-rays, ions and neutrons from the target.

First Wall: *Tungsten armor on Low Activation Steel*
Blanket: Pb-17Li or FLIBE

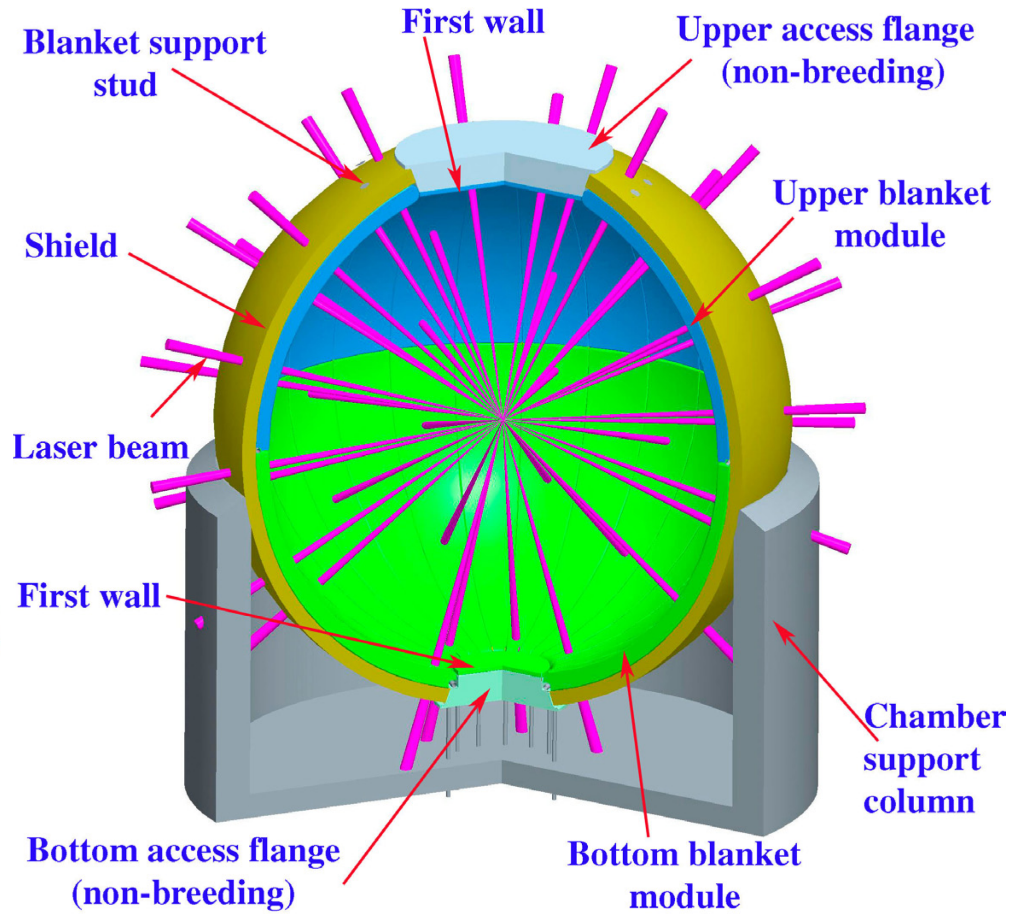


High Average Power Laser (HAPL) Conceptual Design

- Direct drive targets
- Dry wall chamber
- 40 KrF laser beams
- 367.1 MJ target yield
- 5 Hz Rep Rate



Design with Magnetic Intervention

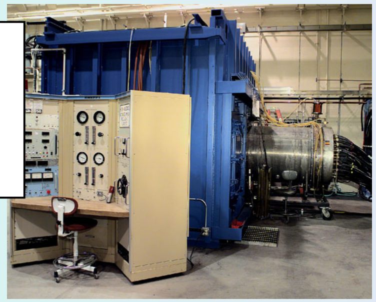


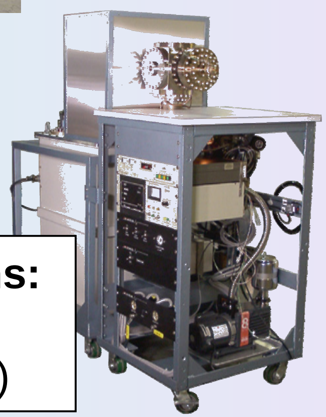
Large Chamber Design

Chamber Wall Experiments: Several facilities used to study effect of target emissions on first wall

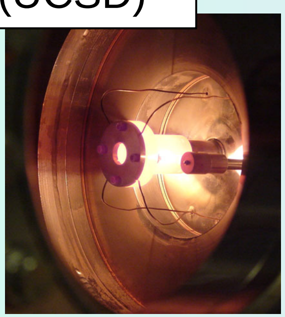
Thermo-mechanical Cyclic Stress

Ions:
RHEPP
(SNL)

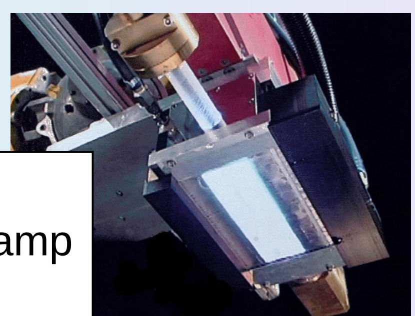




Laser:
Dragonfire
(UCSD)



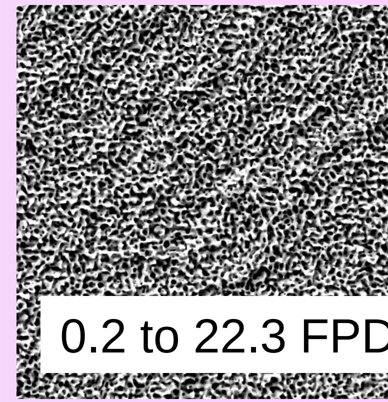
Electrons:
PETS
(ORNL)



Interface
Plasma Arc Lamp
(ORNL)

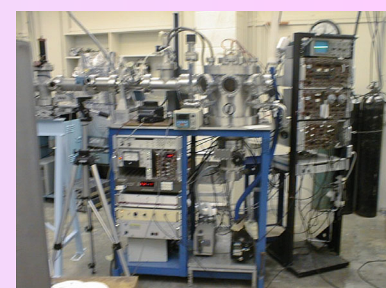
Helium Retention

IEC (Wisconsin)



0.2 to 22.3 FPD

Van de Graff (UNC)



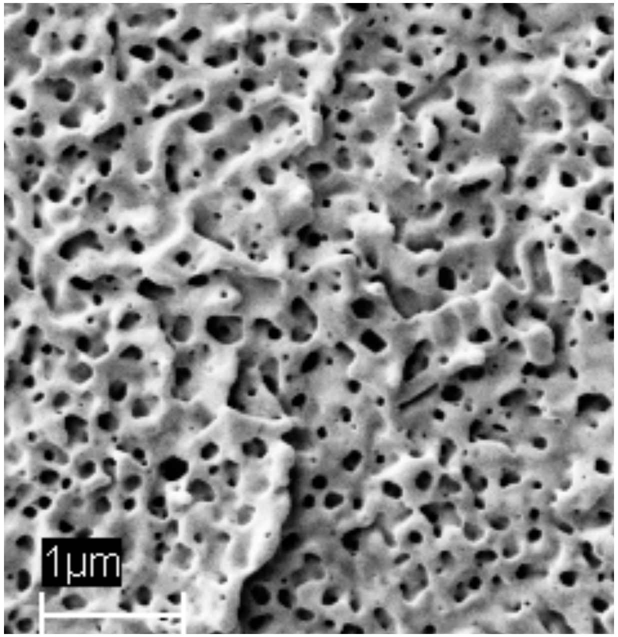
Ion Implantation (in particular He) in Dry Chamber Wall is a Major Concern

- **Can lead to exfoliation and premature failure of the armor (even for large chamber)**
- **Use of engineered armor**
  - **provide short pathway for implanted He to be released**
  - **microstructure could provide better accommodation of high thermal gradients**
  - **different possible concepts**

Other solutions

- **Magnetic intervention to steer ions away from main chamber**
- **Mobile C tiles: replacing or replenishing surface regularly**

Example Case for 6×10^{22} He^+/m^2
40 kV, 60 mA Pulsed (1170±20°C baseline), 72 minute runtime on W armor
(UW IEC Facility)



Solid Wall Chamber options

♦ Engineered Materials (the "scientific" solution)

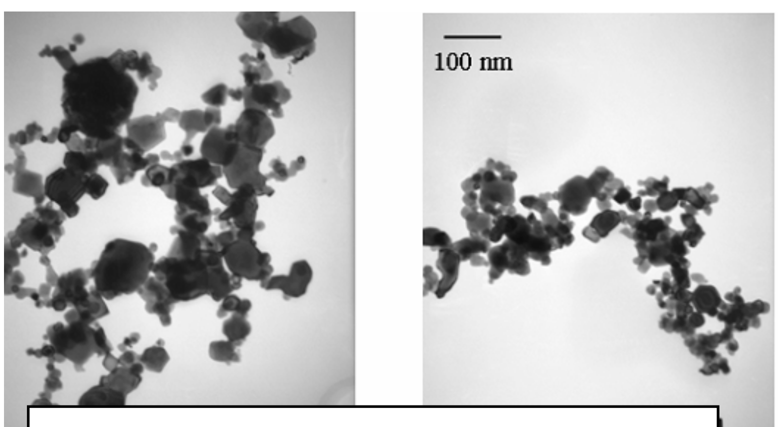
♦ Mobile Tiles (the "live with it" solution)

Engineered Materials

High Porosity Tungsten
Fiber/foam/nano-powder, etc)

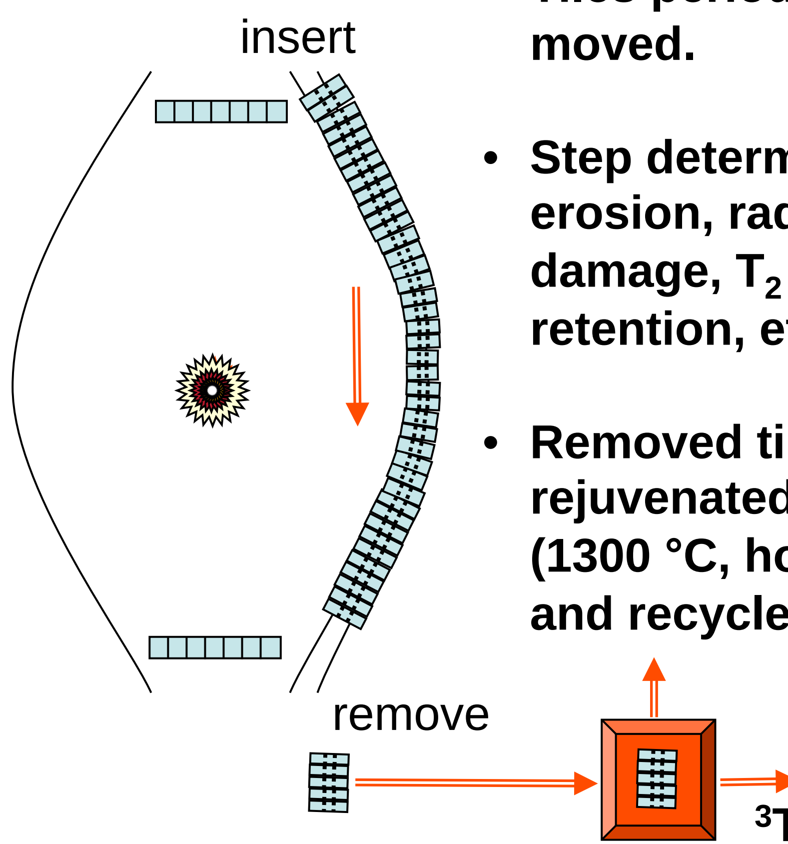
Scale size less than He migration
< 100 nm

Space allows material to "breathe"

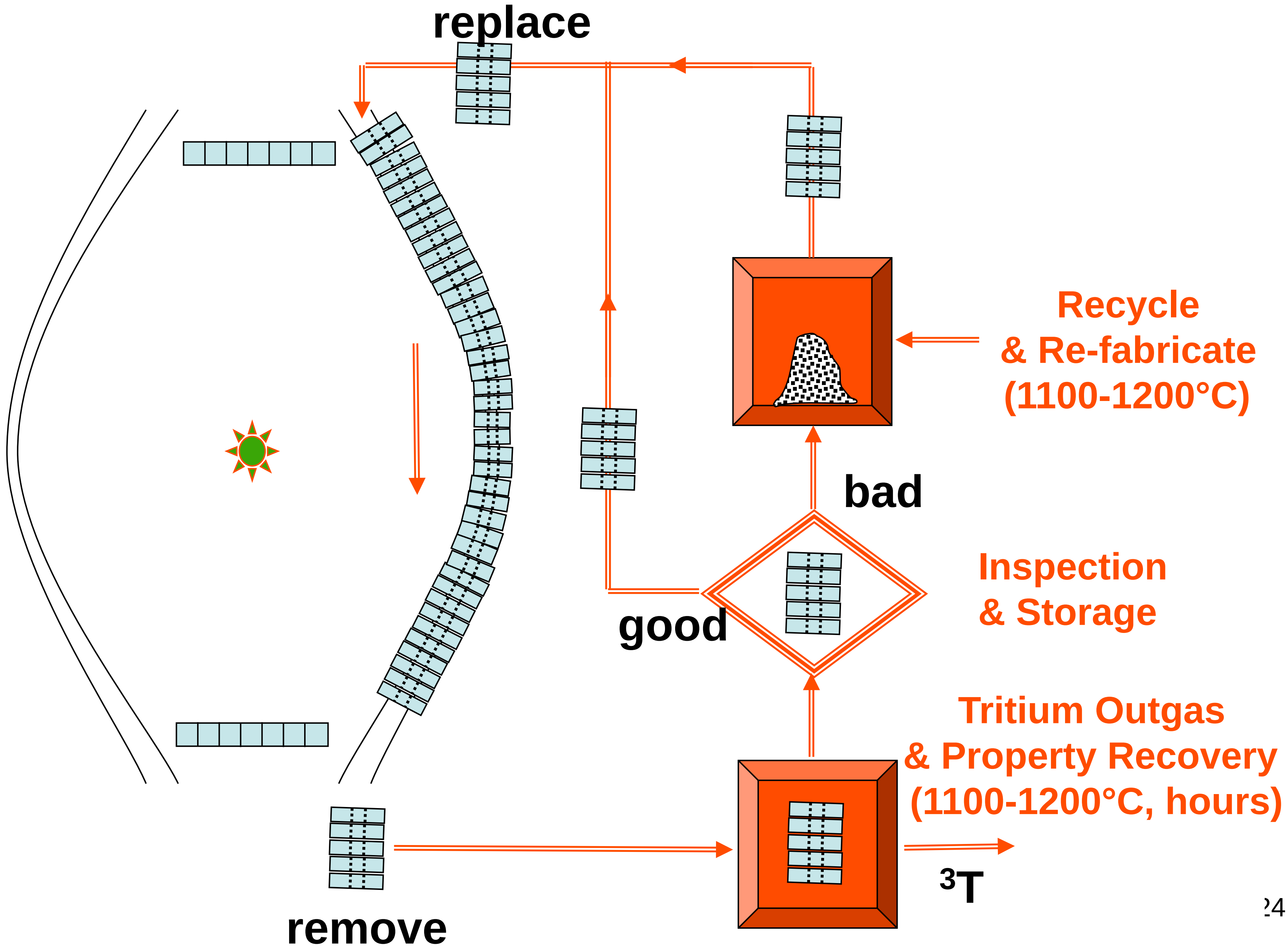


Ultra Fine Tungsten Feedstock from Plasma Processes, Inc

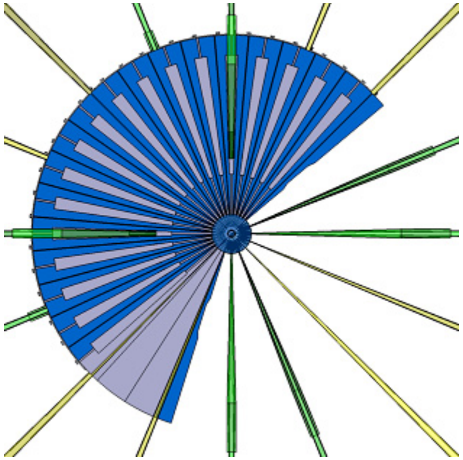
Mobil Tiles



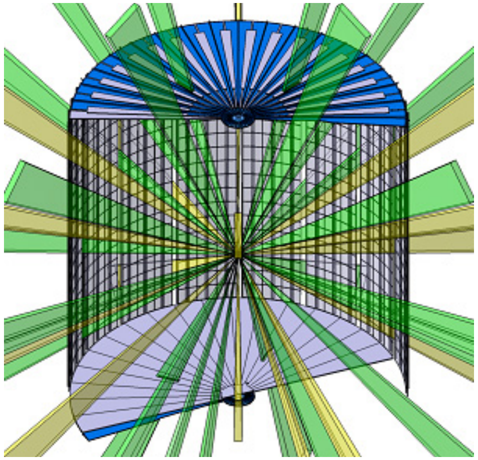
- **Tiles periodically moved.**
- **Step determined by erosion, radiation damage, T_2 and He retention, etc.**
- **Removed tiles rejuvenated (1300 °C, hours) and recycled**


replace
Recycle
& Re-fabricate
(1100-1200°C)
bad
Inspection
& Storage
good
Tritium Outgas
& Property Recovery
(1100-1200°C, hours)
3T
remove

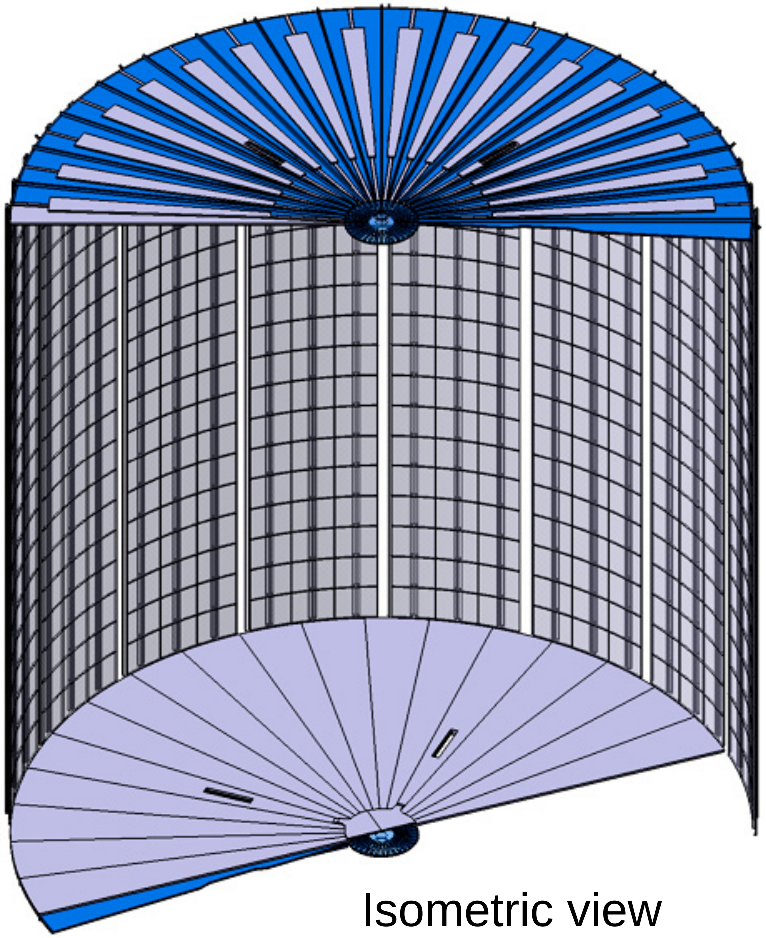
Full Chamber Representation



Top view with lasers



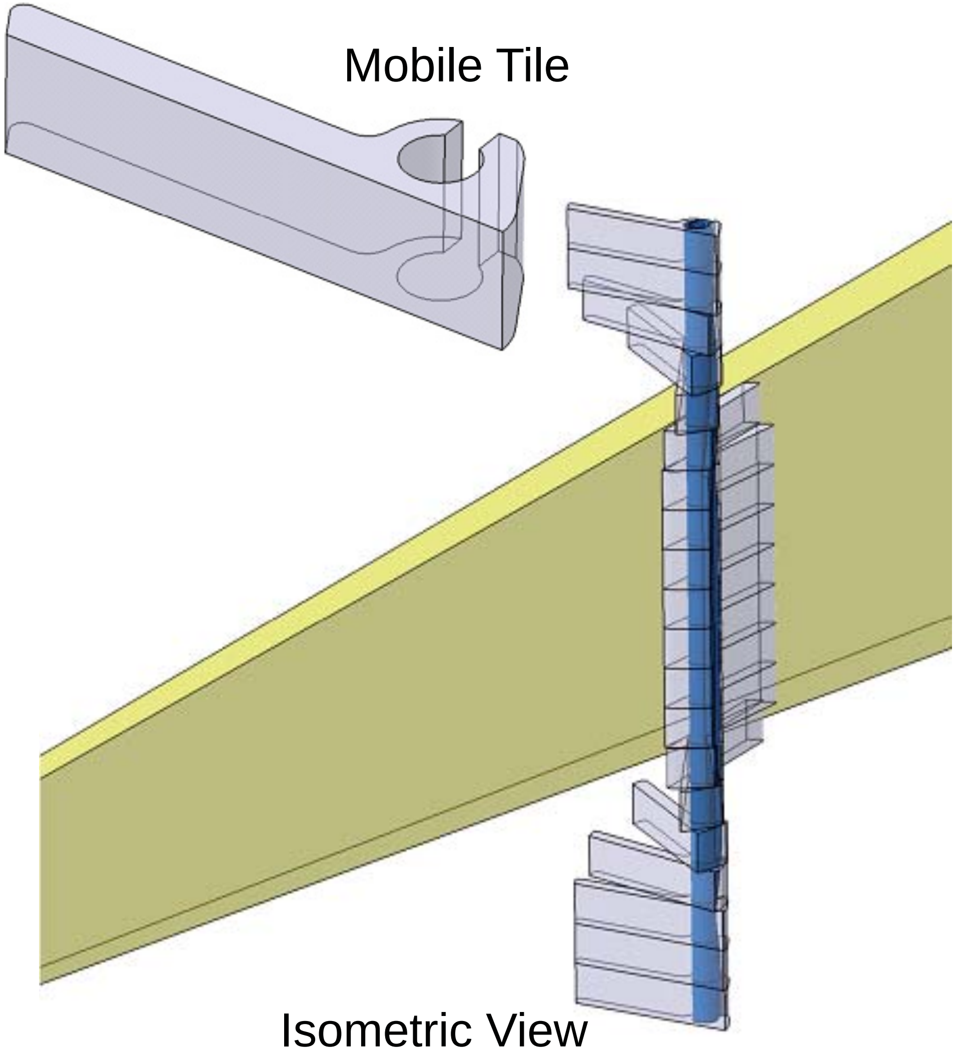
Isometric view with lasers



Isometric view without lasers

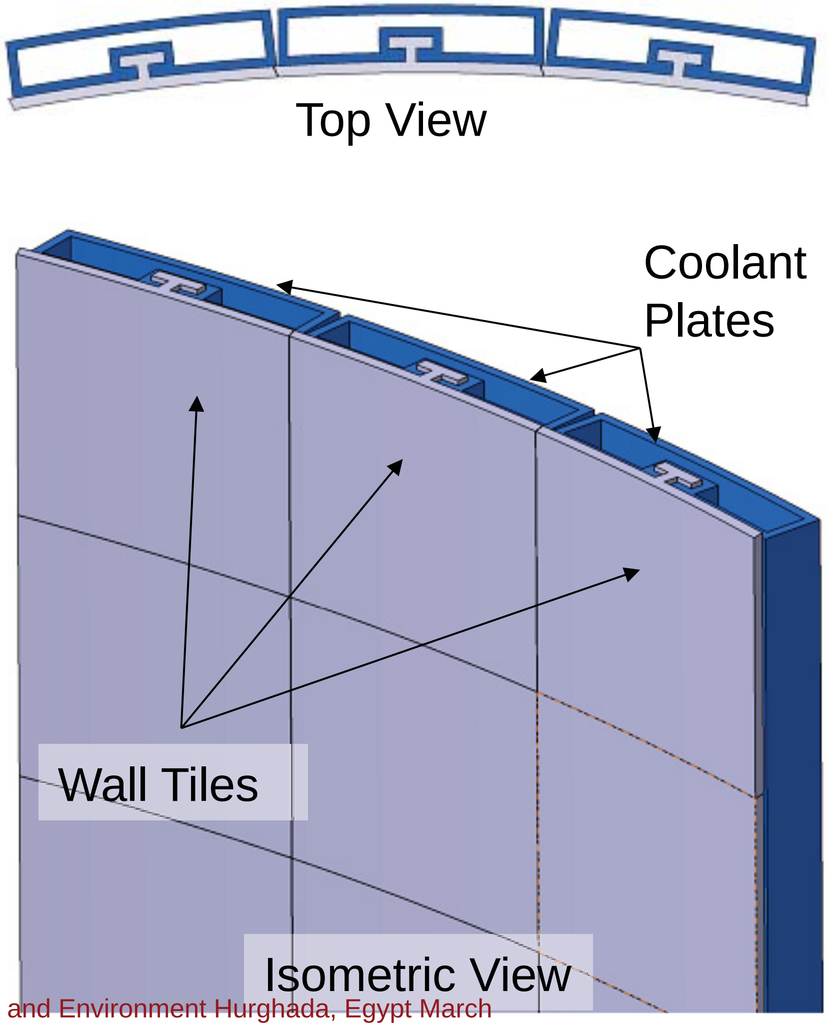
Laser Port Tiles

- These tiles traverse the chamber along a coolant rod (shown in blue)
- At the location of the laser ports, the tiles will rotate around the coolant rod by following a guiding rail on the coolant rod

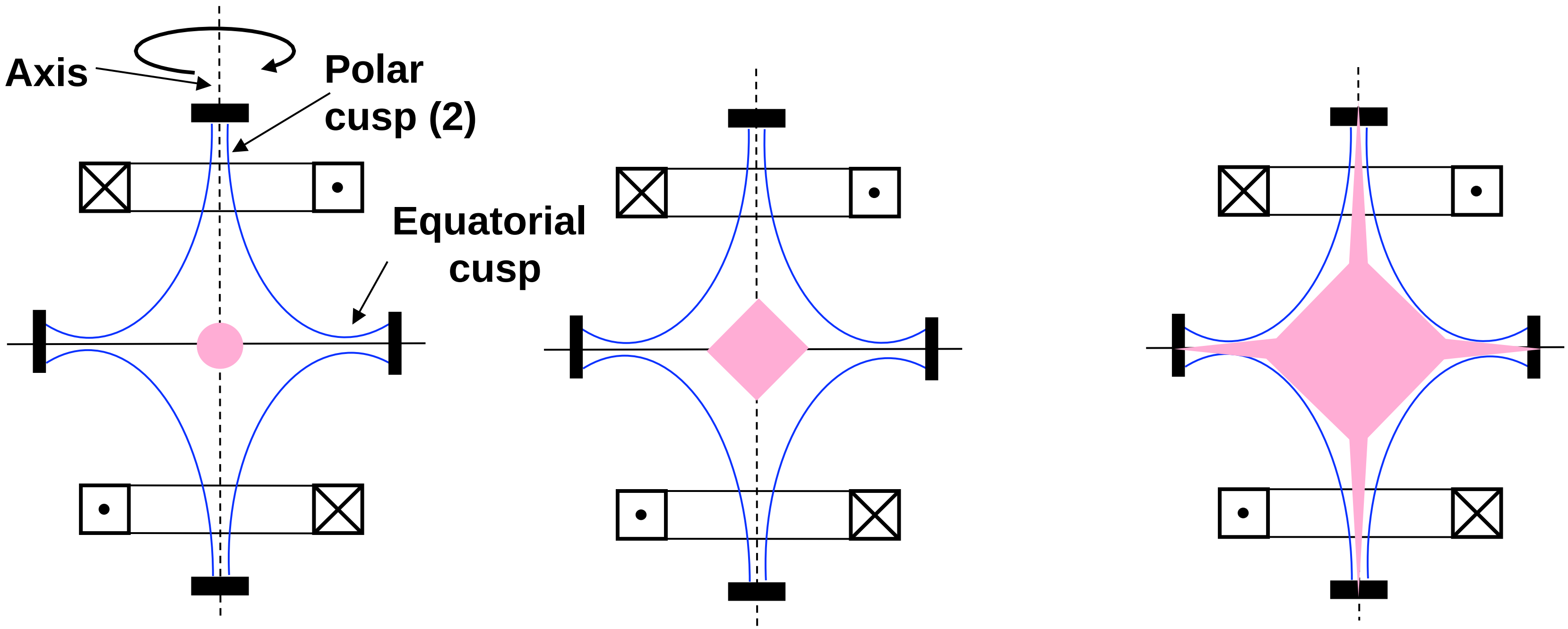


Chamber Wall Tiles

- For sections of chamber walls without laser beam penetration, larger tiles will be used
- These tiles will traverse vertically through the chamber without the need to twist to open for lasers



Magnetic Intervention
Divert Ions off the wall (the "end run" solution)



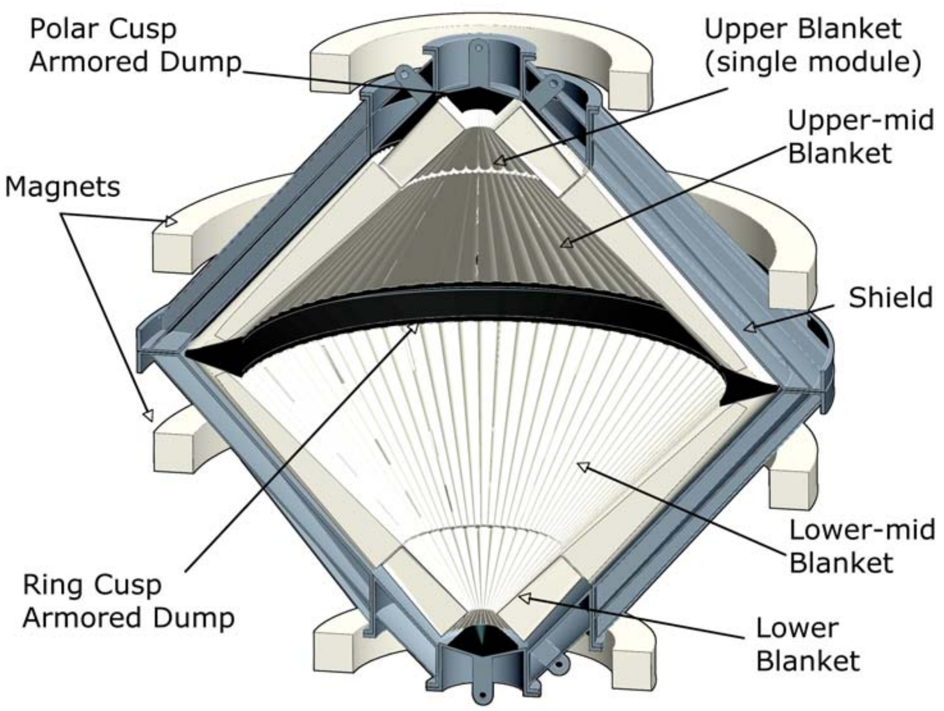
Plasma expansion initially spherical	Ion cloud deforms as it encounters cusp	Ions, *at reduced power*, leak out through cusps, into external dumps

1. **Physics demonstrated in 1979 NRL experiment:**
   R. E. Pechacek, et al., Phys. Rev. Lett. 45, 256 (1980).
2. **NRL experiment modeled by D. Rose at Voss Scientific**

MI Concept proposed by A.E. Robson

Biconical Chamber Well Suited to Simple Cusp Coil Geometry and Utilizing SiC_f/SiC for Resistive Dissipation

- SiC_f/SiC blanket with Pb-17Li or flibe as liquid breeder (tight assembly of submodules), coupled to Brayton cycle.
- Water-cooled steel shield is lifetime component and protects the coil (can also be locally placed around coils).
- Although resistive dissipation of > 50% of the ion energy seemed possible, there were concerns about the high voltages generated between the blanket modules.
- Armored ion dumps schematically shown inside chamber, but preferably placed outside for easier maintenance access.

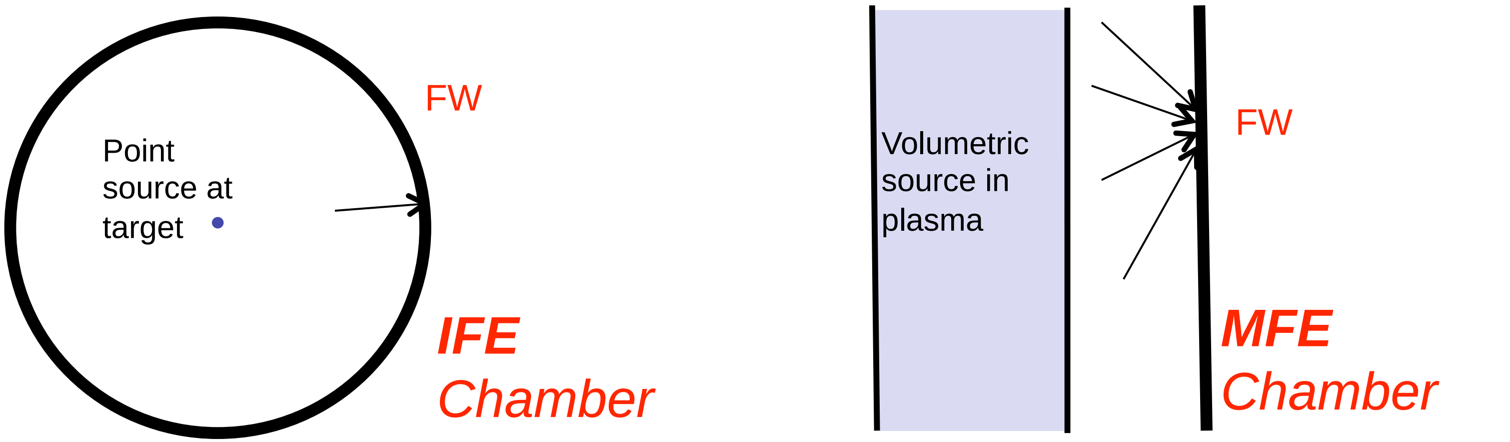


Different Features of IFE Systems

Significant geometrical, spectral and temporal differences between IFE and MFE systems affect radiation damage levels with impact on lifetime assessment

Geometrical differences:

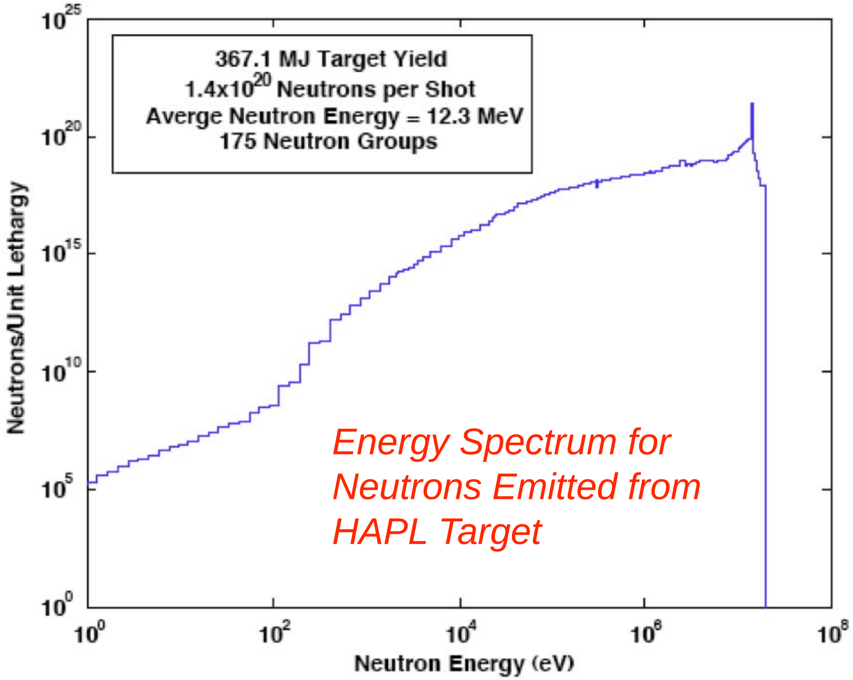
Point source in IFE ⇒ Source neutrons in IFE chambers impinge on the FW/blanket in a perpendicular direction ⇒ For same NWL, lower radiation effects at FW with smaller radial gradient in blanket



Different Features of IFE Systems

Spectral differences:

- Fusion neutron interactions in compressed IFE target result in considerable softening of neutron spectrum incident on the FW/blanket in IFE chambers
- Softened source neutron spectrum with 10-13 MeV average energy depending on target ρR with some neutron multiplication (~1.05)

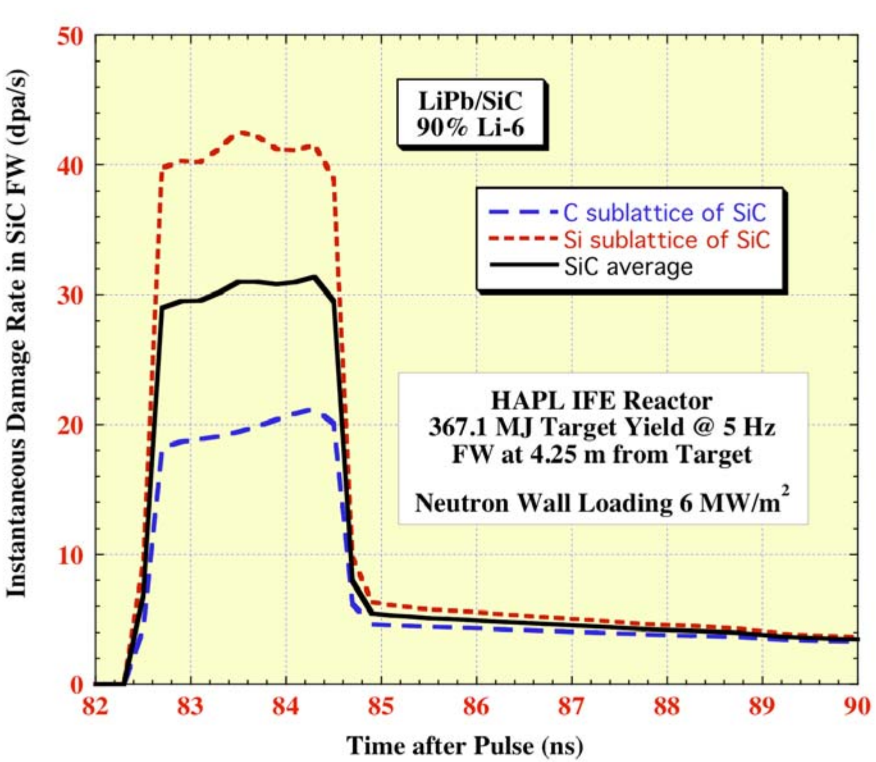


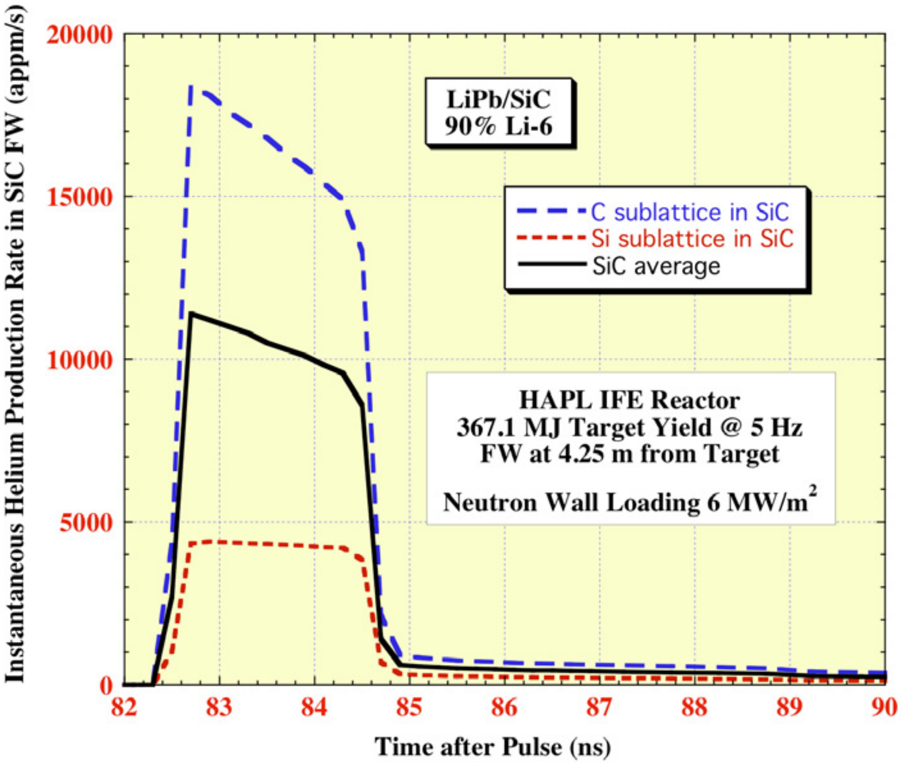
- Combined geometrical and spectral differences impact time-integrated radiation damage parameters
- Simple scaling of radiation effects with neutron wall loading between IFE and MFE systems is inappropriate

Pulsed Effects in IFE Systems

- In IFE chamber neutron source has a pulsed nature
- Energy spectrum of neutrons from target results in time of flight spread and backscattering from blanket extends period over which a particular radiation effect takes place
- Time spread is larger for radiation effects produced by lower energy neutrons (time spread of dpa larger than that for gas production and transmutation)
- Peak instantaneous damage rates in IFE FW/blanket are ~5 to 8 orders of magnitude higher than steady state damage rates produced in MFE systems
- Difference in time spread results in higher instantaneous He/dpa ratios in IFE systems compared to MFE systems
- Time dependent neutronics analysis is necessary for subsequent microstructure evolution analysis
- Analysis is underway to determine pulsed instantaneous damage parameters in SiC/SiC FW of HAPL and couple results with microstructure evolution analysis

Pulsed Damage parameters in HAPL FW





- Temporal peaking factor is significantly higher for He production than for atomic displacement (8.7×10^7 vs. 1.1×10^7)
- Peak instantaneous He/dpa ratio is much higher than that determined from the temporal average (cumulative) values (368 vs. 47)

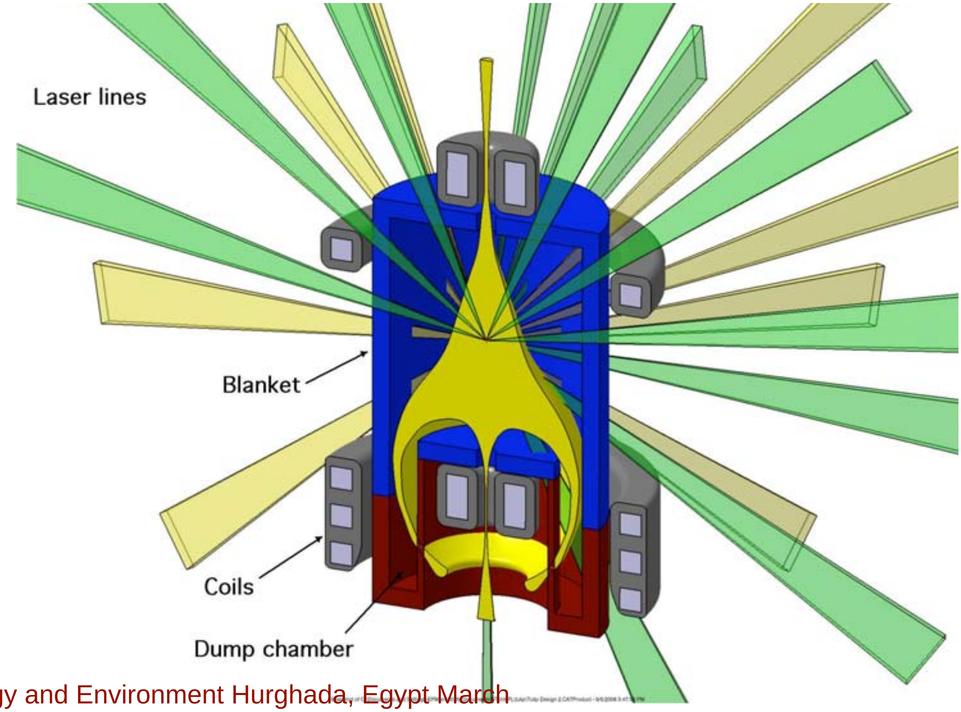
Overall Chamber and Reactor Concept with Bell Cusp Configuration

- **Two laser lines intersect the dump chamber region.**
  - **Vapor pressure prior to each shot should be low enough not to impact the laser propagation.**

- **The closest FW region to the center of the chamber is 4.5 m with a corresponding neutron wall load of 5.4 MW/m^2.**

- **Both blanket concepts considered for the biconical chamber could be utilized in this configuration**
  - **TBR >1.1 (with 7.5-10% ^{6}Li and including loss of coverage due to ports and cusp openings).**

- **Other nuclear requirements also accommodated.**
  - **a combined blanket/shield thickness of 1.25 m.**
  - **a vacuum vessel thickness of 10 cm.**
  - **FS shield and VV are lifetime components with peak end-of-life radiation damage <<200 dpa.**
  - **VV is reweldable with peak end-of-life He production <1 He appm.**
  - **Magnets are lifetime components with peak fast neutron (E>0.1 MeV) fluence <10^{19} n/cm^2 and peak insulator dose <10^{10} Rads.**

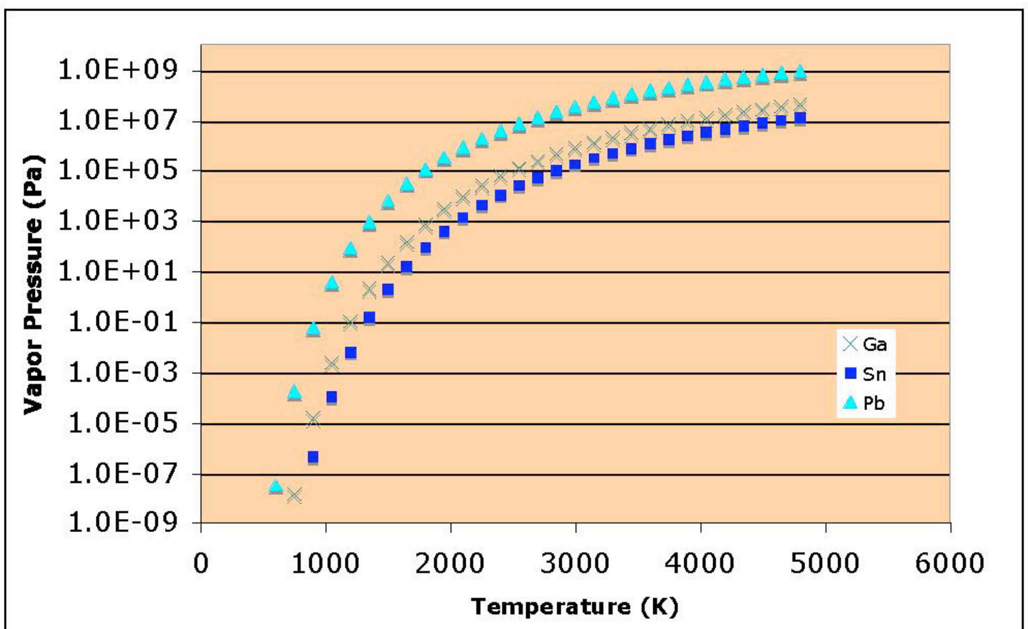


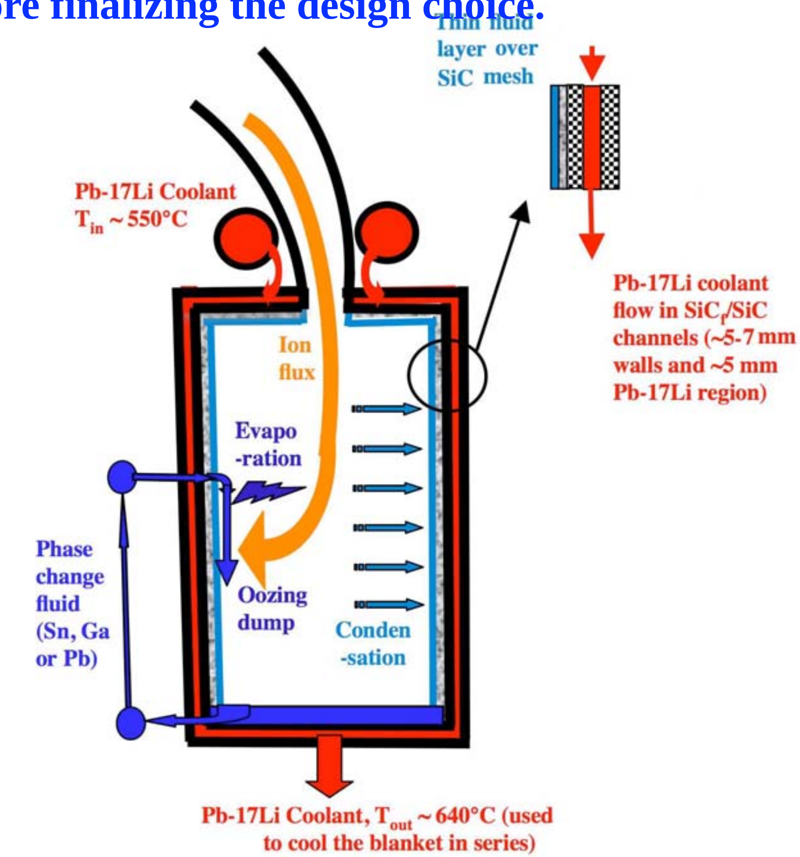
Evaporation/Condensation Studies for Bell Cusp

- **Three candidate fluids were considered for the dump chamber: Pb, Sn and Ga**

Fluid	Pb	Sn	G a
Density (kg/m^3)	11300	6919	5904
h_{fg} (J/kg)	$8.6x10^5$	$2.4x10^6$	$3.79x10^6$
Base temp.	500°C	500°C	500°C
Cp (J/kg-K)	142	300	370
k (W/m-K)	16	35	41
Melting point (°C)	327.6	232	29.8
Boiling point (°C)	1740	2270	2204
Energy to evap. (J/m^3)	$1.171x10^{10}$	$2.028x10^{10}$	$2.61x10^{10}$

- Sn and Ga have high latent heats; Sn is attractive because of its low vapor pressure, while Ga's low melting point would help to start up the dump chamber without having to heat and melt the liquid first.
- However, other factors including material compatibility would need to be considered before finalizing the design choice.





Conclusions

- There is a substantial world research program (≈ 2 \$B/y) to harness Fusion as a major environmentally friendly energy source in the 21st Century with nearly inexhaustible resources
- While most of the world program is concentrated on magnetically confined plasmas, the inertial fusion program will probably reach ignition and breakeven first
- Direct drive laser fusion has several attractive features for energy production
- On-going R&D activities are addressing the challenging technical issues for development of laser fusion energy