IFE Target Fabrication, Delivery, and Cost Estimates

N. B. Alexander, L. Brown, D. Callahan, P. Ebey, D. Frey, R. Gallix, D. A. Geller, C. Gibson, J. Hoffer, J. Karnes, J. Maxwell, A. Nikroo, A. Nobile, C. Olson, N. Petta, R. Petzoldt, R. Raffray, W. Rickman, G. Rochau, D. Schroen, J. Sethian, J. D. Sheliak, J. Streit, M. Tillack, E.I. Valmianski

Presented by Dan Goodin

at the

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GENERAL ATOMICS

Main messages and conclusions of this talk…….

1. ***IFE target technology builds upon the larger ICF program***
   - Not starting from "zero" for IFE
   - Large effort for NIC fosters efficiency (e.g., foam shells)

2. **The recent IFE target technology ("mass production") work has been on laser fusion**
   - High Average Power Laser (HAPL) program
   - Heavy Ion Fusion and Z-pinch targets briefly noted briefly here

3. **For laser fusion:**
   - All process steps identified; suitable for mass production
   - Ongoing work = near-term laboratory <u>demonstration</u> of feasibility for each step

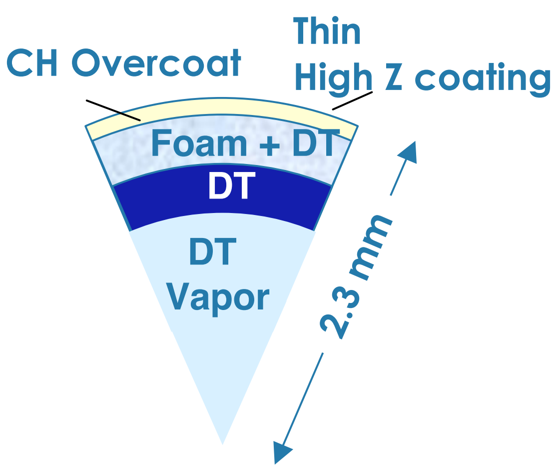
Good progress has been made on these laser fusion demonstration programs….

Target development is an essential component of any inertial fusion concept…

- **Three main IFE concepts**
  - Strong synergism but key differences that lead to specific technologies

Laser Fusion

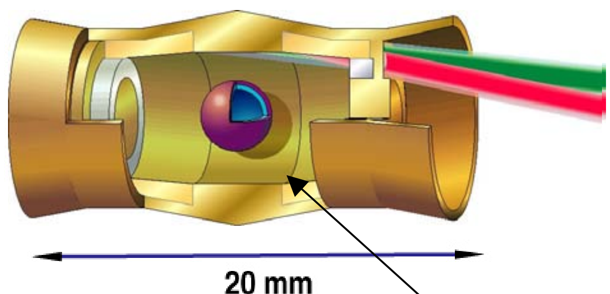
- **Foam capsule with overcoat**



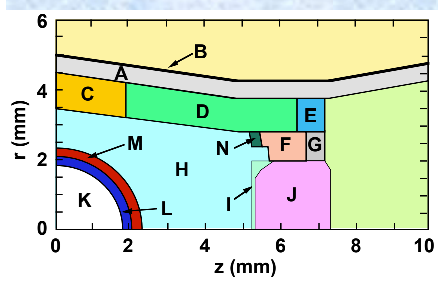
NRL High Gain Target

Heavy Ion Fusion

- **Advanced manufacturing methods**



HIF Distributed Radiator

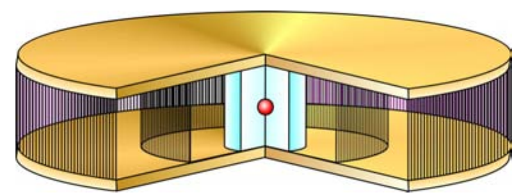


Low density metal foams

historical

Z-Pinch IFE (ZFE)

- **Emerging requirement's & concepts**



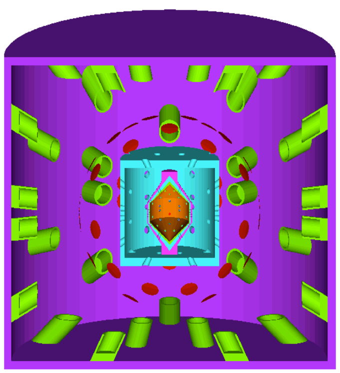
SNL Dynamic Hohlraum

Key = time for transport & loading

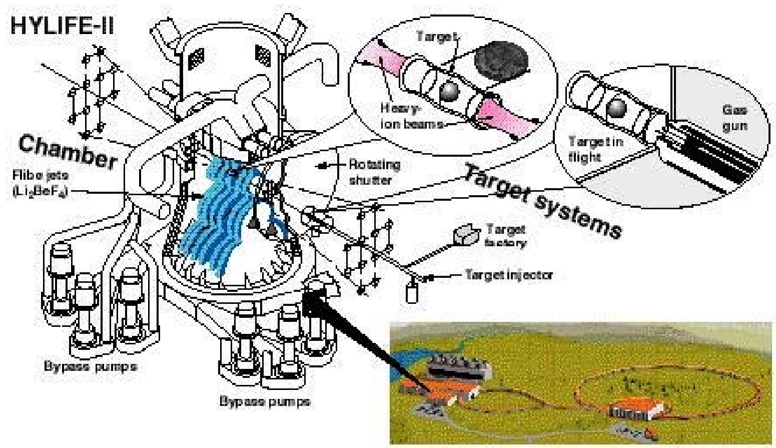
Top level target technology requirements

- **Basic requirements**
  - Supply about 500,000 targets per day for a ~1000 MW(e) laser fusion or HIF power plant *(~88,000 for ZFE at 0.1 Hz, 10 chambers)*
  - Do it cheaply, each laser fusion/HIF target has an energy value of about $3.00 ($22.50 for ZFE)

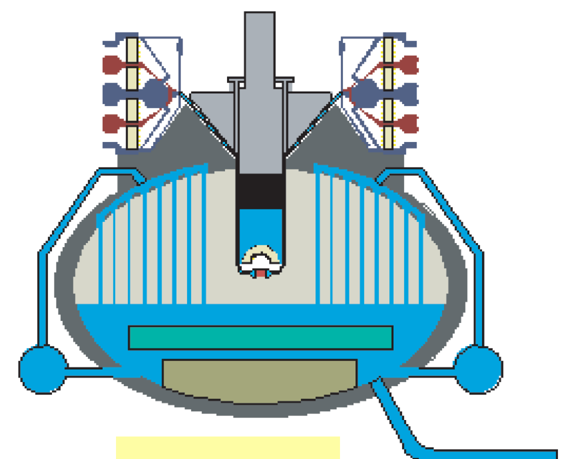
Specific target requirements have been defined to varying degrees…



Laser Fusion



HIF - HYLIFE-II



ZFE

An initial cost analysis has been done for an "*nth-of-a-kind*" IFE target manufacturing

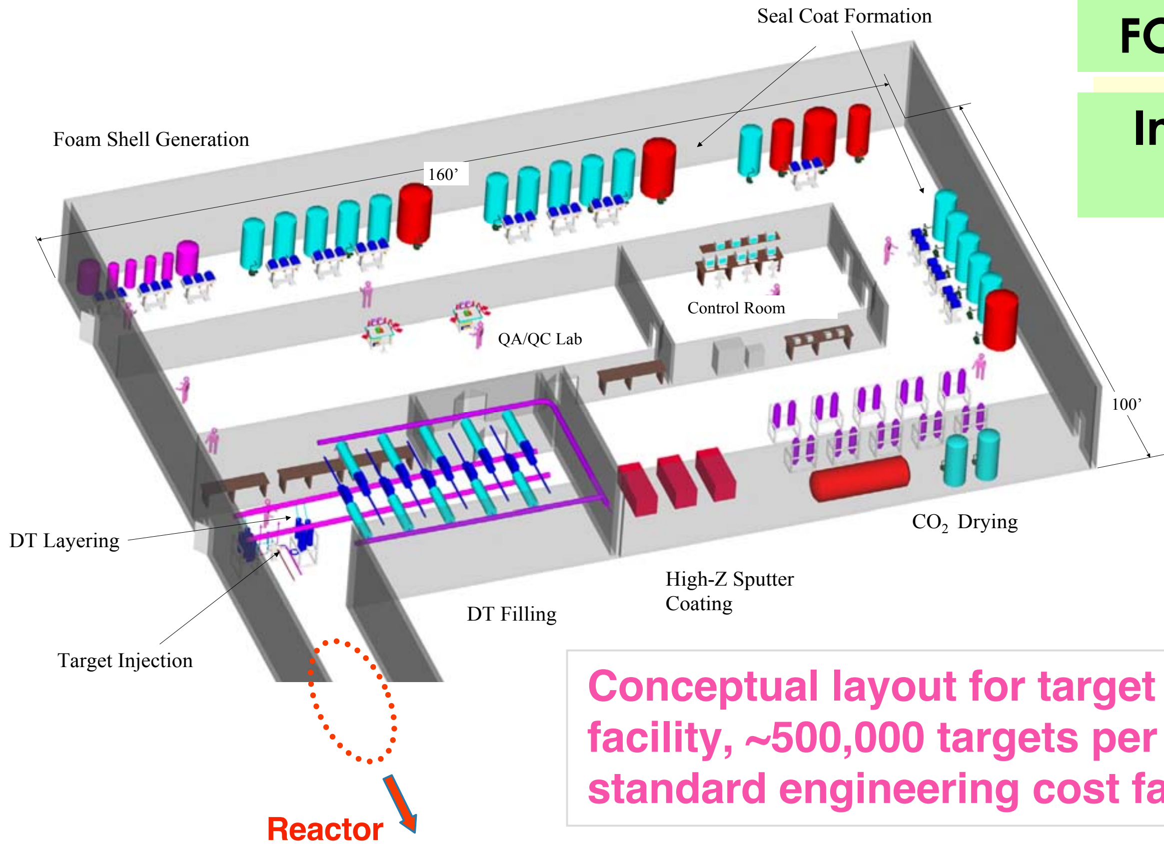
- Major "paradigm shift" from current day
- Installed capital ~$97M, annual operating $19M → **est'd 16.6 cents/target**

Eliminating FOAK Costs

Increasing Yield

Reducing Characterization

Increasing Batch Sizes



While development programs are still significant, cost studies are promising!

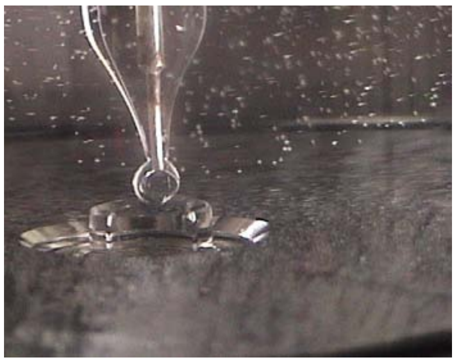
Conceptual layout for target fabrication facility, ~500,000 targets per day, standard engineering cost factors

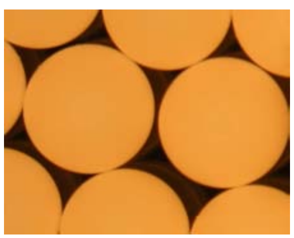
Goodin, D.T., et al, "A cost-effective target supply for inertial fusion energy", Nuclear Fusion 44 (2004).

Outline of processes for the HAPL target supply

1) Fabricate foam capsules

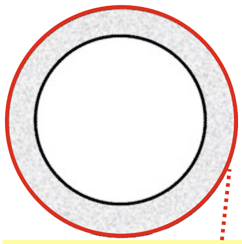
Micro-encapsulation



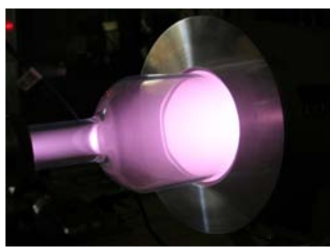


FTF-sized (2.4 mm OD) foam capsules

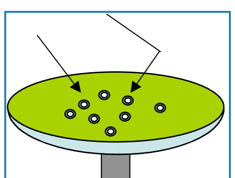
2) Overcoats



A) Interfacial reaction



B) GDP coating



C) Sputter coating of metal (Au/Pd)

Highly isothermal environment

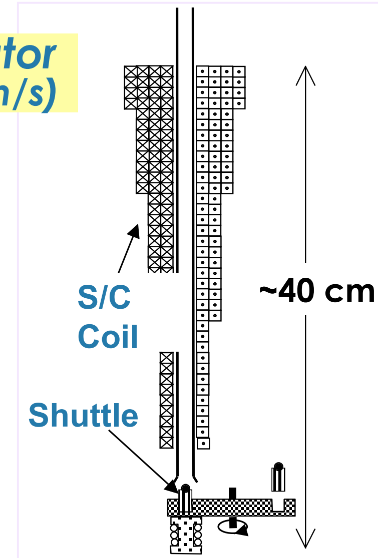
3) DT Fuel Layer

Layering cryostat

Fluidized bed

4) Inject Target

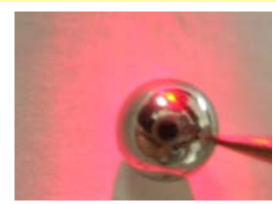
Accelerator (~50-100 m/s)



5) Track Target

Optical systems

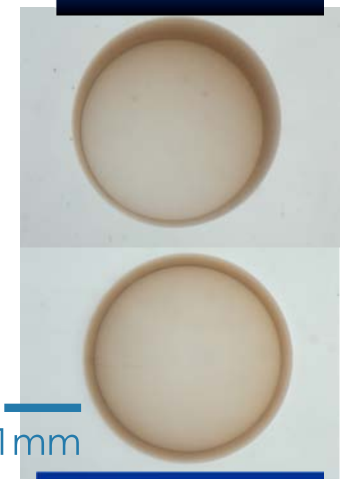
"glint" for tracking



1) We can make the HAPL foam capsule (divinyl benzene)

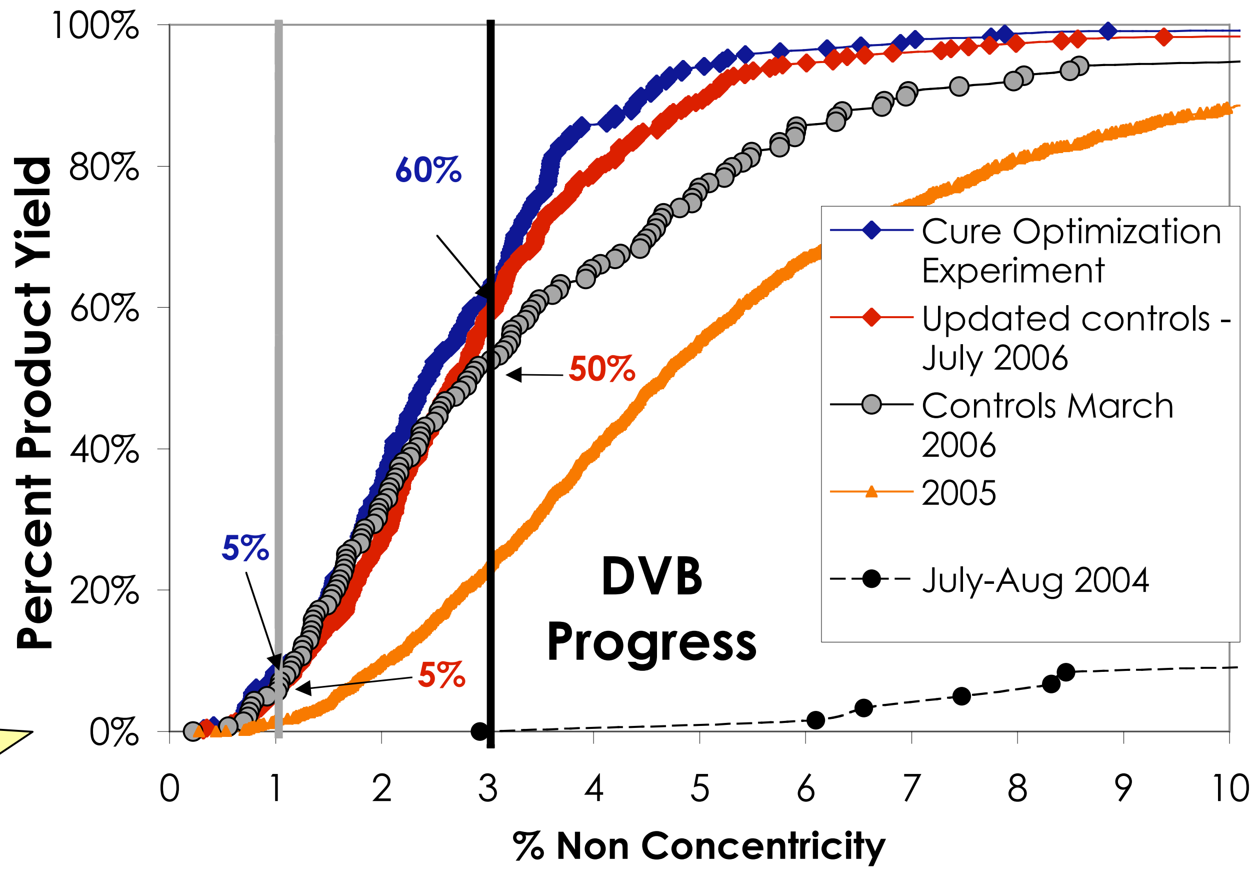
- Systematic, parametric studies have led to ability to control capsule parameters (material, OD, wall thickness, sphericity, density……)

Poor NC



Better NC

Non-concentricity (NC) is a "wall uniformity" defect



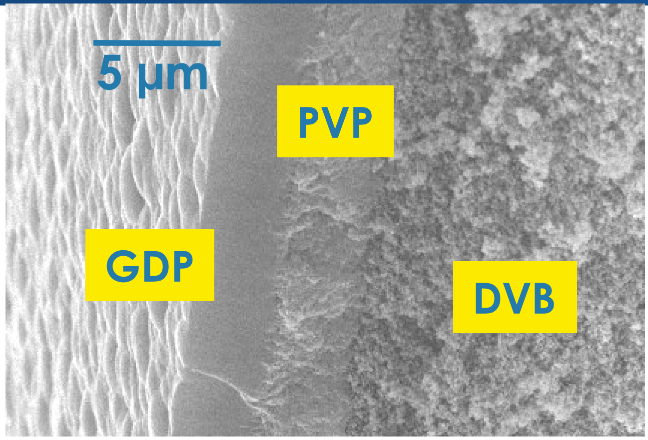
Do we meet foam capsule requirements?
divinyl benzene (DVB) and resorcinol formaldehyde (RF)

Attribute	Value	Tolerance	DVB	RF	Comments
Diameter	4.6 mm	± 0.2	Pass 0.025 mm range	Pass ± 0.06 mm range	Real-time feedback control demonstrated
Wall thickness	180 µm	± 20	Pass (± 20 um)	In progress	RF is a more recent development
Density	20-120 mg/cc	[25%]	Pass (97± 5 mg/cc)	Pass	
Pore size	<3 µm		Pass (~1 um)	Pass (~0.01 um)	Based on SEM
Out of round	<1 % of radius	--	Pass (<0.3 %)	Borderline (1% average)	Measured on dry foam shells
Non-concentricity	< 1-3% of wall th.	--	Pass (~60% of shells <3% NC)	In Progress (10% of shells <3% NC	Improving
Areal density	< 0.3%	Modes 100 to 500	In progress	In progress	Contact radiography to determine density variation.

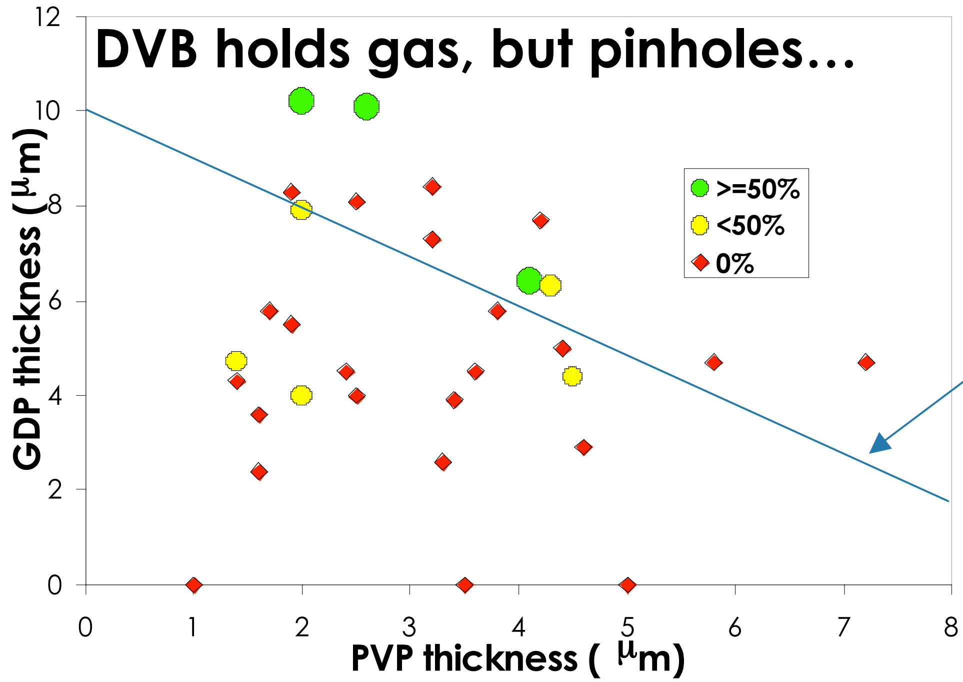
2) It's the overcoat …
(it must be gastight as well as have a "smooth" surface finish)

Potential pathways for overcoat:

1. *Interfacial reaction*
2. *Direct (GDP) coating (with smaller-pore RF)*
3. *2-step process w/ interfacial plus a GDP coat*



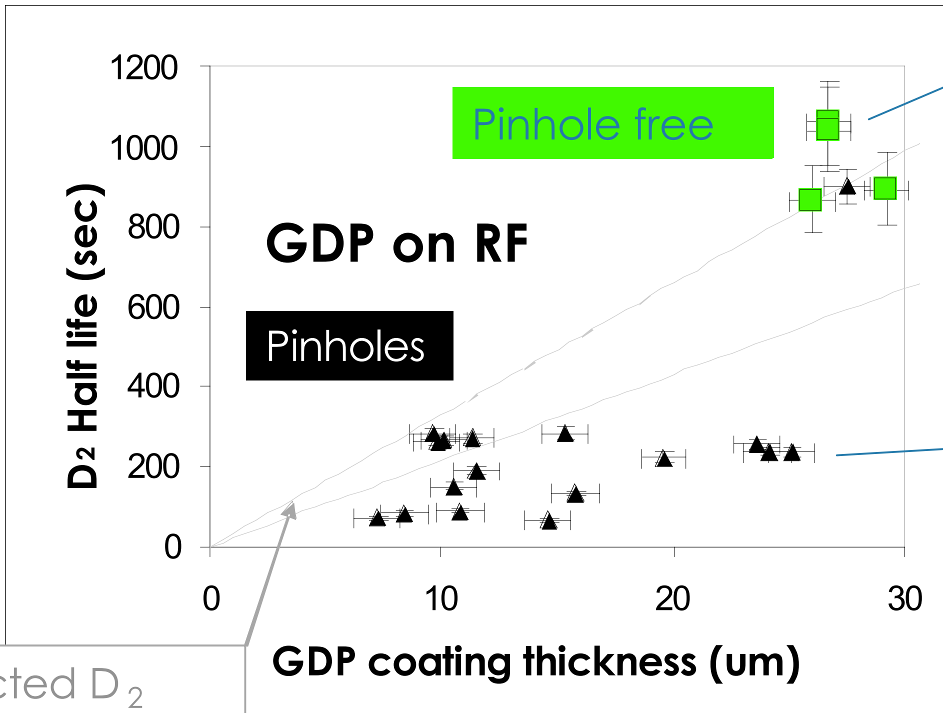
(PVP/GDP), Interfacial layer to cover pores, GDP to seal….



Current Spec
<10 microns

2) A current focus is on the overcoat…

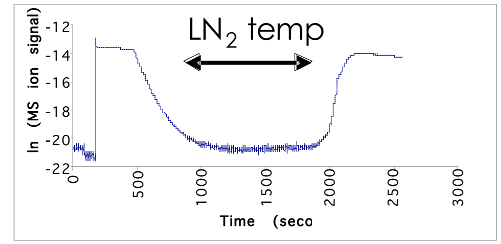
- **D_2 testing, leak rate measured with mass spectrometer**



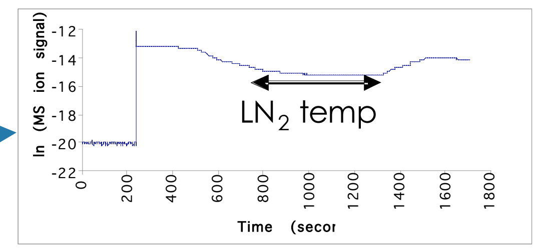
Predicted D_2 permeation rate

Leak Mechanisms:

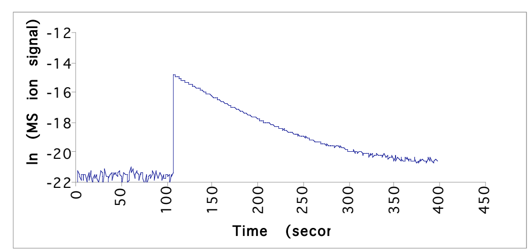
Good – permeation leak only



Bad – pinhole leak

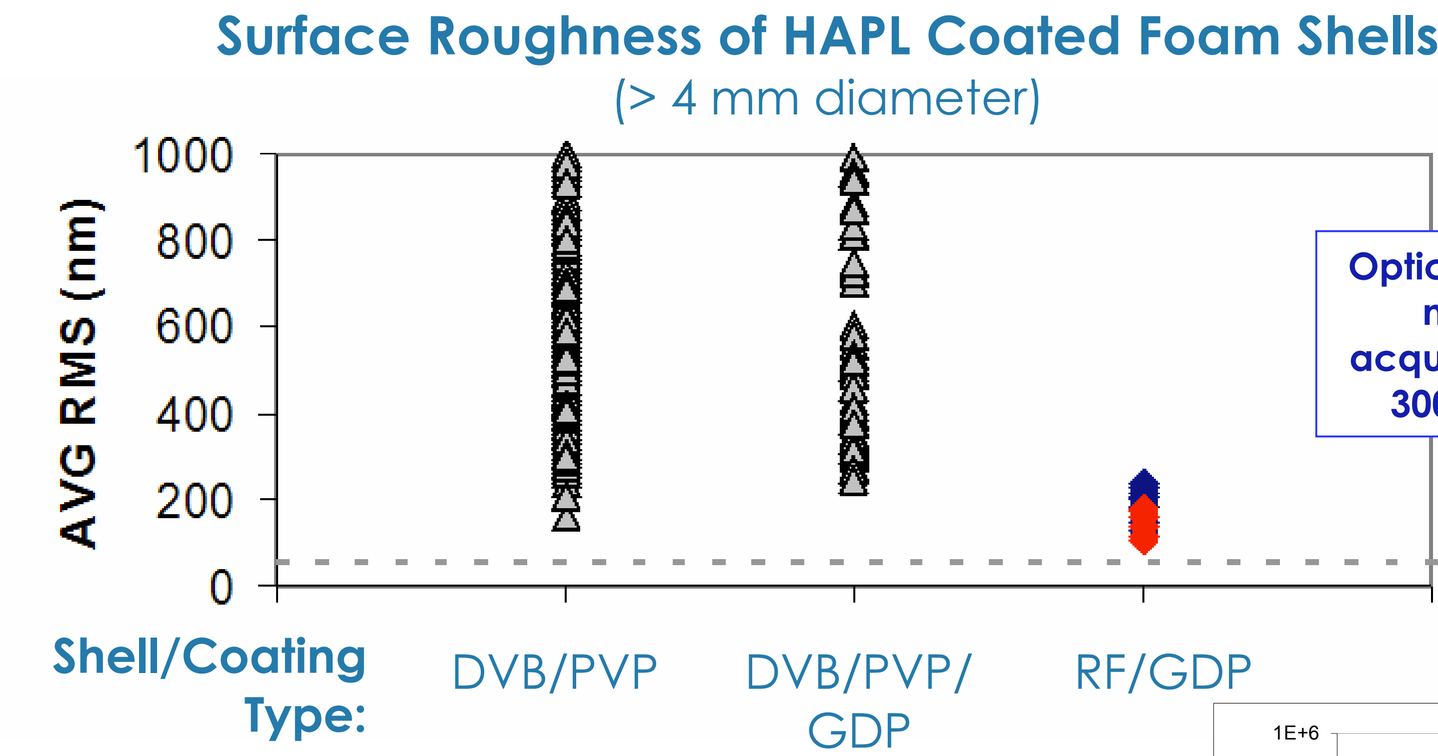


Ugly – viscous flow leak

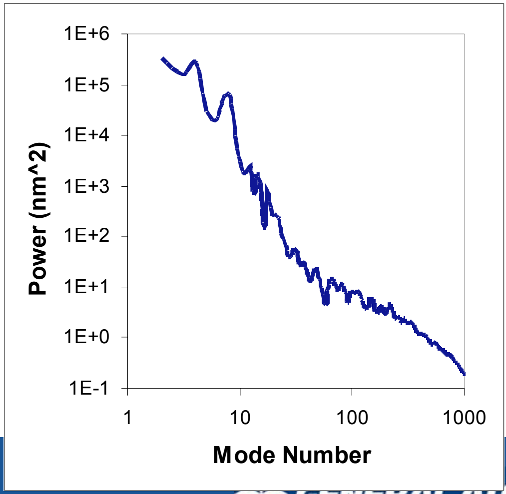


The shells are tested to be "gas tight" and can survive cryo cooling and warming cycle

Overcoated R/F foam shells are also smoother than coated DVB shells



Optical Profiler (WYKO) measurements acquired at 20x, with a 300 x 200 um area

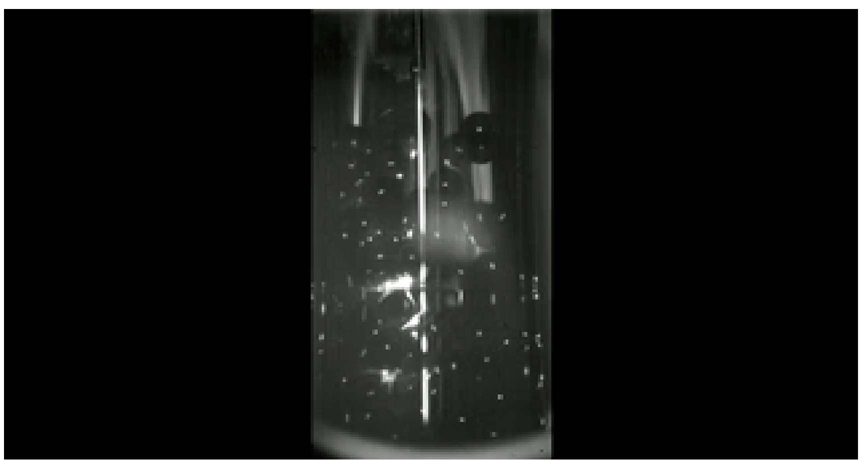


"Spheremapper"

- Our ultimate test of surface finish
- Power Spectrum of Surface Roughness
- GDP/RF = 42 nm RMS for modes 50 to 1000

3) Mass production layering experiment is being brought online …

- *Static controlled*
- *Scoping tests show randomization*
- *Initial cryostat cooldowns to ~ 11K*
- *Method to “grab” one shell for characterization has been done at cryogenic conditions*



Shells at 11 Kelvin

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(4) Target injection has several acceleration options …

Injection demo for >400 m/s

Gas supply (He)

Gas removal equipment

8 meter gun barrel

Simulated target chamber center (~25 meters total length)

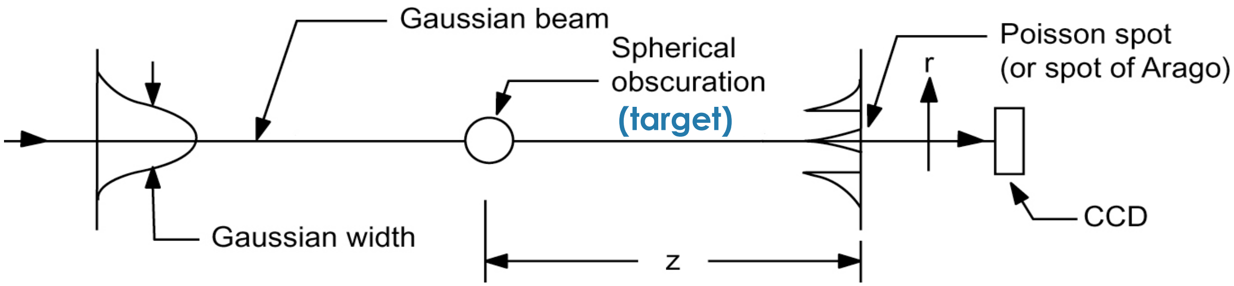
Tracking systems

Magnetic diversion - reduces gas in chamber and heating and give more options ⇨

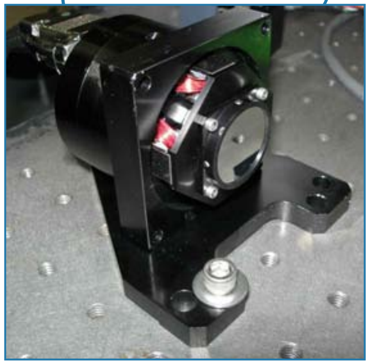
1. **"Mechanical" (~50-100 m/s)**
2. **EM "Slingshot" (~60-85 m/s)**

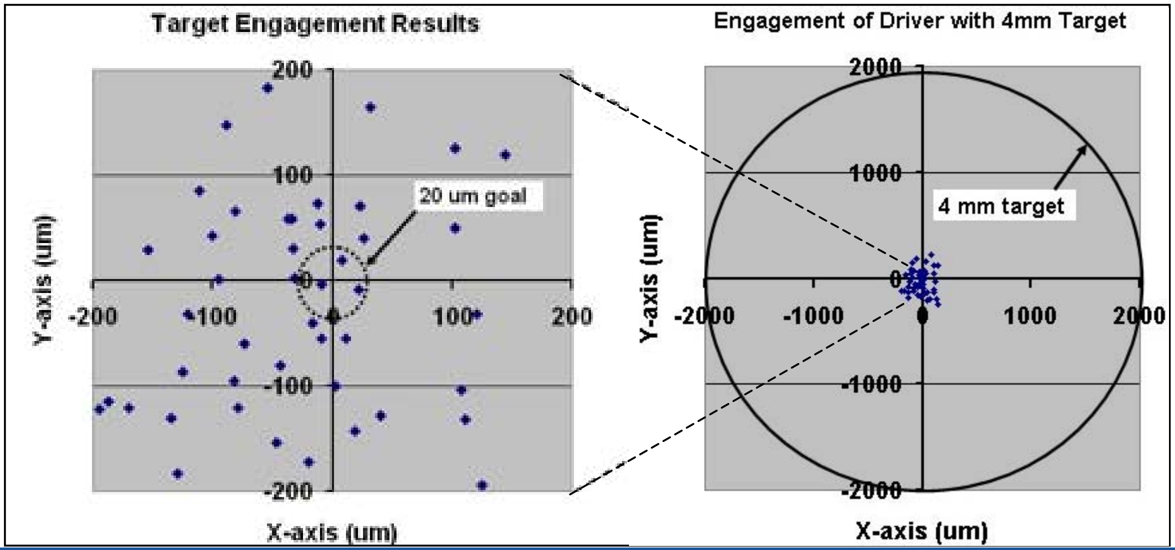
5) Tracking and alignment concepts identified and demonstrations underway

- **Requirement is alignment of lasers and target to 20 μm**
- **System using lasers, optics and fast steering mirror**
- **Also - "glint" from target ~1 ms before the shot aligns optical train (target itself is the reference point)**



Fast steering mirror for demo (commercial)





Scaled experiment, velocity ~ 5 m/s

Accuracy of hitting "on-the-fly" is ~125 microns now (1σ)

Working toward 20 micron goal for demo

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GENERAL ATOMICS

Summary and conclusions

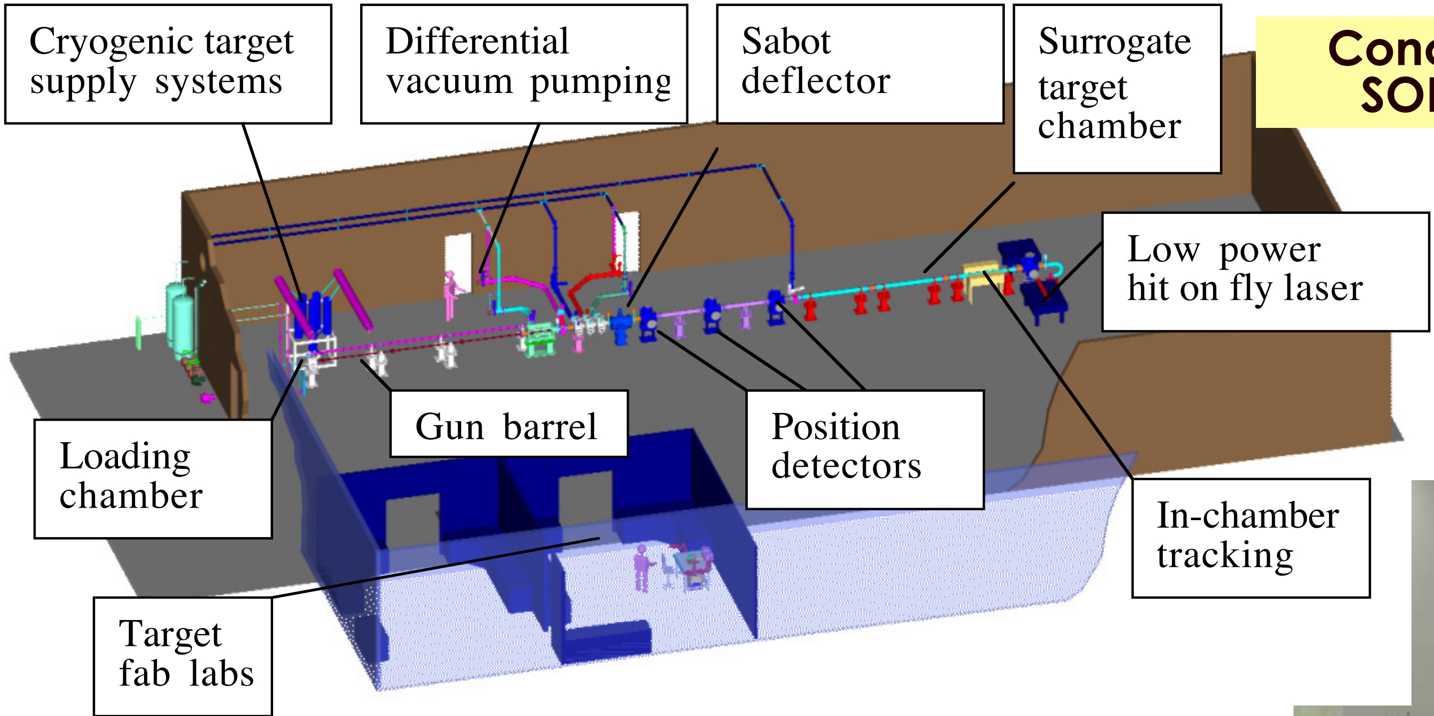
1. *IFE target technology is leveraging the ICF program to maximum extent possible*

2. *Target supply scenarios have been identified for the laser fusion target supply*

3. *The HAPL program emphasis is on near-term laboratory demonstrations of feasibility*

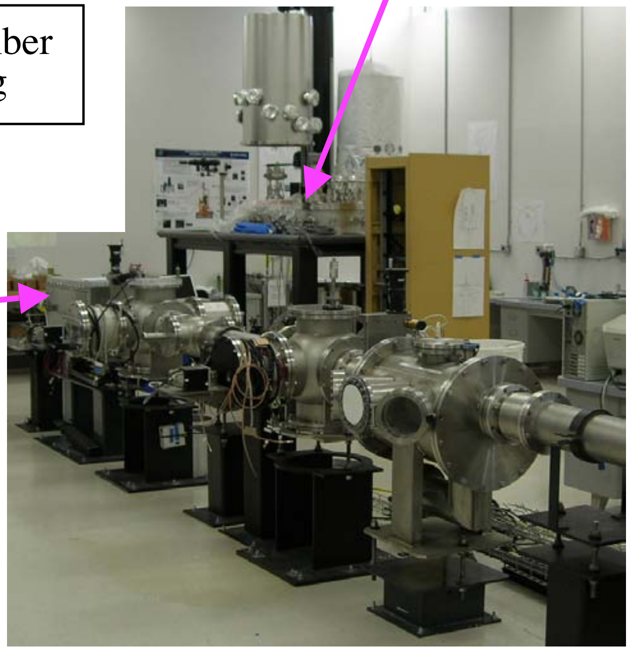
Backup slides

To the future - integration of cryogenics w/ injector



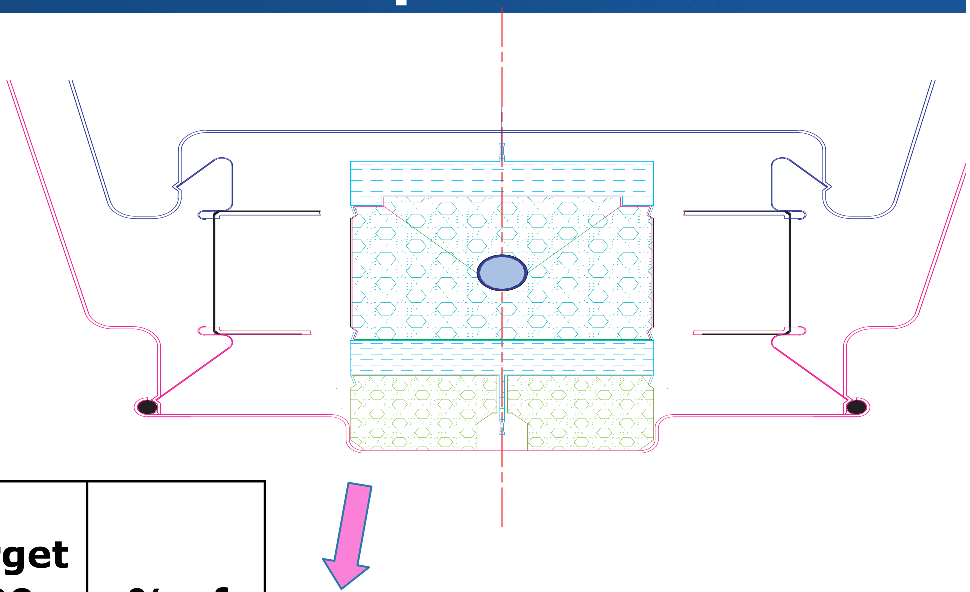
Concept from SOFE- 2003

M. S. Tillack et al, "A Target Fabrication and Injection Facility for Laser-IFE" SOFE-2003 14-17 October 2003, San Diego CA.



ZFE target conceptual design allows an initial cost comparison for all three concepts

- **ZFE "target load" has liquid hydrogen cooling buffers**
- **Allows temperature control during loading process**



IFE Target Cost Comparison

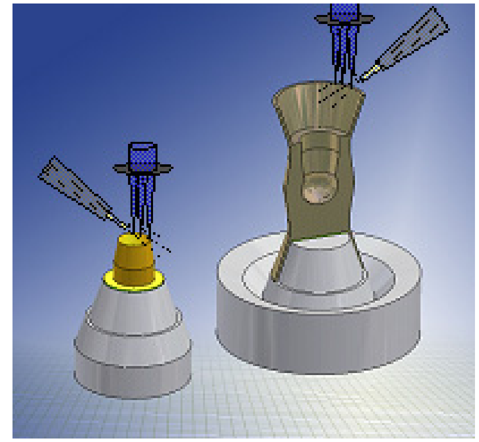
IFE Concept	Target Design	Target Yield (MJ)	Est'd Cost/target for 1000 MW(e)	% of E-value
Laser Fusion	Direct drive foam capsule	~400	$0.17	~6
HIF	Indirect drive distributed radiator	~400	$0.41	~14
ZFE	Dynamic hohlraum "target load"	~3000	$2.86	~13

Assumptions:
- development programs done
- n^{th}-of-a-kind plant
- does not include RTL

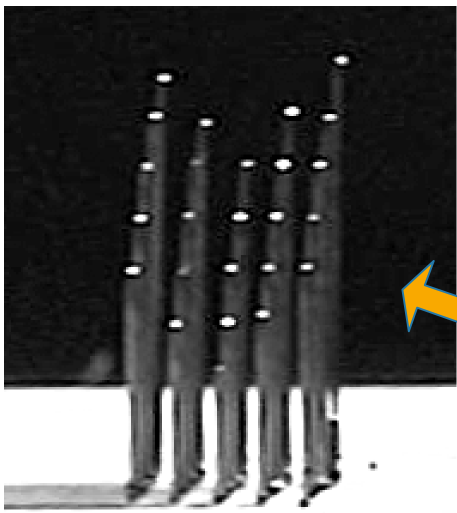
Goodin, D.T., et al, "A cost-effective target supply for inertial fusion energy", Nuclear Fusion 44 (2004), S254-265.

HIF - laser-assisted chemical vapor deposition (LCVD) to manufacture the HIF hohlraum

- **Low-density, high-Z only materials needed**
- **Proposed concept - micro-engineered matl's**
  - Build from "inside out", avoid machining and handling low-density foam



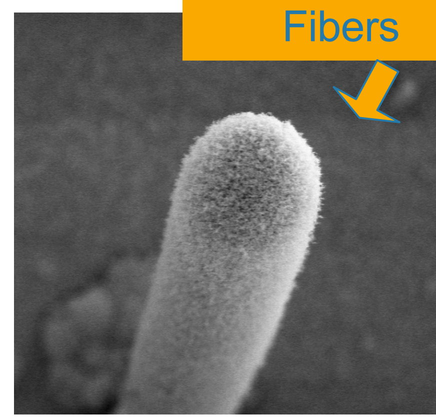
3D-LCVD hohlraum fabrication



Arrays demo'd via Diffractive Optics; enables low-density blocks and engineered foams.

LCVD for alloys of normally immiscible materials (NIM's)

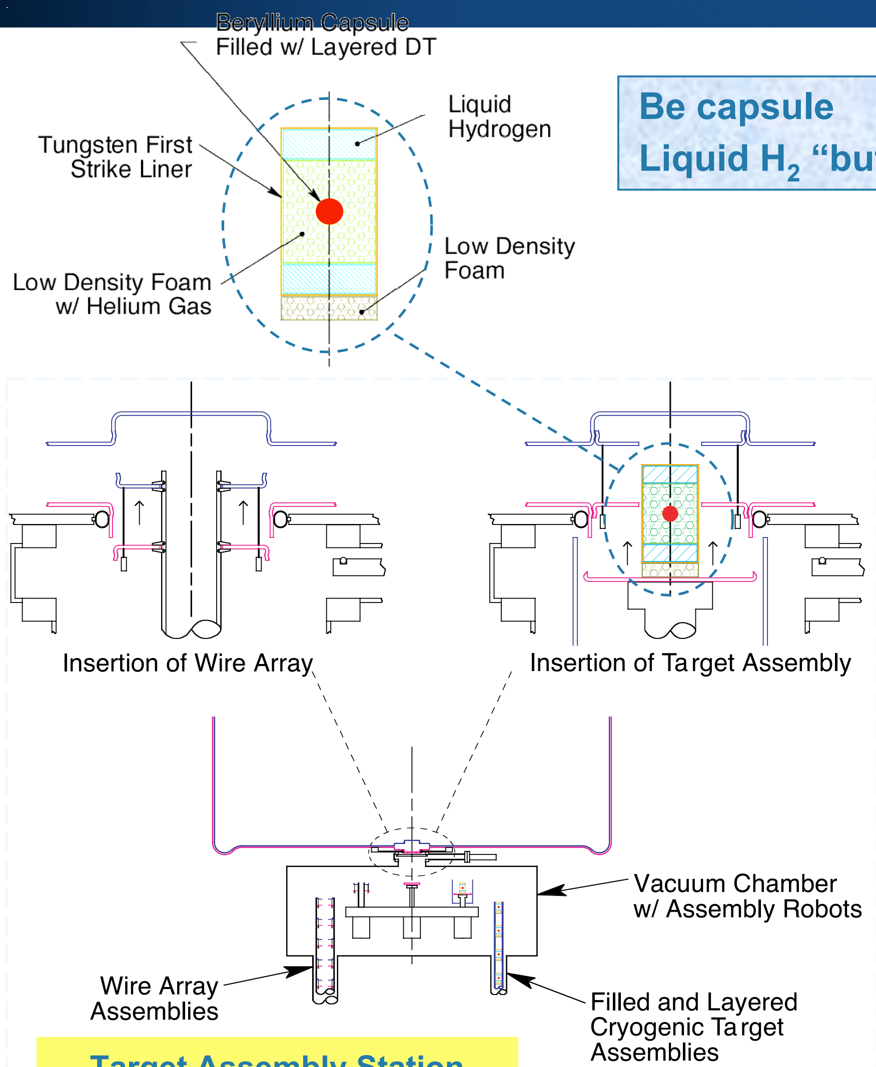
Si-W Alloy Fibers



Goodin, D.T., et al, "Progress in Heavy Ion Driven Target Fabrication and Injection", Nuclear Instruments and Methods in Physics Research, A, Vol 544, 2005, 34-41,

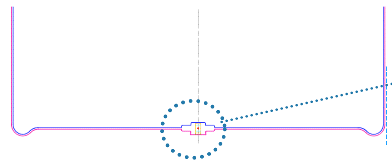
Maxwell, James, et.al., A Process-Structure Map for Diamond-like Carbon Fibers from 1-Ethene at Hyperbaric Pressures, Advanced Functional Matl's, 15, 7, 2005, 1077-1087.

IFE are being developed

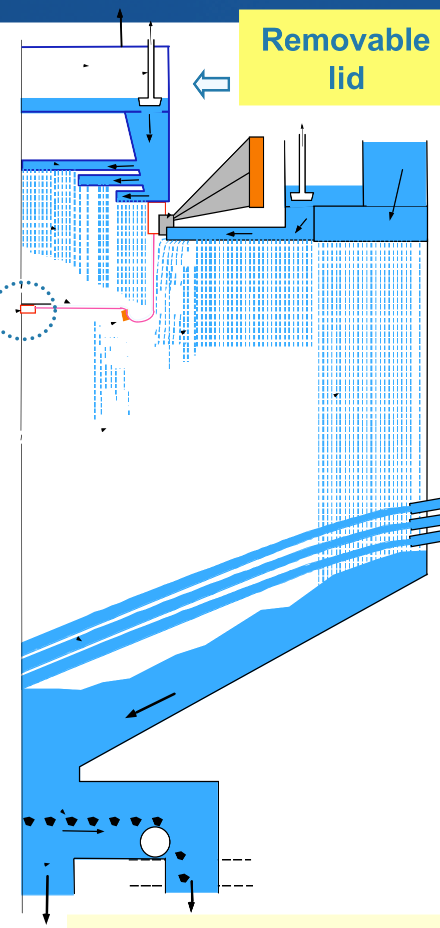


Target Assembly Station

Be capsule
Liquid H_2 “buffers”



Assembled RTL/target in transit



Removable lid

Flibe-protected ZFE chamber concept

Plant Design Data

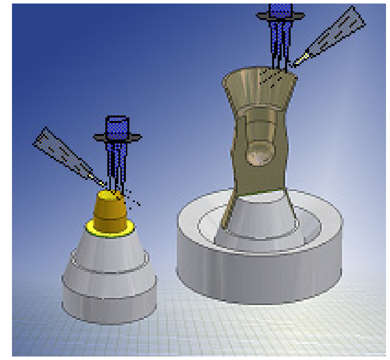
Rep-rate = 0.1 Hz
Yield = 3 to 20 GJ
Power = ~1100 MW(e)

See “ZP-3, A Power Plant Utilizing Z-Pinch Fusion Technology”, Rochau et al. IFSA2001

.... Design concepts have been prepared indicating time frames for cryogenic target assembly and handling are feasible

Estimates for indirect drive (HIF) target production costs

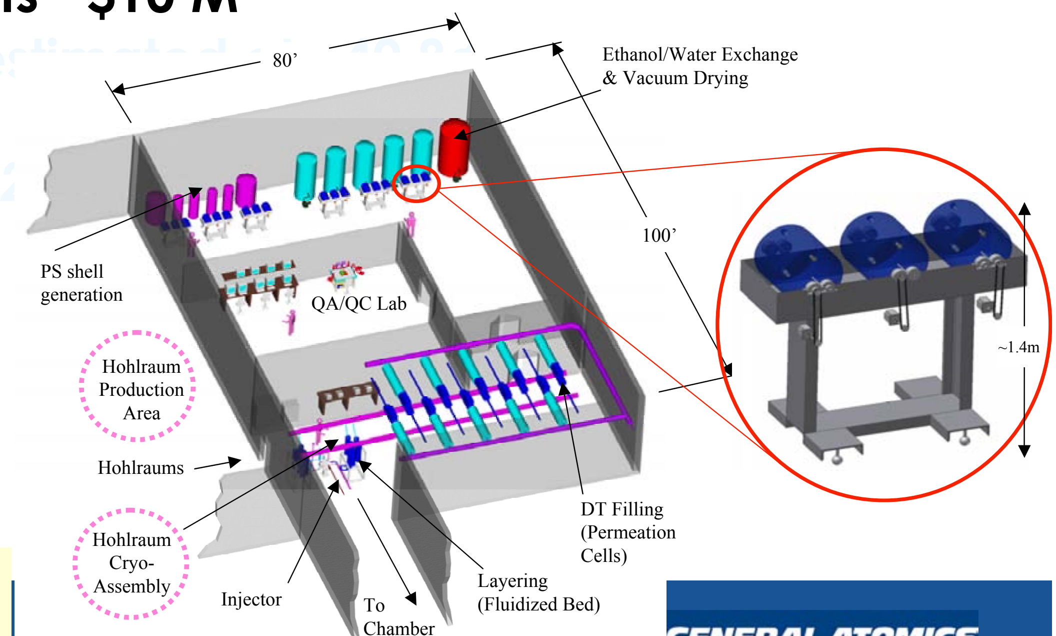
1) Production rate ~500,000 targets/day - 1000 MW(e) plant
2) Pb/Hf (70:30) is high Z material (single use)
3) Installed capital cost ~ $304M ($38 M annualized cost)
4) Annual materials and utilities ~$11M
5) Annual maintenance costs (labor and materials) ~$18M
6) Annual operating labor costs ~$10 M



LCVD systems are major capital cost

Assumptions:

1) R&D programs done
2) Major "paradigm shift" from current targets - no first-of-a-kind costs, statistical characterization, increased yield, larger batch sizes
3) "nth-of-a-kind" plant, standard engineering cost factors



TFF layout for capsule, filling, layering, injection

GENERAL ATOMICS

2) How well are we meeting the overcoat specs…?

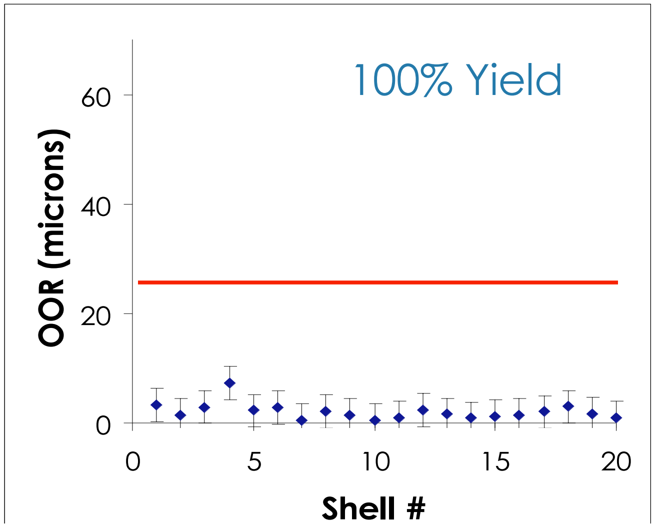
Attribute	Value	Tolerance	DVB	RF	Comments
Coating composition	CHNO		PVP/GDP (CHO)	GDP (CH)	N, O now acceptable
Coating Thickness	<5-10 μm	+/- (30 – 300) nm	+/- 2 μm	+/- 2 μm	
Power spectrum (surface finish)	<50 nm	--	> 500 nm	Getting close (50 - 200 nm)	
Permeability (gas tight) and yield	TBD	--	Fail at 10 um	Fail at 10um, some good at > 20 um	For current techniques require ~20 um thickness, working to minimize
Strength (for filling)	TBD	--		> 2 atm	For a >20 um thick coating

These specs are evolving as more simulations are done by the designers

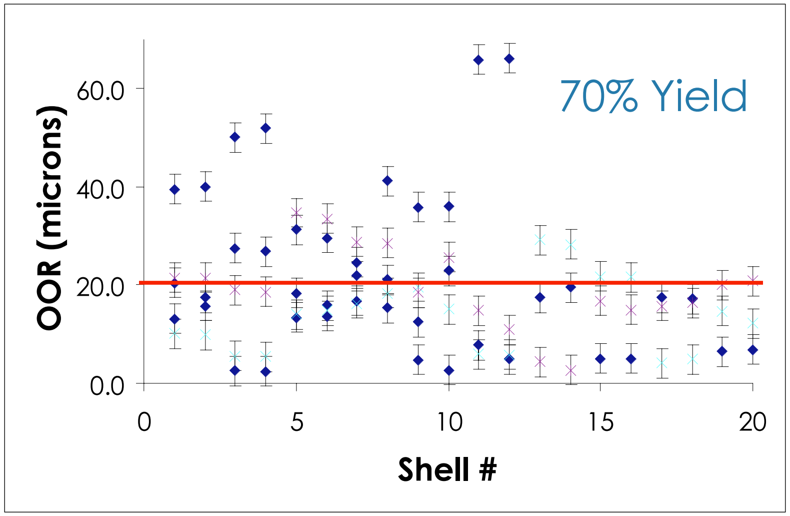
The DVB capsule meets the sphericity specification, but RF still requires work

- **The yield of RF shells that meet the 1% of radius Out-of-Round (OOR) specification is 70%**

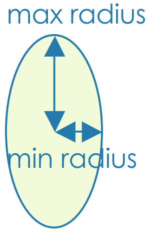
DVB Shell Data



RF Shell Data



OOR = (max radius – min radius)



A possible fix for this is to increase the interfacial tension of the RF system before curing

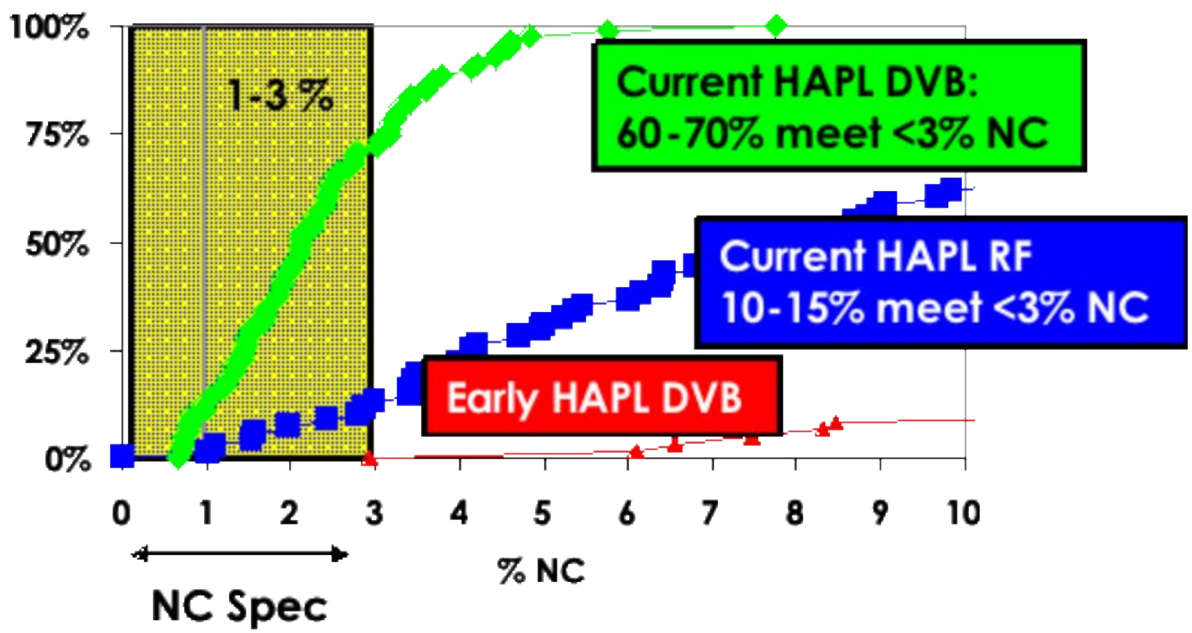
Currently DVB shells have a better yield of shells that meet the wall uniformity specification

- **Uniformity defined in terms Nonconcentricity (NC)**

$$NC = \frac{\text{offset}}{\text{avg. shell thickness}}$$

Offset = distance between centers of inner and outer wall

Percentile Plot of Foam Wall Uniformity



DVB is better for the NC specification (at the moment)