Technologies for Mass Producing IFE Targets and Determining Their Survival in an IFE Target Chamber

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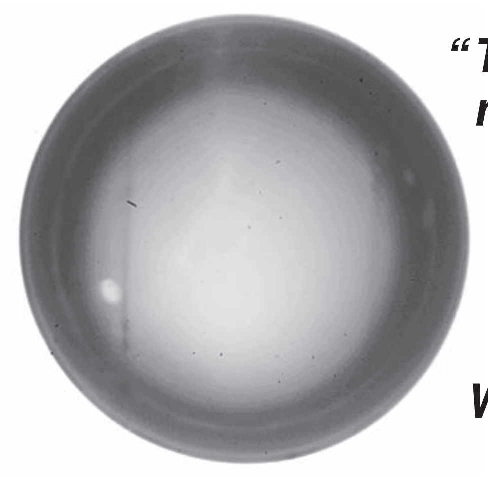

> *"The big lie in (laser–based) fusion is that we can make these target capsules for a nickel a piece"*
>
> – Professor Edward C. Morse, March 2010 issue of Scientific American (page 57)

We need to reduce the cost of the target by a factor of ~100,000

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NAS/NAE Committee on the
Prospects for IFE Systems
San Ramon, CA
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UNIVERSITY of ROCHESTER

Summary

Prospects for making IFE targets to the desired specifications (including cost) are promising

- The ICF program has developed techniques for making targets with the required specifications
  - the choice of techniques prioritized success and flexibility over cost

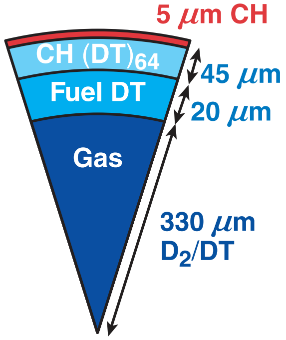
- Mass-producing a single type of target for less than $0.50 each requires the production process to be more precise, repeatable, and reliable

- We are developing electric-field mediated microfluidic techniques for making direct-drive fusion energy targets
  - complete "cradle-to-grave" concept
  - completed studies confirm high through-put and high precision
  - considerable additional work is needed
  - key issues of precision, miniaturization, automation, target survival into the target chamber, and tritium considerations are addressed

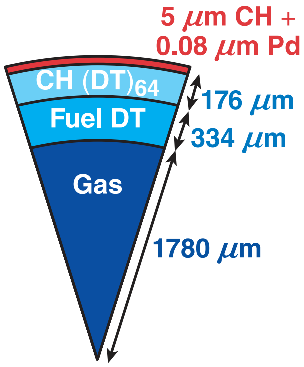
OMEGA-scale DT-wetted foam targets have demonstrated acceptable capsule and ice specifications

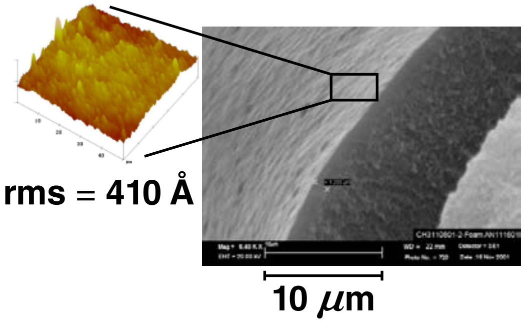
ICF target

OMEGA



IFE target

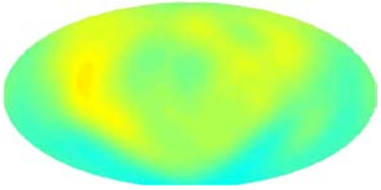




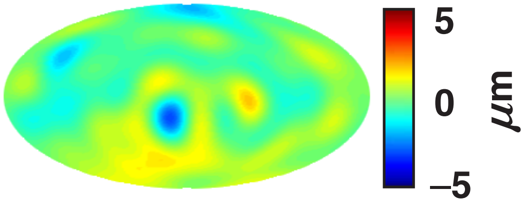
Foam capsule: <50-nm-rms roughness and <3-μm variation in foam thickness

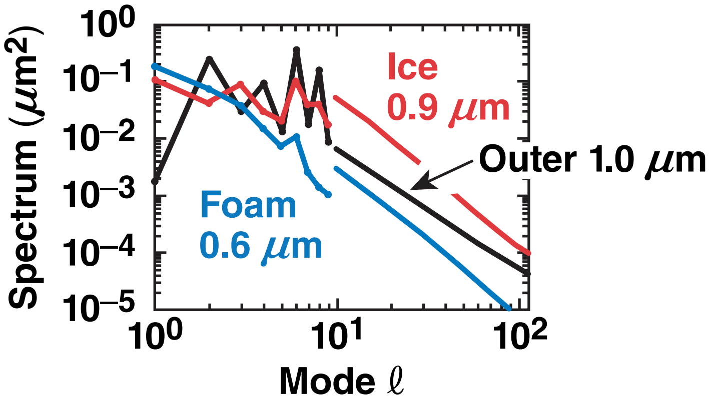
DT ice layer in the foam capsule –1-μm-rms roughness

Thickness uniformity of the foam wall



Ice-thickness distribution

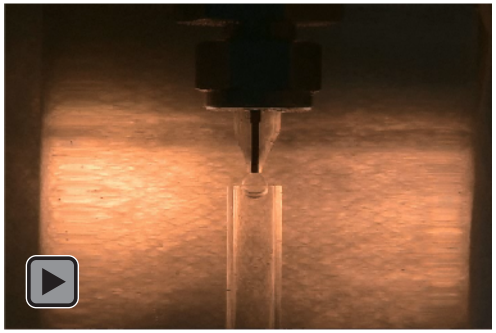


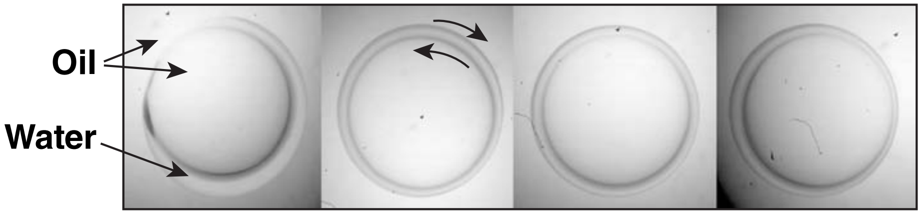


Developing IFE targets that are 5× larger than OMEGA targets would be done as part of an IFE program.

The main issues with using the current foam-target fabrication process for IFE is the low yield (<10%) and high tritium inventory

(i) **Microencapsulation: oil–water–oil double emulsion** ✓ (ii) **Wall-thickness control** ?



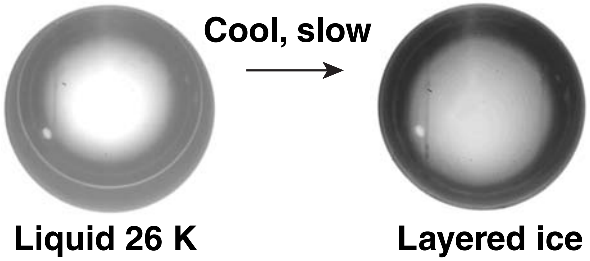


(iii) **Solvent removal—CO_2 critical point drying** ✓

(iv) **Overcoat—5-μm CH permeation barrier (yield <10%),** ? **100-nm Au/Pd radiation barrier**

(v) **DT permeation** **ICF target:** requires 1000 atm DT and takes 3 days
IFE target: requires 1100 atm DT and takes 7 days – 1 atm ^{3}He and 7 kg T_2

(vi) **DT ice layer formation—14 hr to achieve full density and single crystal structure**

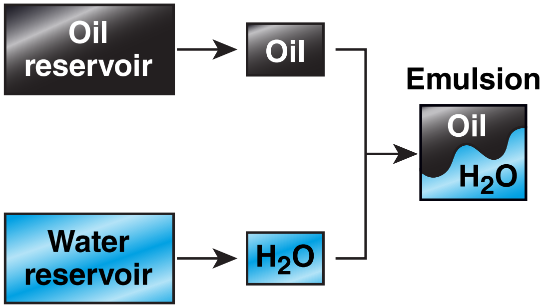


Technologies based upon electric-field mediated microfluidics may offer an alternative way to mass produce targets that is more deterministic and better suited for automation

Step 1

Dispense fluids and combine them to make an oil–water emulsion

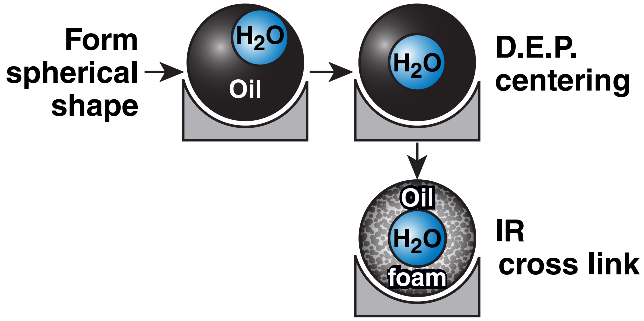
Demonstrated



Step 2

Center the emulsion using an electric field and polymerize the shell

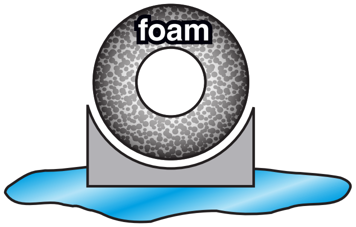
In Progress



Step 3

Remove fluid from the polymerized shell

Evaluating techniques other than critical-point drying



Solvent removal

Step 4

Dispense DT droplet and add to the foam shell

Demonstrated with D_2

Step 5

Add Ne/Ar/Xe overcoat

Conceptual stage

Step 6

Layering: mass production

Conceptual stage

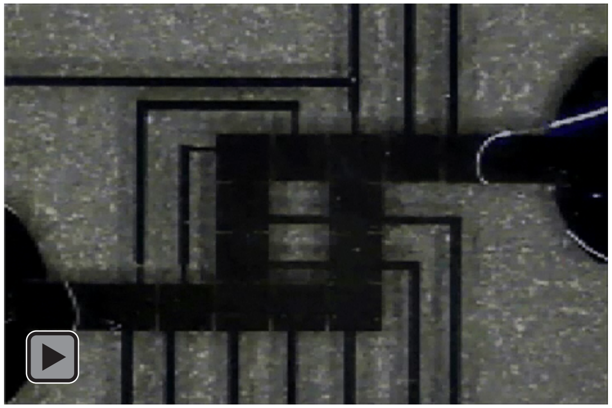
Step 7

Target injection and survival

Preliminary data

We have demonstrated the capabilities and limitations of this concept for producing capsules; the discrete steps need to be integrated

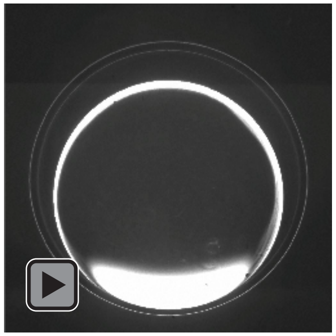
(i) Formed and moved droplets into an emulsion



Water reservoir

Oil reservoir

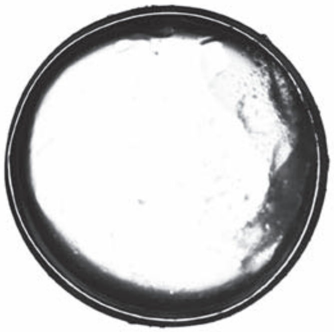
(ii) Centered the emulsion



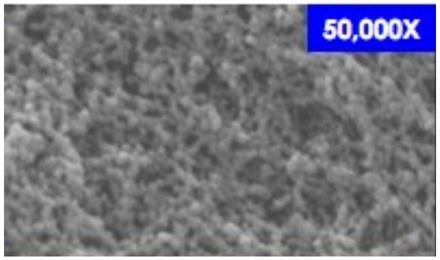
<u>Oil/water/oil</u>

E_o = 6000 V/m
f = 20 MHz
Shell conductivity = 2.4×10^{-3} S/m

(iii) Formed a photo-initiated polymer capsule



(iv) Developing a photo-initiated foam with the desired properties*



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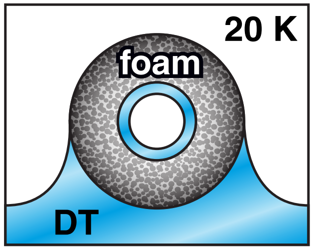
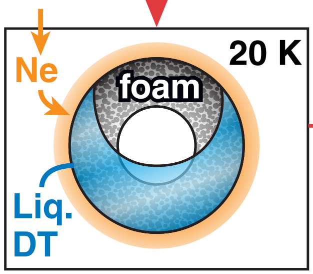
*R. R. Paguio *et al.*, presented at the 2010 MRS Fall Meeting, Boston, MA, 29 November–3 December 2010 (Paper BB12.5).

The feasibility of extending the "lab-on-a-chip" concept to forming the DT-ice layer is being investigated

1. Form liquid DT into discrete droplets
2. Wick liquid into the foam shell



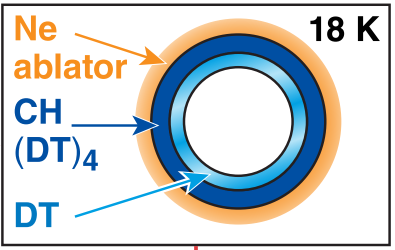
3. Condense Ne (Ar,Kr,Xe) as a barrier coating onto the foam



Transport electrostatically

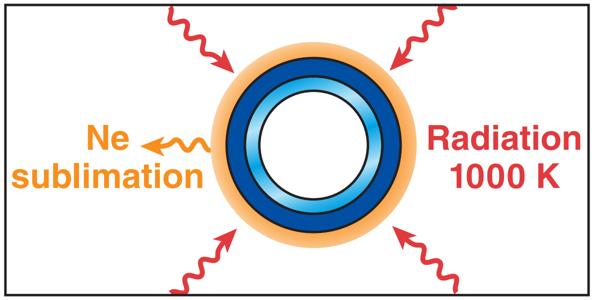
Thermal gradient
20 K → 18 K

4. Form ice layer – move through a thermal gradient (20 K → 19.5 K) at 0.001 K/5 min



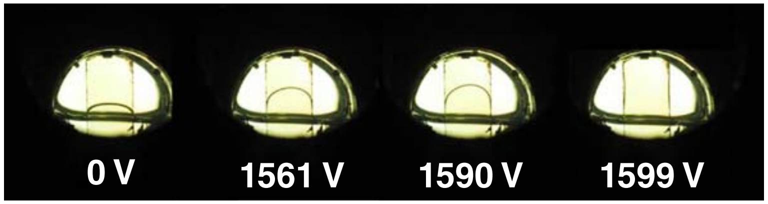
5. Inject target – Ne overcoat ablated during transit

   Tailor Ne thickness to insulate the target



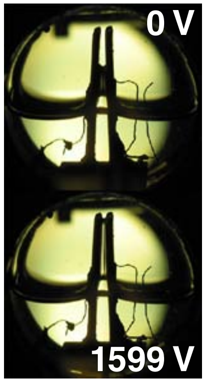
An electro-mechanical microfluidic scheme is proposed for filling the target with DT.

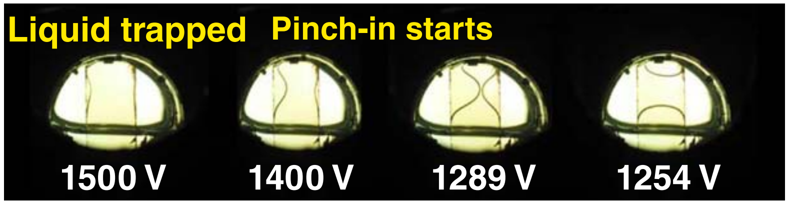
An E-field has been used to levitate a column of liquid D_2 and form a droplet of the desired volume (14 μL)



1. An electric field elevates a column of liquid D_2

Rotated 90°

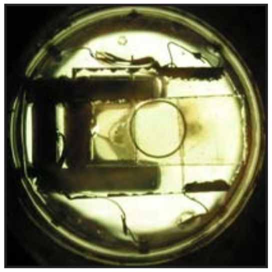




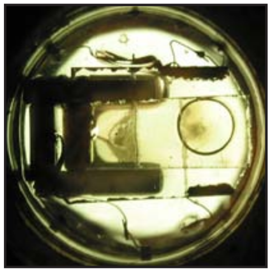
2. Lowering the voltage leaves a trapped volume of D_2

3. The D_2 droplets can be moved laterally

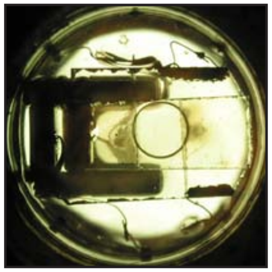
14-μL D_2 droplet



Electrodes de-powered



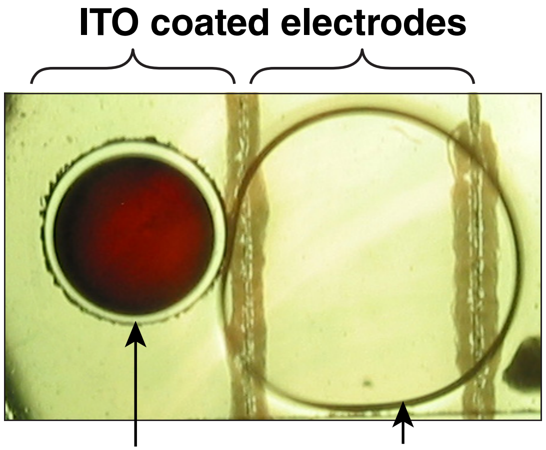
1.8 KV on the rightmost electrode



Electrodes de-powered

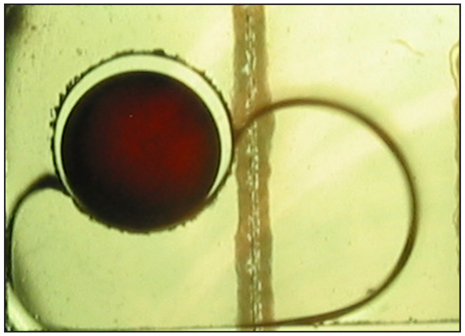
This is a first demonstration of dielectrophoretic behavior in a cryogenic liquid.

Liquid D_2 (14 ml) is rapidly absorbed (<10 s) into a foam shell at 25 K

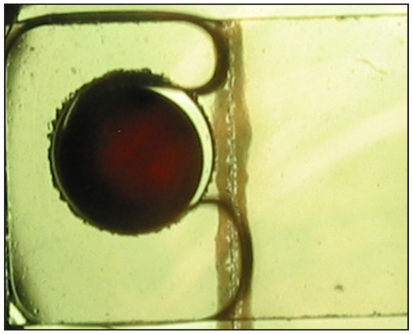


(i) 3.2 mm dia;
0.1 gm/cc R-F foam
shell (350 μm wall)

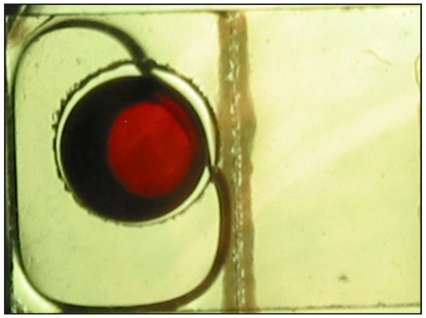
Liquid D_2
droplet



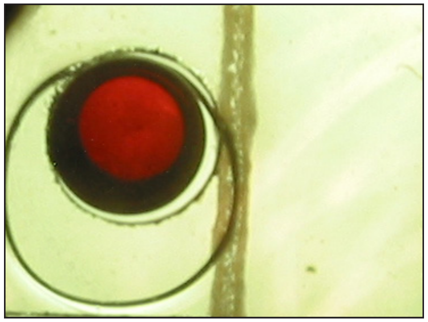
(ii) Liquid moved to the
electrode containing
foam shell



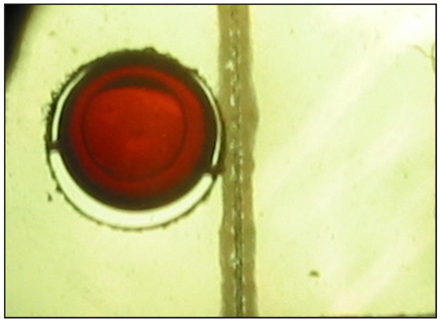
(iii) Liquid encapsulating
and infiltrating the
foam shell



(iv) Encapsulation
and infiltration continues...



(v) Liquid infiltrating
the foam wall



(vi) Liquid fully absorbed
in the foam wall, shell void
is not filled

Developing a viable condensed-gas seal coat is critical to simplifying the DT-filling and target injection operations

Advantages:

- Faster filling; reduces the amount of tritium
- Eliminates need for Pd radiation barrier
  - sublimation protects against heat load
  - heat load: 0.2 to 10 W; (2 mJ needed to sublime a monolayer Ne ⇒ ~100-nm layer)

Issues to be addressed:

- Required thickness and composition of the overcoat
- Demonstrate uniform sublimation during target injection

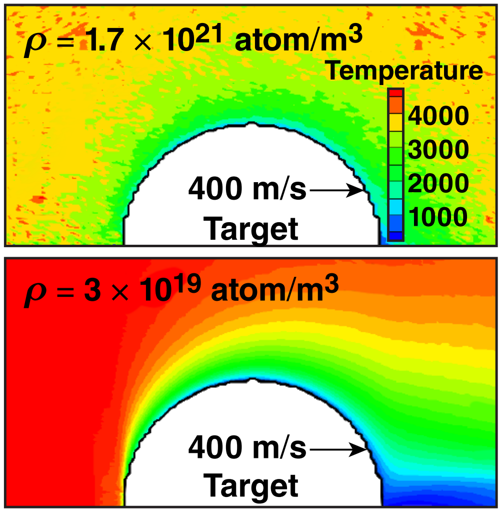
Candidate materials and considerations

Gas	Properties
Ne	• High P_{vapor} at 18 K • Heat conducting gas for layering • Low $E_{sublimation}$, sublimes rapidly during target injection
Xe	• 100-μm × 0.1-μm grain size (FCC crystal) • Low P_{vapor} (~10^{-13} torr) readily condenses at 38 K • High $E_{sublimation}$ → slow removal during injection

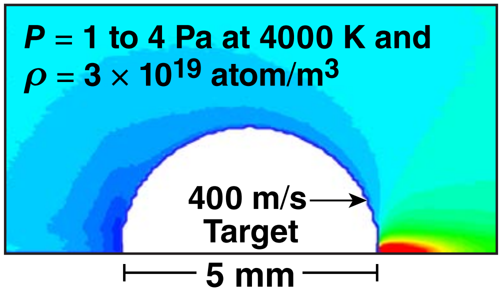
The heat load to the target and the effect on the ice during injection into the chamber were estimated using Monte Carlo and CFD models

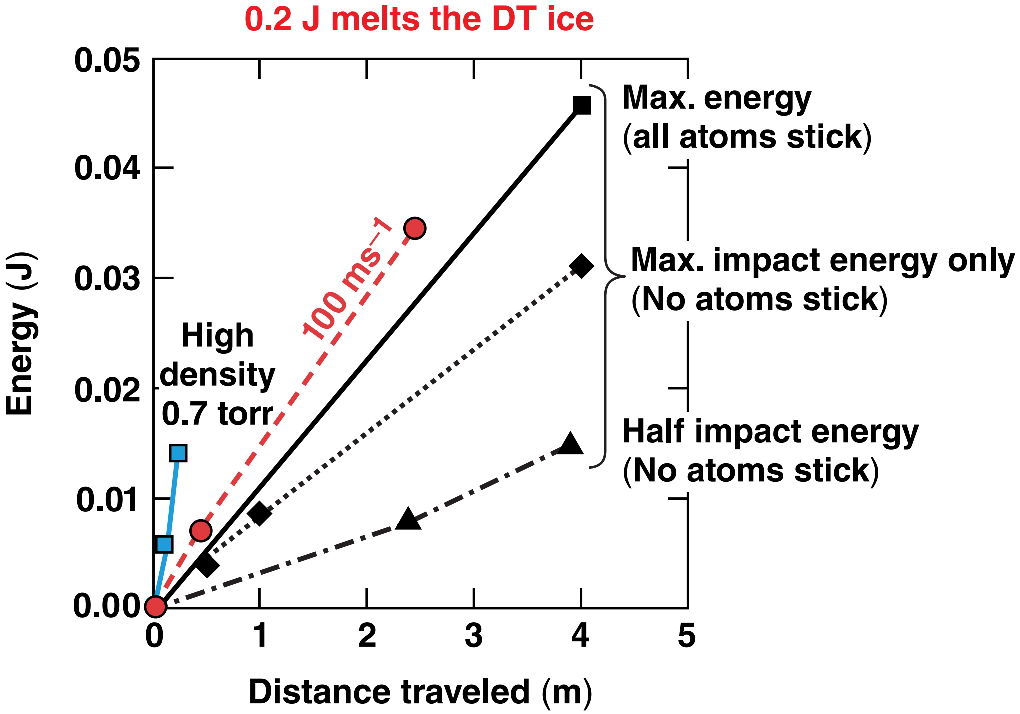
Conditions: 4000 K gas temperature; 400 ms^{-1} target velocity; 0.05-torr Xenon gas

Temperature distribution



Pressure distribution



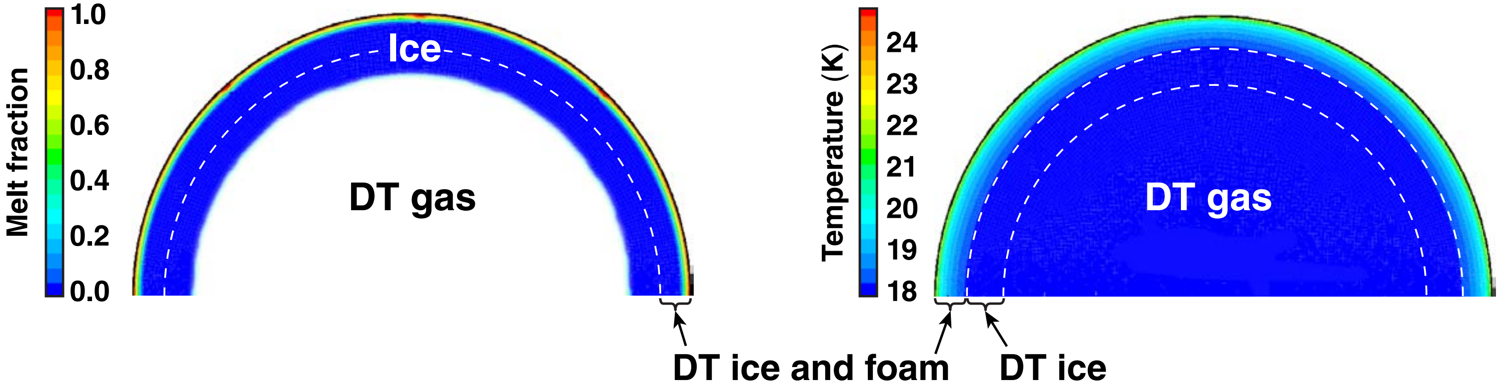


The heat load varies from 0.25 to 25 W depending upon the conditions and the gas-surface dynamics.

Comparatively high heat loads (1.4 W) have no effect on the inner ice surface because of the low thermal diffusivity and brief residence time in the chamber

- Model includes sublimation and melting
- Model assumes a radiation barrier and no outer sacrificial Xe overcoat

Melt fraction and temperature distribution of the ice after 0.05 s (anticipated time for target to traverse the chamber radius)



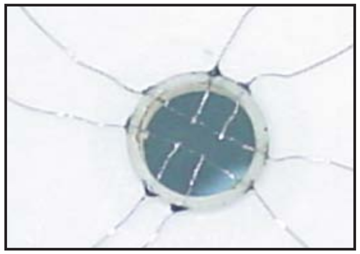
- Inner-ice-surface temperature preserved by the low thermal diffusivity and the high H_{fusion} of DT

1.4 W for the 0.05-s estimated transit time to TCC melts the outer surface of the ice layer but leaves the inner surface unaffected – an outer Xe/Ne insulation layer on the target would provide further protection.

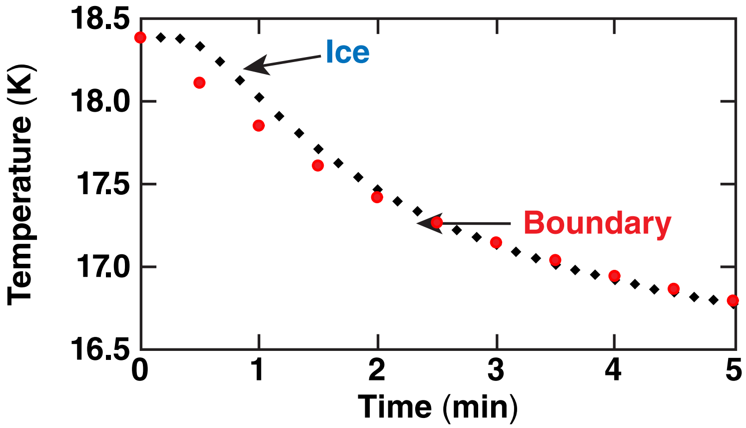
The calculated effects of a high temperature gas on the ice layer can be tested in existing equipment

"Surrogate IFE chamber" –
e-beam heated tungsten nozzle producing a supersonic beam of Xenon atoms

"Surrogate target" – cylinder filled with D_2 and embedded with temperature sensors that also measure the rate the liquid/solid phase changes

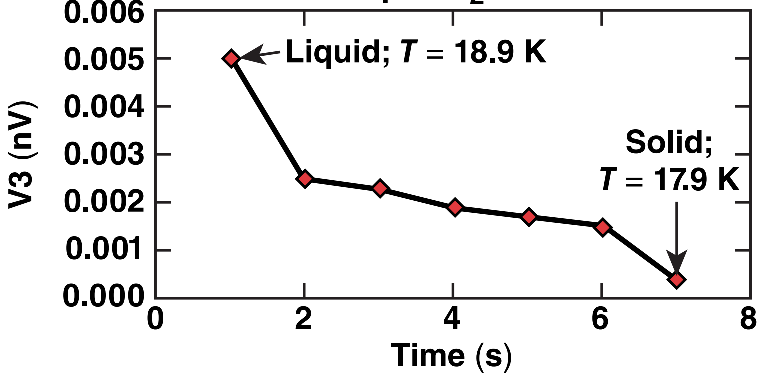


Time resolution for measuring heat flow is 1 s and power resolution is ~1 W (equiv – 1 nV)



- gas temperature > 2000°C
- heat flux – 14 kW/m^2
- atomic flux 3 × 10^{22} atom/m^2
- gas pressure of 0.001 torr

Rate liquid D_2 solidifies



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