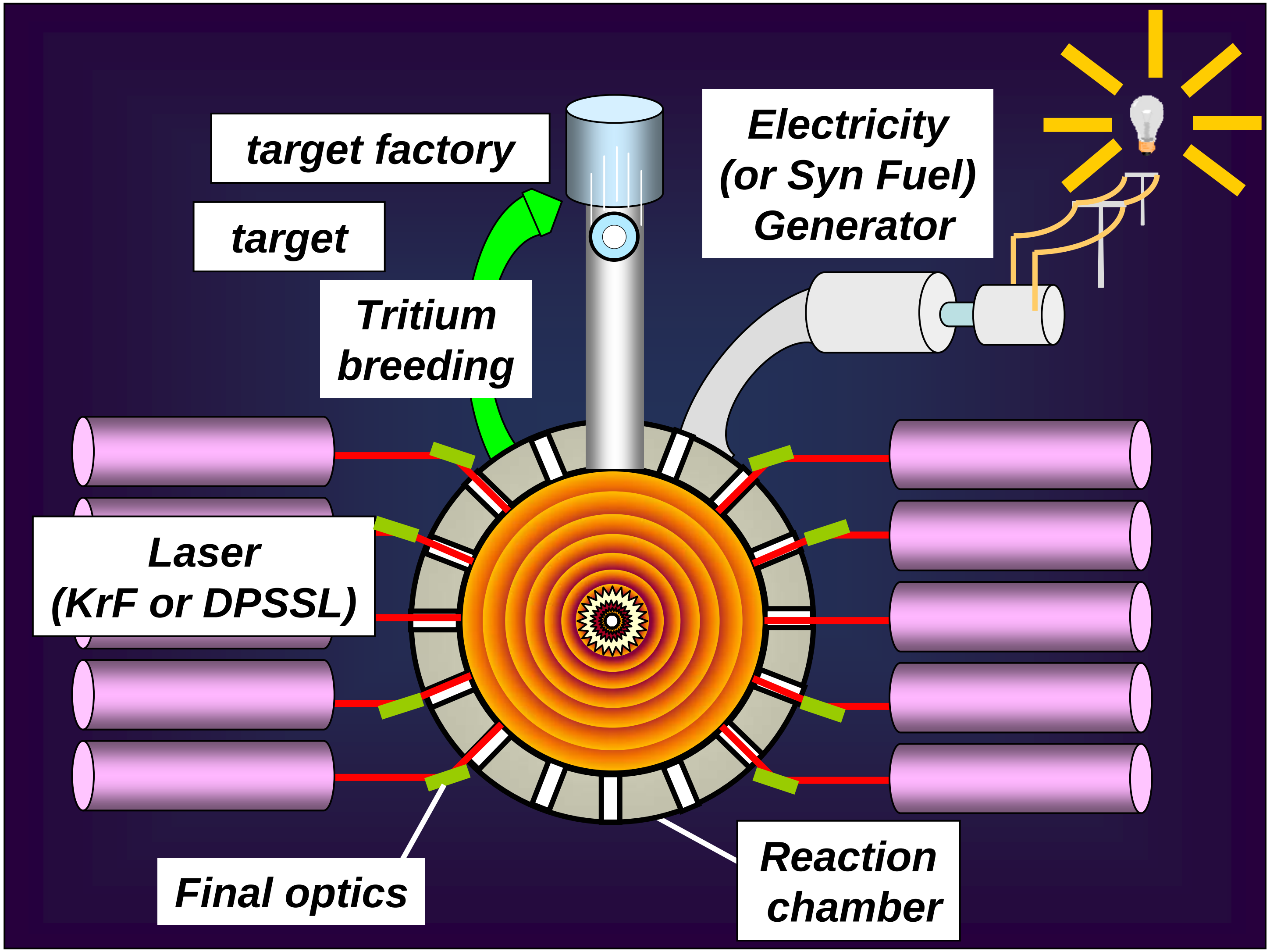
The Science and Technologies for Laser Fusion Direct drive

John Sethian
Naval Research Laboratory

June 15, 2010

19th HAPL meeting
Oct 22-23, 2008
Madison WI
54 participants, 20 institutions 10 students

Fusion Energy with Lasers and Direct Drive



Summary

1. We have carried out an integrated program to develop the science and technology basis for IFE, based on the simplicity and higher performance potential of laser direct drive

2. We developed credible approaches for most all the key components
   a. Lasers
   b. Final Optics
   c. Target Fabrication
   d. Target Injection
   e. Target Engagement
   f. Chamber Technolgies
   g. Auxilliary systems (tritium processing, vacuum, maintenance)

3. Many of these were demonstrated in subscale experiments.

Outline

1. NRL advocates phased, competitive approach to fusion energy (reprise)
   a. Phase I: Demonstrate principles with sub scale components
   b. Phase II: Full Scale Components
   c. Phase III: Integrated, fusion test facility

2. Business model for the HAPL Program
   a. Multi institutional
   b. Value: simplicity, durability, cost, ability to test on small scale
   c. Emphasis on experimental verification

3. Development of key components:
   a. Options considered
   b. Basis for choice
   c. Progress

4. Report Card
   1. What have we done
   2. What do we still need to demonstrate to go to Phase II

High Average Power Laser Program (HAPL) History

- *FY 1999 & FY 2000:* Lasers only: KrF and DPSSL
- *FY 2001 - March 11, 2009:* Lasers plus key components
  - Equal resources to KrF and DPSSL lasers
  - Sponsored by NNSA, following Congressional Direction

- HAPL PROGRAM NUMBERS
  - 19 Meetings
  - > 30 institutions participated
    - National Labs, Industry, Universities, Small Businesses, DoD Lab
  - ~ 31 Students (16 PhDs)
  - > 15 awards from fusion community
  - > 210 Archival Referred Publications

- Direct Drive Target R&D:
  - NRL: KrF laser IFE target designs/experiments (NOT UNDER HAPL)
  - LLE : Glass laser ICF/IFE designs/experiments (NOT UNDER HAPL)
  - LLNL: KrF and DPSSL (glass) based IFE target designs
  - Wisconsin: IFE target designs

HAPL "Business Model" for IFE development

1. Develop science & technology as an integrated system

2. Managed by one institution, partnership among many.
    a. Synergies with other fusion approaches
    b. Engage non fusion community (e.g. materials)
    c. Encourages alternative views, avoids "groupthink"

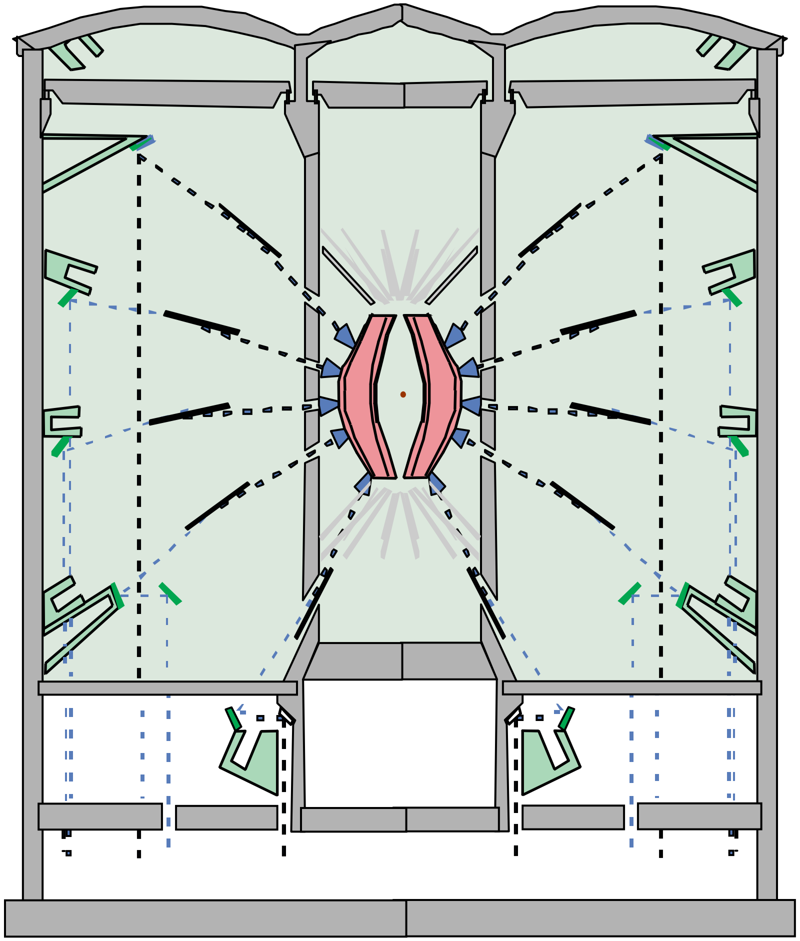
3. Valued: Simplicity, Durability, and Performance.
    a. Including COST TO DEVELOP

4. Developed maintenance /servicing concepts
    a. Enough to assess viability

5. Experimental Verification of Concepts

The Sombrero Power Plant study gave economic guidance, and a starting point

Sombrero: Fusion Technology, **21**,1470, (1992)

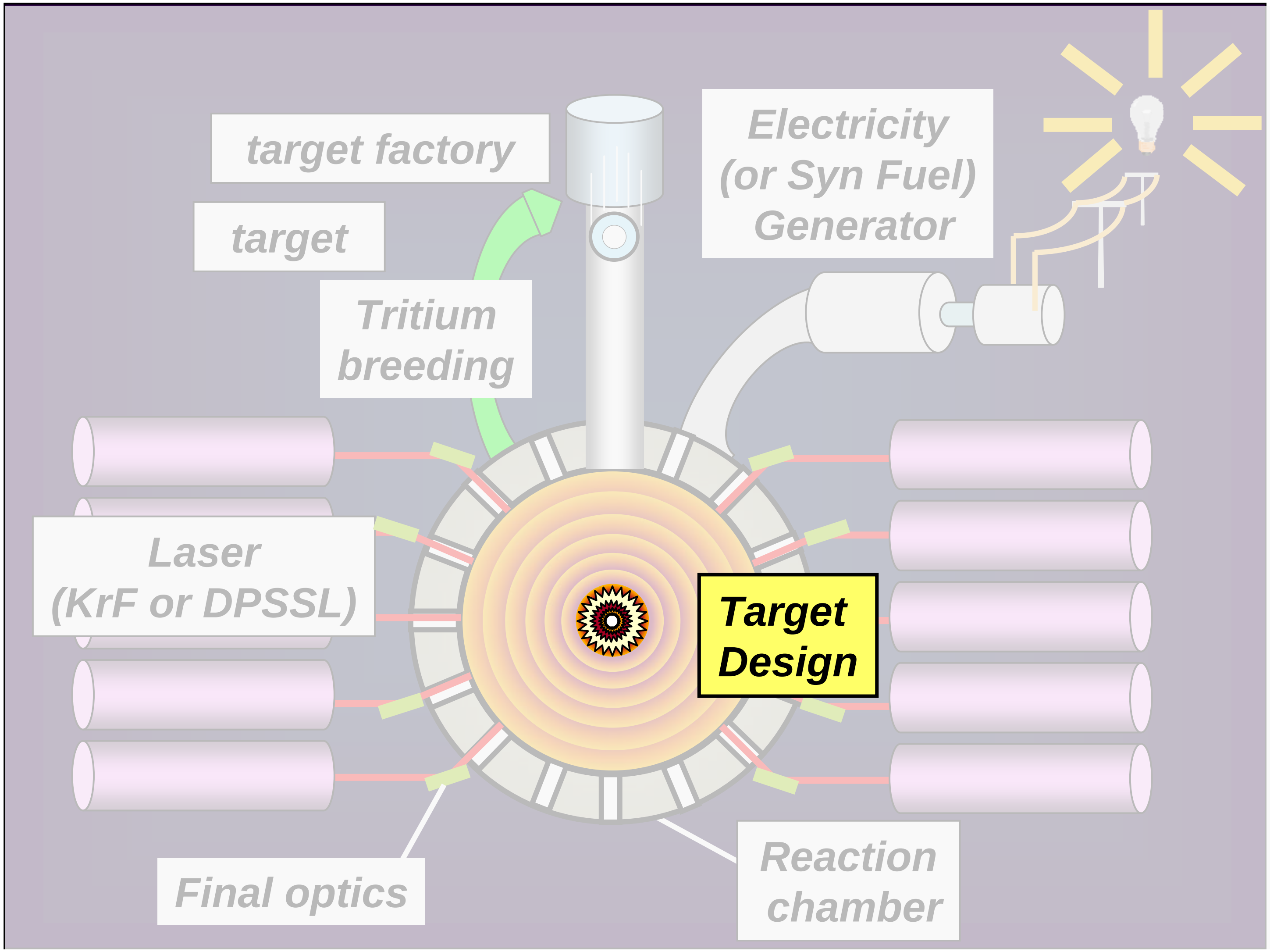


1000 MWe,
Gain 110
Cost of Electricity: $0.04-$0.08/kWh

System efficiency	**6-7%**
Cost of entire laser(1)	**$225/J(laser)**
Cost of pulsed power(1)	**$5-10/J(e-beam)**
Rep-Rate	**5 Hz**
Durability (shots) (2)	**3 x 10^8**
Lifetime (shots)	**10^{10}**

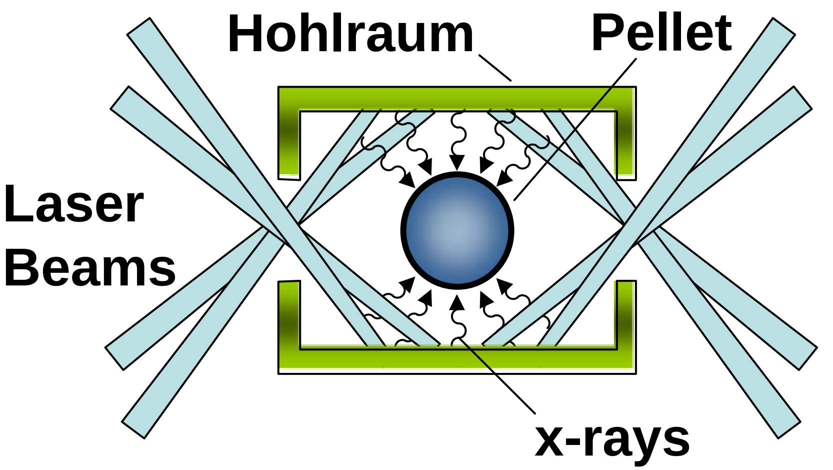
1. 1999 $. Sombrero (1992) gave $180/J and $4.00/J
2. Shots between major maintenance (2.0 years)

HIGH GAIN TARGET DESIGN



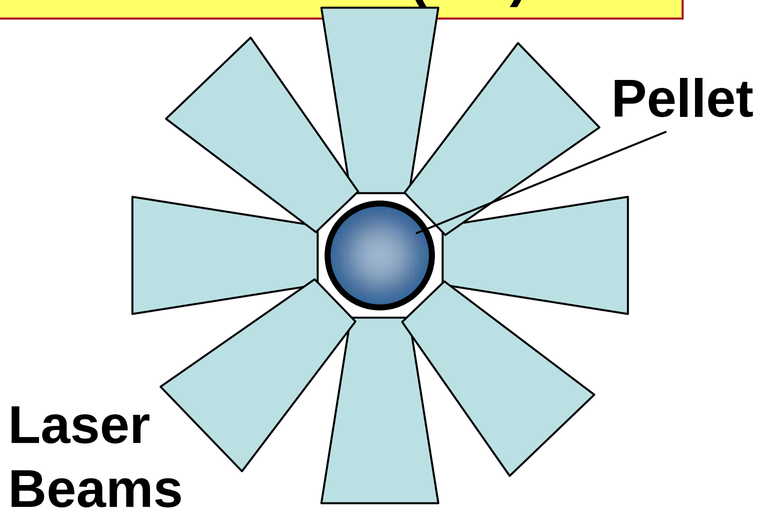
We chose Direct Drive for IFE (Research in US by NRL and LLE)

Indirect (path chosen for NIF)



- Inefficient illumination on target
  - Lasers to x-rays
- More complex physics
- Relaxed laser uniformity requirements

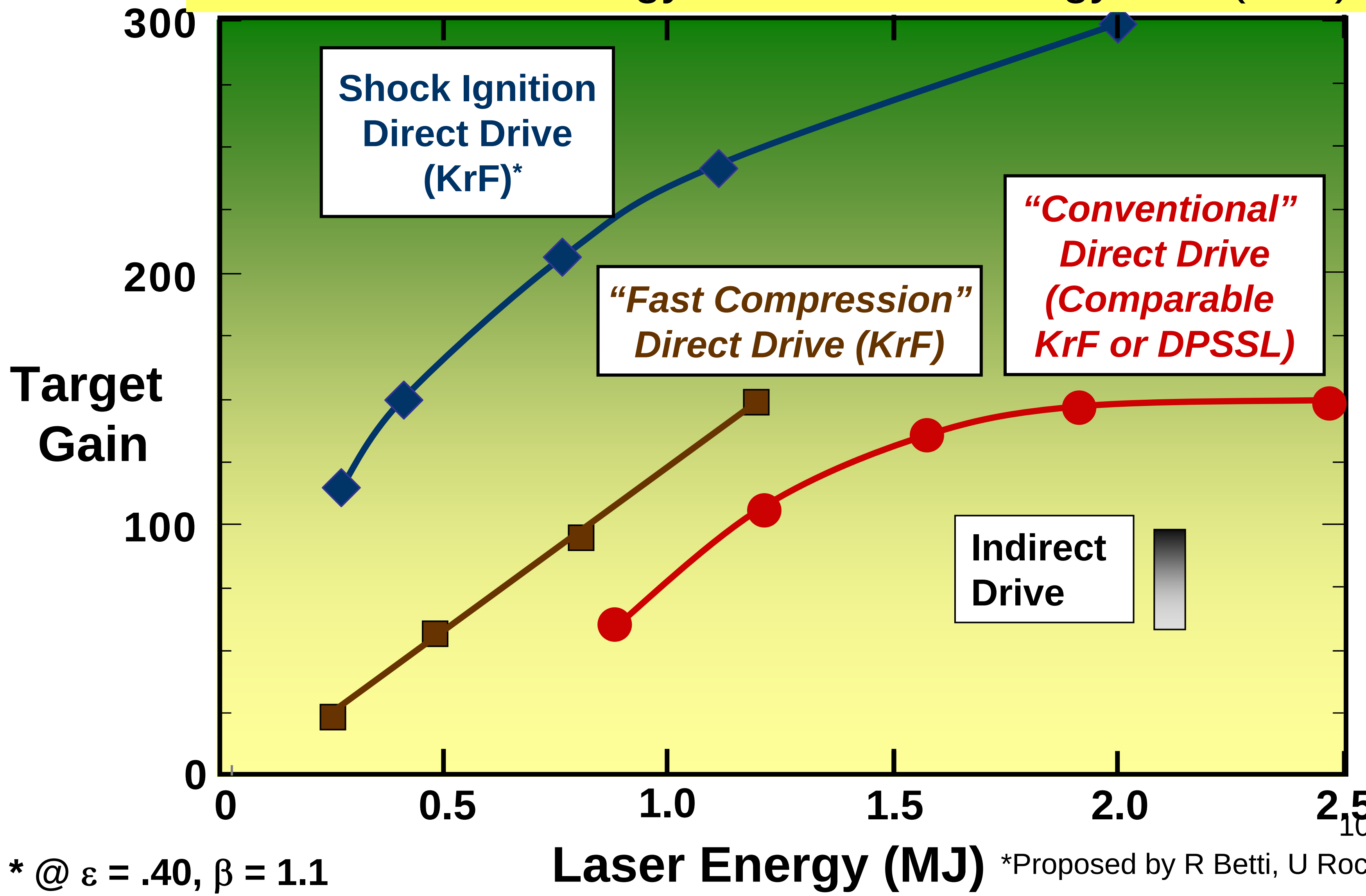
Direct Drive (IFE)



- Efficient illumination
- Simpler physics
- Advances in lasers and target designs overcome uniformity requirements

Direct Drive designs predict higher gain than Indirect Drive. KrF predicts higher gains than DPSSL (glass)

Gain = Fusion Energy "out"/Laser Energy "in" (ROI)

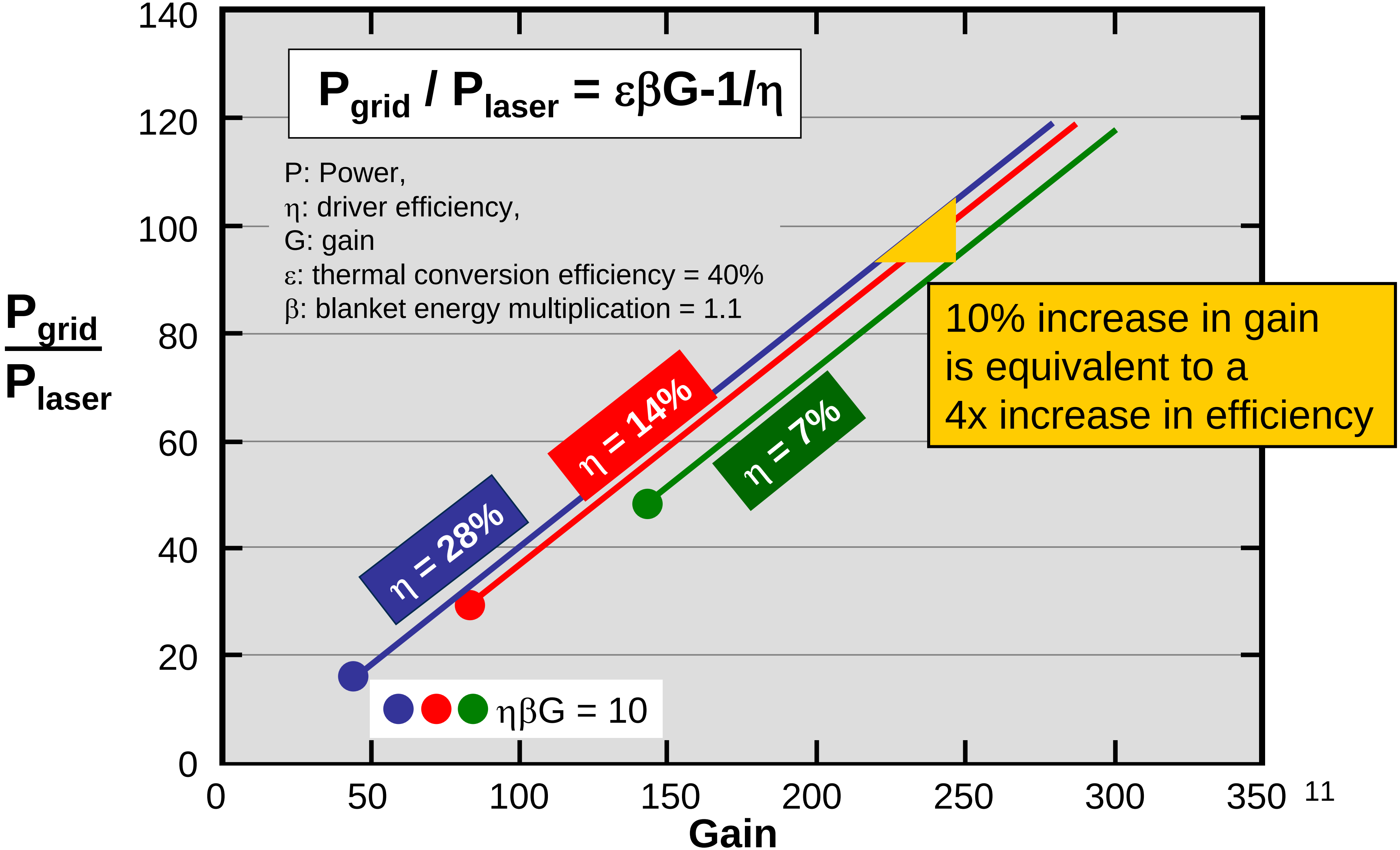


* @ ε = .40, β = 1.1

*Proposed by R Betti, U Rochester

Benefits of higher gain (G):

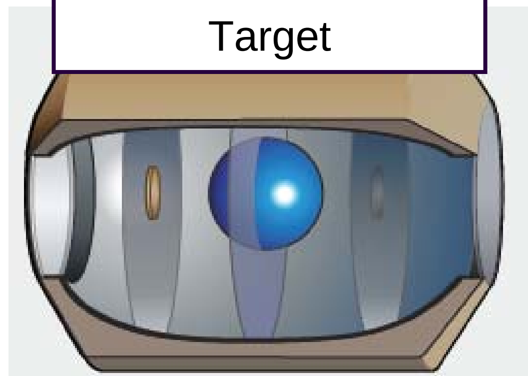
1) More electrical power output for smaller (lower cost) driver
2) Gives more robust margin
3) Bigger lever than efficiency



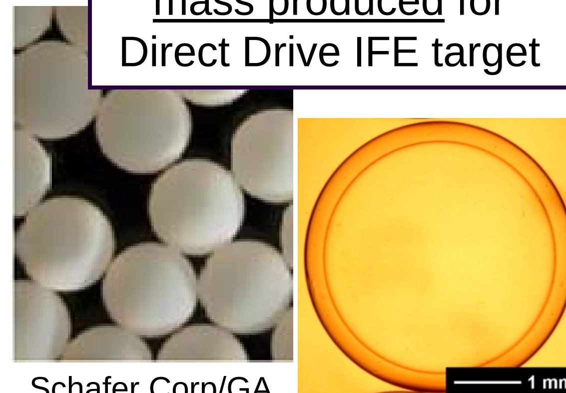
Direct Drive: targets less expensive, easier to recycle

1. Simpler Target Fabrication

Concept for Indirect Drive IFE* Target



Foam shells, mass produced for Direct Drive IFE target



Schafer Corp/GA

* J. Latkowski, NAS Panel Presentation, 29 Jan, 2011

2. Lower estimated cost

(Chart from D.T. Goodin, NAS Panel Presentation, 30 Jan, 2011)

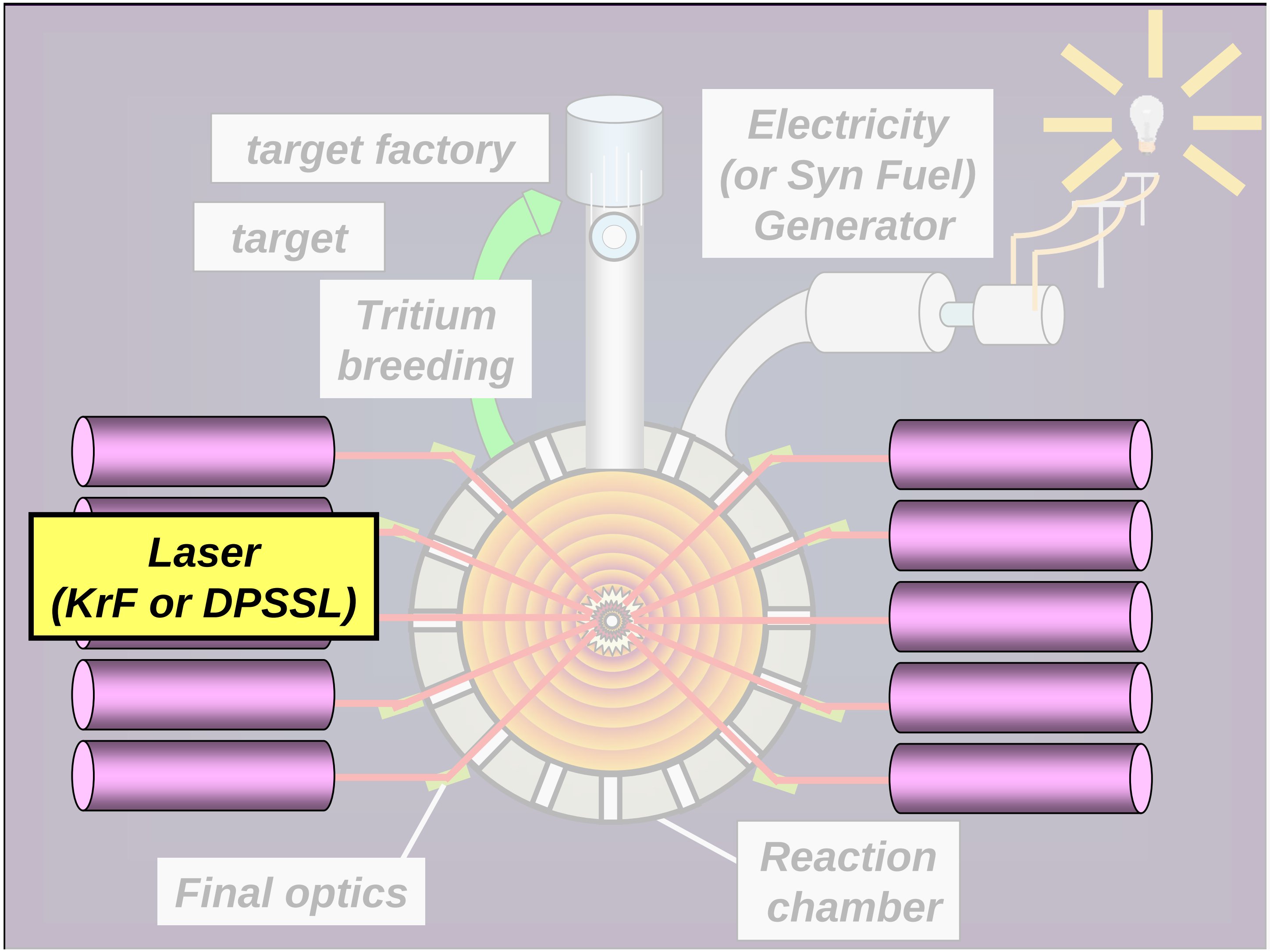
IFE Concept	Target Design	Target Yield (MJ)	Est'd Cost/target for 1000 MW(e)	% of E-value
Laser Fusion	Direct drive foam capsule	~400	$0.17	~6
LIFE	Indirect drive Pb rugby hohlraum	~132	~$0.30	~30

3. Less material to recycle

Direct Drive constituents: D, T, H, C, plus 0.00013 g Au/Pd = 44 lb/year @ 5 Hz

Indirect Drive constituents: D, T, H, C, plus 1.3 g Pb = 1,168,000 lb/year @ 13 Hz

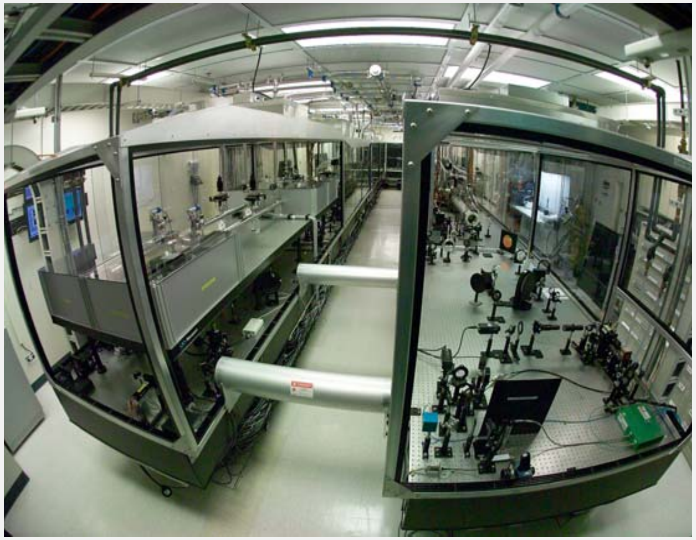
LASERS


target factory
target
Electricity
(or Syn Fuel)
Generator
Tritium
breeding
Laser
(KrF or DPSSL)
Final optics
Reaction
chamber

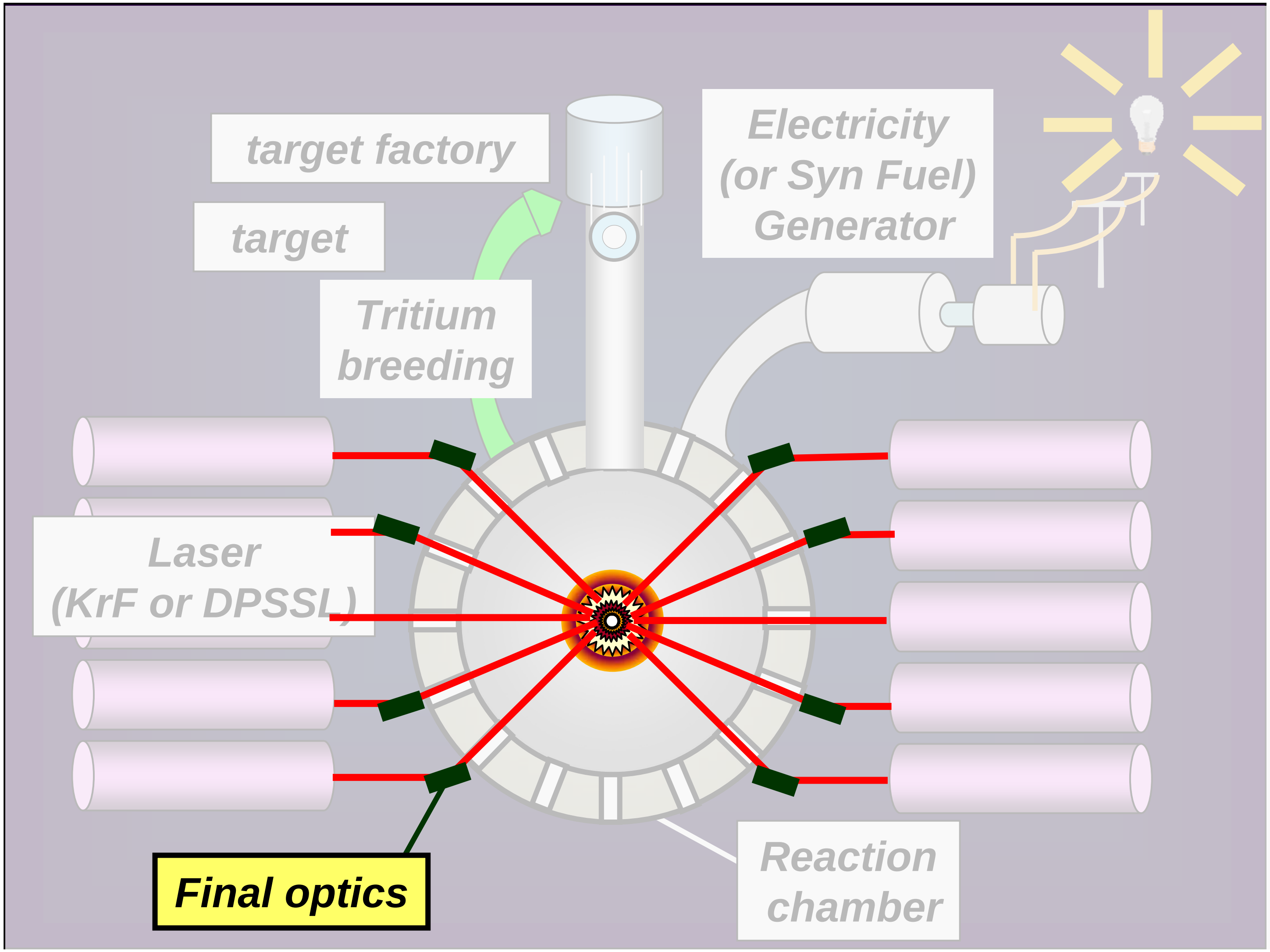
Two laser options for Direct Drive.
Both have potential to meet the IFE requirements

Electra KrF Laser (NRL)
λ = 248 nm (fundamental)
Gas Laser

Mercury DPSSL Laser (LLNL)
λ = 351 nm (tripled)
Solid State Laser

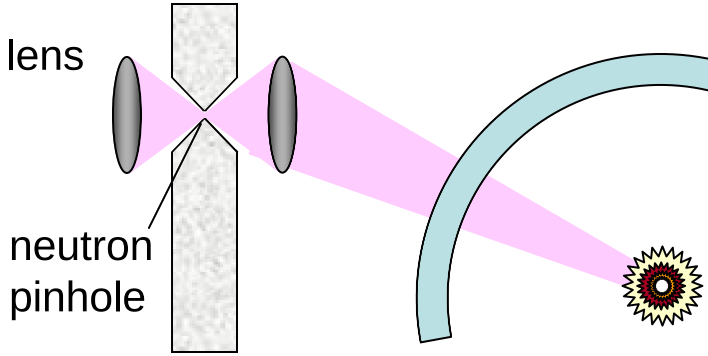


FINAL OPTICS



Final Optic Options evaluated

Lens plus pinhole



Good:

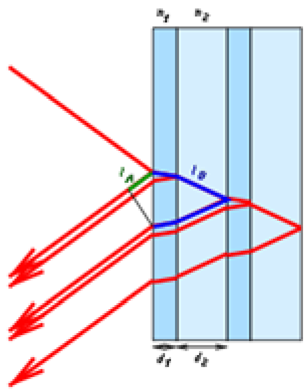
- ♦ Neutron damage annealed > 500 °C

(351 nm only)

Challenge:

- ♦ No KrF material identified
- ♦ Fielding large, heated, thin, optic
- ♦ Pinhole may constrain target optics
- ♦ Long term residual damage?

Dielectric Mirror



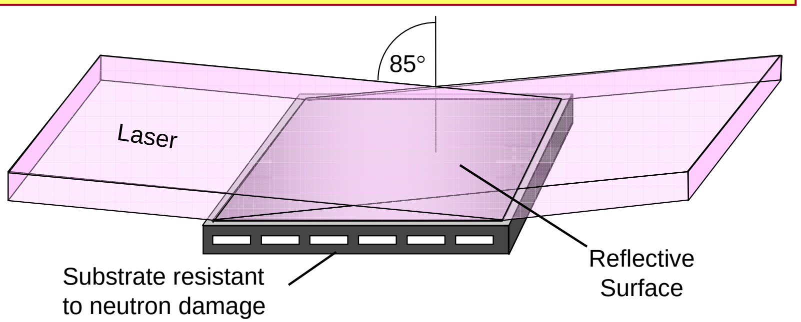
Good:

- ♦ Very high reflectivity
- ♦ High laser damage threshold

Challenge:

- ♦ Literature shows neutron damage

Grazing Incidence Metal Mirror



Good:

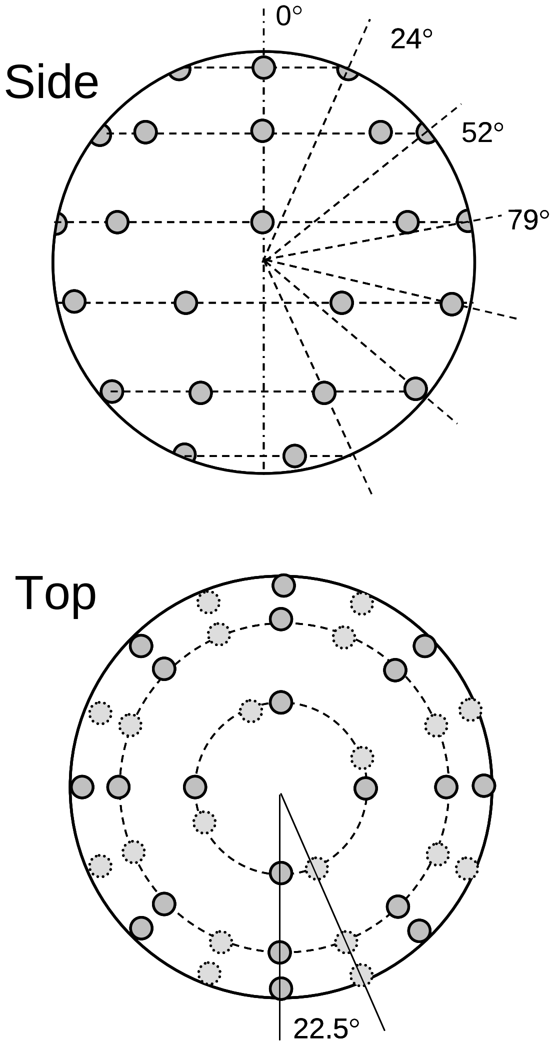
- ♦ Can make base resistant to neutrons

Challenges:

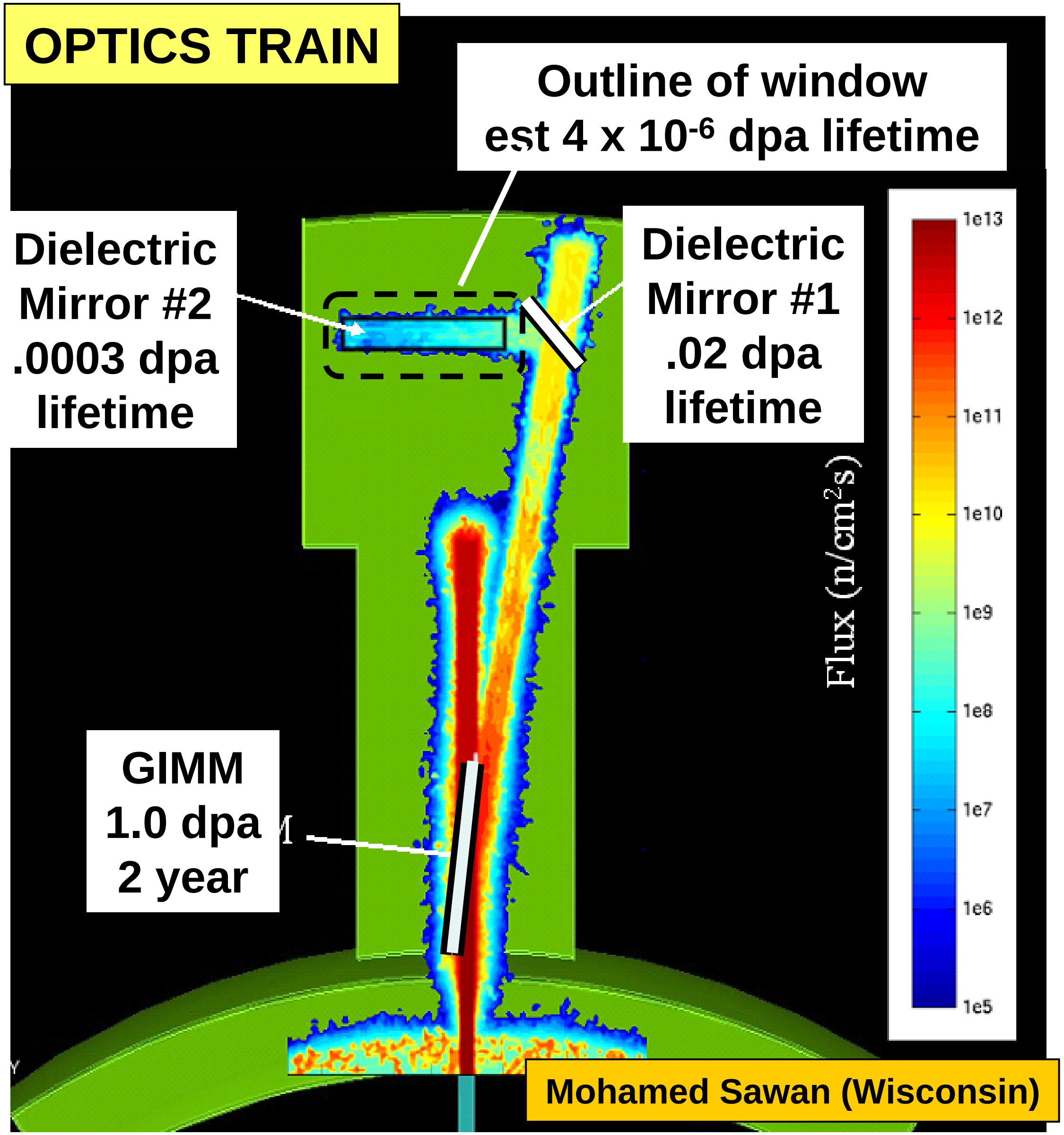
- ♦ Laser damage threshold unknown
- ♦ Large optic

Chamber Ports and Optical Train

PORT POSITIONS

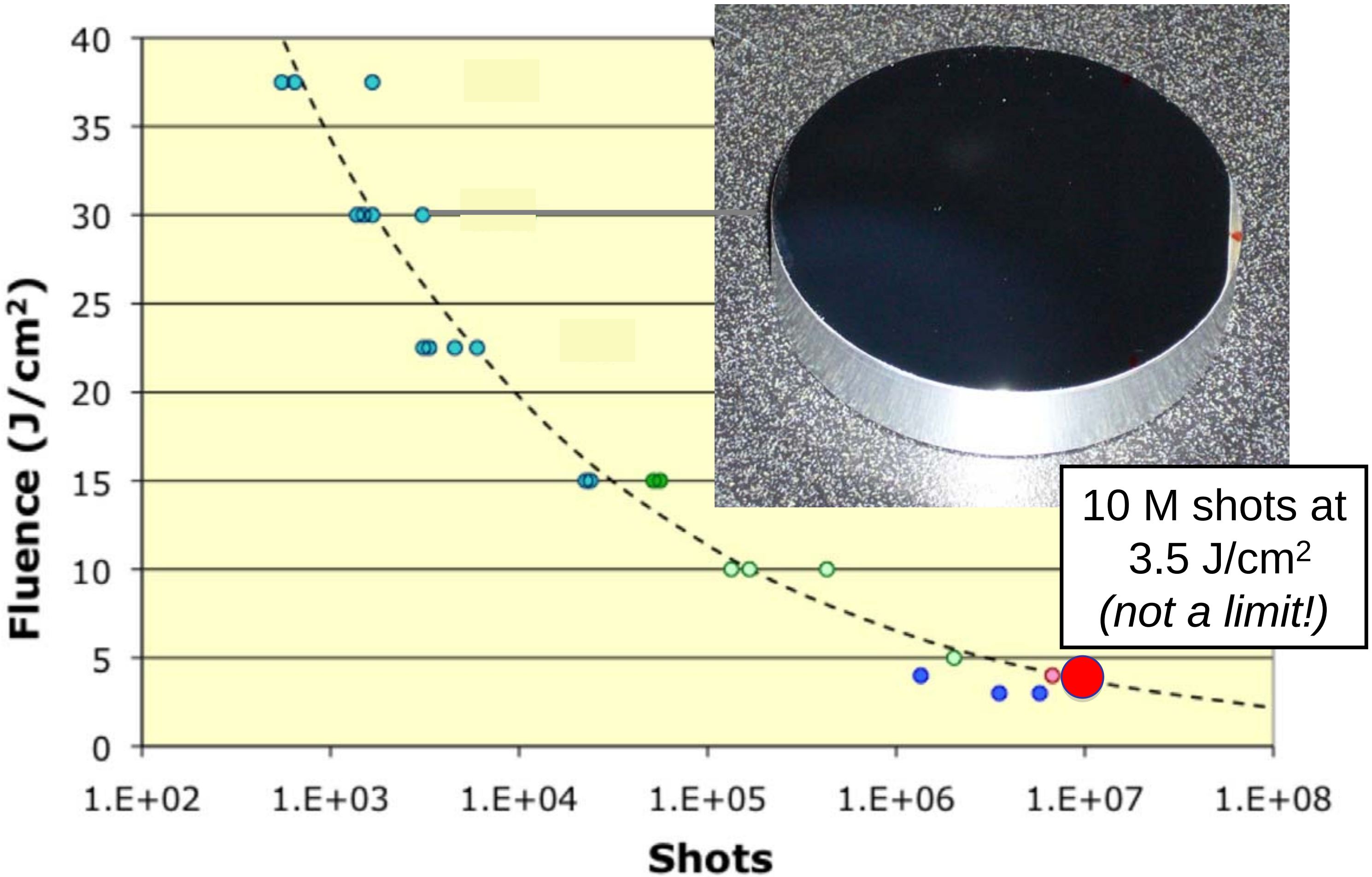


OPTICS TRAIN



Mohamed Sawan (Wisconsin)

GIMM laser damage threshold:
> 3.5 J/cm^2 @ 10 M shots



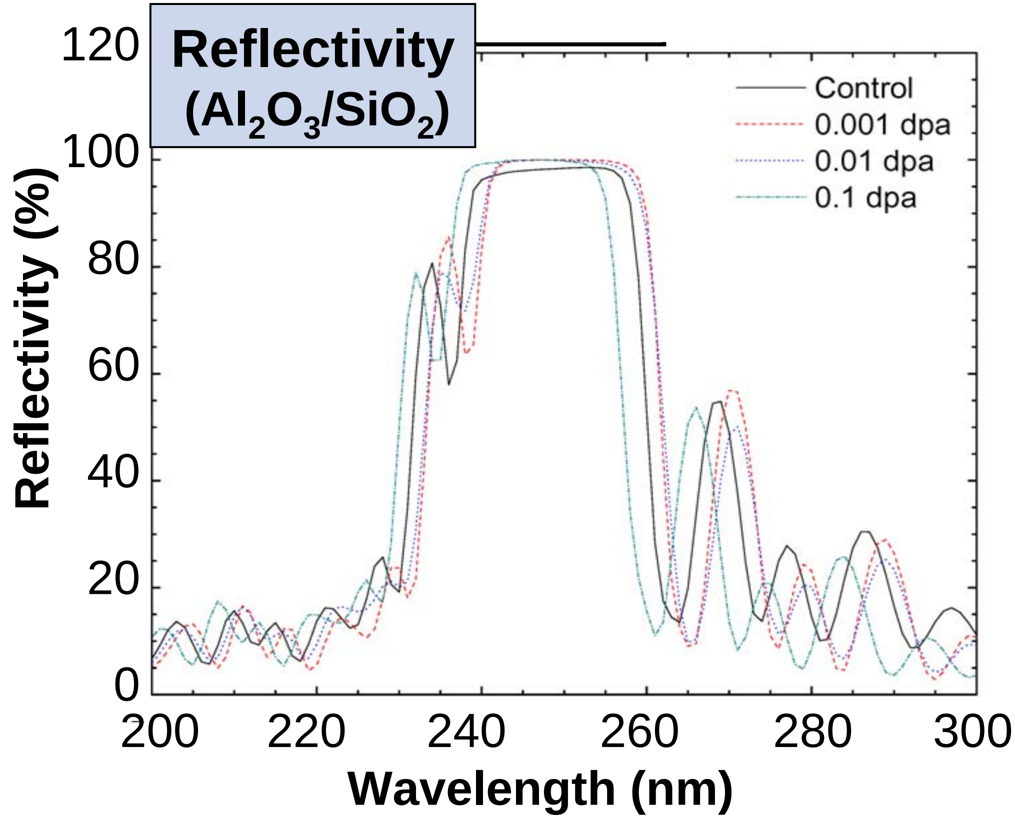
Mark Tillack (UCSD)

First dielectric mirror predicted to be subject to 0.02 dpa. New dielectric design exceeds this by at least 5 x.

The "key":
- **Match neutron-induced swelling in substrate and mirror layers**

Experiment:
- **Expose in HIFR (ORNL Reactor)**
- **Prototypical fluence, temperature**

Measurements:
- **Reflectivity**
- **Laser damage threshold**

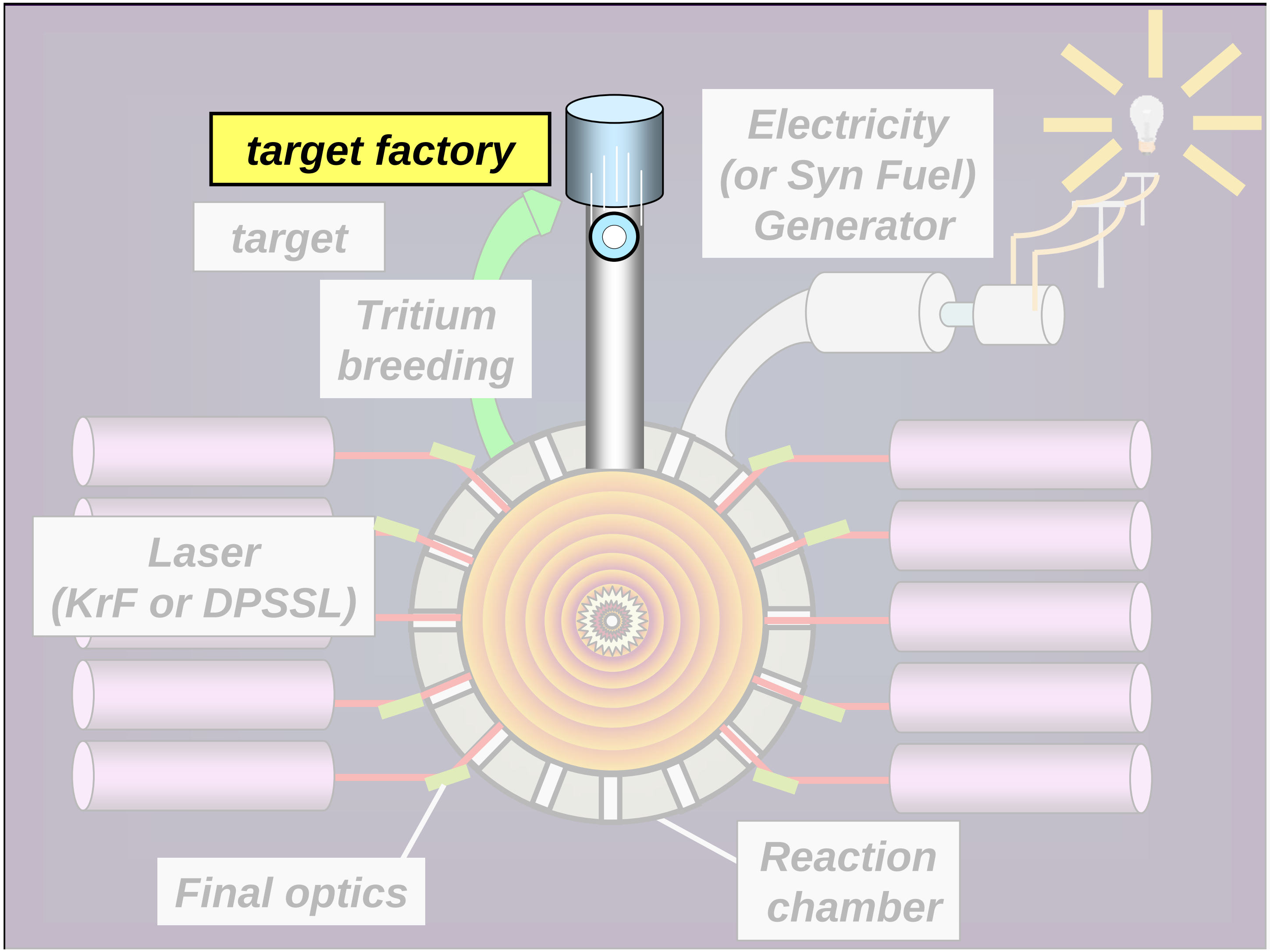


Laser Damage Threshold (Al_2O_3/SiO_2)

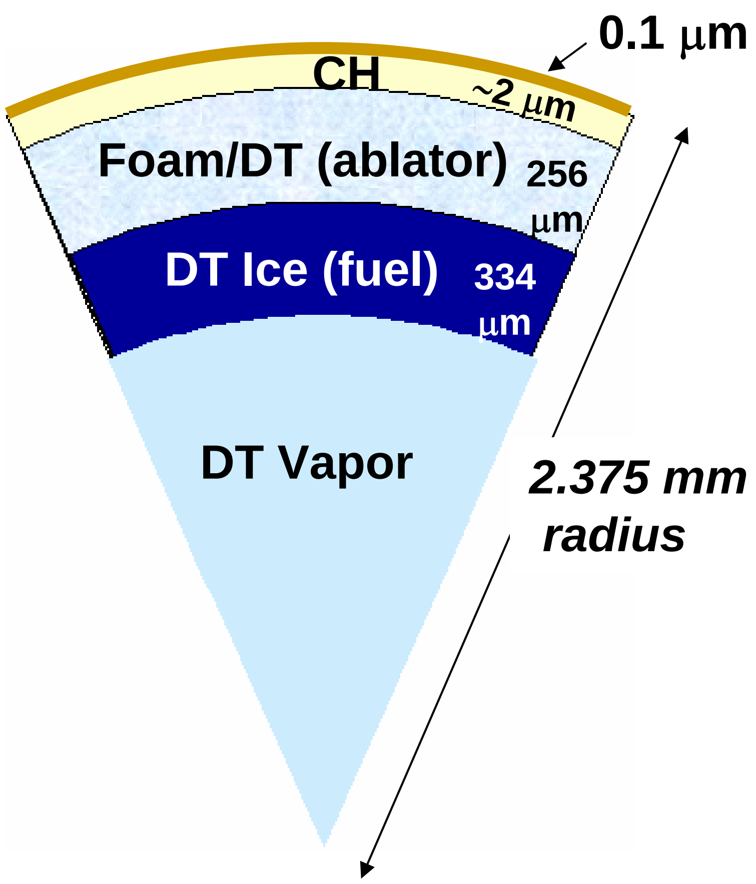
No dpa	0.001 dpa	0.01dpa	0.1 dpa
86-87%	84-86%	78-83%	83-84%

Lance Snead (ORNL)
Tom Lehecka (Penn State)
Mohamed Sawan (Wisconsin)

TARGET FABRICATION



Typical Direct Drive Target Components



Choices for foam shell

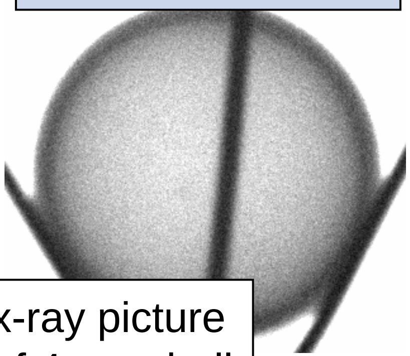
- Form in droplet generator by micro encapsulation
  - Apply CH overcoat after or during shell formation
- Lab on Chip (LLE)

Notes:
- dimensions vary by target
- foam is ~ 50-100 mg/cc
- can be DVB or RF

Target fabrication:

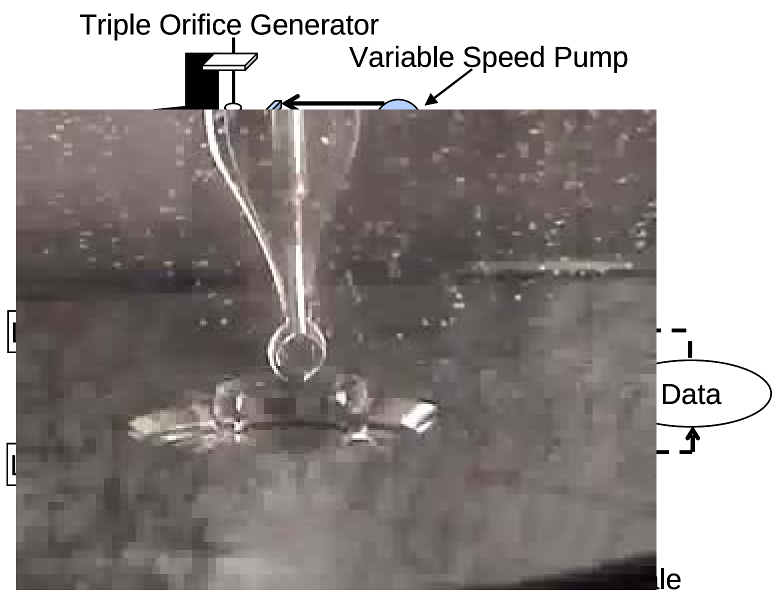
- Mass produce foam shells that meet specs
- Fluidized bed for mass cryo layering
- Estimate Cost < $0.17 each

Foam shells (100 mg/cc)



x-ray picture of 4mm shell

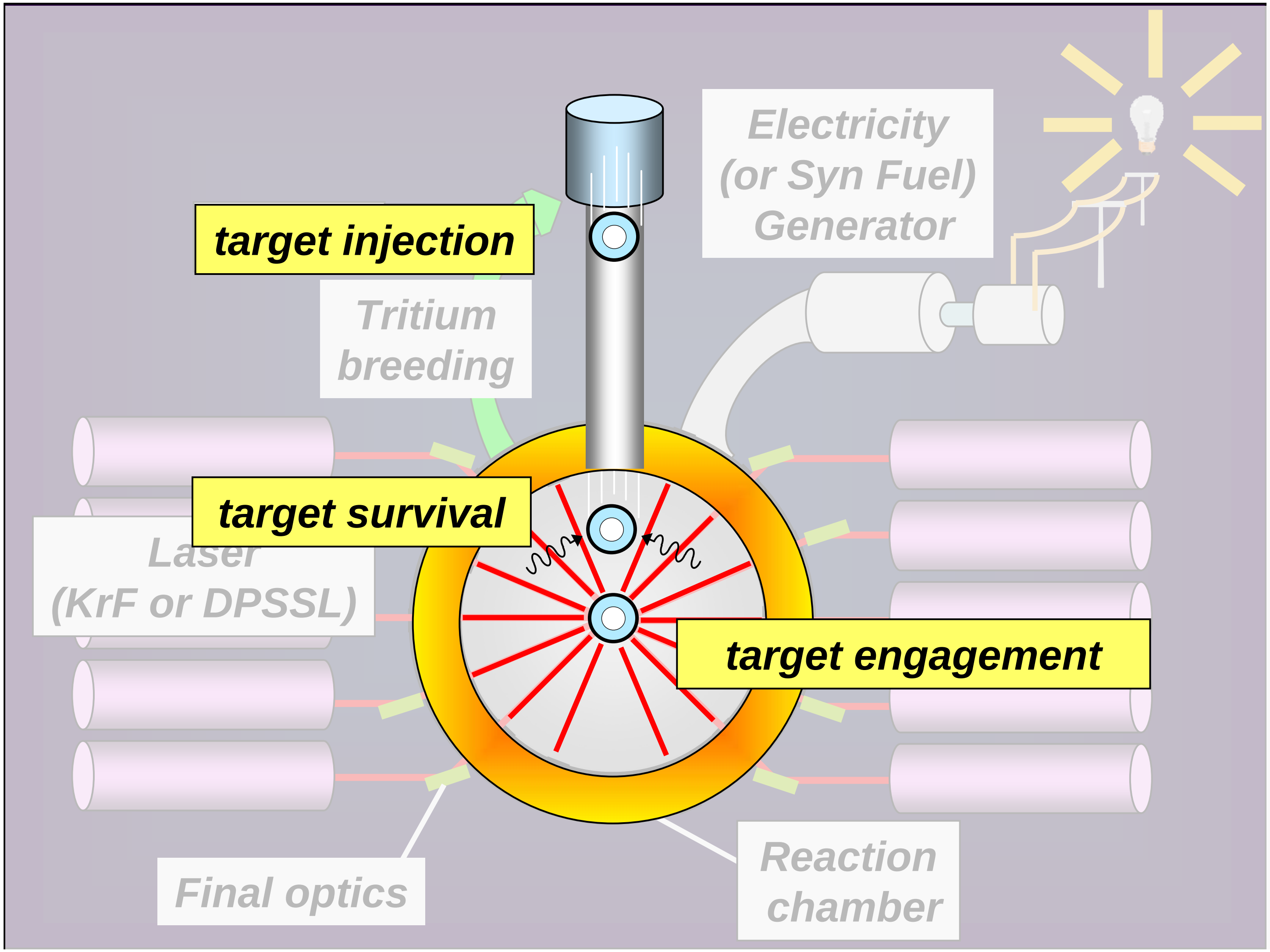
Mass Production: 22 shells/min



Cryogenic Fluidized bed to make smooth DT ice

GA, Schaffer, UCSD

TARGET:
INJECTION, SURVIVAL, and ENGAGEMENT



Target Injection choices we made

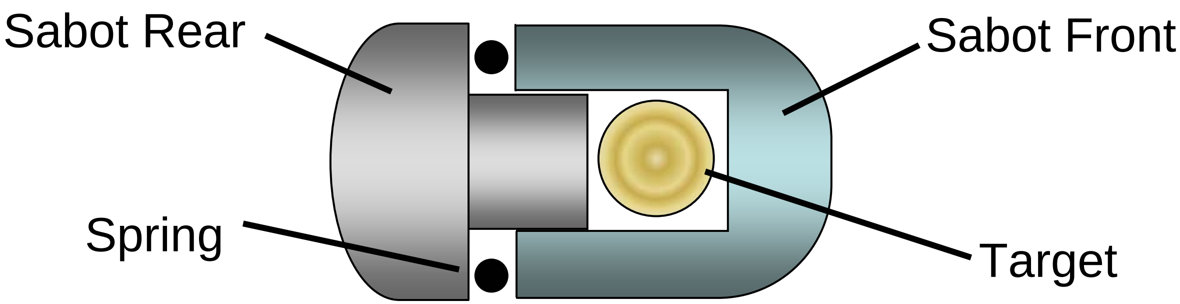
1. Light Gas Gun. Cryogenically cooled sabot	Sabot *mechanically* diverted in muzzle	Target placed within 10 mm of chamber center
2. Electromagnetic Launcher. Superconducting Sabot	Sabot *magnetically* diverted in muzzle	Engagement system does final pointing

Light Gas Gun Prototype Injector

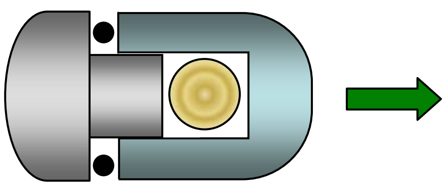
- Demonstrated 5 Hz operation
- Achieved required 400 m/sec
- Demonstrated separable sabot (and recovery)
- Target placement accuracy +/-10 mm

General Atomics

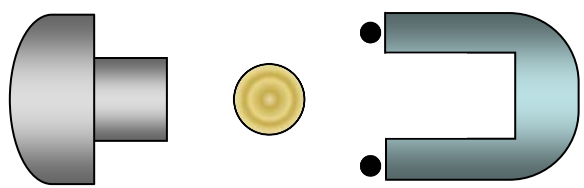
Demonstrated in flight sabot separation and capture



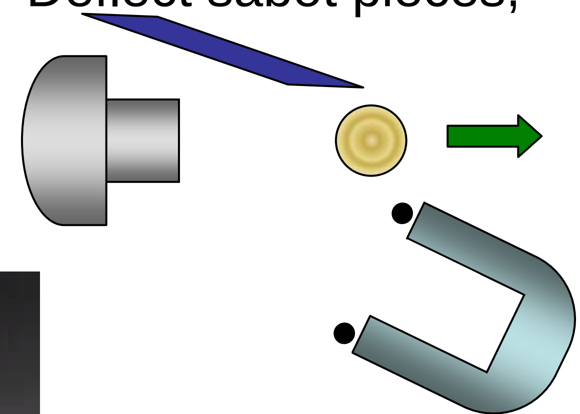
STEP 1
Launch



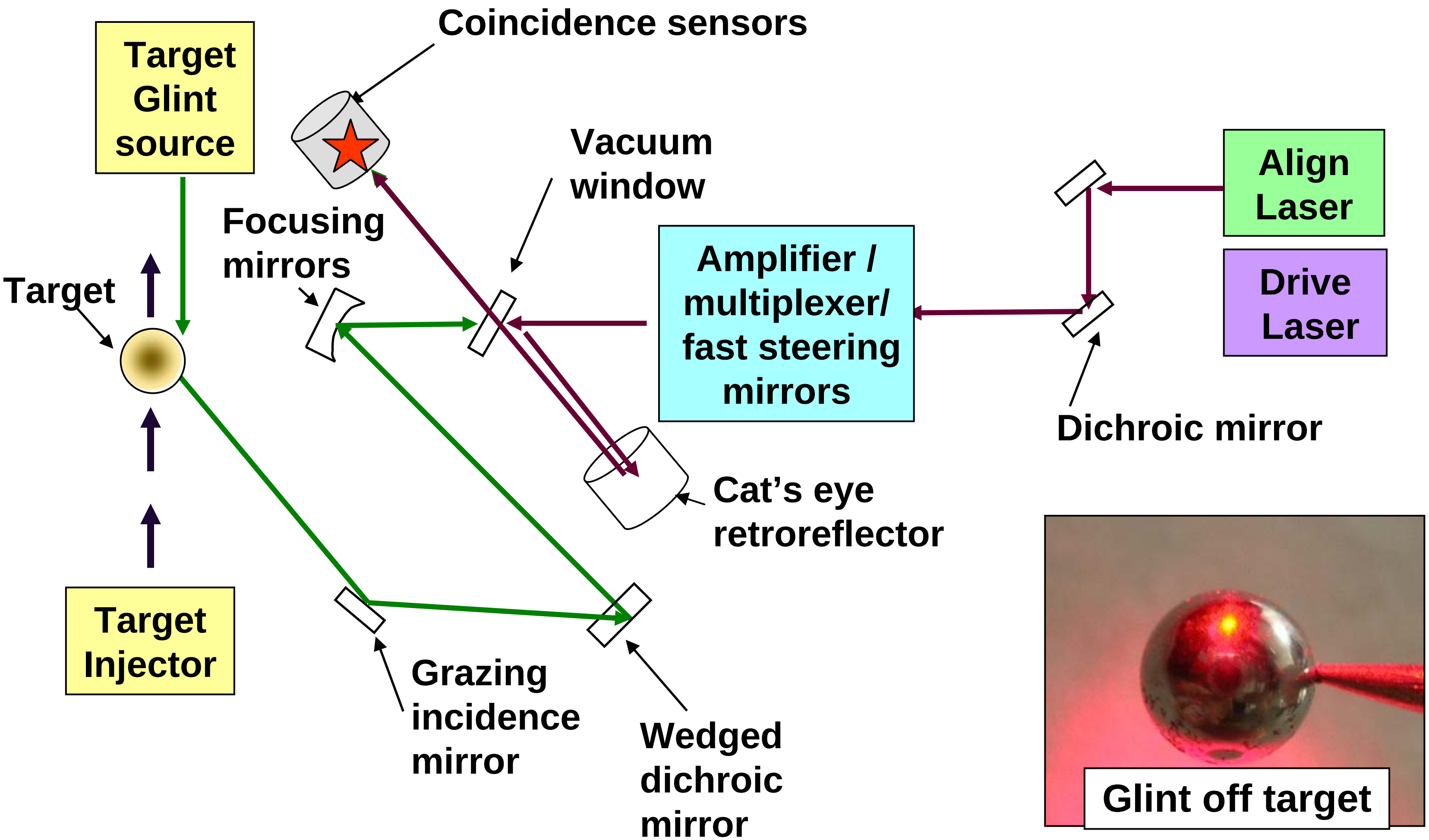
STEP 2
In flight separation



STEP 3
Deflect sabot pieces,

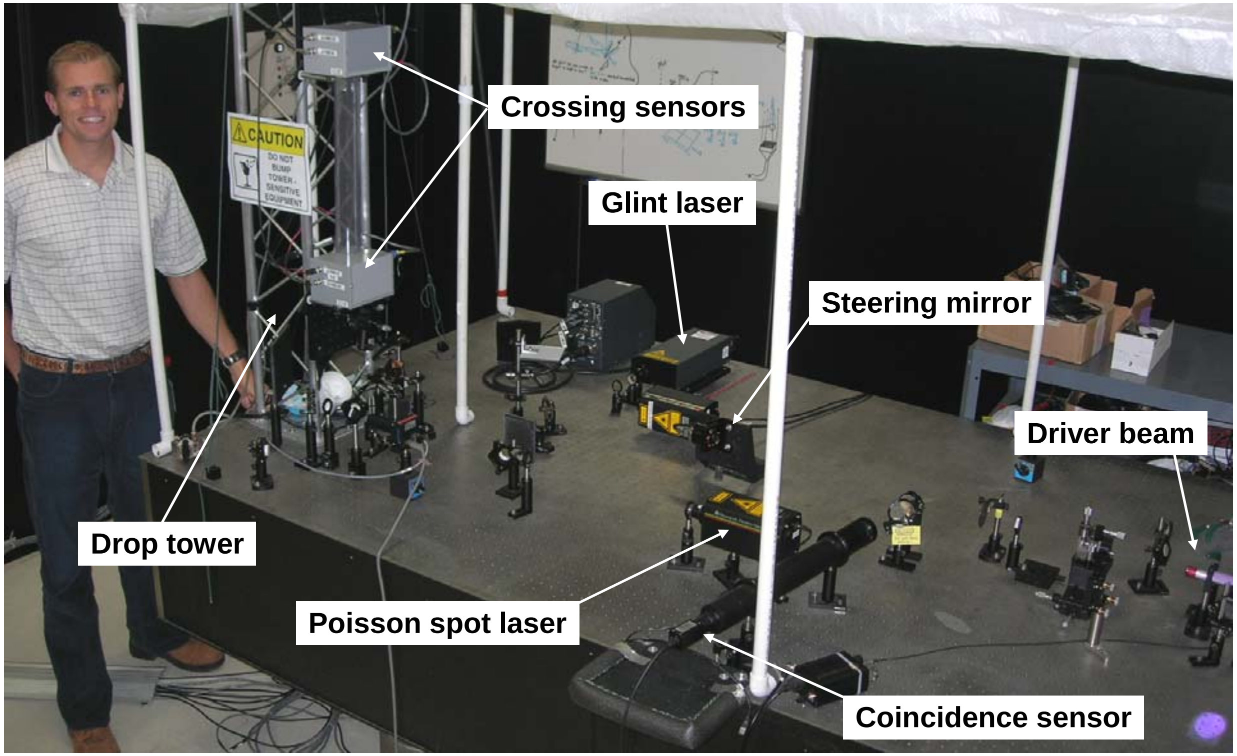


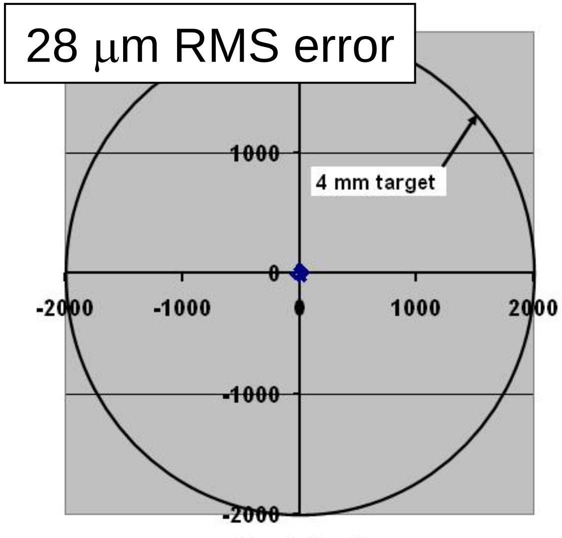
Target Engagement:
Concept based on detecting "Glint" off the target.



Lane Carlson (UCSD)
General Atomics

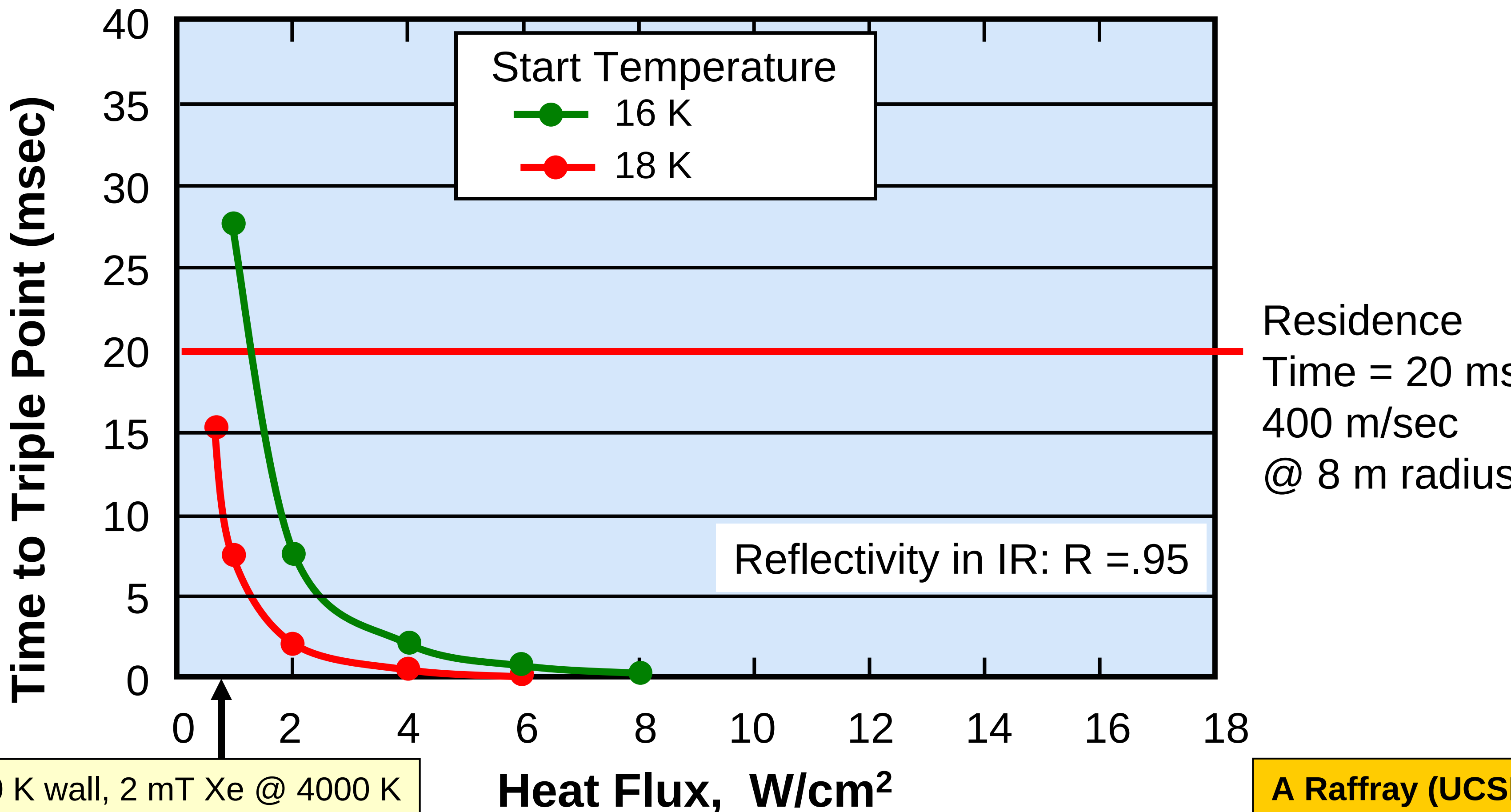
Target Engagement: Bench test: Mirror steers laser beam to target within 28 um. Need ~20





Lane Carlson (UCSD)
General Atomics

Calculations shows Direct Drive Targets can “survive” injection into the chamber



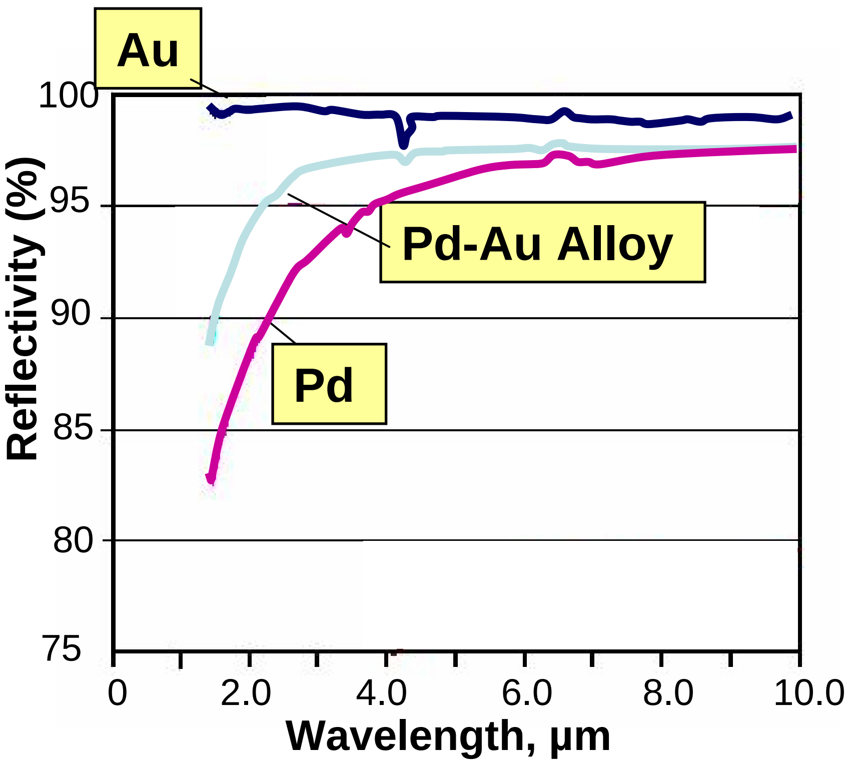
800 K wall, 2 mT Xe @ 4000 K
expected flux = 0.8W/cm^2

A Raffray (UCSD)

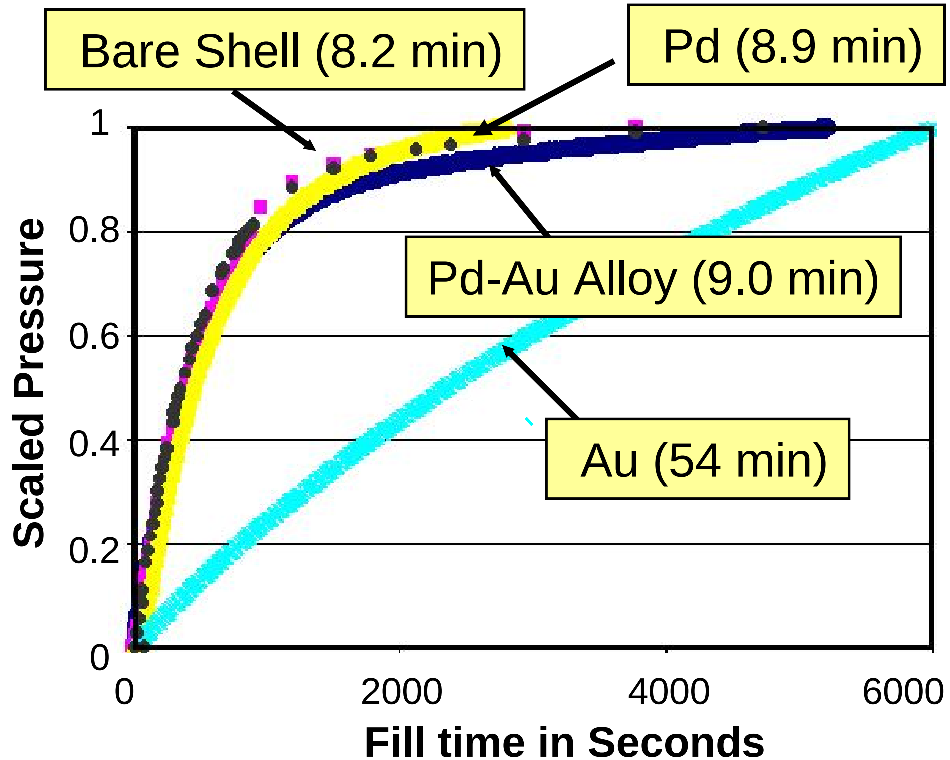
Questions:
- Can get R > .95?
- Can we start at 16 K?
- Is triple point the limit?... Could it be higher

Pd/Au coating meets requirement for R > .95 (high IR reflectivity) and high DT permeability

IR Reflectivity:
Pd-Au comparable to Au



Permeability:
Au-Pd similar to Pd



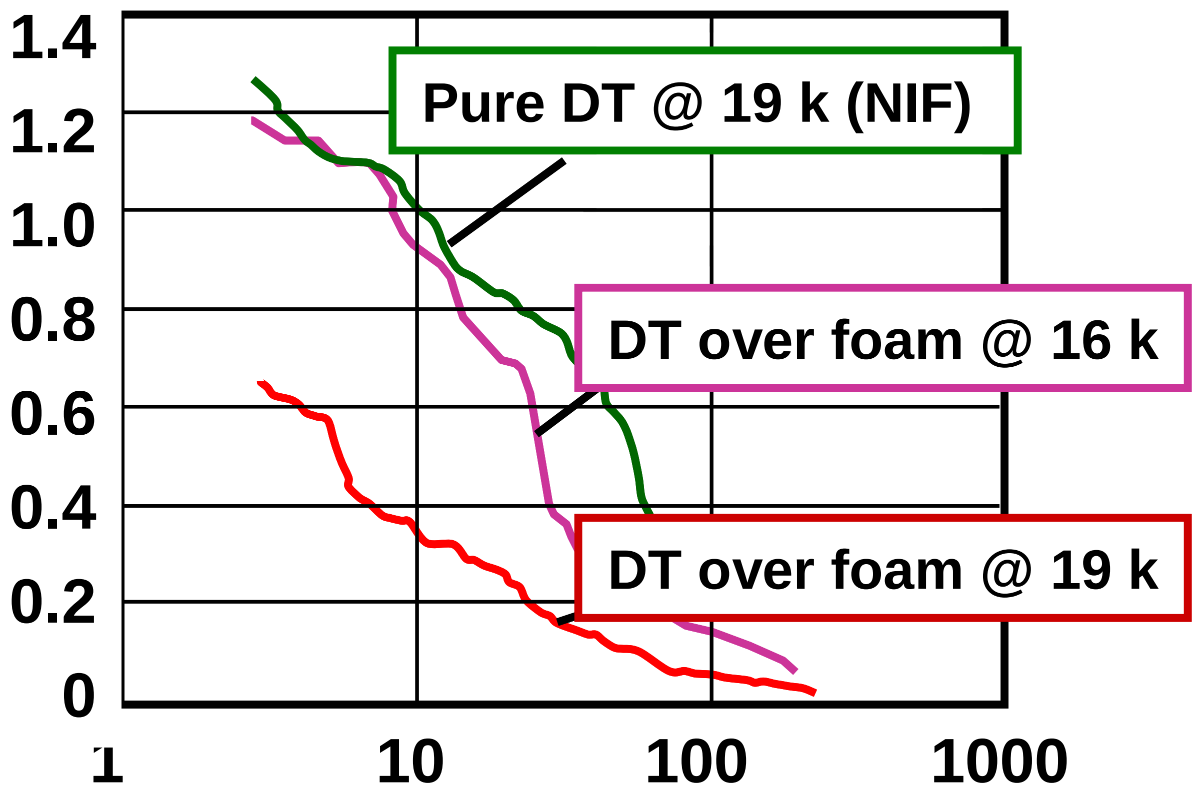
General Atomics

Experiments:
Initial target temperature can be at least as low as 16 °K

DT ice layer over foam demonstrated to be smoothest, thermally robust

Allows warm up of ~ 3° during injection without compromising DT ice layer

Cumulative Reverse Spectra RMS (μm) vs L Mode number

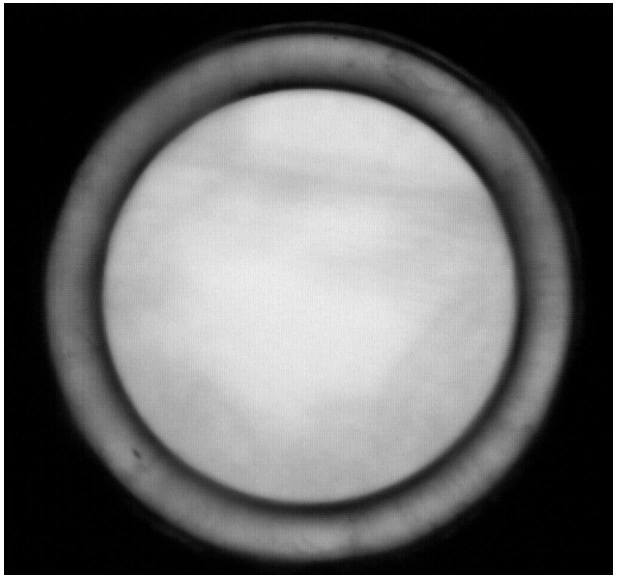


J. Hoffer and D Geller (LANL)

First Experiments: D-T layer subjected to rapid heat flux suggests target should survive injection.

Start:

Pure DT Ice layer
460 μm thick
@ 19 °K
No foam, high start temp, no IR protection



Heat (applied electrically):

0.5 W/cm^2
~60% of prototypical heat flux*

Response:

Layer degrades at 20 msec

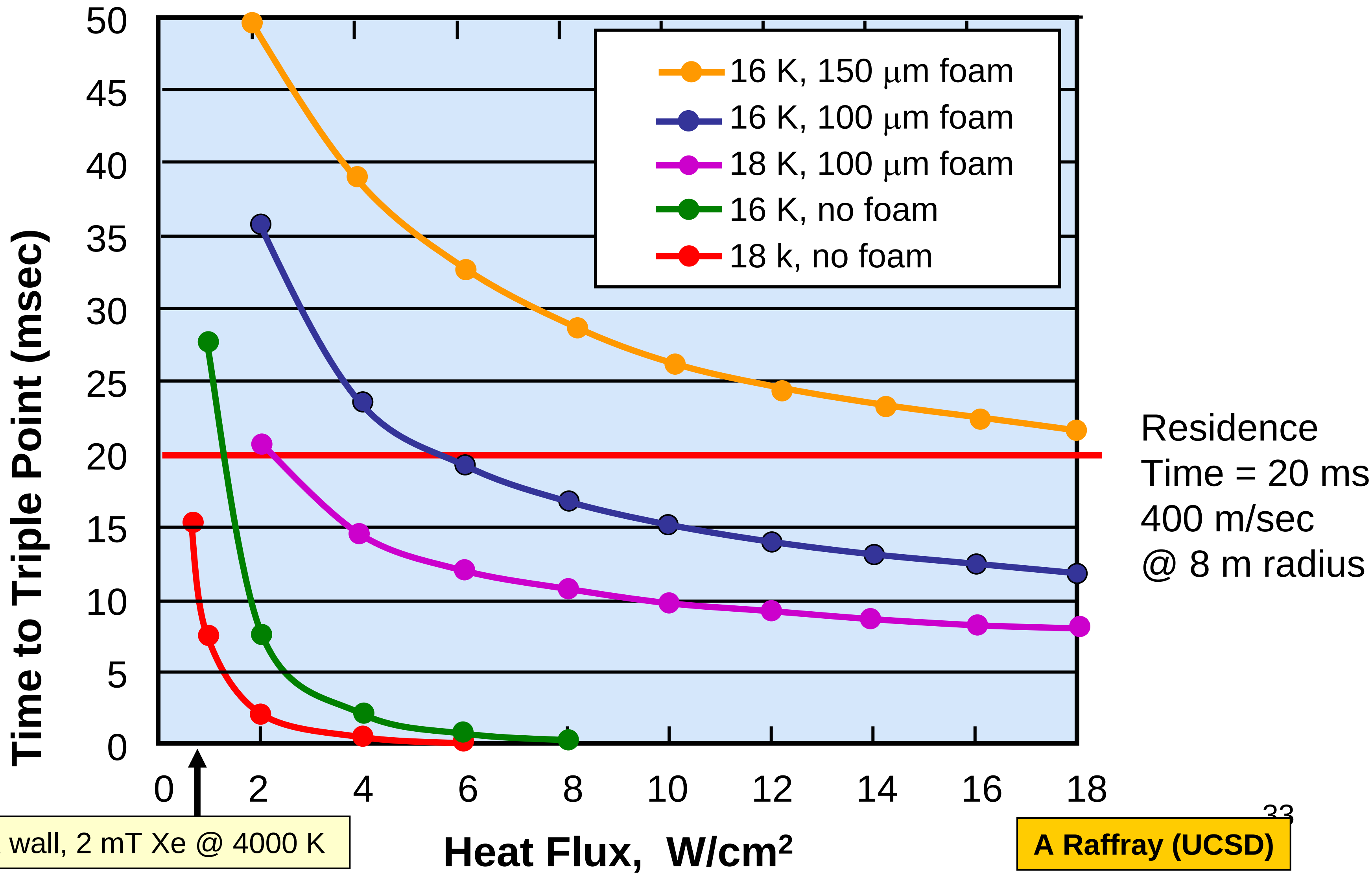
Target "in chamber residence time" is 20 msec*

* 0.8 W/cm^2 for chamber at 800 °K, 2mTorr gas at 4000 °K, 8 m radius chamber, 400 m/sec injection velocity

J. Hoffer and D Geller (LANL)

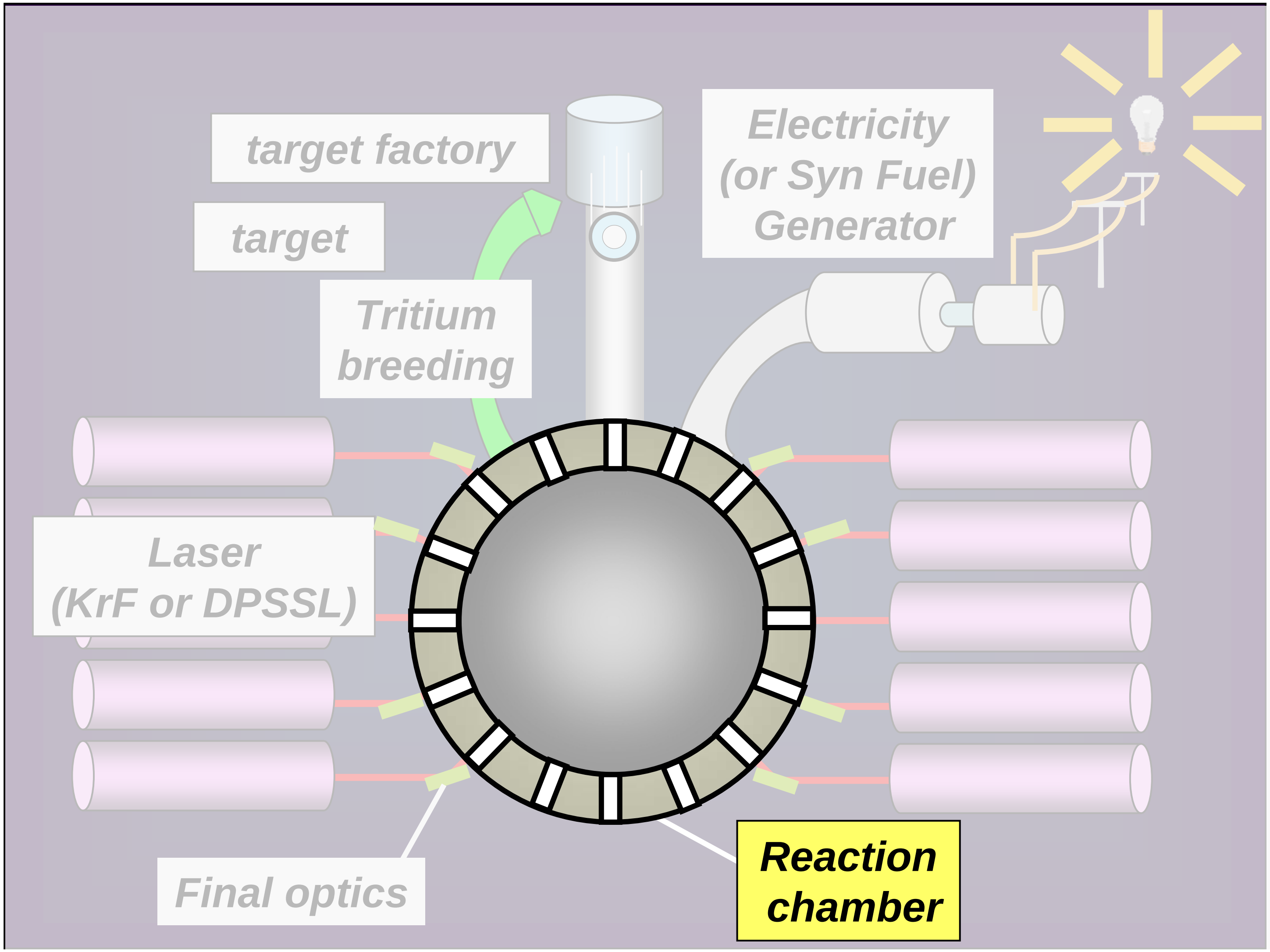
More advanced target designs allow better thermal protection and/or addition of chamber buffer gas

Effect of adding low density (100 mg/cc) foam on *outside* of target

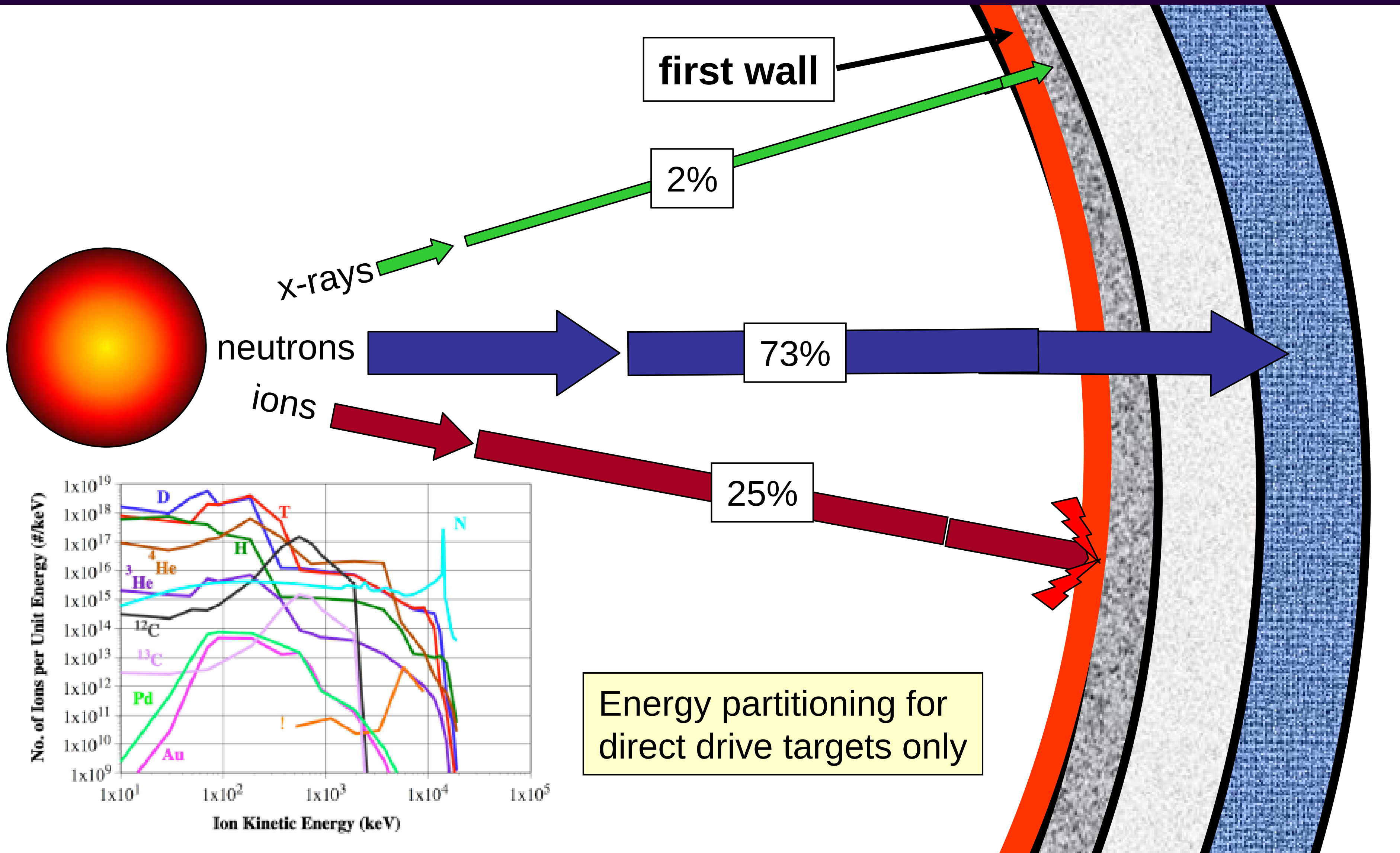


A Raffray (UCSD)

REACTION CHAMBER

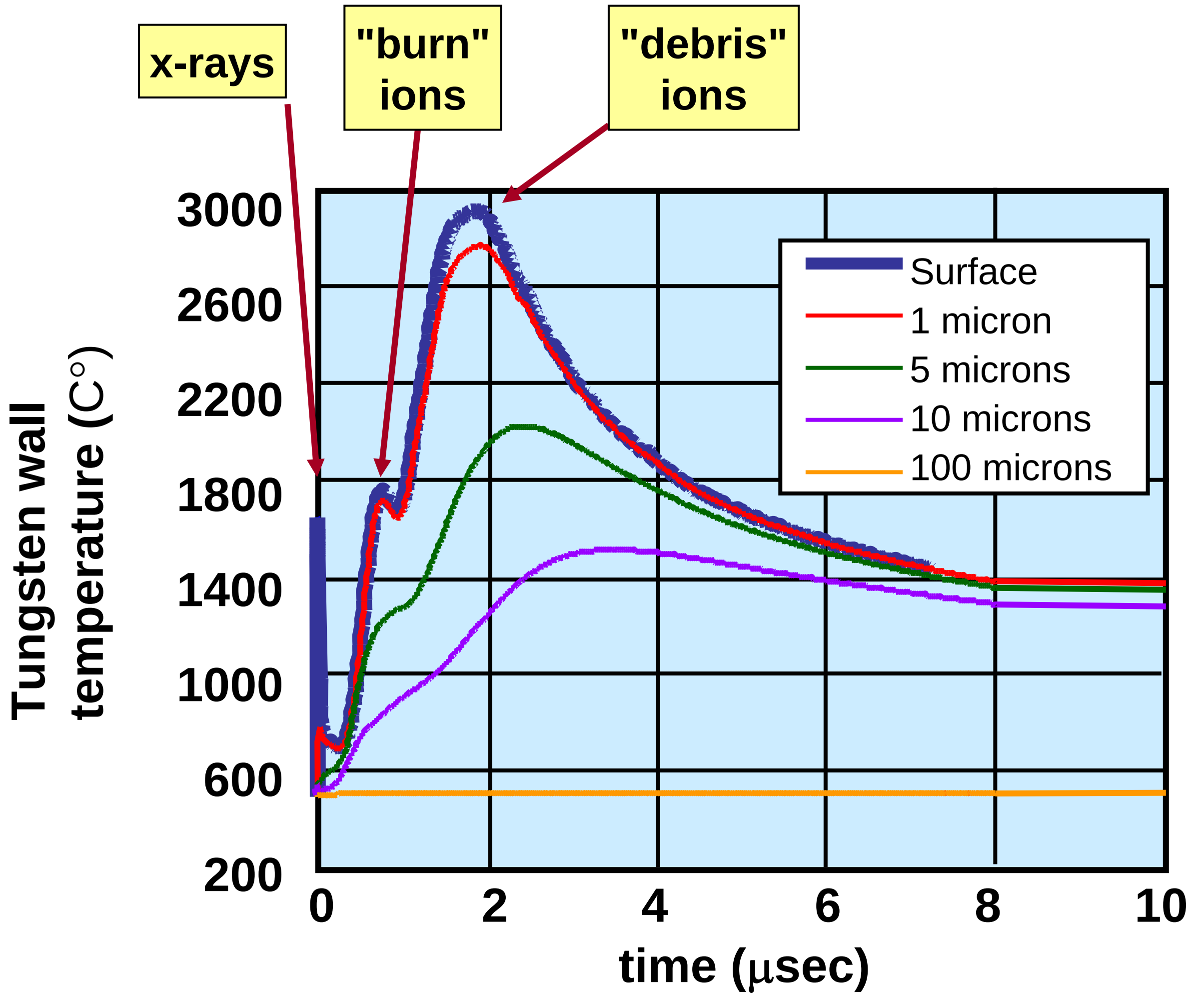


The "first wall" of the reaction chamber must withstand the steady pulses of x-rays, ions and neutrons from the target.



Energy partitioning for direct drive targets only

Typical Calculated First Wall Response



154 MJ Target
@ 6.5 m radius
No gas in chamber

A Raffray (UCSD)

Chamber options we considered

Solid wall / vacuum	**Simplest..easiest to test** **Eases laser / target issues** ***Materials challenge***
Magnetic Intervention / Vacuum	**Small chamber** **Really Eases laser / target issues** ***The ion dumps***
Replaceable solid wall / vacuum	**Eases laser / target issues** ***Mechanical/operational complexity***
Gas in chamber	**Smaller chamber** ***Challenging laser / target* issues*** ***Chamber recovery (plasma?)***
Thick liquid walls	**No materials issues (i.e.neutronics)** ***Challenging laser / target* issues*** ***Droplet formation/ complexity***

*Less target issues with indirect drive

combo

We need gas relief!

The top six reasons to eliminate the **buffer** gas:

1. Allows "simple" (non-insulated) target

2. Slower injection velocity (primary heat load is radiation)

3. Minimizes difficulty in engaging target
   Target placement limited only by injector accuracy.

4. No need to handle a "foreign" gas
   50 mT Xe (STP), 5 m radius @ 5 Hz, 10 % recycled
   = 3,500 tons/yr,   2,000,000 liters/yr

5. Easier and faster to "reset" chamber for next shot

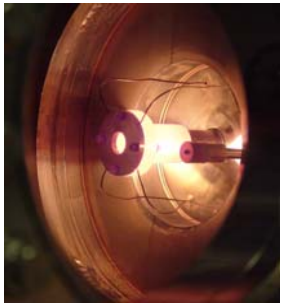
6. Threat spectra on wall tough to calculate, very difficult to test

Solid Wall Chamber: Experiments/Modeling

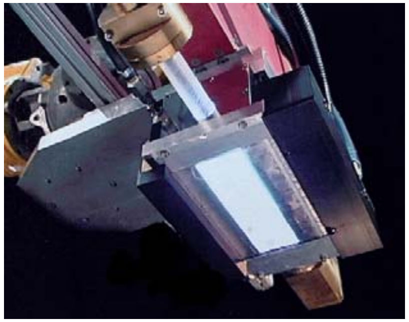
Thermo-mechanical cyclic stress (surface and interface): *Mostly Solved*

Ions: *RHEPP* (SNL)

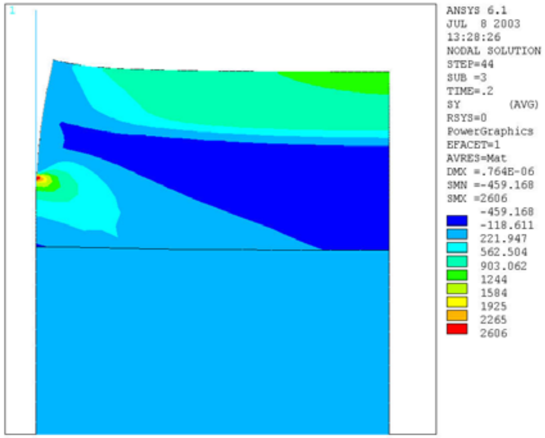
Laser: *Dragonfire* (UCSD)



Plasma Arc Lamp (ORNL)

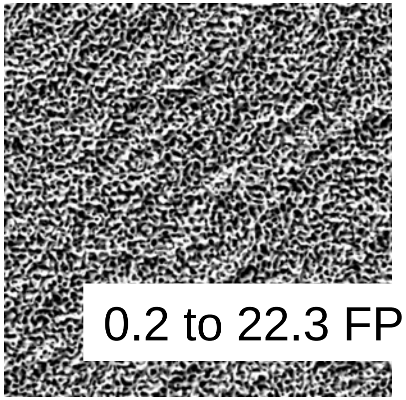


Modeling (Wisc/UCLA)



Helium Retention: *Remaining Major Challenge*

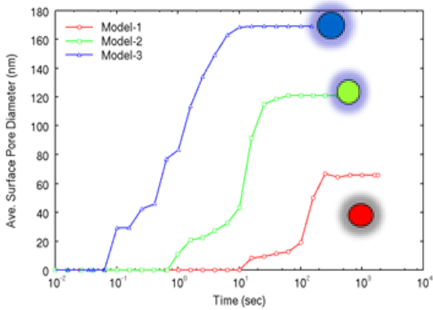
IEC (Wisconsin)



0.2 to 22.3 FPD

Van de Graff (UNC)

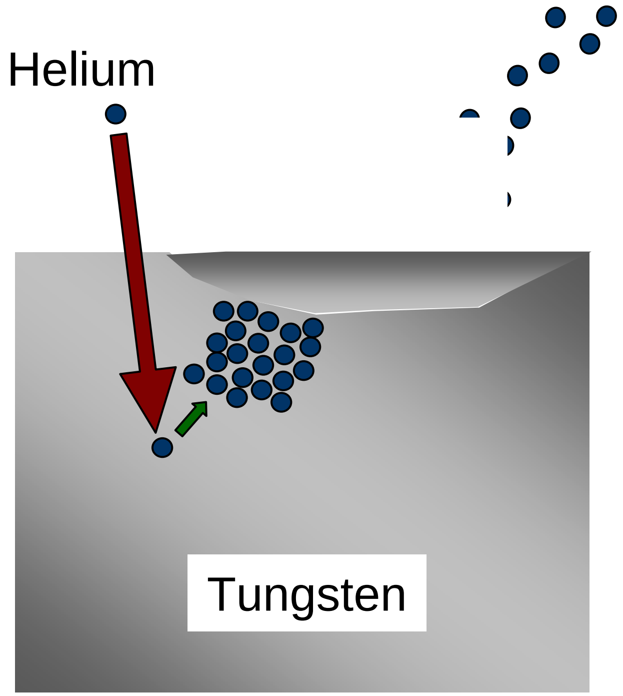
Modeling (UCLA/Wisc)

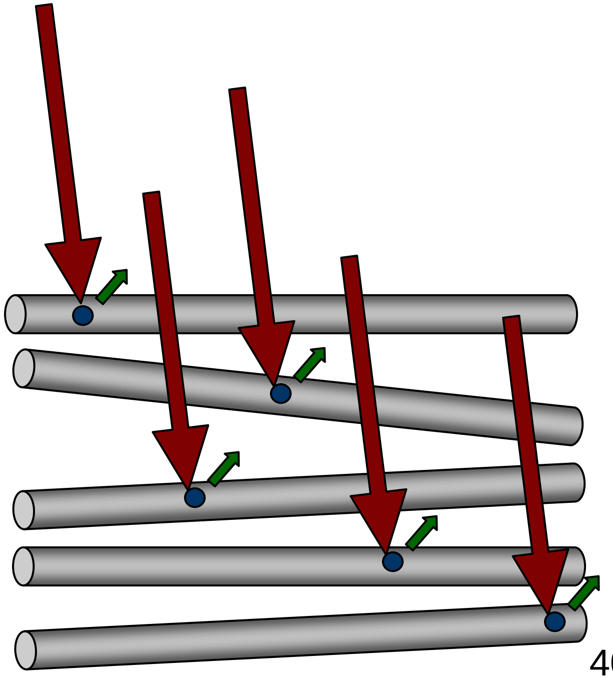


The problem of helium retention may be solved with "nano-engineered" armor

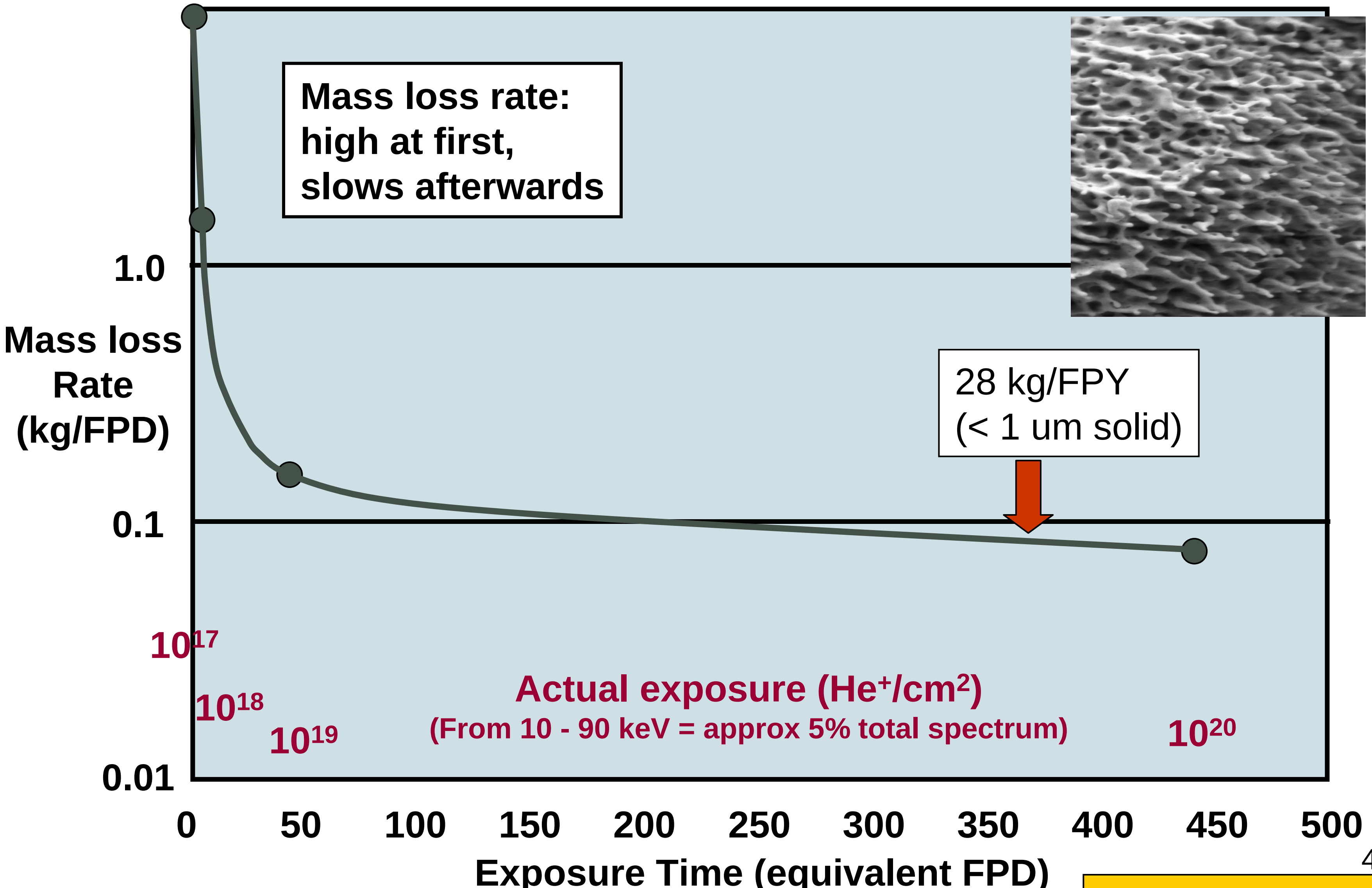
The Problem:
- He ions penetrate deeply (1-5 μm)
- Have short migration length (150 nm)
- Agglomerate into bubbles
- Exfoliate the wall

The Solution:
- Make armor from tungsten fibers
- Diameter < 150 nm
- Helium stops close to free surface
- He migrates out (cyclic heat helps!)



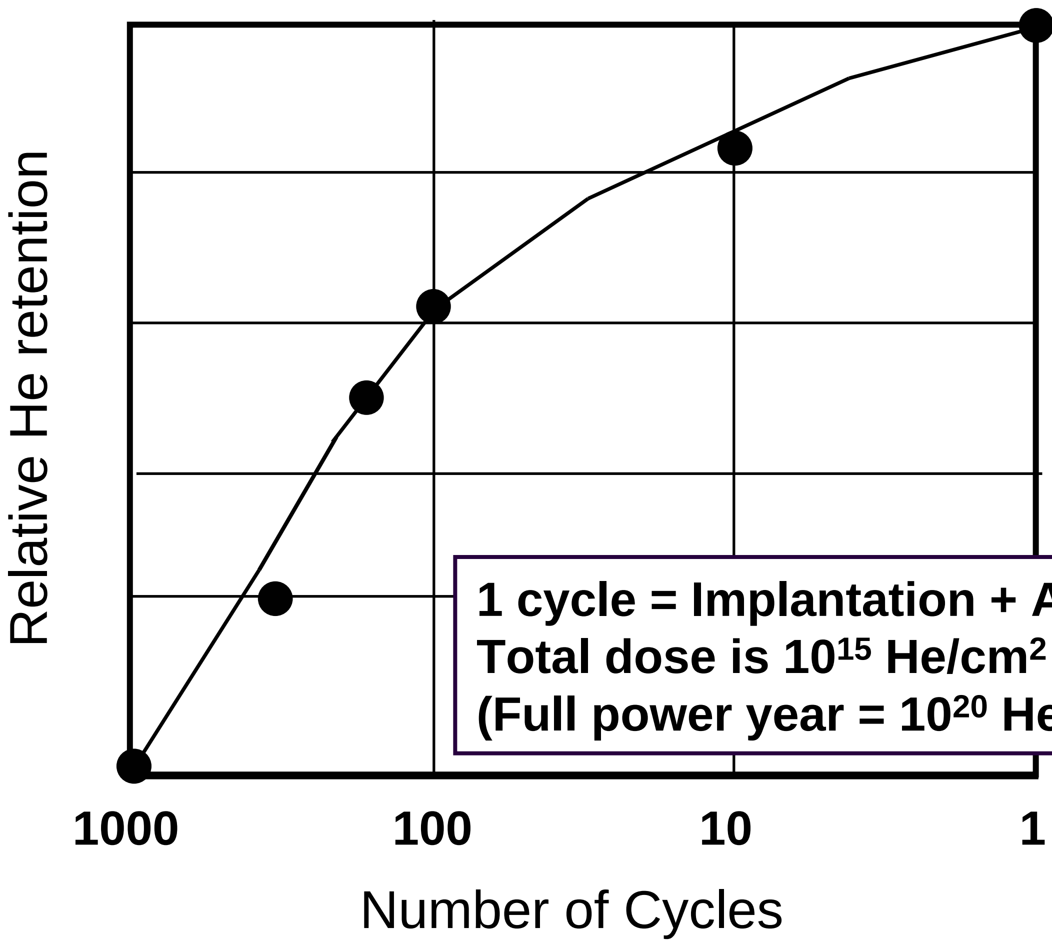


First "Nano-Engineered" Tungsten helium retention experiments are encouraging



Sam Zenobia (Wisconsin)

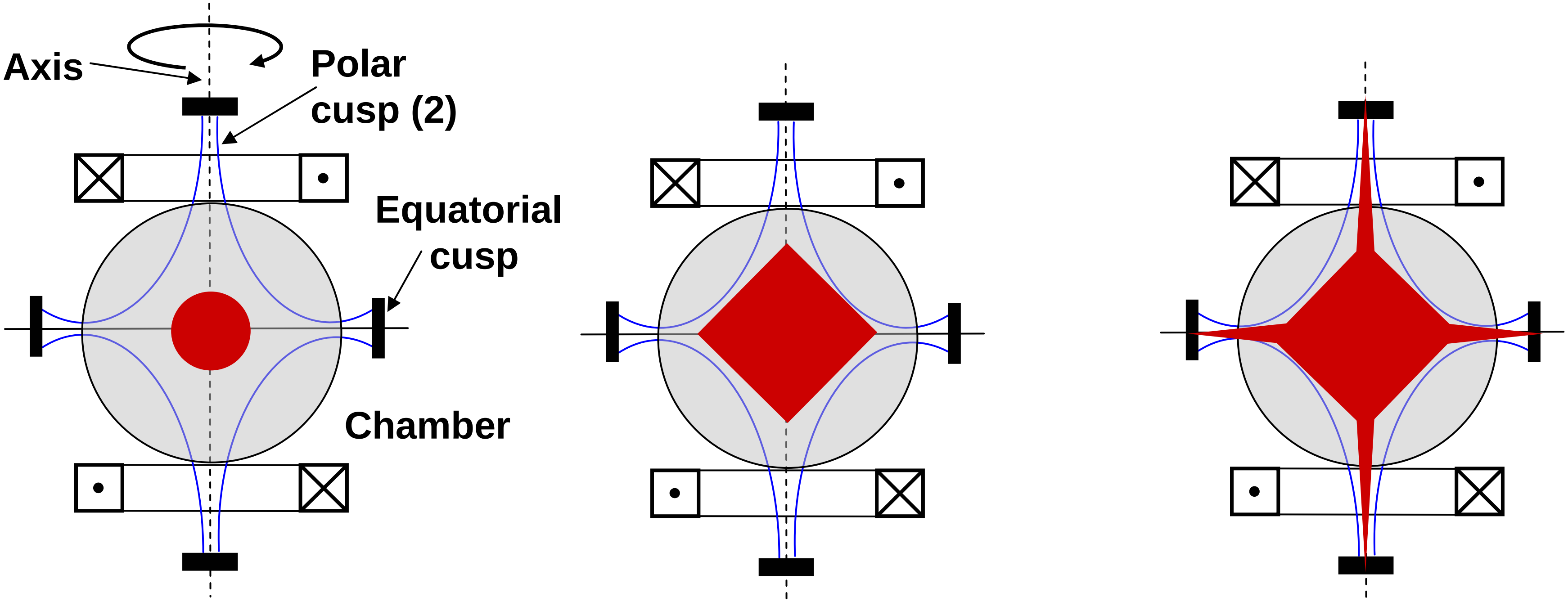
Experiments show IFE wall temperature cycle may also mitigation of He retention.
Basis: get the He out before it forms into bubbles



1 cycle = Implantation + Anneal @ 2500 °C
Total dose is 10^{15} He/cm^2
(Full power year = 10^{20} He/cm^2)

L. Snead (ORNL)
N. Parikh (UNC-Chapel Hill)

Magnetic Intervention:
Cusp magnetic field keeps ions off the wall
(in Plasma Physics terms: Conservation of $P_\theta = mrv_\theta + (q/c)\, rA_\theta = 0$



- **Plasma starts at center ($A_\theta = 0, v_\theta = 0$)**
- **Expansion initially spherical**

- **Ions expand into increasing field.**
- **Expansion stops when $mrv_\theta = (q/c)rA_\theta$**

- **Ions, *at reduced power*, leak into external dumps**

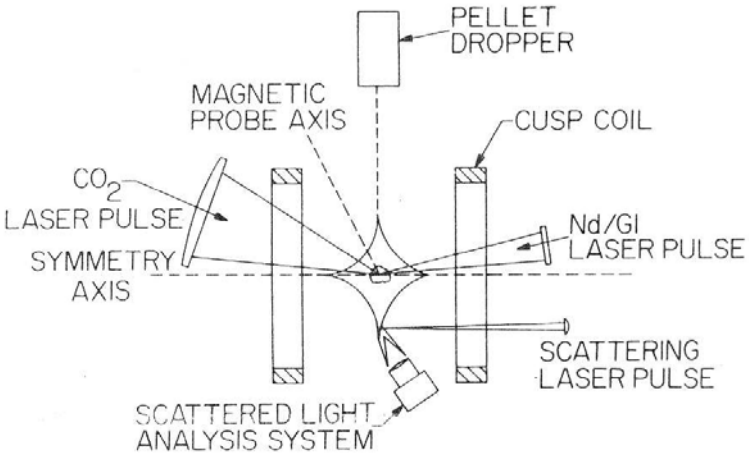
m = mass
q = charge

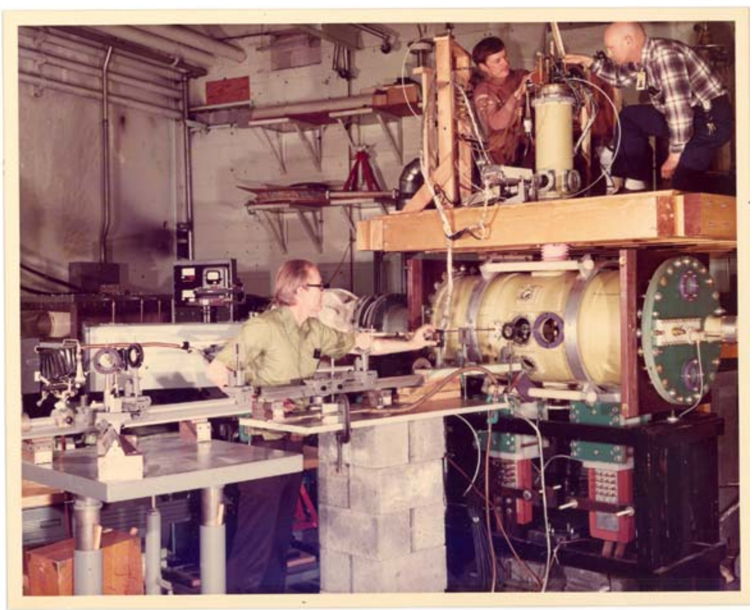
v_θ = azimuthal velocity
A_θ = azimuthal vector potential

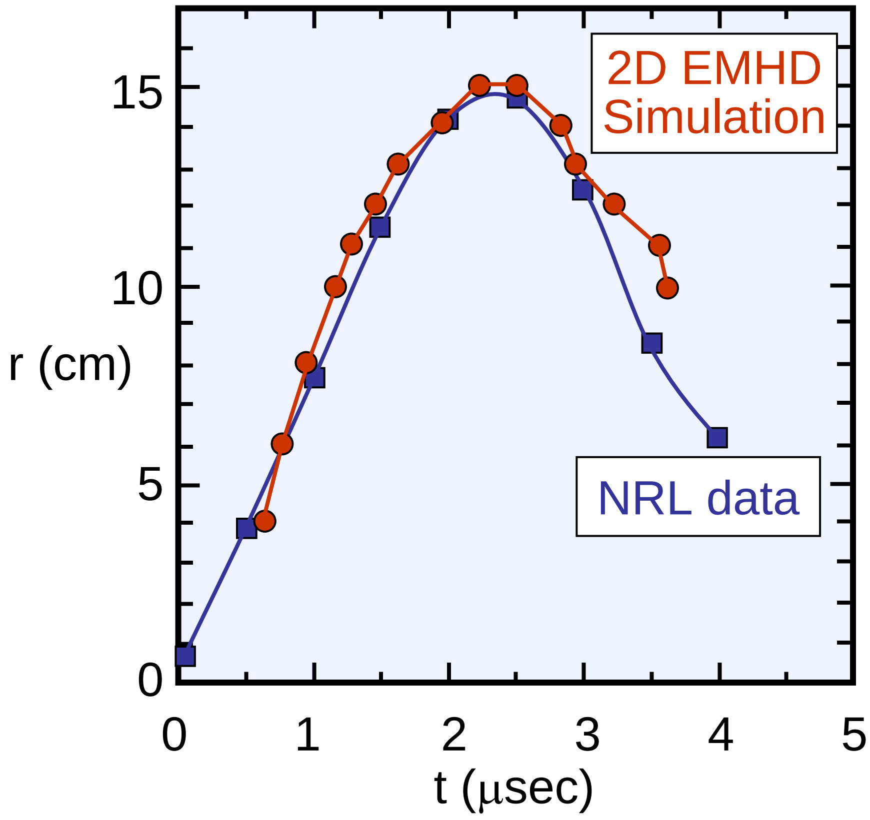
Advantages of Magnetic Intervention

- End runs the helium retention / heat load challenge
- Small chamber (5.5 m radius at 350 MJ yield)
  - Less material to handle
  - Eases target injection (velocity ~ 100 m/sec, vs 400 m/sec)
  - Eases target placement
- Armor can be SiC
  - Better neutron resistance/thermal properties than tungsten
  - Temperature rise only 140 °C (vs 1000 – 1500 °C with tungsten)
- Simple field coils
- Physics demonstrated on small scale
  - Supported by modeling

- 1979 NRL experiment showed principle of MI.
- Recent simulations predict plasma & ion motion





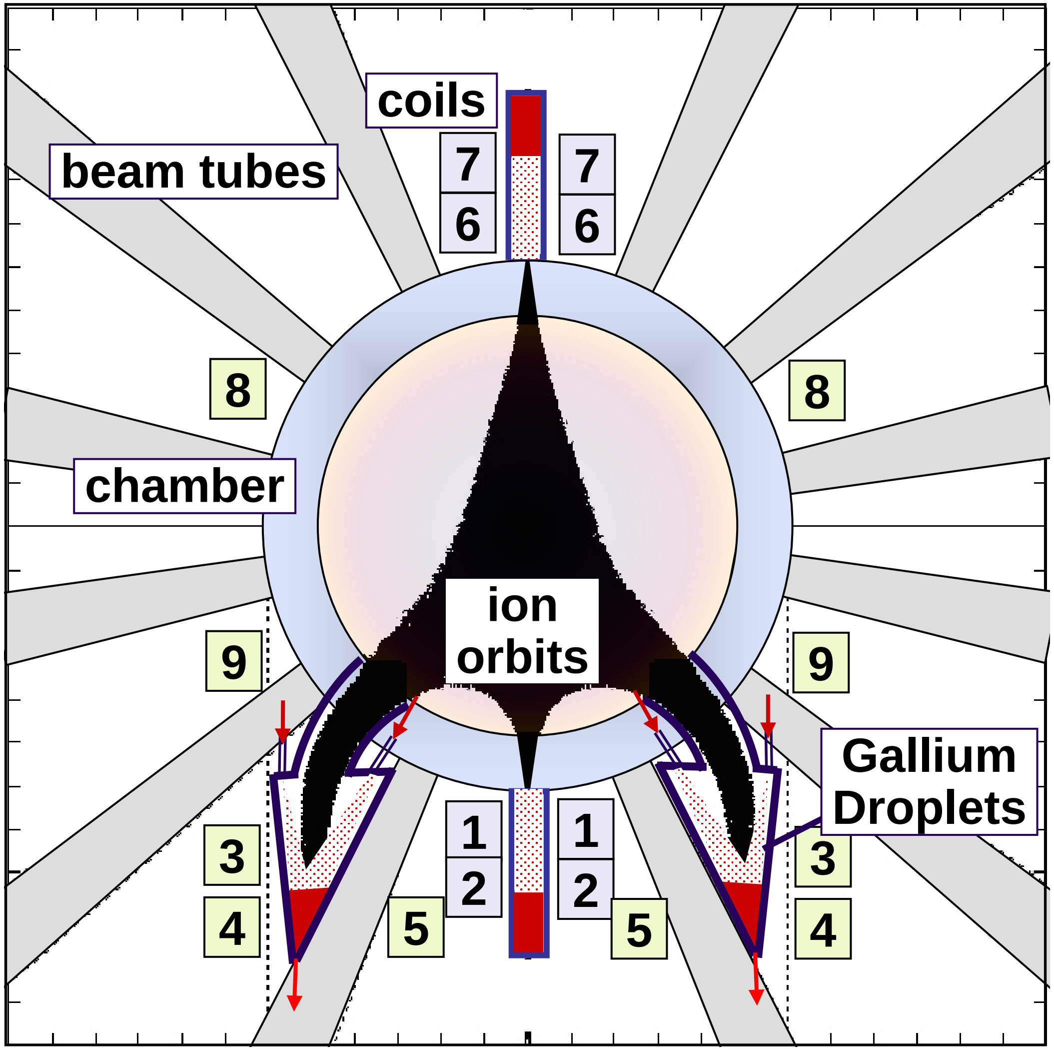


*R. E. Pechacek, *et al*., Phys. Rev. Lett. **45**, 256 (1980).

NRL
A.E. Robson (NRL-Consultant)
D.V. Rose (Voss Scientific)

An *example* of a Magnetic Intervention Chamber

Ions deflected downward by magnetic fields
Ion energy absorbed in Gallium Rain Ion Dissipaters™



Chamber radius: 5 m
Point cusps: 10 T
Main coils: 0.75 T

Energy absorption in Ga:
85% in first 10 mg/cm^2
15% in next 100 mg/cm^2

Only first layer evaporates

Gallium inventory enough so mean temp rise < 300°C

NB Vapor P of Ga = 10^{-6}T at 720 C

A.E. Robson (NRL-Consultant)

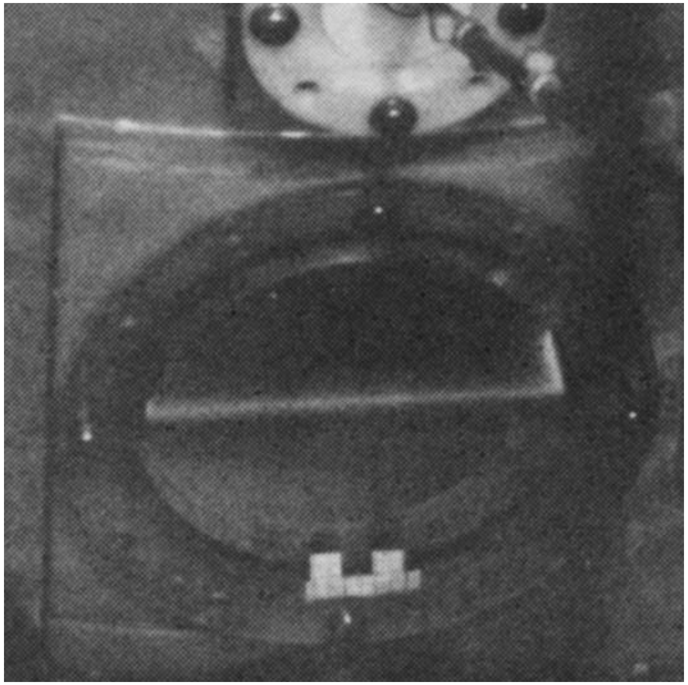
Magnetic Intervention: FAQ

1. WHY A CUSP, and NOT A SOLENOID?

- Physics (conservation of P_θ) guarantees ions won't hit wall
- Cusp has good curvature, stable against interchange and flute modes

2. HOW BIG ARE THE FIELD COILS?

- Belt coils: 0.75 T (7.5 kG)
- Poloidal Coil: 10 - 15 T, but these only 15 cm dia



3. WHERE ARE THE COILS LOCATED?

- Behind blanket
- Do not interfere with beam ports

4. WHAT ABOUT CHARGE EXCHANGE?

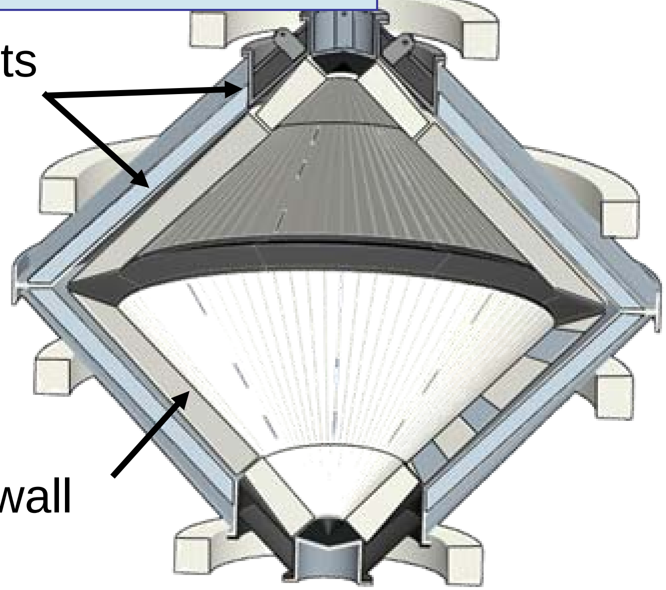
- Vacuum keeps chamber below 1 – 1.5 mTorr

5. WHAT ABOUT INSTABILITIES?

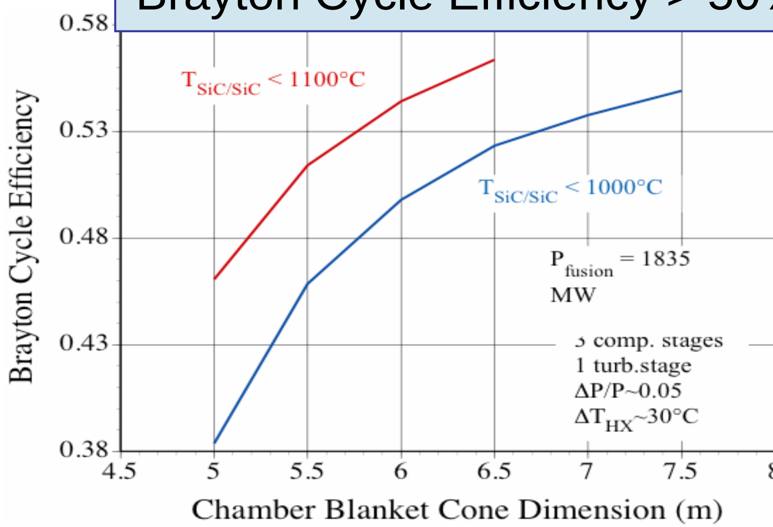
- Mean free path = 10^5 X chamber dimensions>>> No collosions, no MHD
- Streaming instabilities (if present) only affect sheath thickness ($\sim c/\omega_{pi}$)

Breeding, Tritium Processing, Thermal Conversion, Maintenance, etc

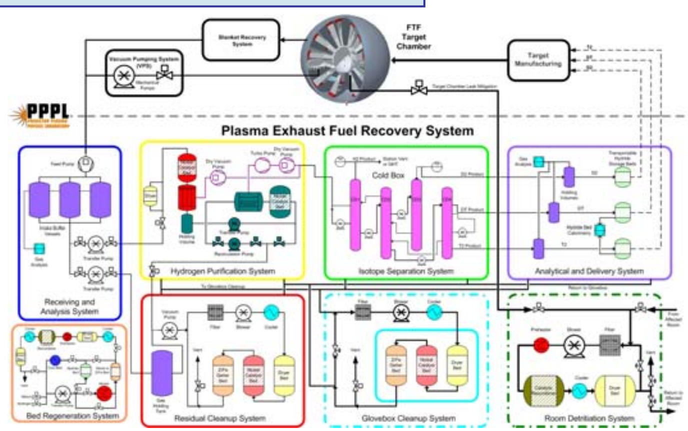
Maintenance/Servicing



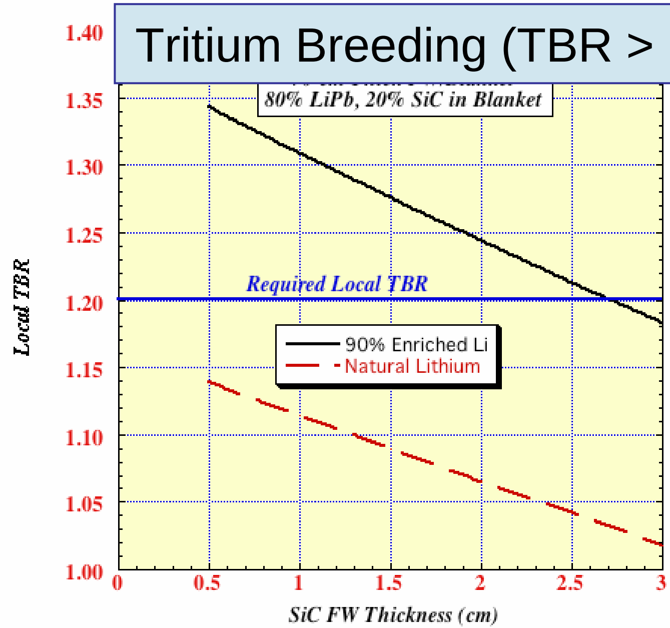
Brayton Cycle Efficiency > 50%



Tritium Processing



Tritium Breeding (TBR > 1.2)



Wisconsin
UCSD
PPPL
LANL
NRL

Report Card: What have we done, and what should we do to justify transition to Phase II

- **Optics components resistant to prototypical neutrons, laser damage**
  - Need larger sizes, need extension to 300 M shots (from 10 M)
- **Can mass produce high precision foam shells for targets**
  - Need higher yield for thin gas tight coating
- **Demonstrated smooth DT ice over foam layer**
  - Need mass production layering demonstration (Fluidized bed)
  - Need higher fidelity DT/foam warm up experiments, better modeling
- **Demonstrated target engagement using glint technique**
  - Need another 8 um pointing (now at 28, need 20)
- **Several viable chamber concepts, backed with experiments/theory**
  - Needs further experimental verification of some key concepts
  - Needs refinement and integrated design
- **Have conceptual designs for ancillary components:**
  - Blanket, tritium handling/processing, vacuum system, power conversion

Summary

1. We have carried out an integrated program to develop the science and technology basis for IFE, based on the simplicity and higher performance potential of laser direct drive

2. We developed credible approaches for most all the key components
   a. Lasers
   b. Final Optics
   c. Target Fabrication
   d. Target Injection
   e. Target Engagement
   f. Chamber Technolgies
   g. Auxilliary systems (tritium processing, vacuum, maintenance)

3. Many of these were demonstrated in subscale experiments.