Target Fabrication and Injection Challenges in Developing an IFE Reactor

NNSA

BERKELEY LAB

Los Alamos NATIONAL LABORATORY

LLNL

Schafer

Sandia National Laboratories

UNIVERSITY of ROCHESTER

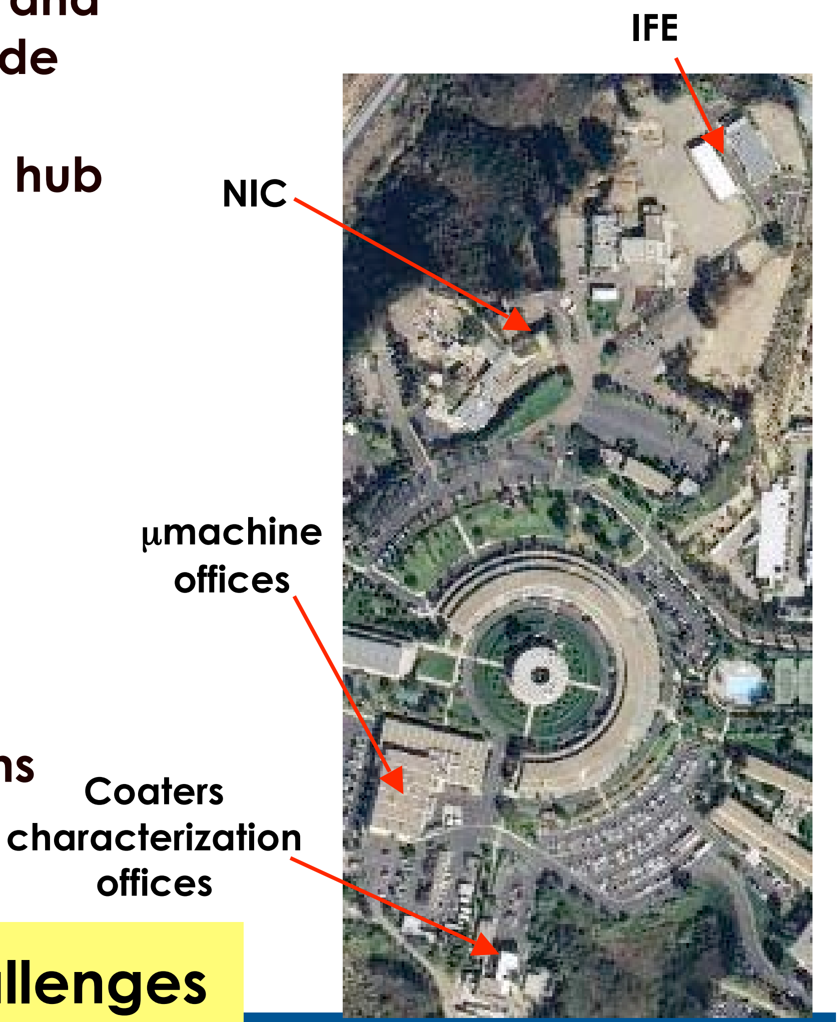
WISCONSIN UNIVERSITY OF WISCONSIN-MADISON

UCSD

GA has a long history with both ICF and IFE targets - HAPL, HIF, ZFE, now LIFE

- Extensive experience in ICF target fabrication :
  - Role: to develop ICF target fabrication and characterization techniques and provide targets
  - Collaboration with all labs as a central hub for targets since 1991
    - Several 1000's targets/year
    - Staff ~100, ~1/4 PhD's
    - Specialized equipment
    - ISO 9001:2008

- Leveraged expertise from ICF to IFE
  - Target fab
  - Injection and tracking
  - Continued tradition of close interactions with national labs



We have a good team to tackle challenges

We believe that targets can be mass-produced for IFE and meet the requirements for fusion energy

- Challenges and critical issues for the IFE target supply chain have been identified
- Much work has been done on the target supply process for a number of IFE approaches – much work remains …
- Mass production of an IFE target is a difficult but manageable task
  - Will require a sustained development effort that should occur in parallel with other reactor technologies
  - Iteration with design is critical - as in the case of ignition targets
  - “Nth-of-a-kind” cost studies have shown that cost-effective target manufacture is possible
- This talk will summarize four different target designs and the work that has been done to define manufacturing methods and to show acceptable cost
  - Show examples with different levels of maturity - many are conceptual

Despite different IFE approaches there are commonalities in much of the basic required target fabrication capabilities

"Critical issues" were identified in program plans more than a decade ago….

"Chamber and Target Technology Development for Inertial Fusion Energy", W. Meier et al, April, 1999, LLNL, UCRL-ID-133629

1- Target fabrication

critical issues:

- a) Ability to fabricate target capsules & hohlraums
- b) Ability to fabricate them economically
- c) Ability to fabricate, assemble, fill and layer at required rates

Power plant studies have concluded that $0.25 targets are needed – reduced 3-4 orders of magnitude from current targets

2- Target injection, tracking

critical issues:

- a) Withstand acceleration during injection
- b) Survive thermal environment
- c) Accuracy and repeatability, tracking

A detailed experimental plan for target injection was prepared - *Nuclear Fusion, 41. May 2001*

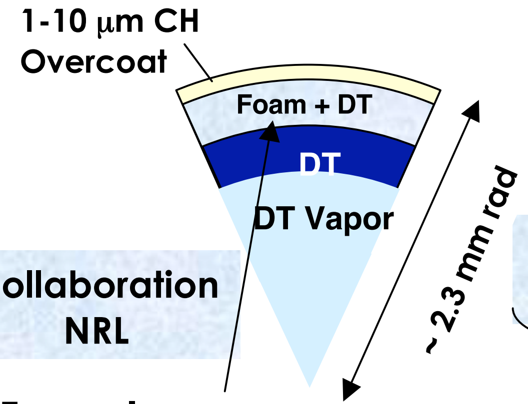
Studies have shown the feasibility of a cost-effective IFE target supply for energy

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

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	~3000	$2.90	~13
LIFE	Indirect drive Pb rugby hohlraum	~132	~$0.30	~30

HAPL

Direct Drive Laser Fusion

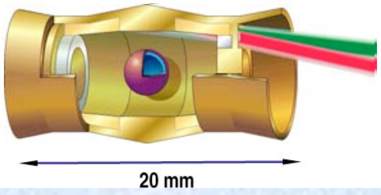


Collaboration NRL

Foam layer: Divinyl Benzene (DVB) or Resorcinol-Formaldehyde (RF)

HIF

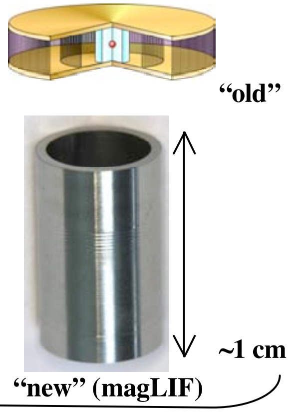
Heavy Ion Fusion



Collaboration with LANL, LLNL, LBNL

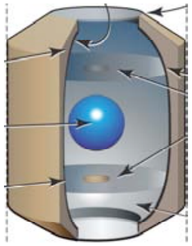
ZFE

Z-Pinch IFE (ZFE)



LIFE

Laser Inertial Fusion Engine (LIFE)



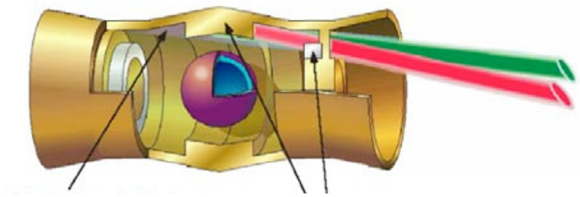
Collaboration with LLNL

Current target designs have evolved - discuss these here for the process

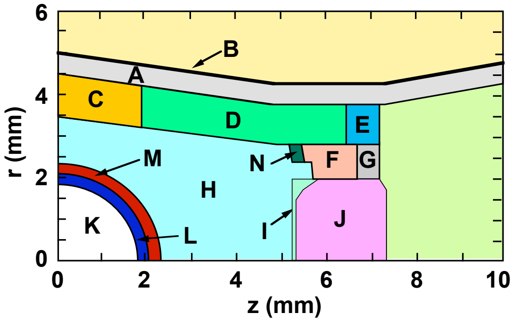
Close interaction and trade off between target designers and fabricators is essential …

Such interactions have been central to identifying and solving target challenges for the various approaches

HIF ***Example:***



The heavy-ion driven target had a number of unique and challenging materials*



**Nuclear Fusion 39, 1547 (1999)*

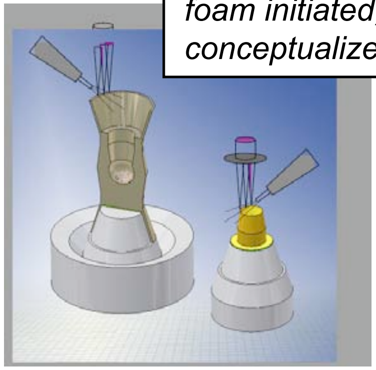
Materials range of 11 - 13,500 mg/cc

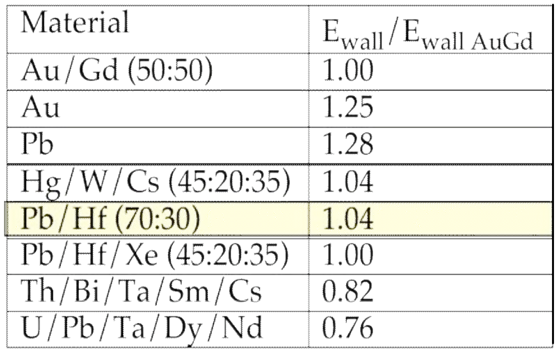
A:	AuGd	0.1 g/cc
B:	AuGd	13.5 g/cc
C:	Fe	0.016 g/cc
D:	$(CH)_{0.97}Au_{0.03}$	0.011 g/cc
E:	AuGd	0.11 g/cc
F:	Al	0.07 g/cc
G:	AuGd	0.26 g/cc
H:	CD_2	0.001 g/cc
I:	Al	0.055 g/cc
J:	AuGd "sandwich"	0.1/1.0/0.5
K:	DT	0.0003 g/cc
L:	DT	0.25 g/cc
M:	$Be_{0.995}Br_{0.005}$	1.845 g/cc
N:	$(CD_2)_{0.97}Au_{0.03}$	0.032 g/cc

Alternatives and example changes:

- **AuGd replaced with Pb/Hf**
- **Doped foam replaced low-density Fe**
- **Al foam replaced with silica aerogel**
- **Tamping gas replaced with He**

LCVD to "grow" hohlraums and foam initiated, a plant was conceptualized…





Material	$E_{wall}/E_{wall\ AuGd}$
Au/Gd (50:50)	1.00
Au	1.25
Pb	1.28
Hg/W/Cs (45:20:35)	1.04
Pb/Hf (70:30)	1.04
Pb/Hf/Xe (45:20:35)	1.00
Th/Bi/Ta/Sm/Cs	0.82
U/Pb/Ta/Dy/Nd	0.76

Iteration with target design - tradeoffs on materials, fabrication, and energy

… allows making the impossible possible

The process to build each component depends upon the material selection

Example for current LIFE target design:

Component	Material	Processes	Alternate materials	Alternate Processes
Hohlraum	Pb; 5% Sn or Sb	Die-cast	Hg, High-Z, plated CH	Stamping, swaging, molding, injection-molding
Capsule				
Ablator	C	CVD	CH;Be,B	micro-encapsulation, stamping, injeciton molding
Dopant	Ta	CVD	Ge	CVD
Foam	DCPD (< 20 mg/cc)	Sol-gel	SiO_2 (5 mg/cc)	Sol-gel
DT	DT			
Support	C	CVD	polyimide	Spin-coat
IR window				
Substrate	C	CVD	polyimide	Spin-coat
Metalization	Al	Sputter	Ag,Au	Evaporation
P2 shield	Pb; 5% Sn or Sb	Stamp	High-Z	Die-cast
LEH window	C-O		C	CVD

For each component there are favored and alternate materials selected

Requirements and "considerations" in designing a target and in selecting fabrication methods all have much in common

- Meet target physics requirements for fusion gain - ALL
- Survive acceleration forces and thermal environment of injection - ALL
- Have position determined relative to laser pointing to within ~20-100 μm (ALL)
- Have materials with low hydrogen content to reduce load to the tritium recovery system - ALL
- …
- Have materials compatible with low cost, high throughput manufacturing techniques - ALL

How do you reduce costs by 3-4 order of magnitude - major "paradigm shift" from current day targets

Ignition target

Eliminating FOAK Costs

Increasing Yield

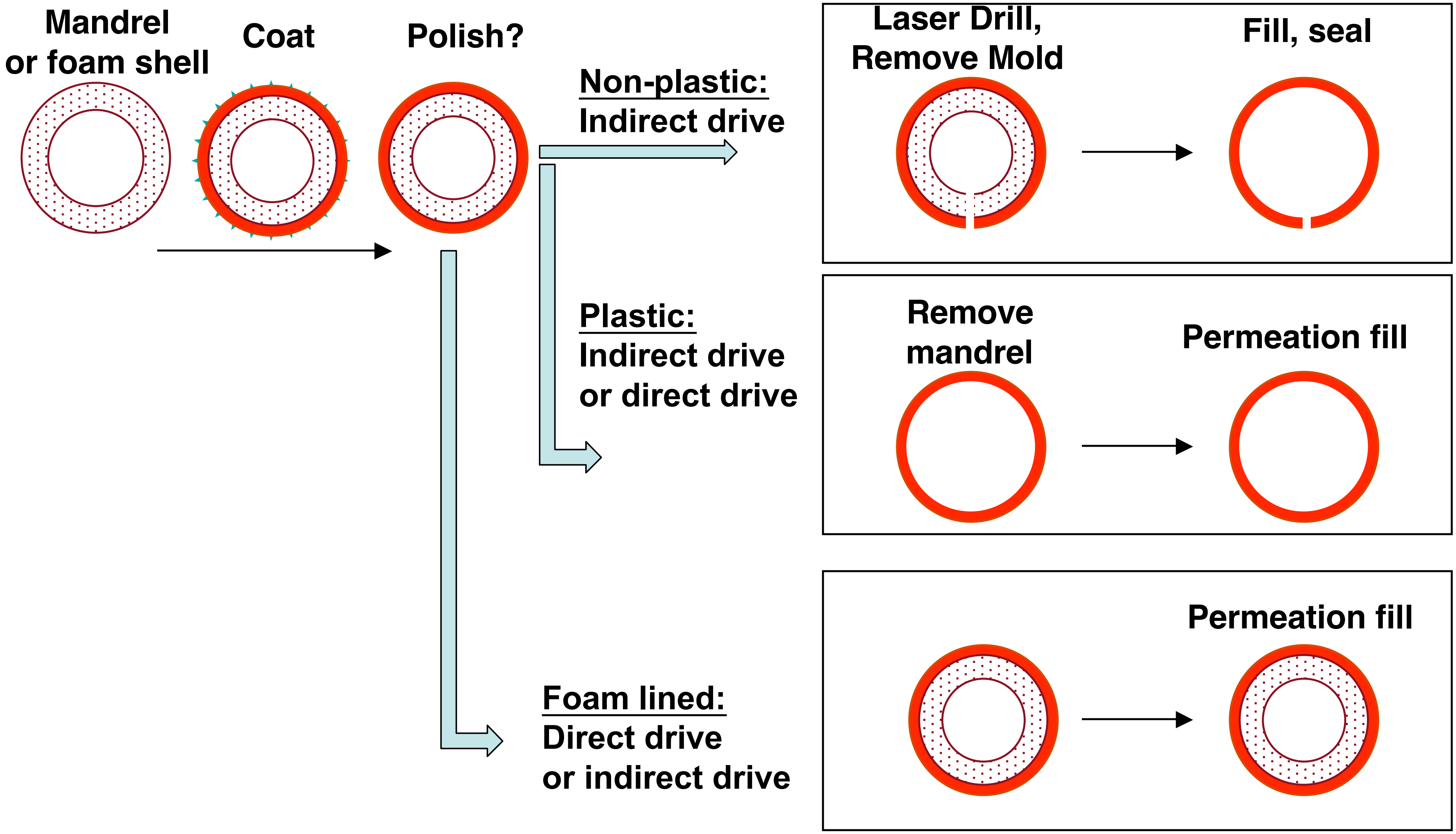
Reducing Characterization

Increasing Batch Sizes

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

High-throughput manufacturing, e.g., deep drawing

Fabrication of IFE capsules for various approaches has many common features



Mandrel
or foam shell

Coat

Polish?

Non-plastic:
Indirect drive

Laser Drill,
Remove Mold

Fill, seal

Plastic:
Indirect drive
or direct drive

Remove
mandrel

Permeation fill

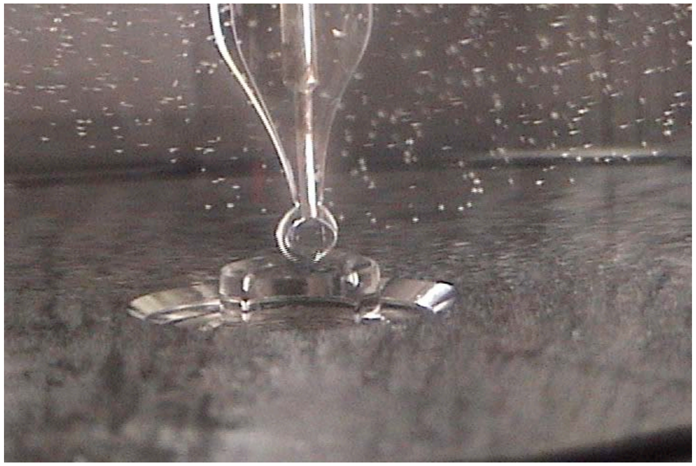
Foam lined:
Direct drive
or indirect drive

Permeation fill

Much work was done for the "direct approach" of making a HAPL foam capsule

Fabricate foam capsules

Micro-encapsulation

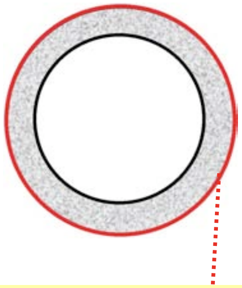


FTF-sized (2.4 mm OD) foam capsules

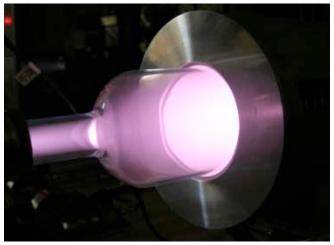
IFE (~4.6 mm OD) foam capsules

- **HAPL program dealt with throughput and dimensionality issues**
- **Wall uniformity, surface finish, and reliable gas retention remained**

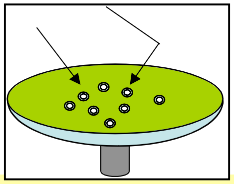
Addn'l Overcoats



A) Interfacial reaction



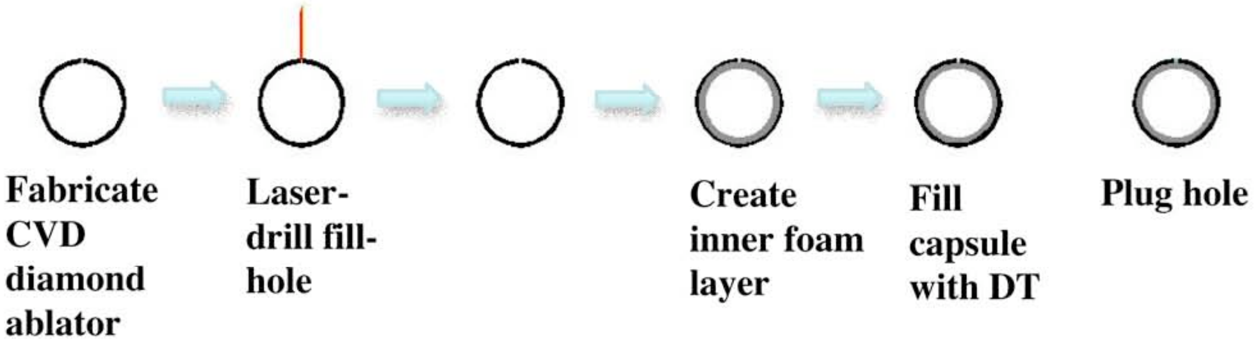
B) GDP coating



C) Sputter coating of metal (Au/Pd)

Approach = apply laboratory demo for everything…

The mandrel method is the primary technique being considered for LIFE capsules

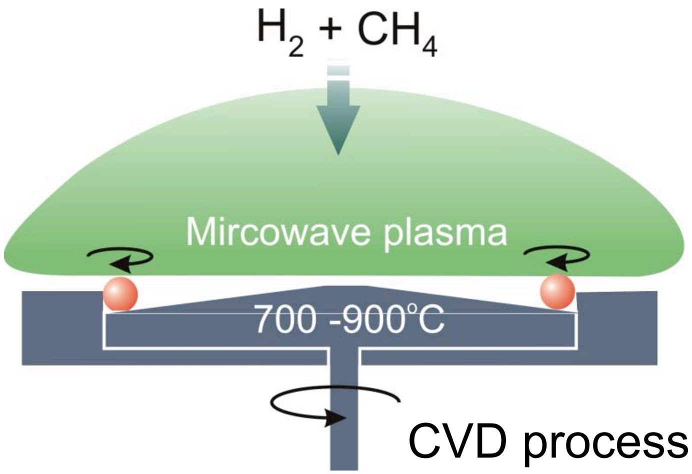


- **Starts with silicon mandrel**
- **Strong-walled capsule allows handling to create foam on inside**
- **Holds DT fill pressure at room temperature**

Chemical Vapor Deposition (CVD) diamond coating

Throughput per batch	45,000
Cost/target	~5 cents
Process tolerance	± 5 μm OD; ± 2 μm thk; ~5 nm RMS surface roughness

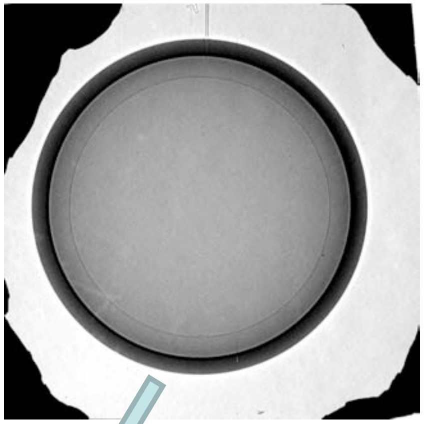
Current CVD diamond capsules satisfy NIC specifications



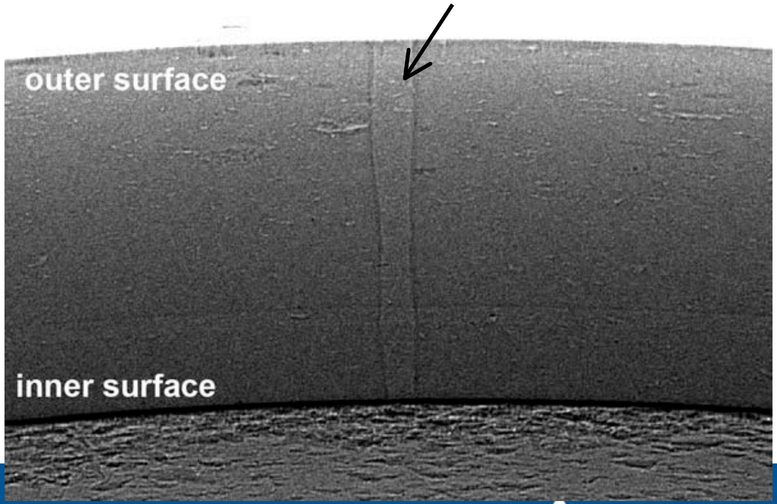
CVD process uses cheap materials

2 mm diameter polished diamond capsule

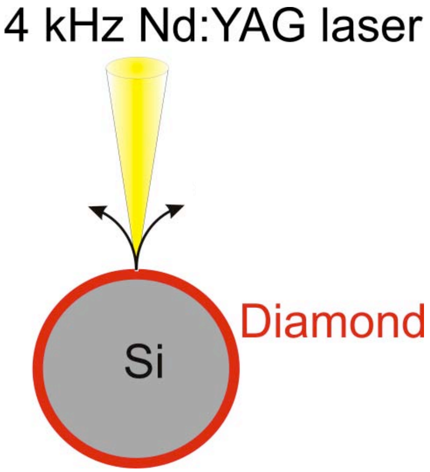
Uniform walls



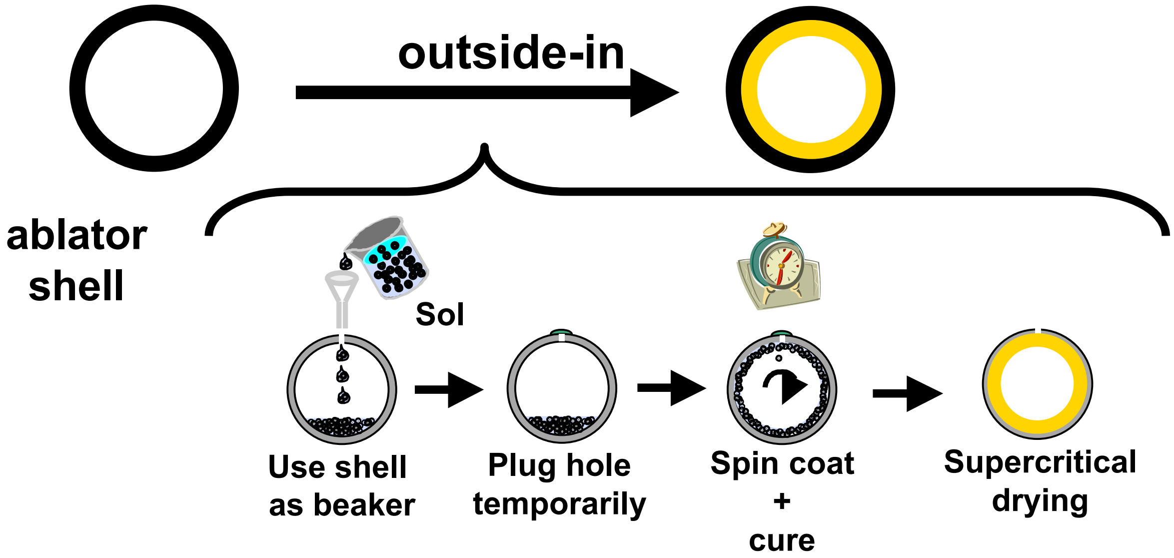
5 micron hole laser drilled for DT fill

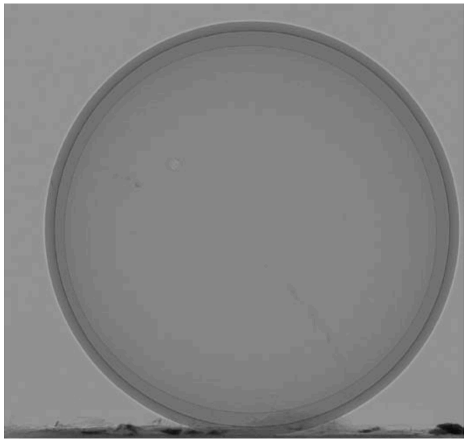


Laser-drill hole for DT fill



Foams in capsule are created by polymerizing solgel in capsule and extracting solvent



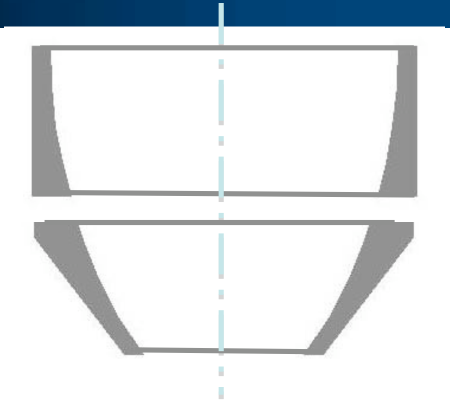


2 mm diamond shell with ~50 μm thick layer of 30 mg/cc DCPD polymer

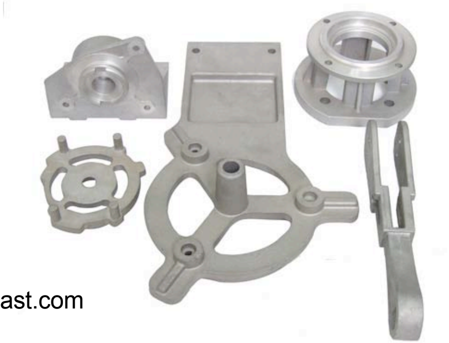
- The <u>interior foam</u> could be a pathway to avoid the difficult process of DT “beta-layering”
- Challenges include dealing with picoliter volumes, and successful wetting of the foam
- Could this approach be used for direct drive as well..?

The chemistry of this process is currently being studied at LLNL

Lead hohlraum parts can be die-cast

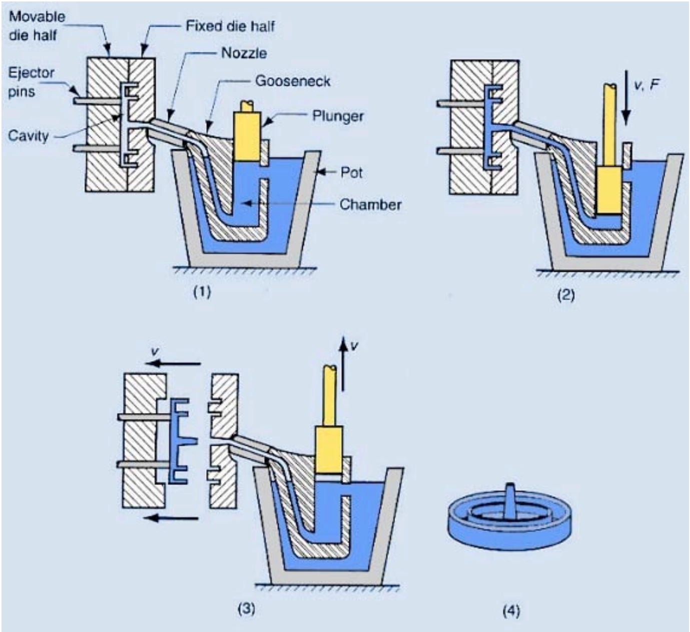


Hohlraum quarters can be die-cast



aludiecast.com

Die-cast parts are used in many consumer products



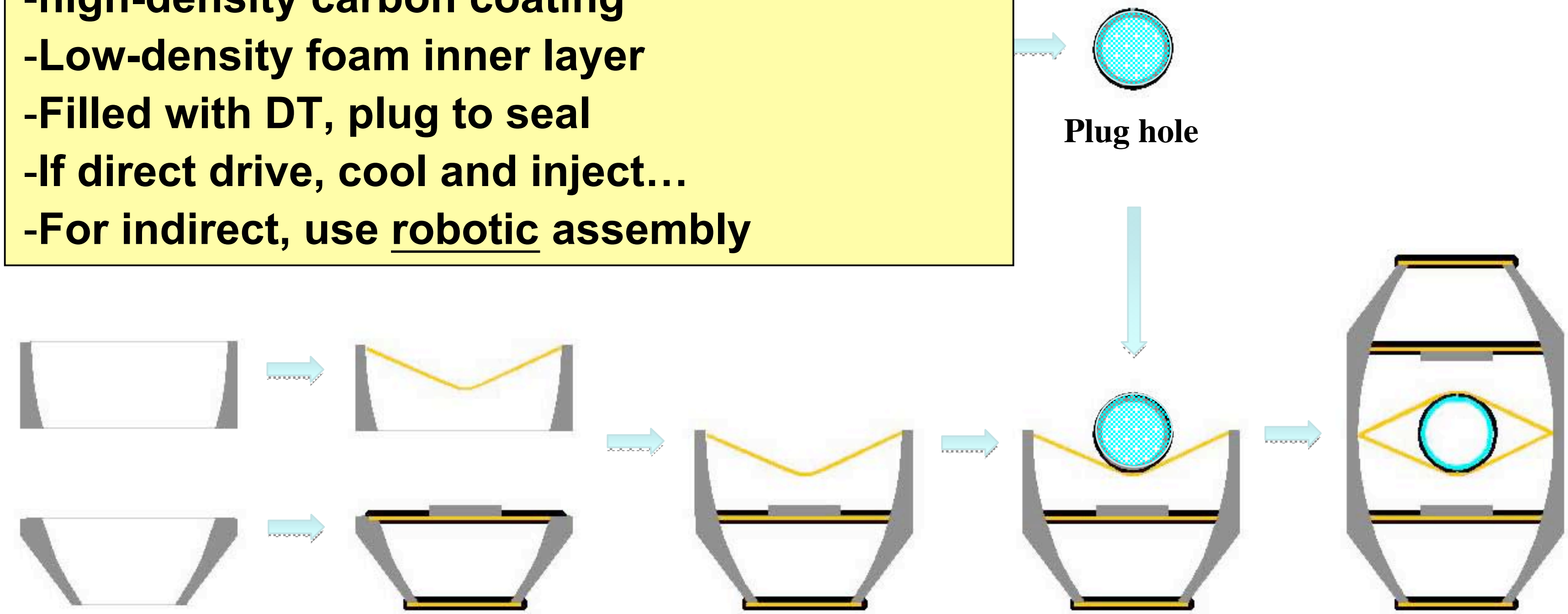
ortal.co.il

Die cast process: molten lead in the chamber (1) can be pumped into the die (2) where it is cooled and removed (3). Post machining on the parts (4) may be required to remove parting lines and sprue defects.

Design simplifications from learning at NIF should make these processes more realizable

How do you assemble full targets?

Prepared capsule with:
-high-density carbon coating
-Low-density foam inner layer
-Filled with DT, plug to seal
-If direct drive, cool and inject…
-For indirect, use robotic assembly



Plug hole

Die-cast Pb hohlraum parts

Attach CVD-diamond membranes
Pre-formed capsule support
IR shield
LEH window (graphene-oxide)

Assemble hohlraum parts

Place capsule into hohlraum

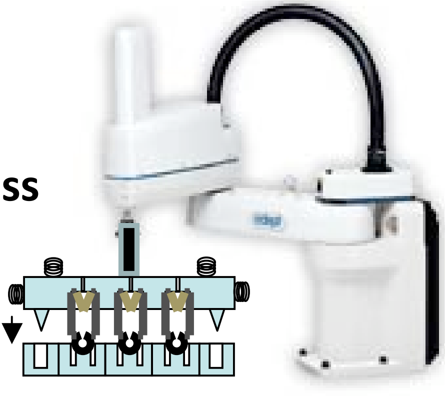
Assemble hohlraum halves
Cool to ~18K, filling foam

Hohlraum

Example of GA-robot assembling 1.5 micron polymer film to surrogate hohlraum

- **Mitsubishi RV series 6-axis industrial robots with 20 μm repeatability**
- **Piezo stage assembly base gives 10 nm resolution**
- **Vision system for guidance**

IFE process



High-speed robots to assemble parts:
- Array processing to speed throughput
- Fixtures to provide alignment
- Features in parts for self-alignment

Components will be designed-for-assembly

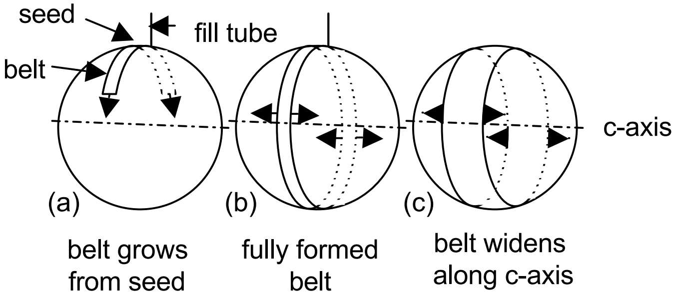
Example of the details in the LIFE cost analysis

Process	**Number of machines**	**Total floorspace (sqrft)**	**WIP (parts)**	**Total capital cost ($)**	**Annulized capital cost ($/yr)**	**Consumables + electricity + maintenance + equip replace + utility($/yr)**	**Personel costs ($/yr)**	**Cost/target**	**Off-site fabication**	**On-site fabrication**
CVD diamond ablator	140	21,323	9,288,015	48,107,750	3,704,297	20,285,676	3,500,000	0.051	0.051	
Capsule foam	8	344	189,000	12,911,000	994,147	7,610,191	200,000	0.018	0.018	
DT Fill	33	1,850	15,315	103,535,000	7,972,195	4,997,969	825,000	0.027		0.027
Hohlraum injection-molded/plated quarters	7	1,190	150	5,783,470	5,783,470	3,558,235	175,000	0.020	0.020	
Capsule-support assy	119	4,199	27,990	9,529,366	9,529,366	5,540,891	2,975,000	0.032	0.032	
IR-window/LEH assy	310	11,338	236,435	323,230,000	24,888,710	13,221,249	7,750,000	0.081	0.081	
Hohraum-half assembly	128	3,072	990	2,858,856	2,858,856	3,798,729	3,200,000	0.014	0.014	
Hohlraum-capsule assy	80	2,256	510	3,653,188	3,653,188	2,631,750	2,000,000	0.013		0.013
DT cool	1	41	108,000	5,756,334	443,238	975,448	25,000	0.003		0.003
Recover and recycle										0.000
Facility management costs		2,000		500,000	38,500	70,420	6,250,000	0.013	0.011	0.002
Total process	826	47,613	9,866,405	515,864,964	59,865,966	62,690,559	26,900,000	**0.272**	**0.226**	**0.046**
Add material								**0.303**		

Total estimated target costs are ~30 cents at 15 Hz

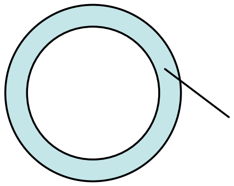
Layering” is the process of re-distributing the DT into a precise, uniform thickness

- **Single crystal beta-layering - slow (10 hours on NIC)**



LIFE

- **Alternative: liquid DT wicked into nanofoam**
  - **-Liquid? (best, smooth!)**
  - **-Liquid survives acceleration?**
  - **-Is vapor pressure low enough?**
  - **-OR - possibly “quick freeze” before grooves can form**



DT-filled nanofoam: pore size ~100 nm, < 30 mg/cc density to permit ignition

Highly isothermal environment necessary

HAPL

DT Fuel Layer

Fluidized bed layering cryostat

- ***HAPL - roughness over foam less severe…?***
- ***Temperature oscillation helpful…***

HAPL

A cryogenic fluidized bed was constructed to demo mass-production layering

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

Fluidized bed

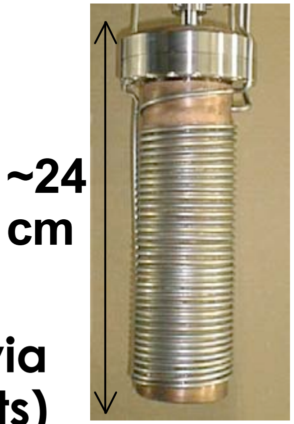
Shells (empty) at 11 Kelvin

Cryocoolers

Cryogenic circulator

Helium Compressors

Hi-P cell (1400 bar)

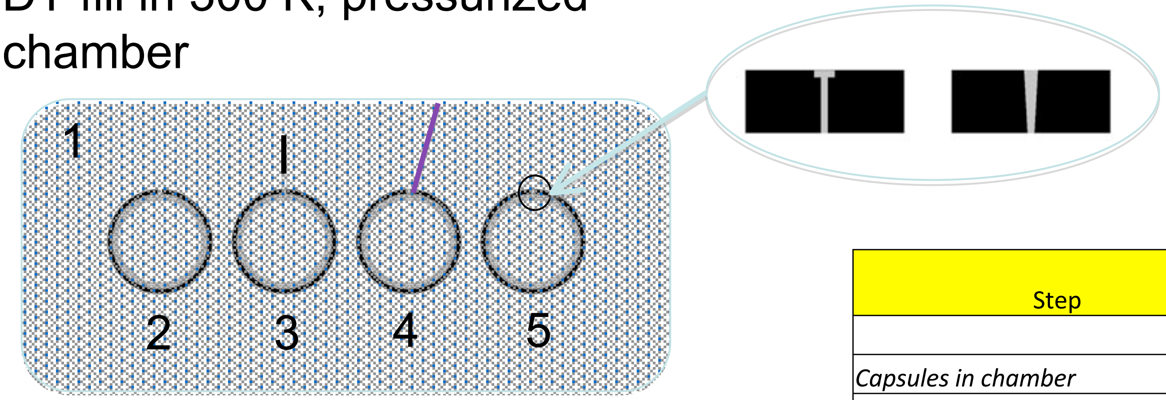


UCSD

Includes filling with HD (via permeation thru overcoats)

DT fill process can be performed in large batches in a pressurized, room temperature chamber

DT fill in 300 K, pressurized chamber



Possible plug configurations feature UV glue-coated carbon plugs

1) Place capsules in pressure chamber at ~264 atm
2) Capsules are filled with DT gas
3) Apply plug
4) UV cure epoxy-coated plug
5) Reduce temperature to 77 K; evacuate chamber

Step	External pressure (atm)	Temperature (K)
Capsules in chamber	**0**	**300**
DT fill	**264**	**300**
Plug fill hole	**264**	**300**
Lower chamber temperature	**68**	**77**
Evacuate DT from chamber	**0**	**77**
Transport	**1**	**77**
Assemble capsule into hohlraum	**6**	**300**
Transport to injector	**1.6**	**77**
Prepare for injection	**0.4**	**18**
Inject into chamber	**0.4**	**17**

Higher temperatures enable bonding; lower temperature during transport reduces diffusion through the ablator parts.

Room temperature processes enable polymer bonds

HAPL The HAPL program demonstrated several acceleration options …

The HAPL program demonstrated (gas-gun):

-Velocity ≥400 m/s, time jitter 0.5 ms, 2-piece sabot separation in vacuum

-Target placement accuracy of 10 mm at 17 meters standoff (1σ) ~590 μrad

2-piece sabot to protect target - "looks like" a hohlraum

HAPL redesigned chamber to reduce heating, and allow slower injection

Range of options, including:

1. Gas-gun for >400 m/s
2. Induction accelerator

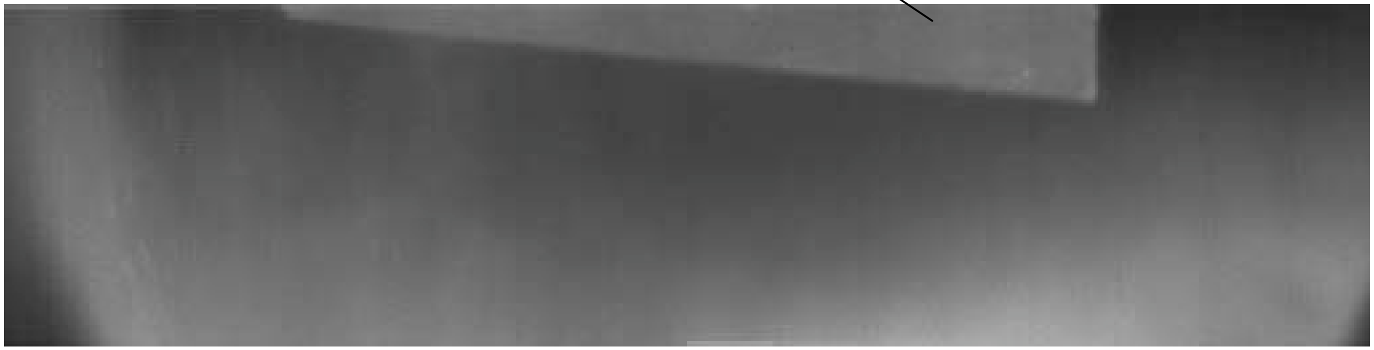
With slower injection, accuracy demo'd at 50 m/s (w.o. 2-piece sabot) → *4 mm at 17 m (1σ)*, with ~1 mg projectiles (direct drive capsules, 235 μrad)

“Sabot separation” was a feature of direct drive injection demo with a gas gun

The HAPL program demonstrated sabot separation in-flight:

- -Sabot with support-film to avoid point-loading
- -Velocity ≥400 m/s

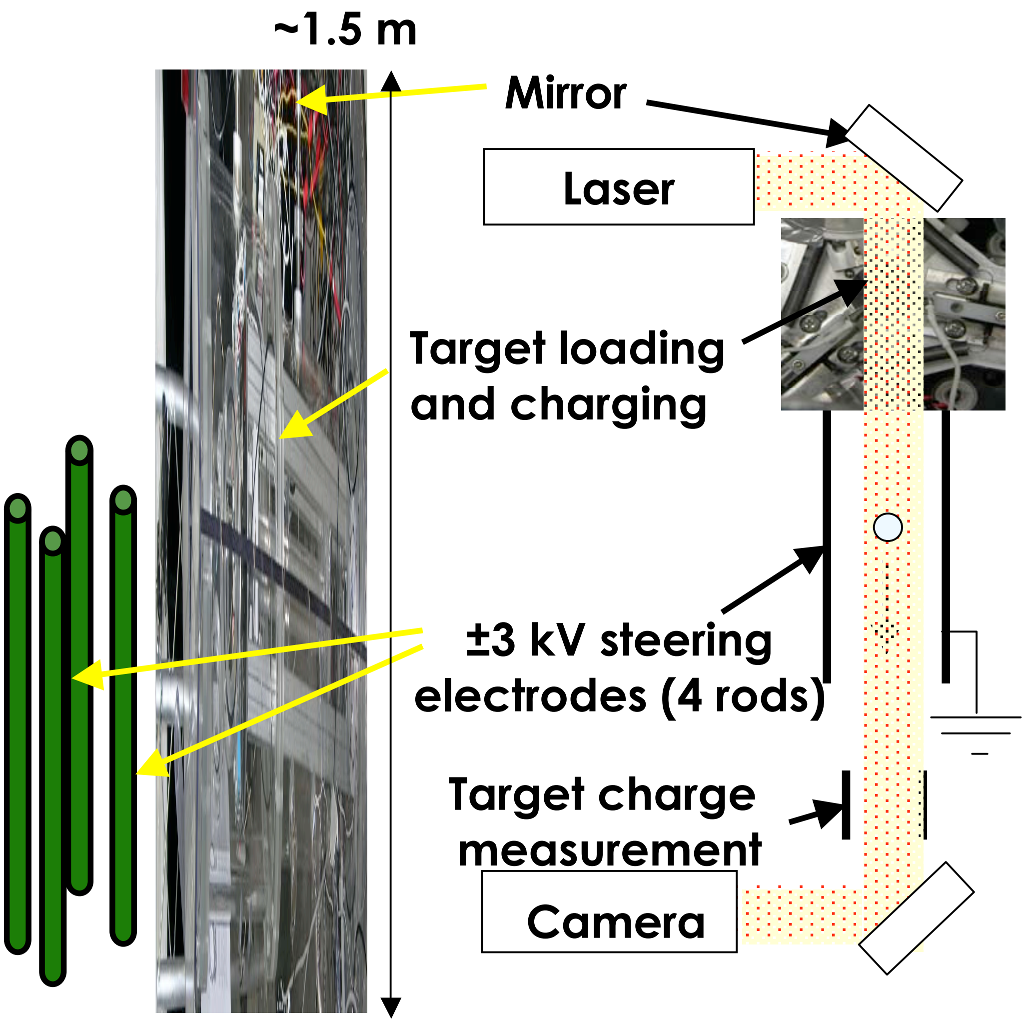
2-piece sabot to protect target



Deflector for sabot pieces

Repeated sabot-separation and deflection was demonstrated

Electrostatic steering has been shown to improve placement accuracy (direct drive)



~1.5 m

Mirror

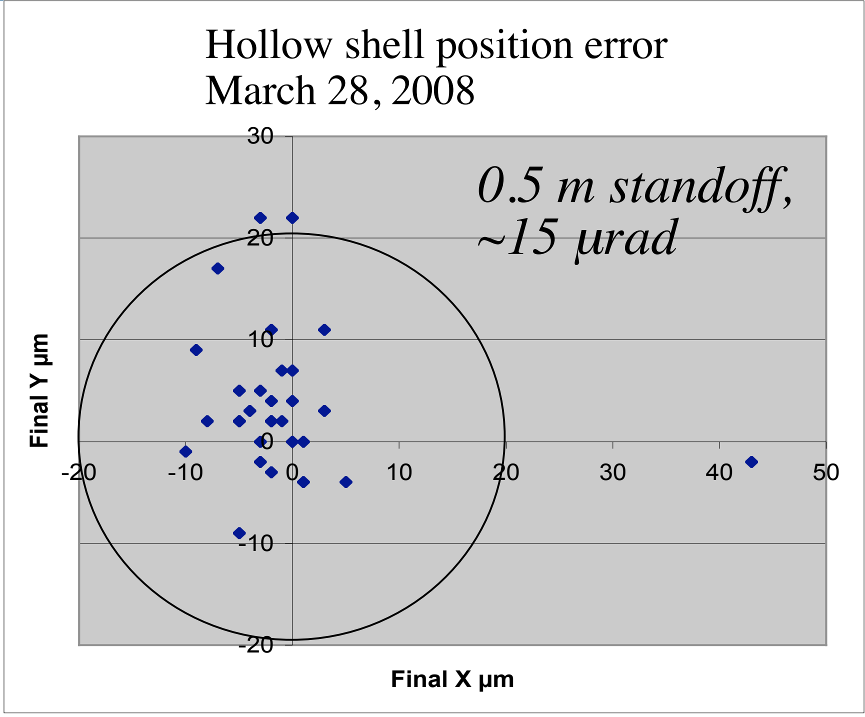
Laser

Target loading and charging

±3 kV steering electrodes (4 rods)

Target charge measurement

Camera



Hollow shell position error
March 28, 2008

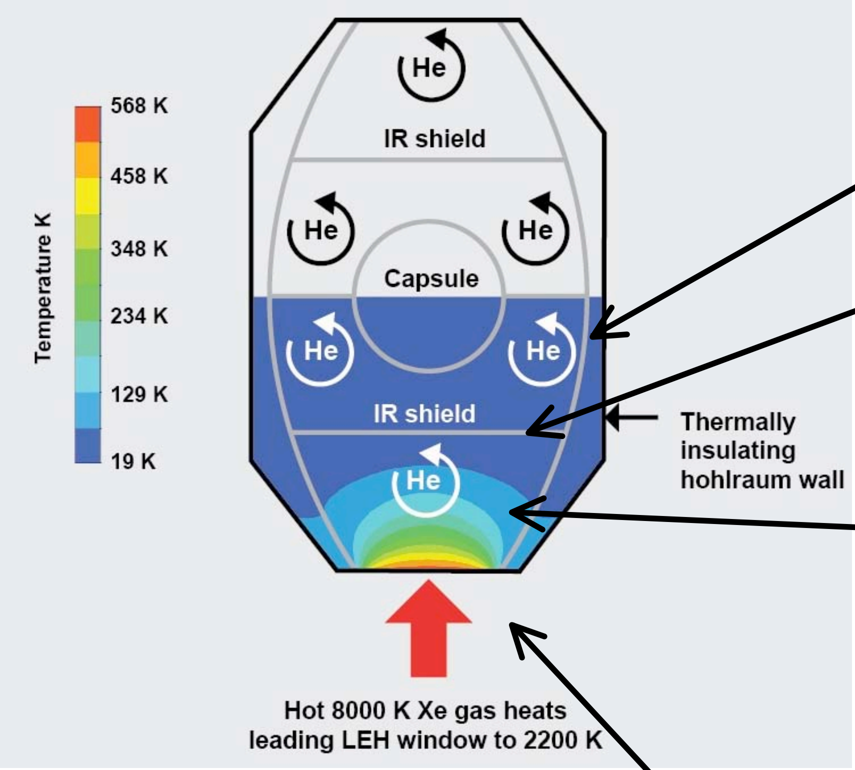
Without target steering
$\sigma_x \approx \sigma_y \approx 500$ μm (~1000 μrad)

With target steering (0.5 m standoff)
$\sigma_x = 9$ μm $\sigma_y = 7$ μm

- **X offset = -1 μm; Y offset = 4 μm**
- **27 of 30 in 20 μm radius from aim point**

In-flight target steering could be used to improve accuracy of a target injection system

LIFE Target heating on injection has been modeled - indicates low heating of DT ice

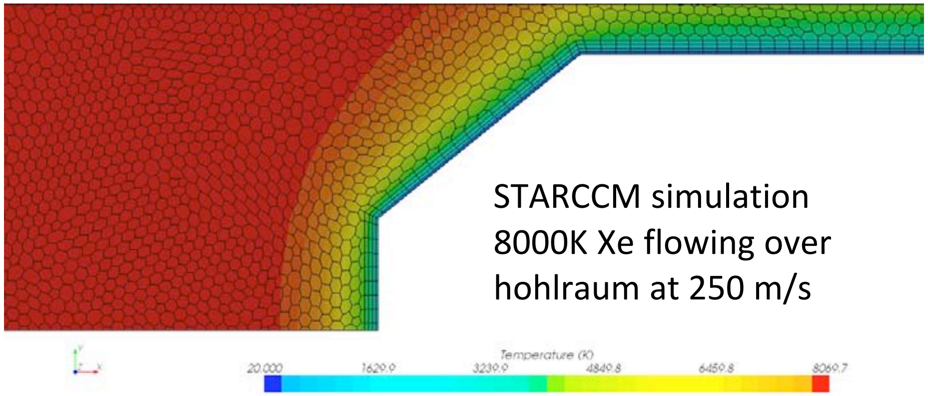


The capsule heats from the circulating He in the second compartment DT= ~85 mK

The front IR shield confines the warming helium to the front quarter of the target

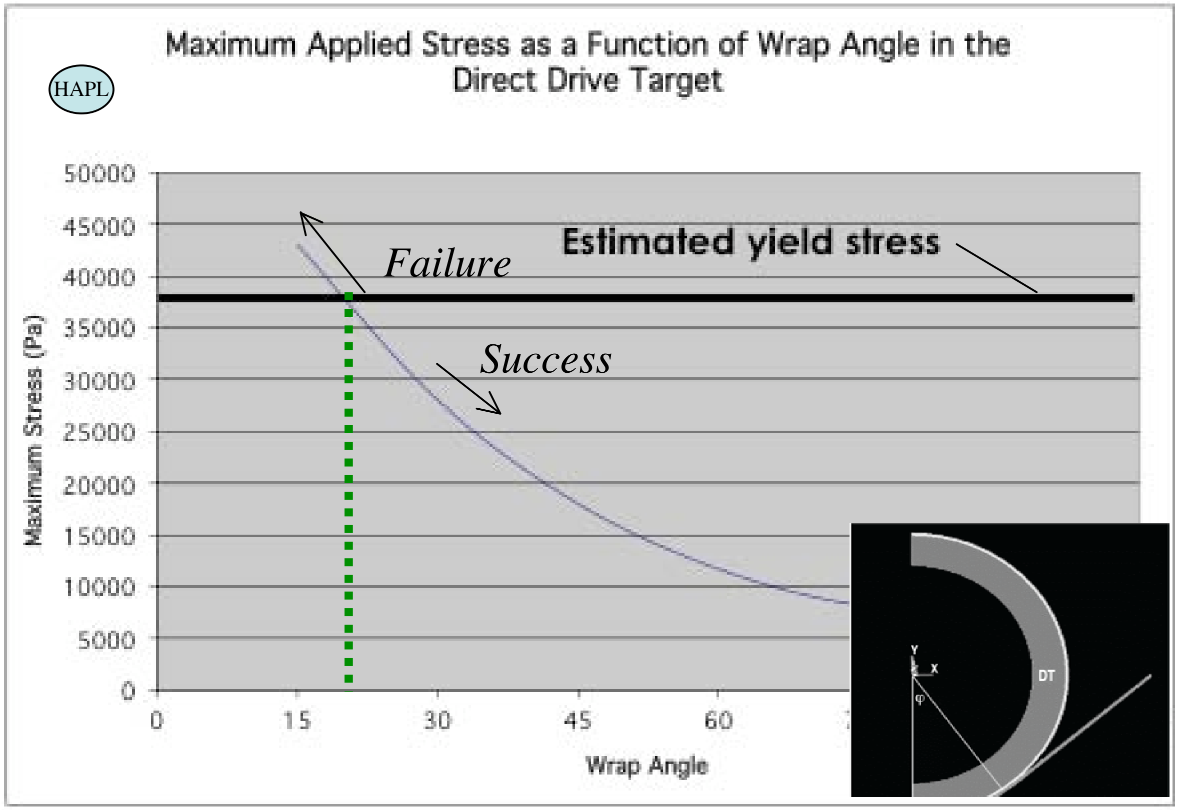
Circulating Helium removes heat from the LEH window and gives it up to the cool Pb side walls

LEH window heats quickly

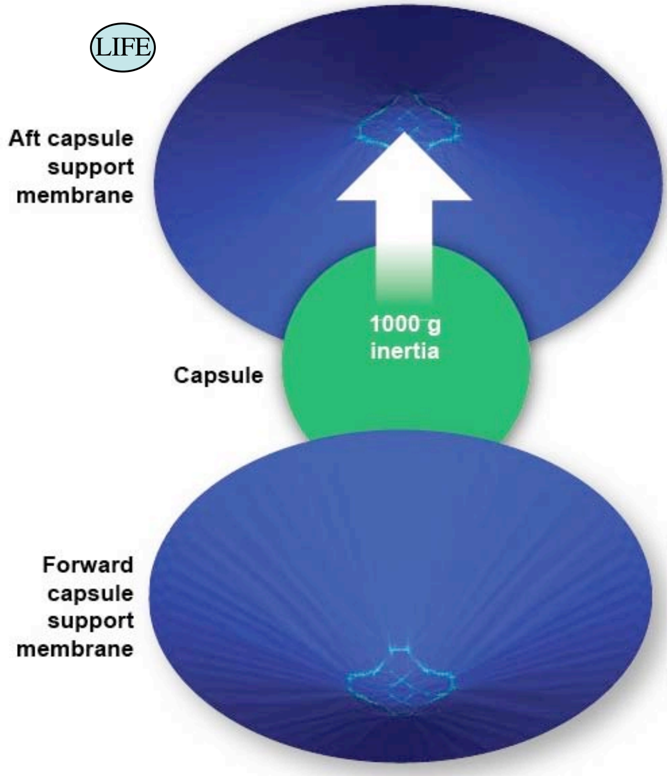


STARCCM simulation
8000K Xe flowing over hohlraum at 250 m/s

Stress during injection has been modeled - DT stress depends on membrane wrap angle



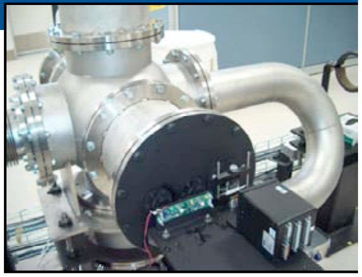
DT stress for 1000 g acceleration at 18 K



- Peak stress ~100 MPa: well under 500 MPa strength for CVD diamond capsule support membranes
- Capsule movement during acceleration < 3 μm

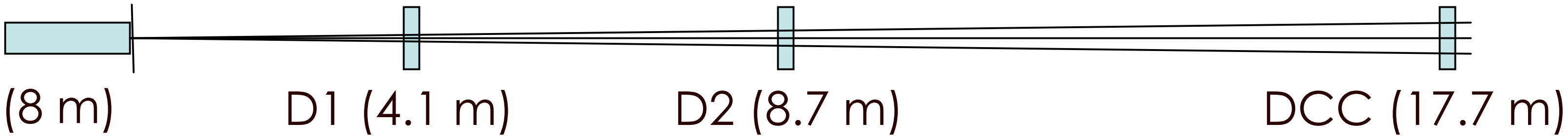
•Membrane support for direct drive target is part of sabot
•Also used to support capsule in hohlraum

Tracking and engagement- hitting a target “on the fly”

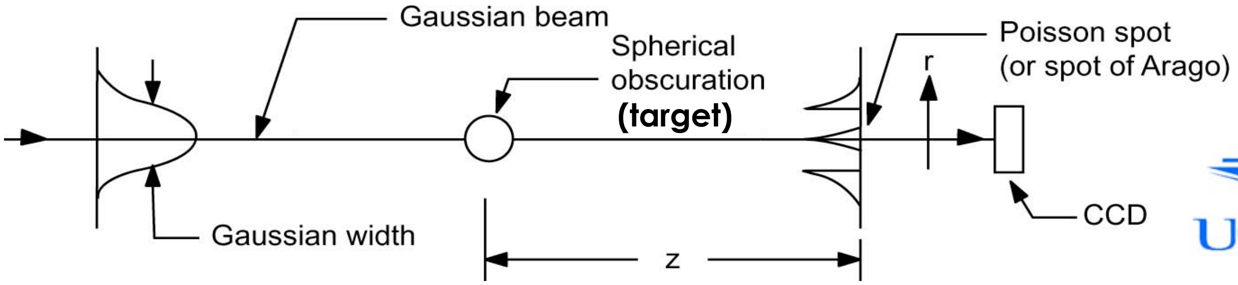


- Direct drive requirement = alignment of lasers and target to 20 μm
- First step - demo “ex-chamber” sensors, prediction to ~500 μm

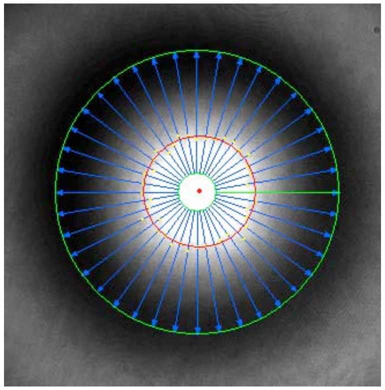
Ex-chamber tracking schematic



- This evolved into “continuous” tracking (in-chamber)
- 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)…



UCSD

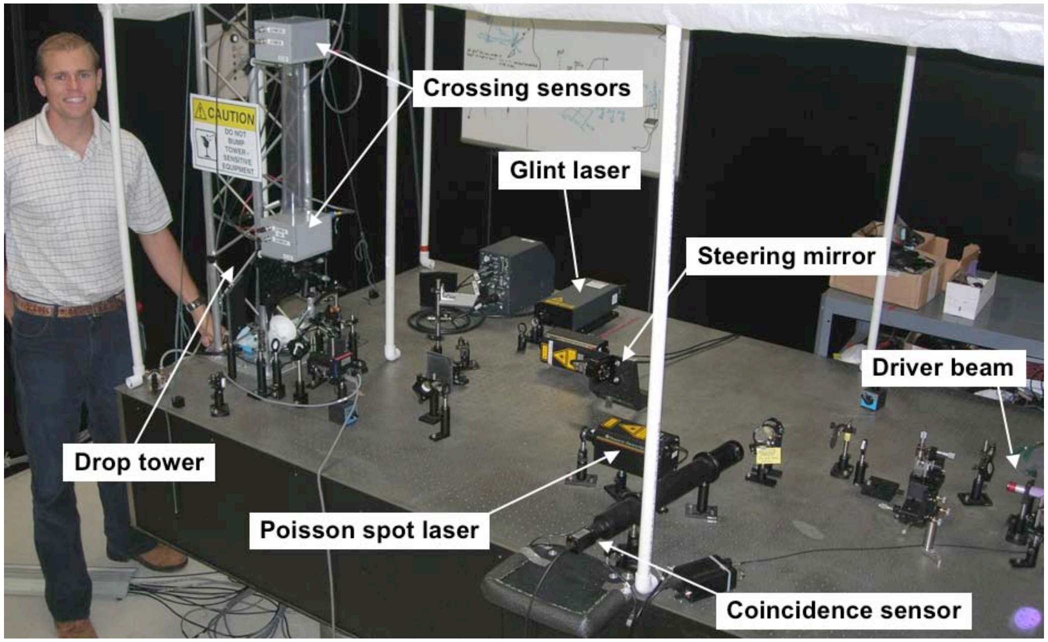


Poisson spot on CCD

L. C. Carlson, et al, “Improving the Accuracy of a Target Engagement Demonstration,” Fusion Science and Technology 56 (1) July 2009

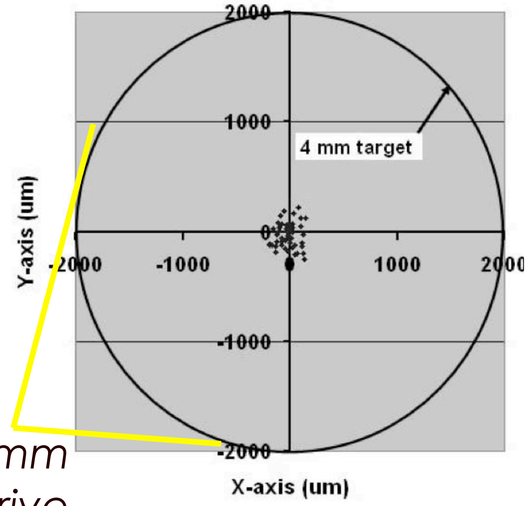
HAPL

Tracking - optical table demo of “hit-on-fly” engagement



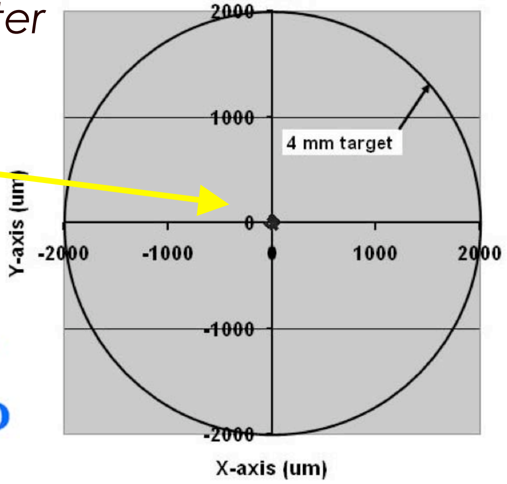
Lane Carlson, GA/UCSD collaboration

4mm Target Engagement by Driver Beam, Aug. 2007



~4 mm direct drive target diameter

4mm Target Engagement by Driver Beam, Aug. 2008



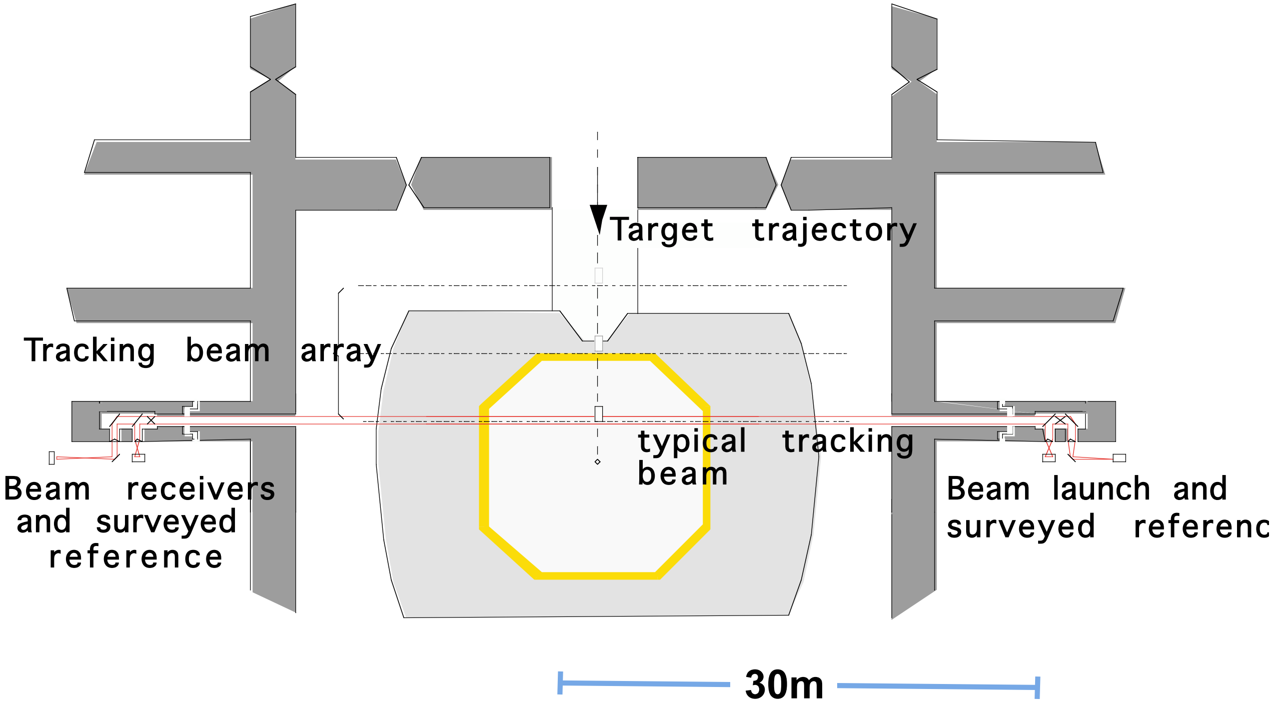
- **Scaled experiment, velocity ~ 5 m/s**
- **Standard deviation accuracy ~28 microns**

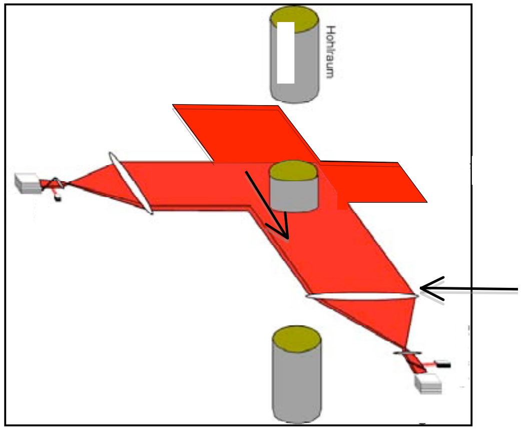
L. C. Carlson, et al, “Completing the Viability Demonstration of Direct-Drive IFE Target Engagement and Assessing Scalability to a Full-Scale Power Plant,” Transactions on Plasma Science 38(3) March 2010, 300-305

UCSD

Tracking beams determine the target's location, timing, transverse position, and tilt

- Tracking beam array mounted on mechanically isolated structures
- Defines the shot coordinate system

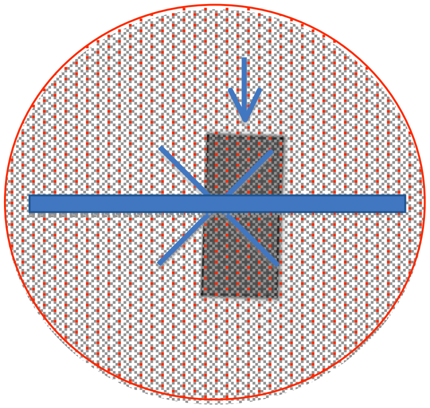


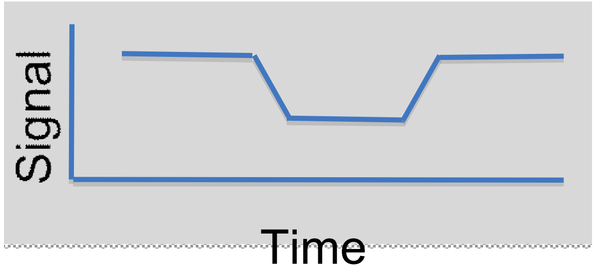


- **A target passing through an orthogonal pair of beams alters the transmitted signals.**

Extracting the timing, the velocity, and the target tilt from the tracking beams

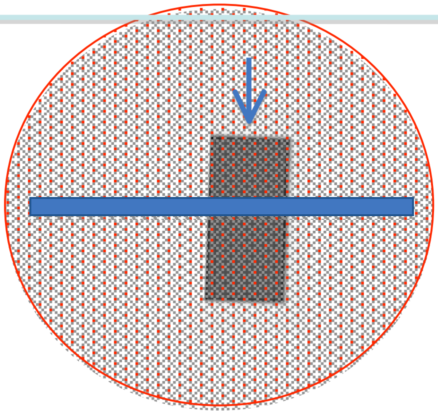
A fast diode records the received signal through a slit.



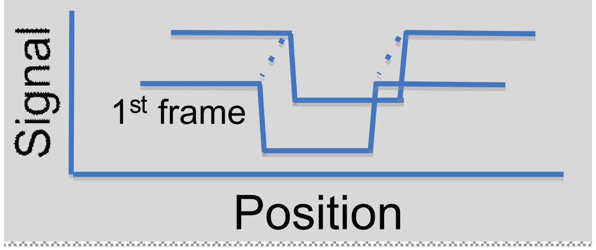


Timing values are extracted from the plot

A linear CCD array detects transverse position versus time.

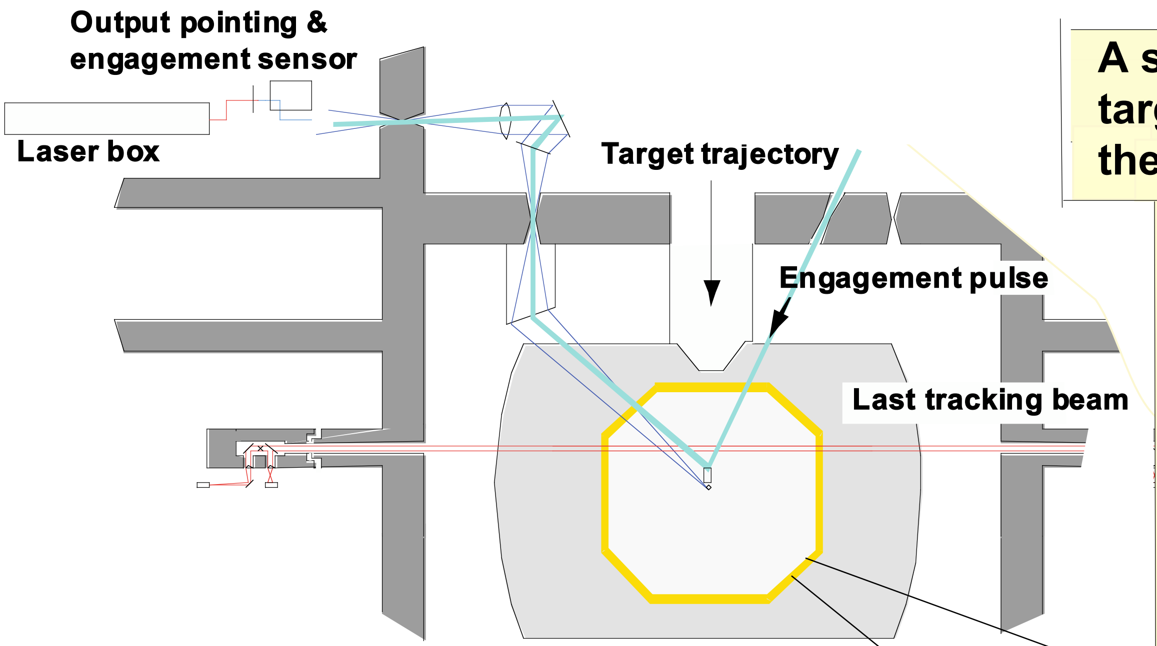


Linear CCD (10 frames)



Position and tilt values are extracted from the plots

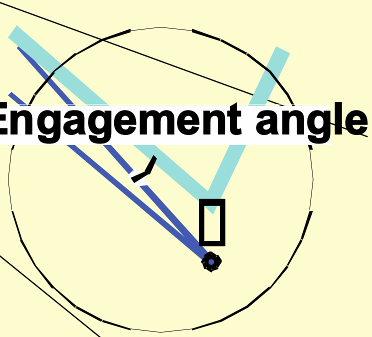
Each beam's pointing offset relative to the target is determined immediately before the shot



A short pulse illuminates the target at a specific distance from the shot point (6-7mm)

The final optic of each beam collects light scattered from the target and sends it back along the main beam path

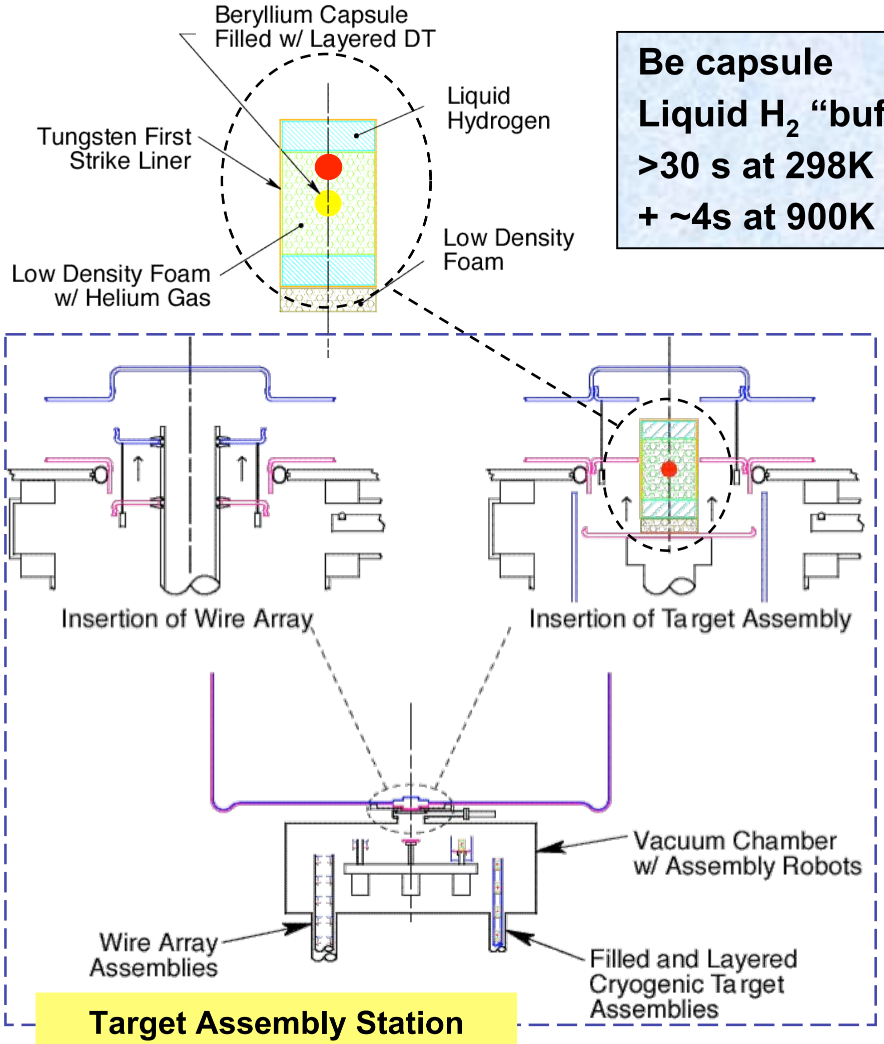
An engagement sensor compares the direction of light from the target with the laser alignment beam



Beam deflectors in the laser box implement pointing corrections

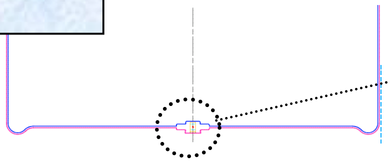
A predetermined engagement angle corresponds to correct alignment at shot time

Working together with SNL and others, target systems for Z-pinch driven IFE were conceptualized

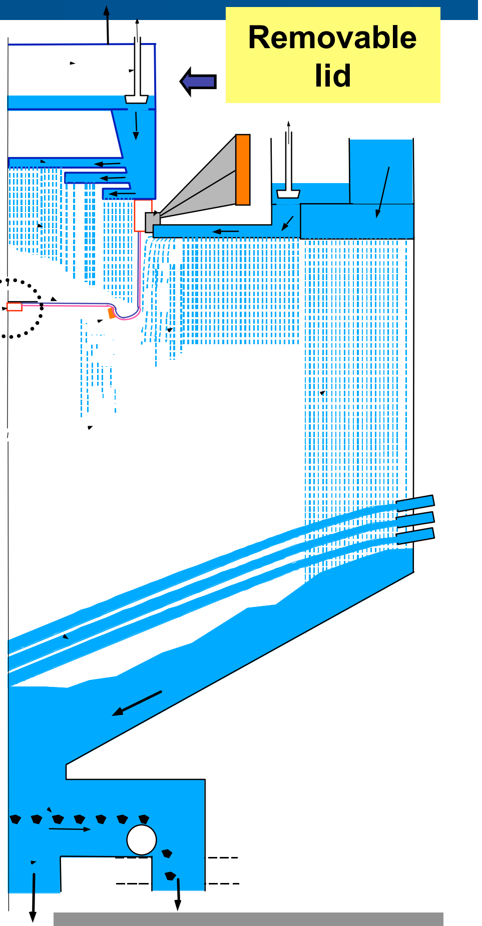


Target Assembly Station

Be capsule
Liquid H_2 "buffers"
>30 s at 298K
+ ~4s at 900K



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)

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

.... Design concepts indicate sufficient time available for cryogenic target assembly and handling

The ICF community has a common viewpoint

- Demonstration of laboratory ignition will establish that the physics underpinning IFE exploitation is fundamentally sound.
- IFE is a field in which the US is a clear world leader – academically, technologically and industrially.
- We have an opportunity to capitalize on this leadership position over the next few years~~,~~ and leverage prior substantial defense program investment.
- Recent action by the DOE to propose a new IFE development program and secure a stable home for IFE is timely and very welcome.
- Moving forward, the IFE program needs to focus on the requirements of an operating power plant, with design choices managed at a systems-level.
- The inherent modularity and separability of IFE provides significant benefits when considering power plant development, operations , and evolution.
- Taking advantage of significant prior research, future development activities in this program need to include IFE scale science and technology development and demonstration.
- IFE is a national scale program requiring a coordinated effort by academic, Laboratory, and industrial partners.
- A phased program with competition and unambiguous selection criteria is needed

Summary and conclusions - target technology

- Targets are a major component of any IFE approach
- Critical issues for the IFE target supply identified
- Much work has been done on the target supply process for a number of IFE approaches
- Mass production of an IFE target is a difficult but manageable task
  - Will require a sustained and properly supported development effort that should occur in parallel with other reactor technologies
  - “Nth-of-a-kind” cost studies have shown that cost-effective target manufacture is possible
- We have summarized here four different target designs and the work that has been done to define manufacturing methods and to show acceptable cost

We believe that targets can be mass-produced for IFE and meet the requirements for fusion energy