



GENERAL ATOMICS
AND AFFILIATED COMPANIES



Status of IFE target fabrication & injection

CRP on Elements of Power Plant Design for Inertial Fusion Energy
IAEA Headquarters, Vienna - November, 2003

Presented by Wayne Meier (LLNL)

Work performed with

Neil Alexander (GA)

Lloyd Brown (GA)

Debbie Callahan (LLNL)

Denis Columbant (NRL)

Drew Geller (LANL)

Jim Hoffer (LANL)

Wayne Meier (LLNL)

James Maxwell (LANL)

Abbas Nikroo (GA)

Art Nobile (LANL)

Ron Petzoldt (GA)

Rene Raffray (UCSD)

Diana Schroen (Schafer)

John Sethian (NRL)

John Sheliak (GA/LANL)

Bob Stemke (GA)

Max Tabak (LLNL)

Mark Tillack (UCSD)

Brian Vermillion (GA)

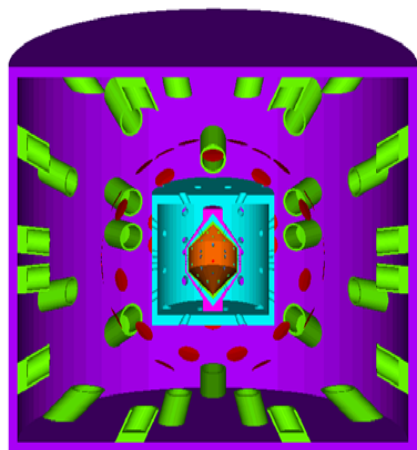
***Funded by High Average Power Laser
(HAPL) program and Office of Fusion
Energy Sciences (OFES)***



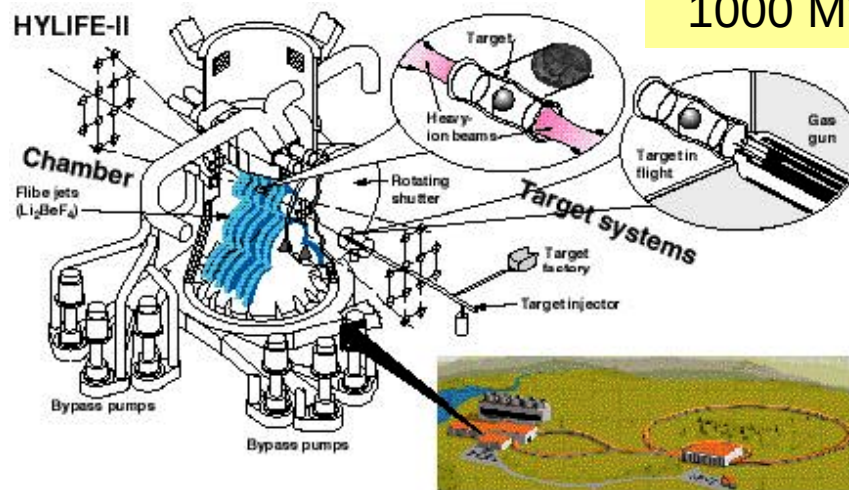
Describe the technical issues, progress, and status of target fabrication and injection for IFE approaches

Outline

- 1) Reference target designs (Laser Fusion and Heavy Ion Fusion)
- 2) Major processing steps for IFE target fabrication and injection
- 3) Key technical issues
- 4) Status of development of target supply systems
- 5) ZFE and Fast Ignition targets
- 6) Future directions



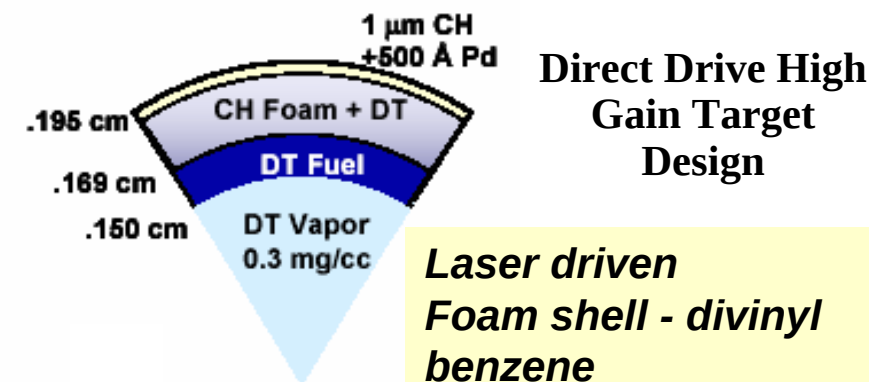
SOMBRERO 3-D model
for neutronics analysis



Concept for “HILIFE-II” IFE
1000 MW(e) Power Plant

Chamber radius
= 3 meters

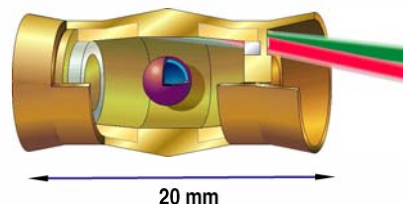
Reference target designs - laser & heavy ion fusion



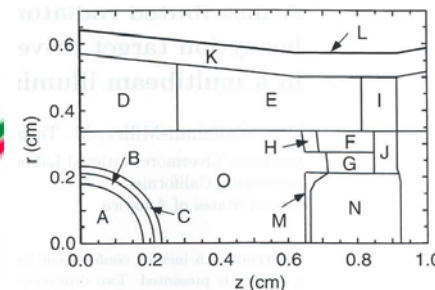
Some Expected Direct Drive Specifications

Capsule Material	CH (DVB) foam
Capsule Diameter	~4 mm
Capsule Wall Thickness	290 μm
Foam shell density	20-120 mg/cc
Out of Round	<1% of radius
Non-Concentricity	<1% of wall thickness
Shell Surface Finish	~20 nm RMS
Ice Surface Finish	<1 μm RMS
Temperature at shot	~15 - 18.5K
Positioning in chamber	± 5 mm
Alignment with beams	<20 μm

LLNL Distributed Radiator Target



being simplified...



*Two sided illumination by heavy ions
Radiation tailored by material density
Newer designs w/o "high-Z only"??*

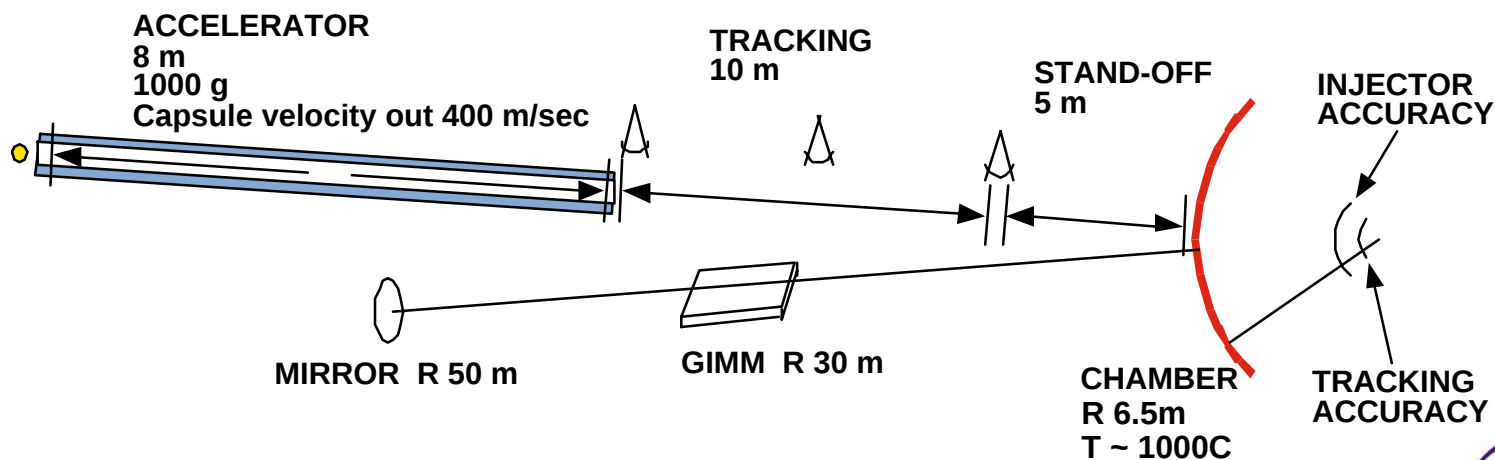
Some Possible Indirect Drive Specifications

Capsule Material	CH or Be
Capsule Diameter	~4.6 mm
Capsule Wall Thickness	250 μm
Out of Round	<1% of radius
Non-Concentricity	<1% of wall thickness
Shell Surface Finish	20-200 nm RMS
Ice Surface Finish	1-10 μm RMS
Temperature at shot	~15 - 18.5K
Positioning in chamber	$\pm 1-5$ mm
Alignment with beams	<200 μm



Target teams are in place and basic requirements are well understood

- GA/Schafer, LANL, and UCSD are part of a team addressing the issues of IFE target supply
 - Close coordination with target designers & IFE community
- Basic requirements = supply about 500,000 targets per day for a 1000 MW(e) power plant (rate of about 6 Hz)
 - Stringent geometric requirements (symmetric, smooth surfaces)
 - Injection placement accuracy to $\pm 1\text{-}5\text{ mm}$
 - Direct/indirect drive tracking and beam steering to $\pm 20/200\text{ }\mu\text{m}$



Basic requirements lead to key issues.....



“Key issues” have been identified and agreed upon

(W. Meier, UCRL-ID-133629, LLNL, April 7, 1999)

Target fabrication critical issues

- 1) Ability to fabricate target capsules & hohlraums (500,000/day)**
- 2) Ability to fabricate them economically (~\$0.25-0.30 each)**
- 3) Ability to fabricate, assemble, fill and layer at required rates (~6 Hz)**

Power plant studies have concluded that \$0.25 - 0.30 targets are needed

Target injection critical issues

- 4) Withstand acceleration (~1000 g's) during injection**
- 5) Survive thermal environment (1250K plus gas at 4000K)**
- 6) Accuracy and repeatability, tracking (± 5 mm, $\pm 20/200$ μ m tracking)**

Experimental plan for target injection is being carried out
(Nuclear Fusion, 41. May 2001)

We have focused our attention on these key issues



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Overall concept for IFE target supply is well established



1) Fabricate Capsules

2) DT Fuel Fill

3) DT Fuel Layer

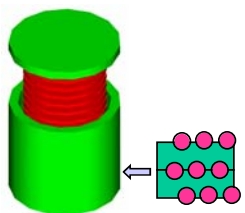
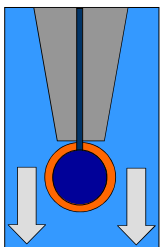
Load capsule in sabot

Load capsule in hohlraum

4) Inject

5) Fabricate hohlraum

Micro-encapsulation

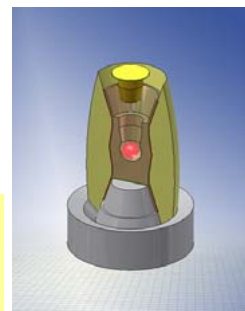


Pressure cell



Fluidized bed

Several advanced manufacturing steps



Injector

Advantage = started with existing experience base

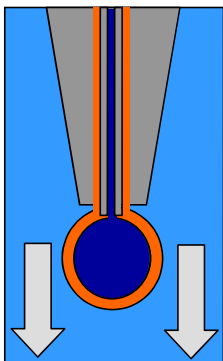
1) Capsules must be fabricated at a rapid rate with high tolerances

Technical Issues

- Rapid (~500,000/day, 20,000/hour, 6 Hz) and reproducible
- Thick (~250 μm) full density CH (HIF, ZFE)
- Multiple foam layers (DD) with CH overcoat and high reflectivity overcoat
- Geometrically precise
 - Out of round = <1% of radius
 - Non-concentricity = <1% of wall thickness
 - Surface finish = 20 - 200 nm

Process = microencapsulation

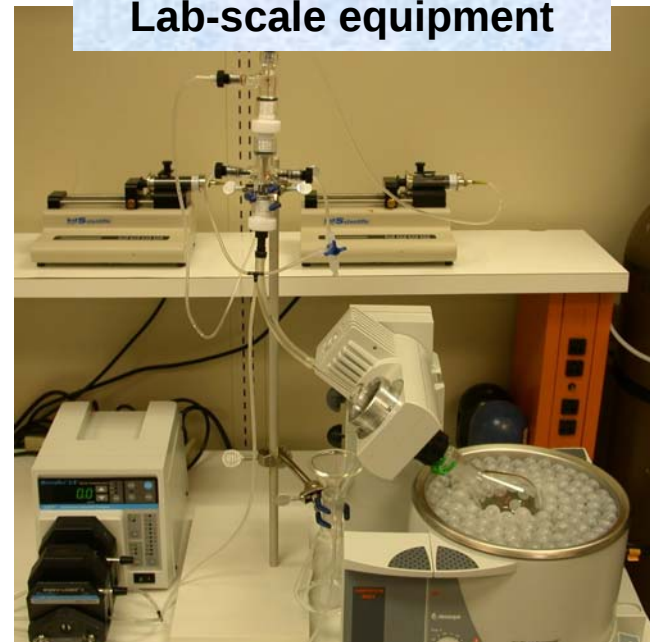
3 Hz for 4 mm capsules



- Inner Water Phase
- Organic Phase
- Stripping Phase



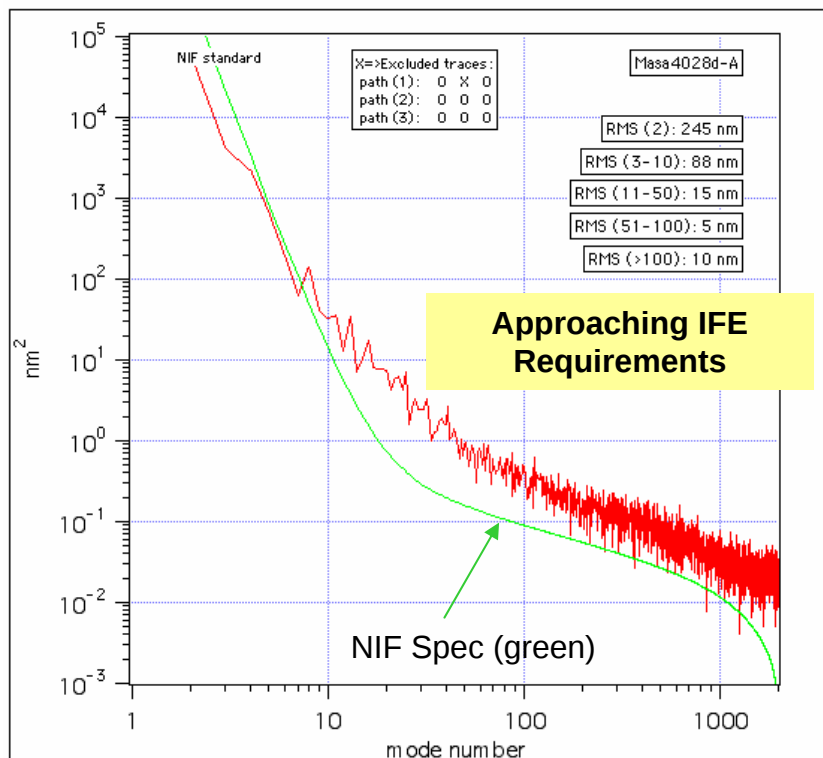
Lab-scale equipment



Capsule technical requirements are well understood

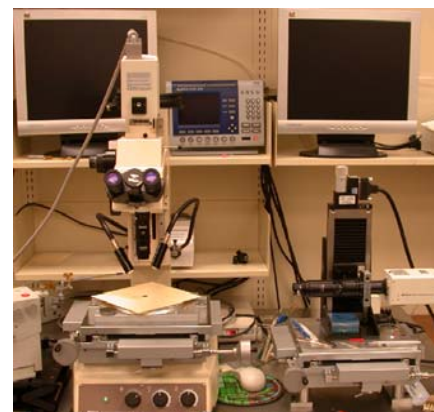
CH capsule (HIF, ZFE)

Power spectrum of 4.6mm CH capsule, 45 μm wall, OOR
<1% of radius, NC <3% of wall, rate 36/minute (GA)



CH overcoated foam capsule (DD)

4 mm dia., 200 μm foam layer, CH overcoat,
production rate - 3 Hz



Capsules are placed
in an optical cell to
obtain two
orthogonal images

The microencapsulation process has demonstrated feasibility
but IFE specifications not yet met

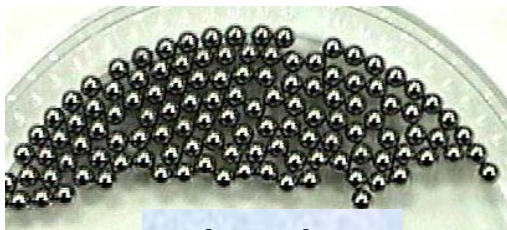


High-Z overcoat applied by physical vapor deposition

- High-Z coating is critical to reduce thermal heat load on direct drive target during injection (want reflectivity in mid-90's%)
- May increase fill time and increase DT inventory



Au coatings
on CH

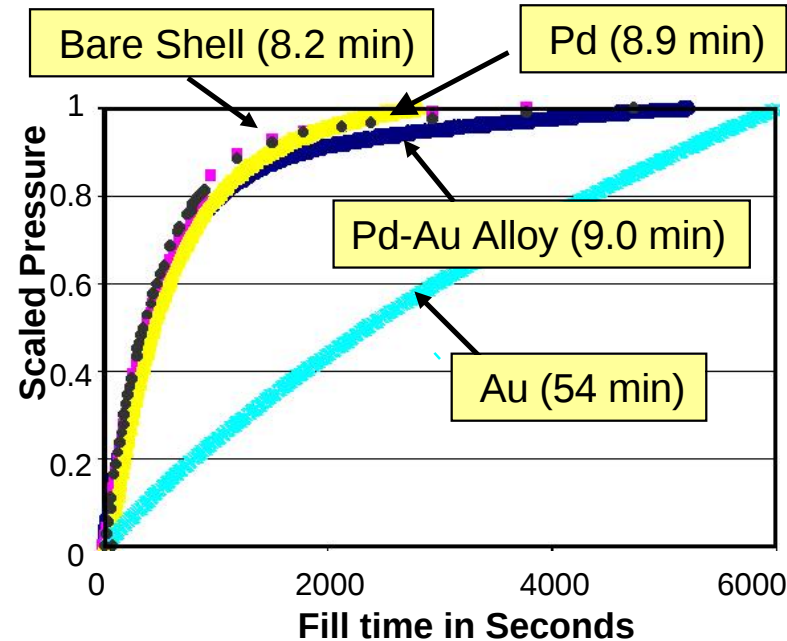


Pd coatings



Industrial roll coater
(typical)

Permeability:
Au-Pd similar to Pd



**High-Z coating for direct drive target is demonstrated -
but needs optimization for IFE**



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Current status of capsule technical issues



- Rapid (~500,000/day, 20,000/hour, 6 Hz) and reproducible
 - 3 Hz for HIF/ZFE capsules, yield is low
 - 3 Hz for foam capsules, not yet able to meet specifications
 - Scaleup by multiple droplet generators is straightforward
- Thick (~250 μm) full density CH (HIF, ZFE)
 - 45 μm wall shells made close to shape specifications, yield is low
- Multiple foam layers (DD) with CH over coat and high reflectivity overcoat
 - Single foam layer shells with CH over coat demonstrated
 - High reflectivity overcoat demonstrated, D_2 permeability data obtained
 - Multiple foam layers not demonstrated, concepts being identified
- Geometrically precise
 - Specifications not yet met for IFE designs
 - Meeting specifications will involve extension of current DP ICF program technology

Capsule fabrication technologies are well-established and well-suited to mass-production - but needs optimization for IFE capsules

Technical Issues

- Rapid filling of many capsules (500,000/day)
- Acceptable tritium inventory
 - Goal = less than ~1 kg

$$\delta P = f P_{buckle} = f \frac{2E}{\sqrt{3(1-\nu^2)}} \left(\frac{w_s}{r_s} \right)^2$$

$$\text{for foams } E = E_{polymer} \left(\frac{\rho_{foam}}{\rho_{polymer}} \right)^2$$

f - fraction - “safety factor”

w_s - thickness of supporting layer

ν - Poisson’s ratio

r_s - radius of target

The fill overpressure, δP , is a function of the mechanical properties of the supporting layer.

Data on HIPE foam:

Foam density = 152 mg/cc
Young’s Modulus = 7.285×10^7 Pa

Permeation filling inventory models have been developed for IFE applications.....



DT inventories have been estimated for permeation filling



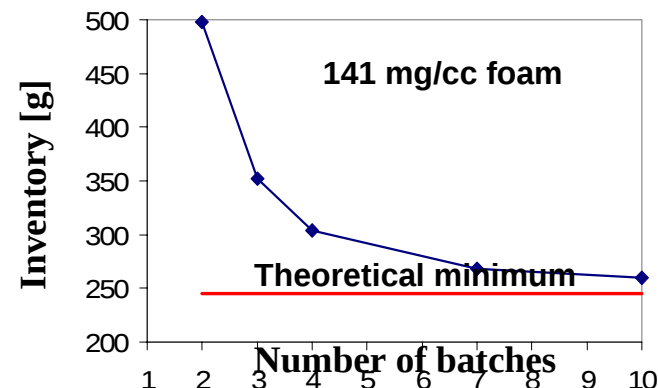
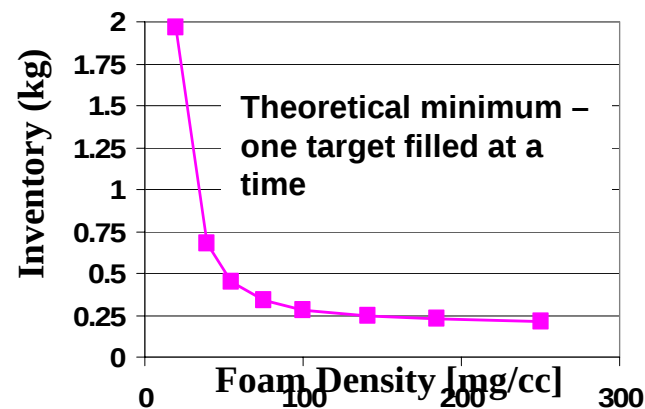
Results from - Art Nobile et al, IAEA TM on Physics and Technology of IFE Targets and Chambers, San Diego, June 2002

HIF Targets

Theoretical minimum DT inventories	HIF-fill in hohlraum	HIF-fill before assembly
Buckle Pressure	533 atm	533 atm
Fill Time	4 hours	4 hours
Tritium Inventory (beta-layering only)	29.4 kg	1.5 kg
Tritium Inventory (beta-layering + IR)	28.9 kg	1.0 kg

Data from: J.M. Williams, J.J. Bartos and M.H. Wilkerson, "Elastic Modulus Dependence on Density for Polymeric Foams with Systemically Changing Microstructures", *Journal of Materials Science* 25, 5134 (1990).

Direct Drive Targets



A. Schwendt et al, *Fusion Science and Technology*, 43, March, 2003

HIF Targets – DT fill must be done before assembly in hohlraum
Direct drive targets – strength properties of foams are needed

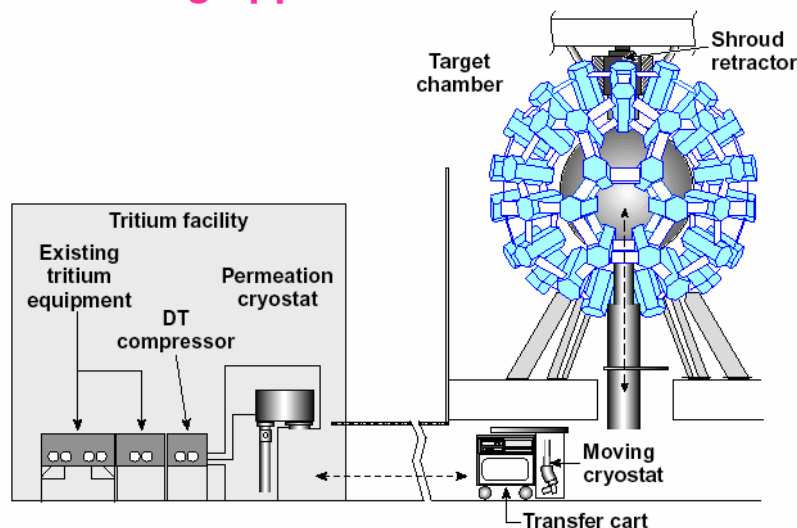


Current status of DT filling technical issues

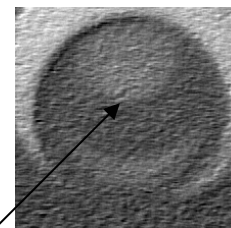


- **Rapid filling of many capsules (500,000/day)**
 - Permeation filling concept is demonstrated, and is routinely done at ORNL, LANL, LLNL (small numbers)
 - Many capsules likely can be filled in larger, high pressure vessels
 - Filling of capsules in batches will be necessary
- **Acceptable tritium inventory (<1 kg)**
 - Models for tritium inventory as a function of target parameters have been developed and used to estimate power plant inventories
 - Inventories less than ~1 kg appear to be feasible

Omega cryo-system at University of Rochester



**H-filled cryo
capsule, 1995**



**Hydrogen
meniscus**

- Permeation filling is simple and well understood
- Possible inventory reduction can be achieved by advanced filling concepts (drill, fill and seal)

3) “Layering” is forming an interior DT ice layer

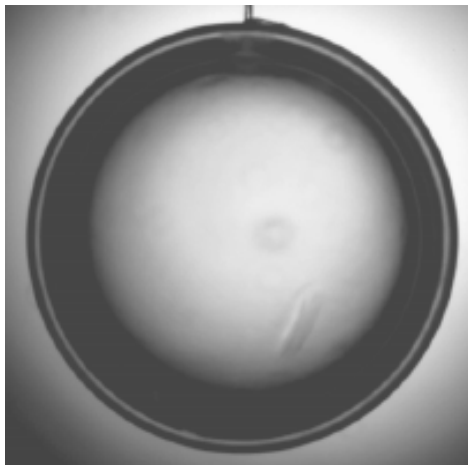


Technical Issues

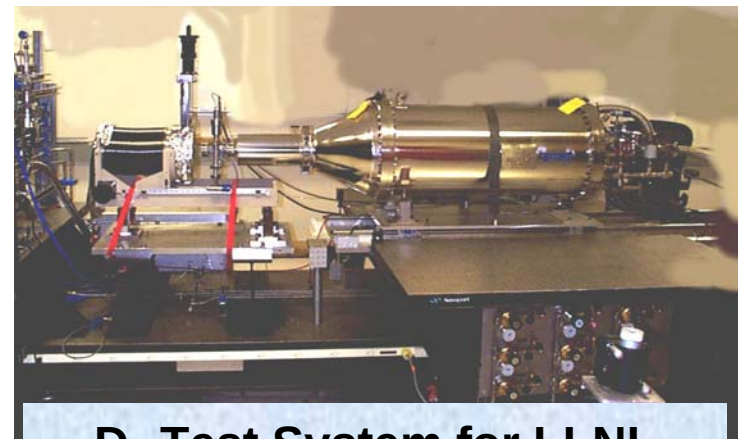
- Rapid formation of layer in many capsules (500,000/day)
- Formation of smooth DT ice layer ($\sim 1\text{-}10\text{ }\mu\text{m}$ rms)

Process = beta layering, and enhanced

- Provide highly isothermal environment ($10\text{-}100\text{ }\mu\text{K}$ across capsule)
- Add IR or Joule heat for “enhanced” layering



125 μm layer
inside 2 mm
diameter 40
 μm capsule
with fill tube
(LLNL)



D₂ Test System for LLNL

A large amount of R&D on layering is being carried out by the ICF program - a critical issue for IFE is mass-production



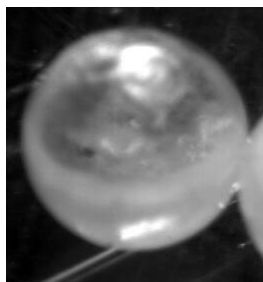
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Two potential mass-production layering methods identified



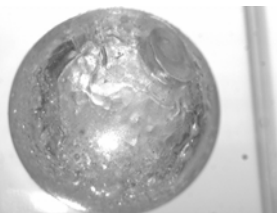
Cryogenic fluidized bed layering

Before



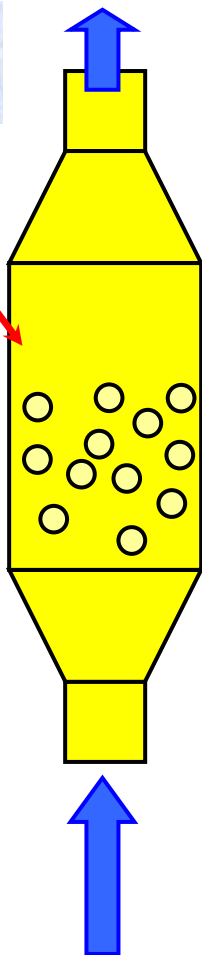
FLUIDIZED
BED WITH
GOLD
PLATED (IR
REFLECTING)
INNER WALL

After



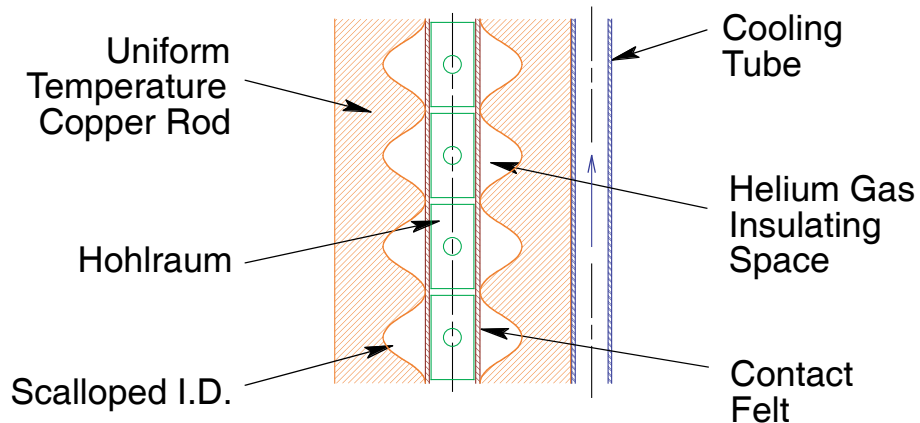
Neopentyl alcohol
surrogate - proof of
principle

INJECT IR



COLD HELIUM

In-hohlraum "tube" layering



- Layering by ICF programs
- Single capsules/hohlraums
- Fluidized bed allows uniform time-averaged temperature
- Lab-scale demonstration being designed for H_2



Fluidized bed
with capsules

A mass-production layering demonstration is one of the key missing elements in the target supply scenario



DT layering studies are underway for IFE



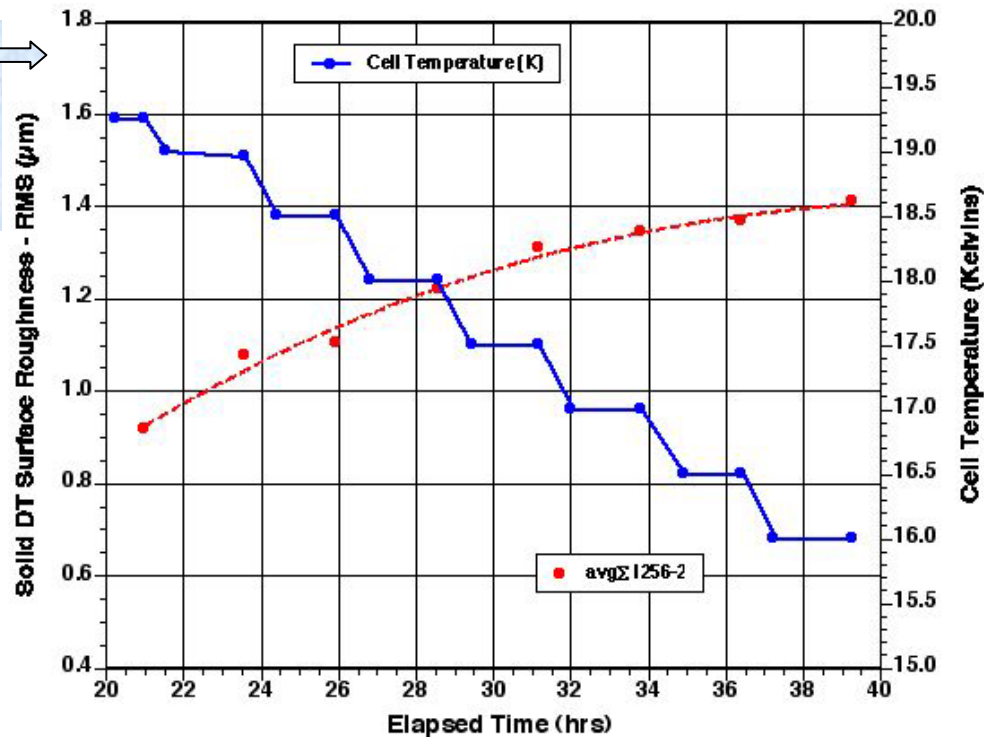
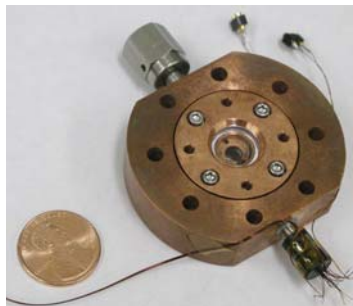
- Results = ice is smoother with foam (DD), can be colder (heatup margin)
- DT layer must withstand acceleration (1000 g) for injection (i.e., strength)
- Colder DT has more strength
- DT experiments also planned for strength, and response to high heat flux

Stepped-ramp cooling to 16 K increased the surface roughness by about 50%, but RMS is still $\sim 1.4 \mu\text{m}$ (Jim Hoffer and John Sheliak)

Cryostat



DT heater cell being installed in cryostat



Status of technical issues = layering is feasible, being highly studied, mass production method demo is needed

4) Injection puts target into reactor chamber



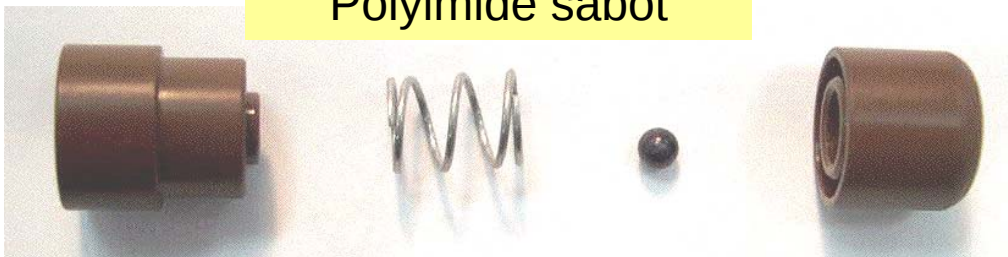
Technical Issues

- Repetitive placement (400 m/s for DD) of target at chamber center to $\pm 1\text{-}5\text{ mm}$
- Tracking for beam steering to $\pm 20\text{ }\mu\text{m}$ (DD) or $200\text{ }\mu\text{m}$ (ID)

Process = gas-gun or EM (backup)

- Gas gun is achieving consistent ($\sim 1\%$) velocities up to **350 m/s**
- Current placement accuracy = 50% in-spec (full range= **$\pm 22\text{ mm}$**)
- Improvements underway = sabot & muzzle design, gas turbulence control
- Preparing revolver for rep-rated (6 Hz) operation
- Tracking system has shown $\sim 3\text{ }\mu\text{m}$ reproducibility in stationary tests

Polyimide sabot



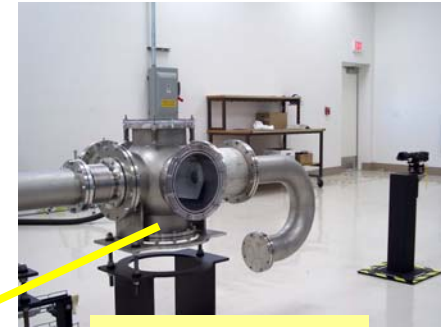
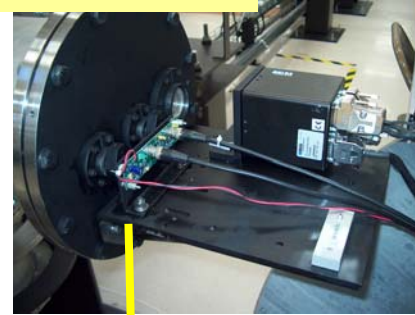
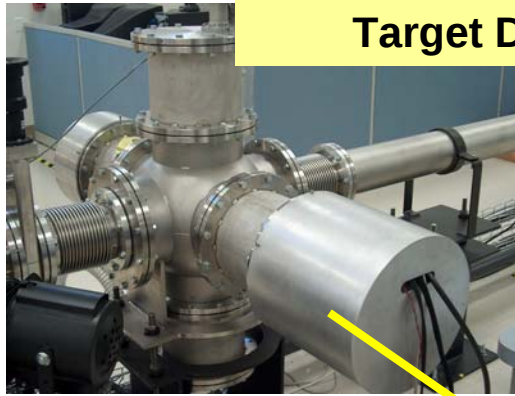
Sabot deflection
at over 300 m/s

Demonstration of accurate injection will address a major feasibility issue for energy from inertial fusion

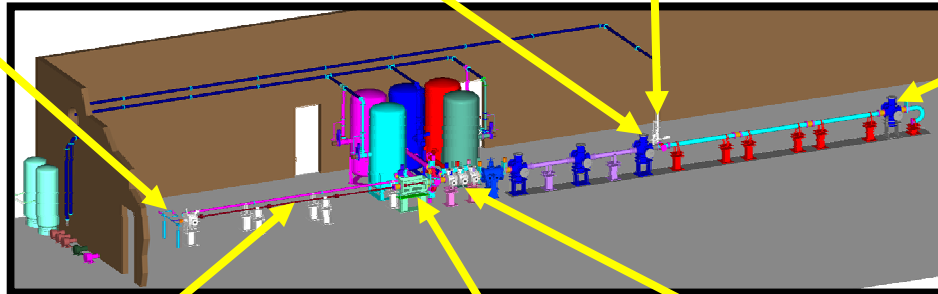
Many injection system components installed



Target Detectors



Prediction Station



Revolver



8 m Gun Barrel



Muzzle Gas Diverter



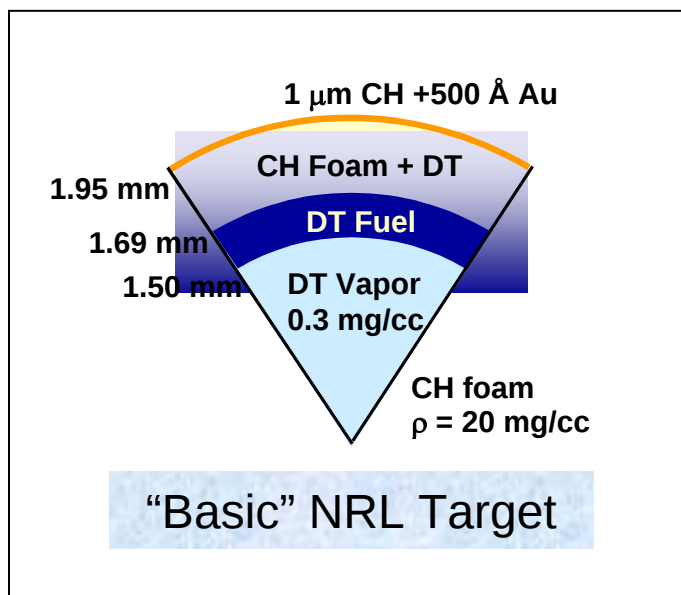
Sabot deflector





Foam insulated target can open chamber “design window”!

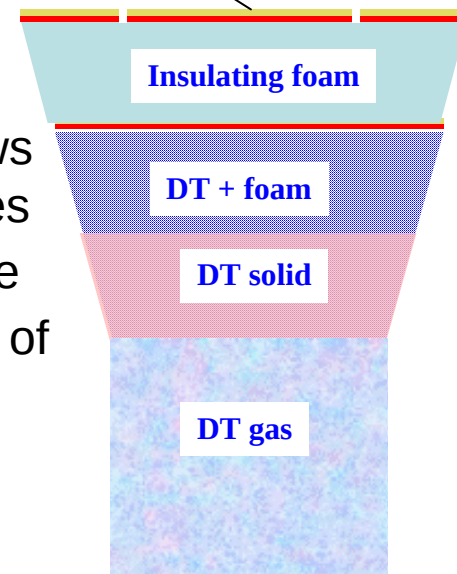
- Adding modest foam insulation improves thermal survival significantly
- Allows addition of gas for chamber wall protection



High-Z coat moved
to outside of foam

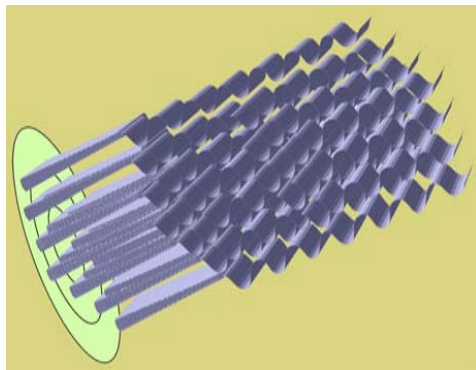
$\approx 1 \mu\text{m}$
holes

- High-Z outside allows multiple $\sim 1 \mu\text{m}$ holes
- Holes reduce fill time
- Holes allow “drying” of outer foam



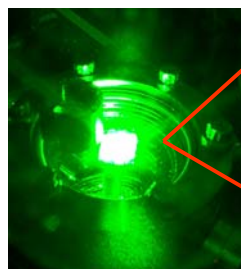
Current status of target injection = calculations show there are methods for survival, DT strength exp's planned, demo of placement and accuracy being brought online

5) Hohlraum component fab is key issue for HIF

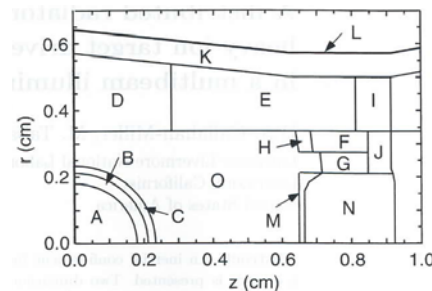


Variable Spacing & Fiber
Diameter → Variable Density

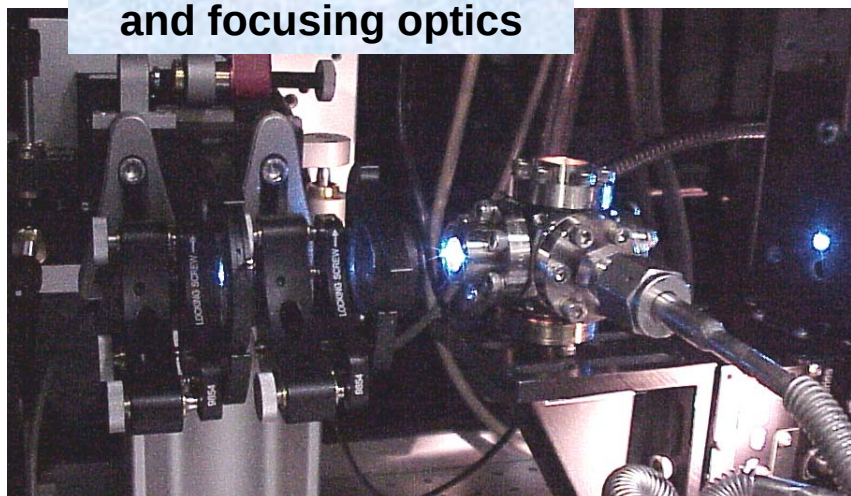
- Indirect drive target issues = hohlraum materials
- Fabrication, assembly, compatibility
- LCVD provides “micro-engineered” pathway
- Fiber arrays have now been grown - critical for mass production



*Materials range
11 - 13,500 mg/cc*



Close-up of chamber
and focusing optics



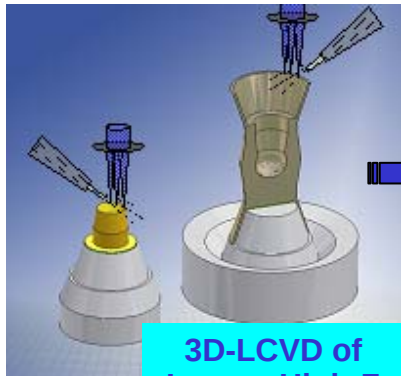
**LCVD
experimental
setup at LANL
(PI - James
Maxwell)**



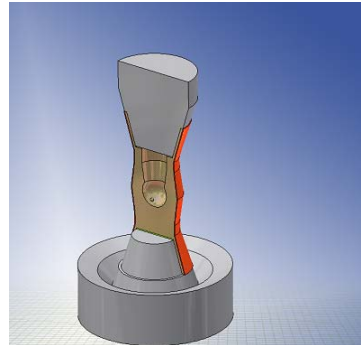
Indirect drive target hohlraum fabrication



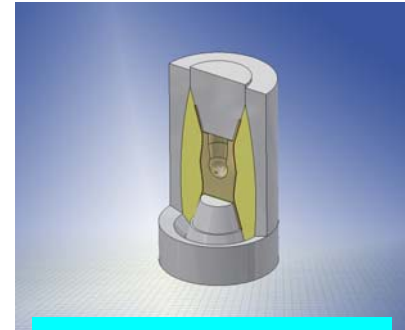
LCVD high-Z foam and assembly process



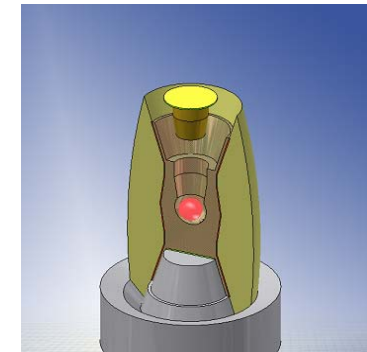
**3D-LCVD of
Low-p, High-Z
Metal Lattices**



**Deposit Hohlraum
Exterior Wall**



**Reactive Injection of
Polymeric Case**



**Capsule/Plug Insertion and
Immediate Target Injection**

- A number of potential hohlraum material options identified
 - Au/Gd published design, but high cost, must re-cycle (\$\$\$\$\$)
 - Hg and HgX good gain but environmental concerns
 - Pb/Hf has 2% E loss, cost study estimated \$0.41 each to make
 - W has 12% E loss, but environmentally “friendly”
- Plant trade (cost) studies would be next step for selection
- Other process steps (capsules, layering, injection) similar to direct drive

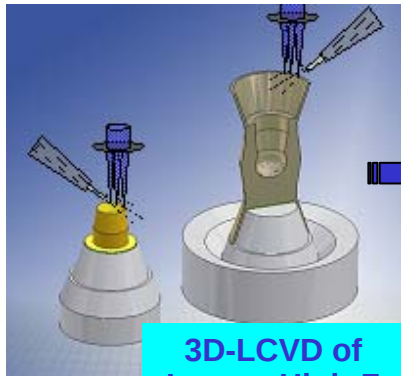
We have identified fabrication pathways for Heavy Ion Fusion targets - and potential hohlraum materials



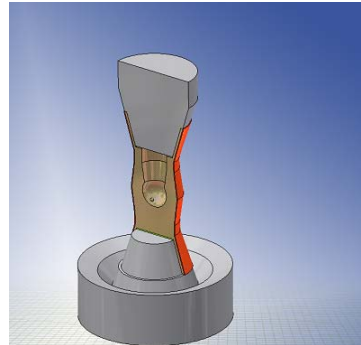
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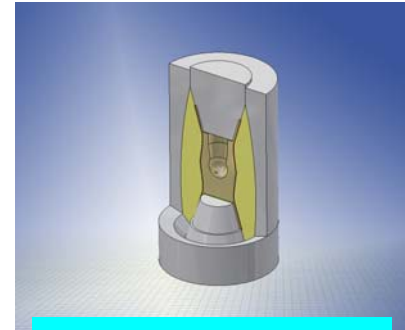
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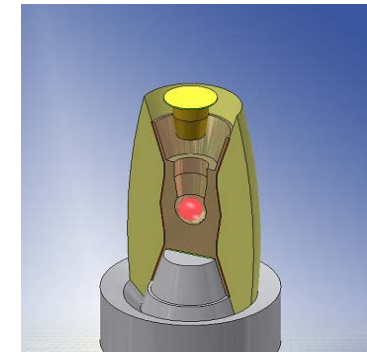
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- Plant trade (cost) studies would be next step for selection
- Other process steps (capsules, layering, injection) similar to direct drive

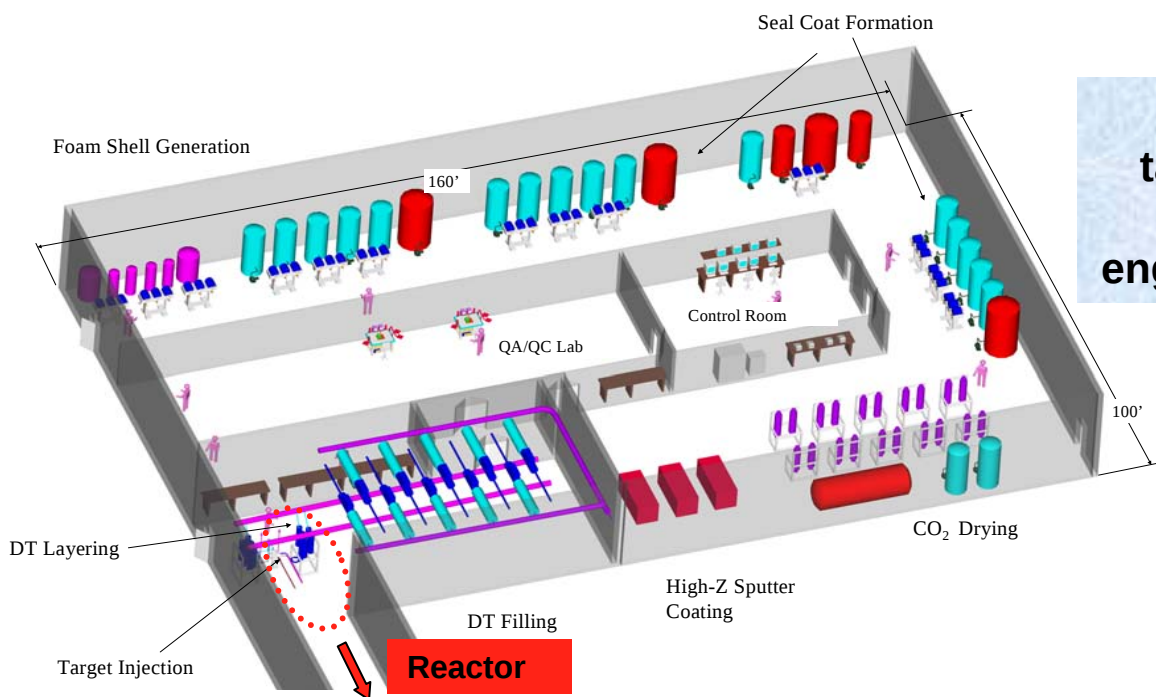
We have identified fabrication pathways for Heavy Ion Fusion targets - and potential hohlraum materials



Preliminary estimates of target production cost made



- Assumes “nth-of-a-kind” plant - development program is done
- Major “paradigm shift” from current experimental target fabrication
 - No First-of-a-Kind costs, reduced characterization, increased yield, increased batch sizes
- Direct drive - Capital of \$100M, operating \$19M, **est'd 16.6 cents/target**
- Indirect drive - Capital of \$300M, operating \$11M, **est'd 41 cents/target**



Assumes 500,000 targets per day (75% yield), standard engineering cost factors

Conceptual layout for direct drive target fabrication facility

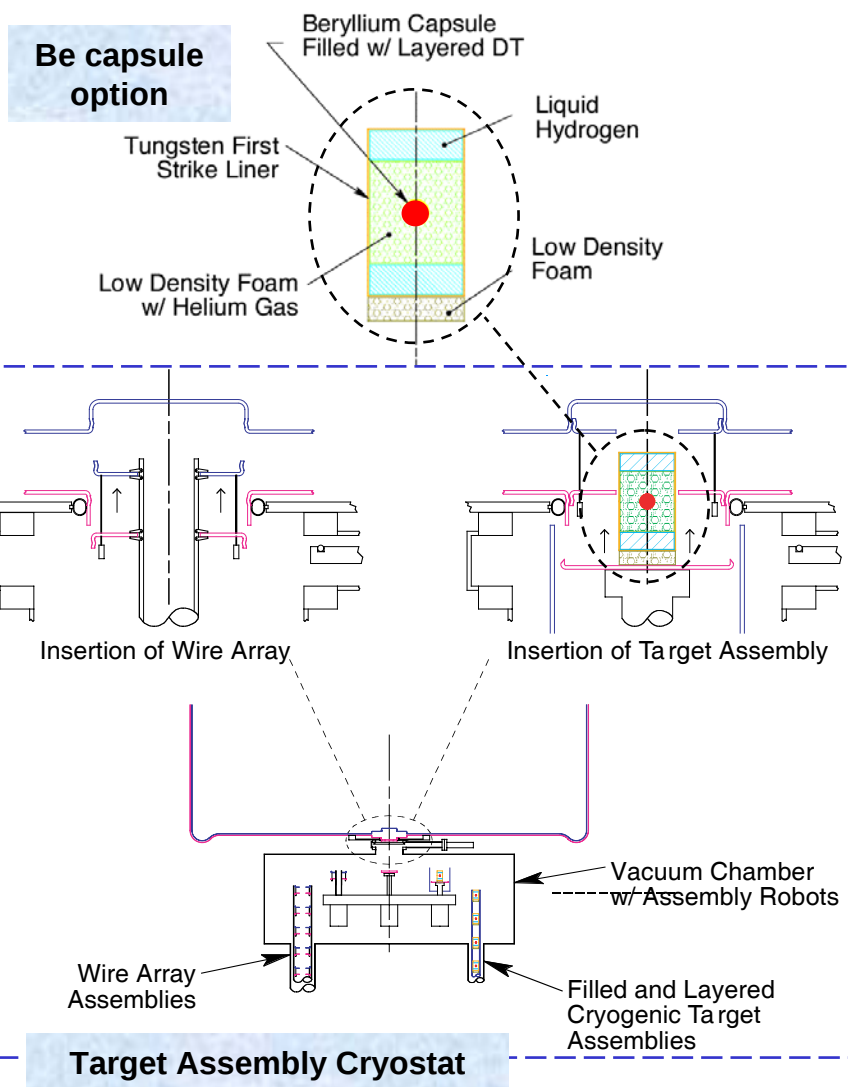
While required development programs are still quite significant, cost studies are promising for energy production



ZFE fielding concepts have been developed for dynamic hohlraum



- Issue = long survival times, assembly
- Options include:
 - 1) Cryo assembly with CH capsule previously layered in fluidized bed
 - 2) Room temperature assembly with Be capsule, layered in assembly
- Finished assembly survives (calculation):
 - 34 seconds of 293K blackbody plus
 - 4 seconds of 923K

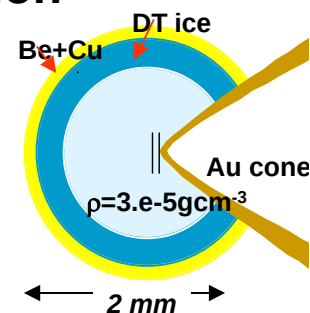
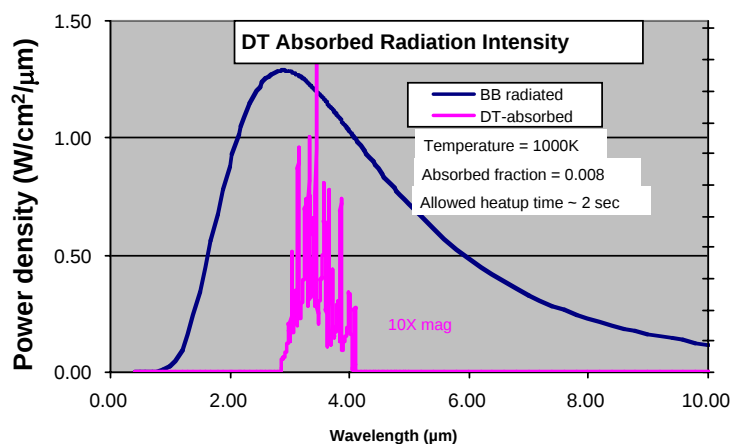
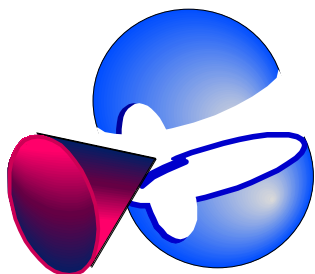


Top view of layering beds and hohlraum loading

Design concepts have been prepared for ZFE target supply, and scoping calculations indicate time frames for handling are sufficient

Fast ignition targets hold potential for relaxed requirements and reduced development programs

- For FI, we propose a major shift in target fabrication concepts
- Propose to stamp (or mold) DT into hemi-shells
- Connect DT to cone with extruded features
 - eliminates diffusion fill and layering
- Easy temperature control (keep very cold)
- Estimates show can survive handling and injection
 - self heating - ~60s, Injection 1000K - ~2s



Ignition scale



Fi ignition targets have been “hand-made”, but are very difficult to assemble

Many issues remain, but FI could allow much simpler targets.....



Conclusions - target fabrication and injection



- **Direct drive targets (laser IFE)**
 - Most difficult issue is injection (survival during injection)
 - Status
 - Well-rounded team and well-defined development plans
 - Processes identified for every part of target supply - being tested
 - Cost study shows the relatively simple target can be mass-produced
 - Will have a prototypical target in every way in a few years
- **Indirect drive targets (distributed radiator for heavy ion fusion)**
 - Most difficult issue is fabrication (injection is “easy”)
 - Status
 - Target being simplified for practical, low-cost mass production
 - Identified potential fabrication pathways for every process step
 - Identified a number of viable hohlraum materials choices
 - Costing analysis study shows costs close to goals
- **ZFE targets - concepts identified, scoping calculations show feasibility**
- **Fast Ignition targets - hold promise of relaxed requirements, but needs development**



Conclusions - top level (*programmatic*)



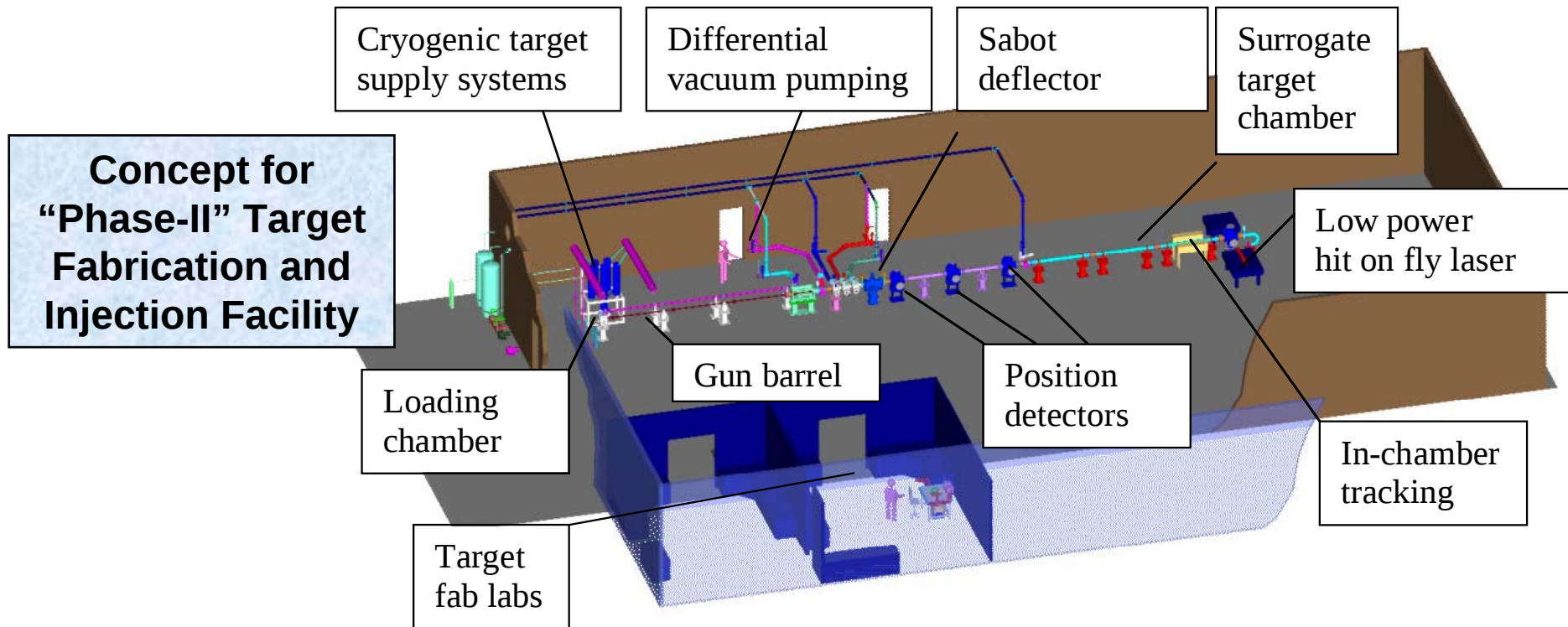
1. Key technical issues for IFE target fabrication and injection have been identified
2. Starting with a large DP/ICF experience base, significant progress has been made in addressing these technical issues
3. A long-term and sustained science-based development program is needed
 - *meeting all target specifications will be a challenge*
 - *target designs will evolve*
4. However, this science-based program must ultimately transition to a scaleup program with pilot-plant activities

IFE is looking towards the next phase of development.....



Future → IFE/HAPL program starting to plan “Phase-II”

HAPL is evaluating readiness for Phase II, i.e., moving from “proof-of-principle” to integrated equipment demonstrations



SOFE2003 San Diego Paper - “A Target Fabrication and Injection Facility for Laser-IFE”, Tillack, Goodin, Alexander, Petzoldt, Raffray, Schroen, Sethian, and Streit



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IFE target fabrication and injection development is well-published and documented



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