Cryogenic Layering Experiments on OMEGA

- CTHS Overview
  - Operation
  - Capability
  - Results (layering and implosion)

- Studies of mutual interest to ICF and IFE
  - Formation of the ice layer
  - Foam
  - Rate of deterioration of the ice layer

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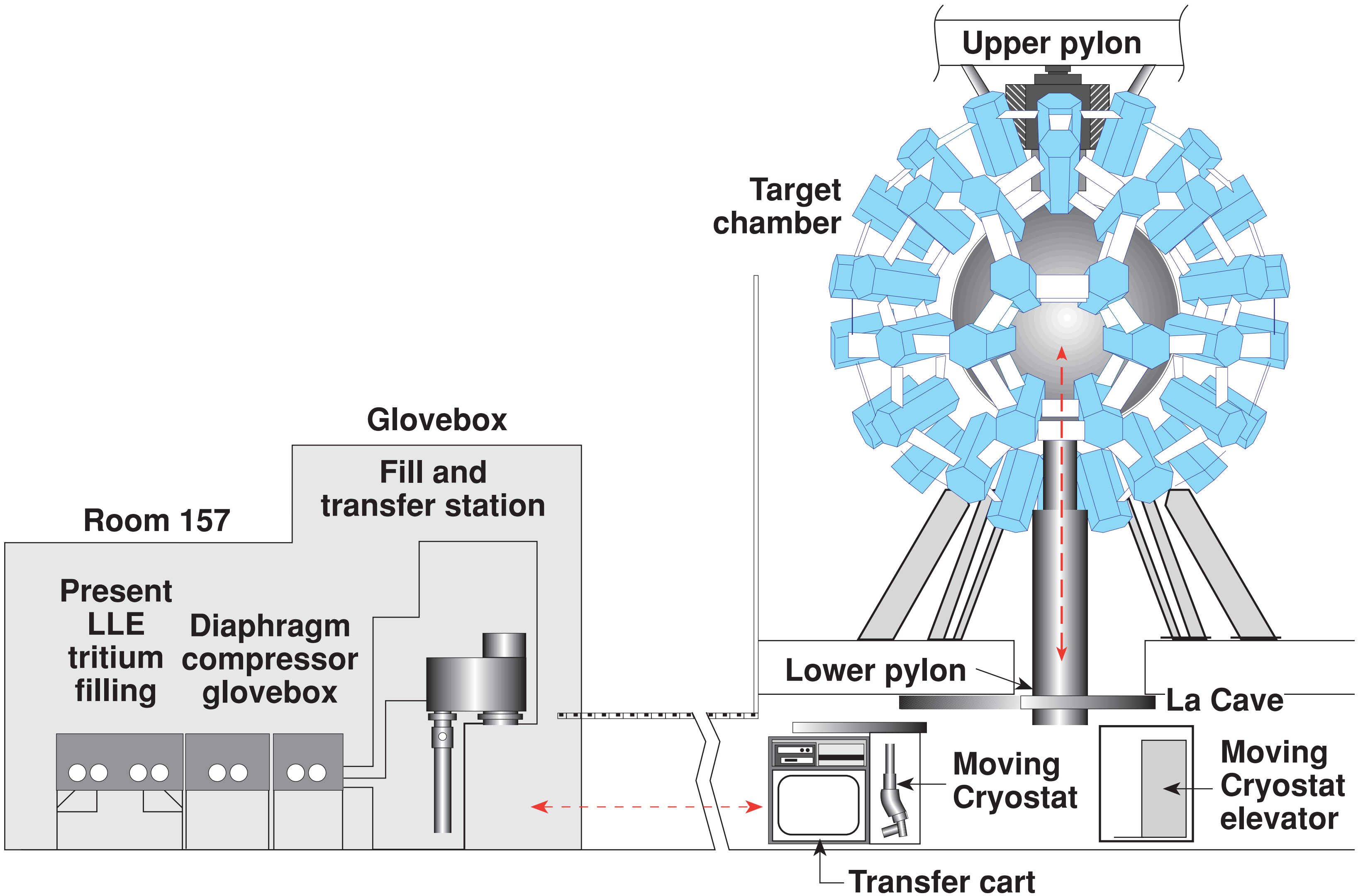
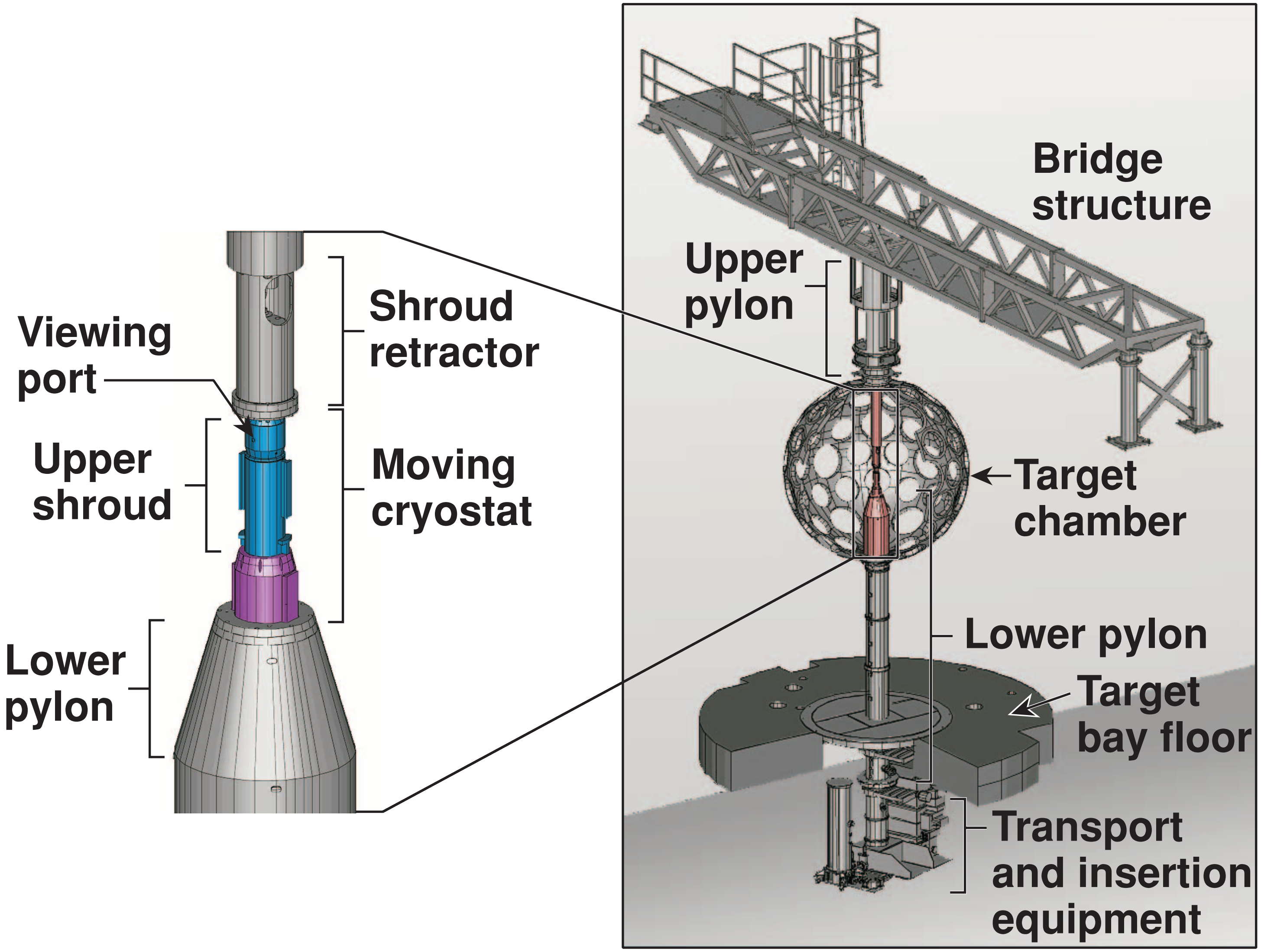
CTHS is physically part of the OMEGA facility and is managed as part of LLE's target fabrication operation



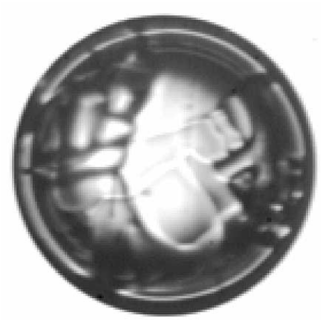
T1338g

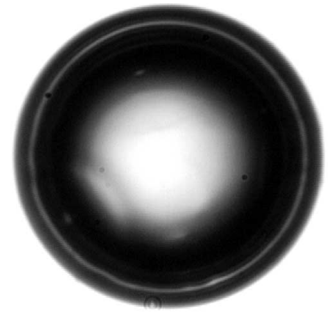
Schematic showing the target insertion and shroud retraction operations



T1541

A comparison of shots 28900 and 26477 clearly shows the result of accurate TCC alignment (with $\alpha \sim 25$)





Drive pulse: 1ns ($\alpha \sim 25$)

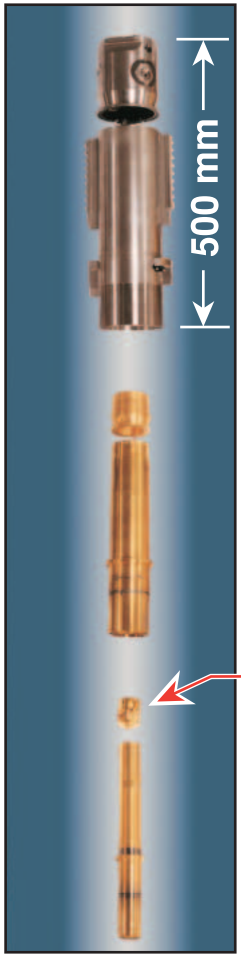
	Shot 28900 Experimental	Clean 1-D (%)	Shot 26477 Experimental	Clean 1-D (%)
Yield (1n):	1.27×10^{11}	96	3.17×10^{10}	31
Yield (2n):	1.17×10^{9}	84	3.05×10^{8}	32
Yield (2p):	2.03×10^{8}	112	2.67×10^{7}	21
$\langle\rho R\rangle$:	61 mg/cm^2	133	30 mg/cm^2	80
T_{ion}:	3.6 keV	157	2.6 keV	117
Y_{2n}/Y_{1n}:	0.0092	85	0.0096	102
Y_{2p}/Y_{1n}:	0.0016	114	0.00084	66
TCC offset:	14±7μm		85-μm	

E12016

The cryo target is delivered to the target chamber in a "moving cryostat"

Cryostat base

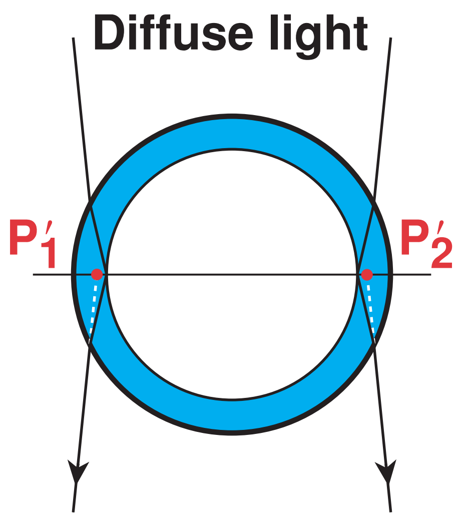
Upper shrouds (exploded view)



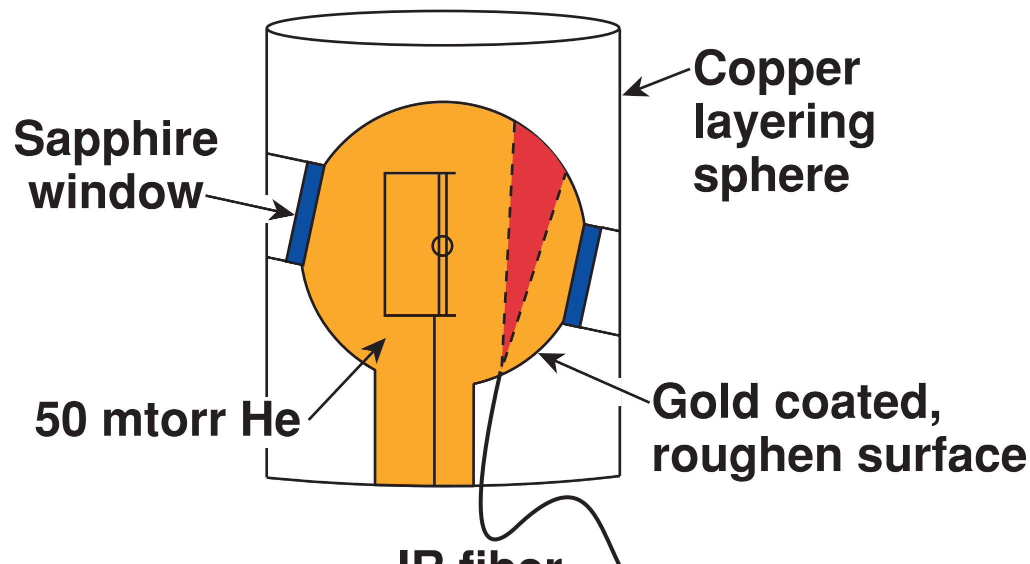
T1656

Shadowgraphic analysis of the ice layer uses multiple views to more fully characterize the inner ice surface

1. The target is backlit with diffuse 660-nm light along two near-orthogonal axes (*f*/12 and *f*/5).
2. A bright band in the transmitted image is due to internal reflection from the ice/gas interface—the image is unique to the region of the ice along a great circle perpendicular to the viewing axis.



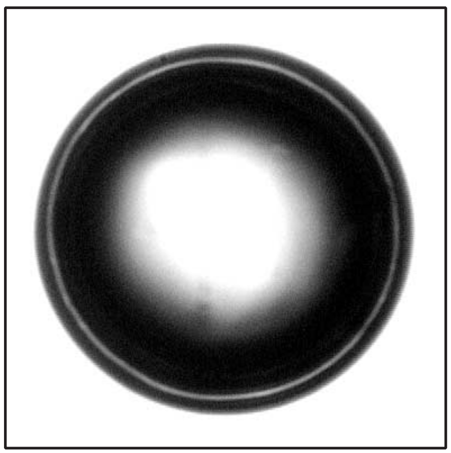
Top view



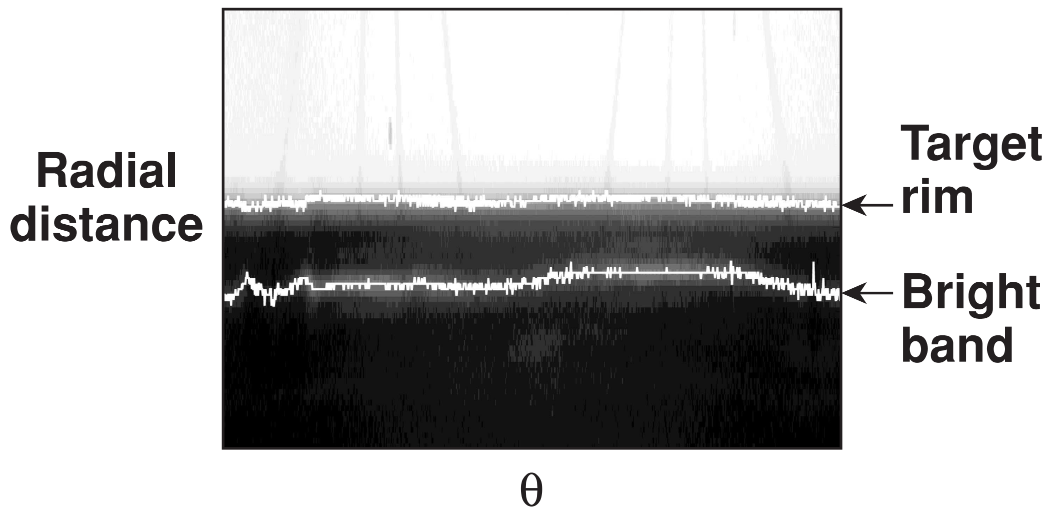
T1651

Shadowgraphic analysis

1. The target is backlit with diffused 660-nm light.
2. A bright band in the transmitted image is due to internal reflection from the ice/gas interface



3.9-μm CD shell (0.92-mm diam) with 80 μm of D_2 ice

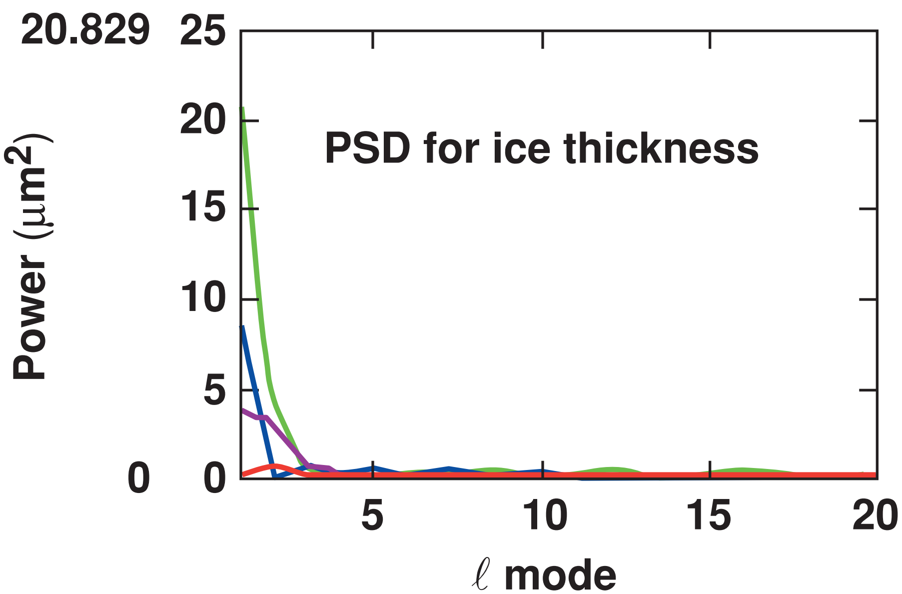


"Unwrapped" image

T1661

Rotating a target allows multiple cross sections through the ice to be sampled to better determine the overall roughness

	ϕ	rms	All coefficients
Red	101°	1.6-μm ℓ (1→30)	3.4 μm
Blue	129°	3.4-μm ℓ (1→30)	5.1 μm
Green	84°	5.4-μm ℓ (1→30)	8.2 μm
Purple	39°	3.0-μm ℓ (1→30)	5.1 μm



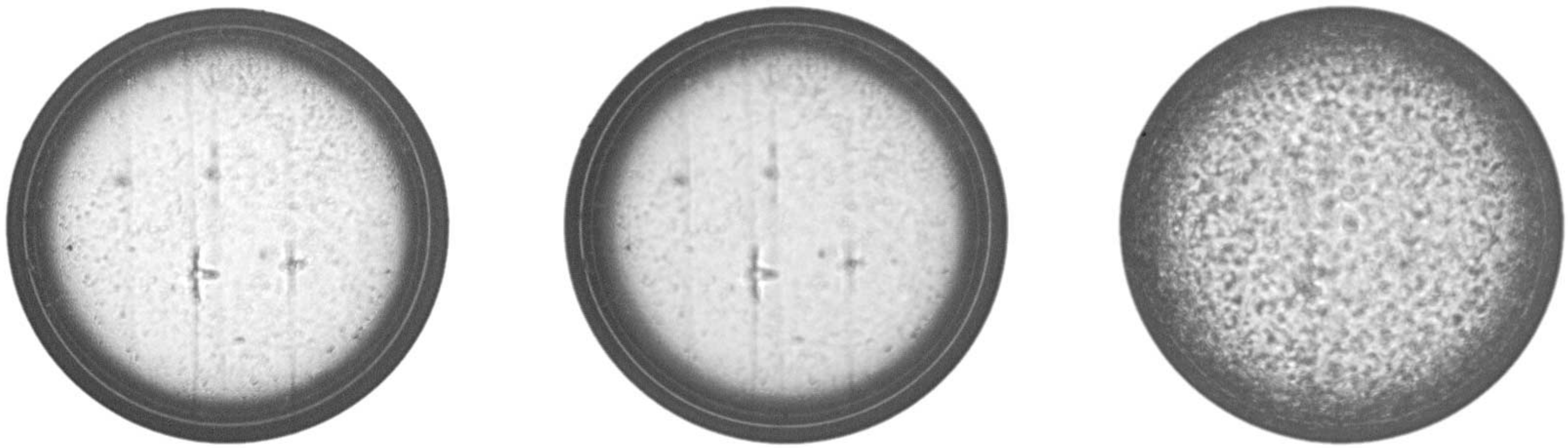
Future plans call for multiple 2-D target images to be combined to form a 3-D reconstruction of the ice and shell.

T1749

The transparency of a foam shell (100-nm pore size) is signicantly reduced when the liquid freezes

1.12-mm OD; 6-mm GDP; 78-μm foam wall; 90 mg/cc; 1000 atm of D_2

Empty | **Liquid (22 K)** | **Ice layer ~ 126 μm**



Questions:

1. Is it possible to form a “single” ice crystal by controlling the crystal growth rate?
2. Is it possible to reduce the number of crystals by annealing the target close to the triple point?
3. Will longer-wavelength illumination improve the transparency?

Planned level of effort: pursue foam studies for 1 week every 3 months

Boundary and initial conditions for the layering process

- A 2.5-cm isothermal integrating sphere contains the target.
- Deuterium requires IR light from an OPO (200 mW max.) to layer.
- Heat coupled into target is 5 to 20 μW (~ 0.5 to 2 Q_{DT}) ~ 0.012% efficiency.
- Exchange gas pressure: 0.5 mtorr to 5 mtorr; mean free path ~ 7 cm to 0.7 cm
  - → Close to molecular flow regime where the analytical heat transfer equation for a sphere-in-a-sphere does not apply ($Q = k^*d_1d_2\Delta T/\Delta d$).
- Heat coupling to the layering sphere is pressure dependent.

  Q = const*pressure*DT: the constant accounts for different areas and includes accommodation coefficients.
- Time scales for heat transport are significantly long, i.e., 90 min required to remove the latent heat from a target 15 mK below T.P.

T1750

The most straight forward way to make an ice layer should be applicable to mass production techniques

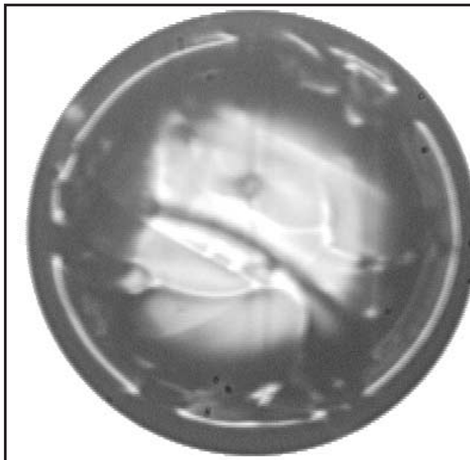
Method 1:

a. Start with a liquid; lower the temperature below the triple point – freezes.

b. Raise temperature close to the triple point.

Proximity to triple point = 0.5 K

t_0 + 1 h: rms ~ 15 μm



t_0 + 45 h: rms ~ 7 μm

Three control variables:

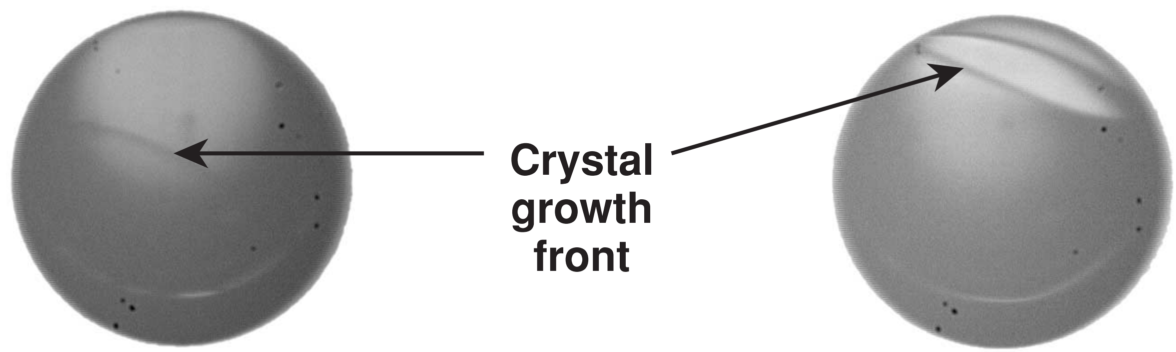
1. Rate of solidification – control IR power (power in) and gas pressure (power out)
2. Proximity to triple point
3. Duration of anneal

The relative importance of each of these parameters is being investigated.

T1751

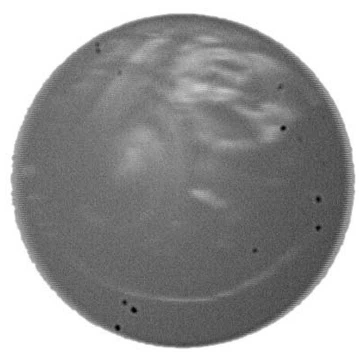
Controlling the solidification rate illustrates the crystal growth process: ice grows from the base and facets appear once the inner surface is covered

Boundary temperature: 18.3 K; initial target temperature > 18.73 K (IR power initially 60 mW, then shuttered); pressure: 5 mtorr; 780-atm fill; flux: 0.16 mW/cm^2

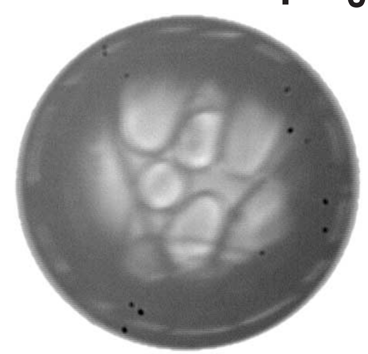


t_0 + 4 min

Ice levels almost at top: t_0 + 11 min



Ice facets form: t_0 + 12 min



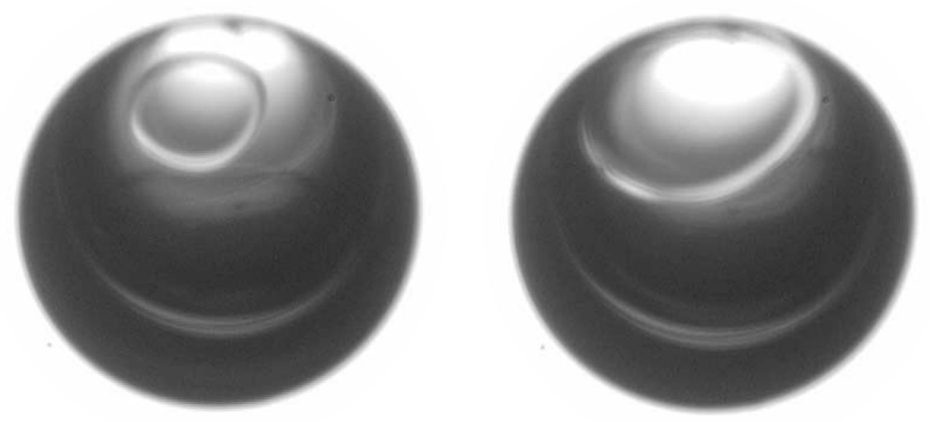
Q_{in} = 5 μW; boundary temp = 18.15 K

The smaller the temperature change, the slower the growth rate.
Studies are in progress to correlate growth rate with ultimate smoothness.

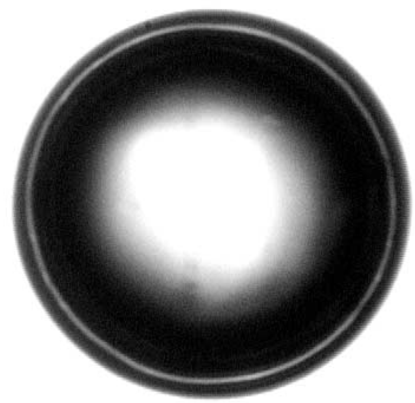
T1752

The technique that yields the smoothest ice layer is to form a seed crystal in the upper hemisphere, then lower the temperature below the triple point

Layering sphere temperature = 16.5 K; 3.9-μm CD shell



Example of crystal starting at the top and growing downward



Ultimate smoothness of the ice is 2 to 4.5 μm, depending upon rotation.

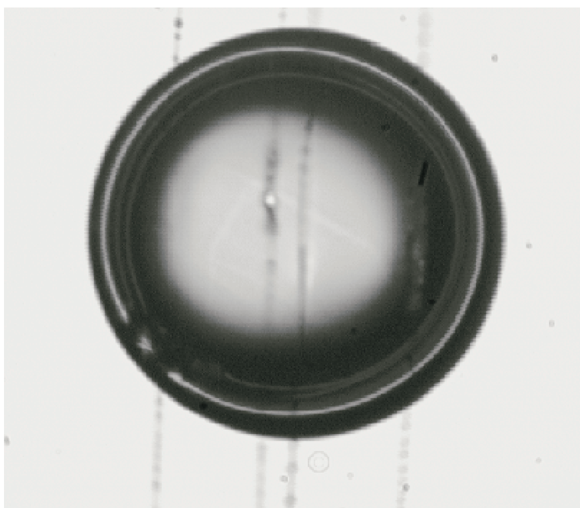
Forming a single seed crystal requires precise control of the thermal time response of the ice layer. Multiple seed crystals result in multifaceted ice layers.

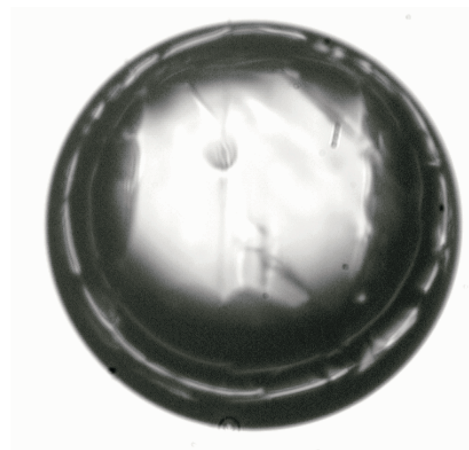
T1753

Irrespective of which technique was used to form the ice layer, low-mode roughness (i.e., variable ice thickness) can occur and is stable. Why?

UR LLE

Cryo shot #28969 (below on the left); 11% YOC; α = 4 pulse; 8.4 μm rms; all power in modes 1 and 2; "thin region" in the "southwest quadrant" – very unusual





Target on the right has a rms = 17 μm; the "thin region" is near the "north pole" (typical). This configuration was stable for 5 days.

T1754

The rate at which an ice layer degrades when an additional heat flux is coupled into the plastic shell can be measured

UR LLE

Observation:

Heating the plastic shell melts the ice at the plastic/ice interface, doubling the time required for the ice to melt.

Process:

1. Form a layer at $\lambda = 3.16$ μm.
2. Stop IR illumination and raise temperature to 18.7 K.
3. Time for the ice layer to slump when illuminated at $Q = 0.2$ mW/cm^2 ~ 2 min.
4. Repeat steps 1 and 2.
5. Change IR illumination to $\lambda = 3.32$ μm–where ice absorption is a minimum and plastic absorption is similar–to simulate heating of only the plastic.
6. Time for the ice layer to slump when illuminated at $\lambda = 3.32$ μm and $Q = 0.8$ mW/cm^2: ~ 1 min., i.e., a 4× greater heat flux causes a comparable response in only half the time.
7. Visually, at $\lambda = 3.32$-μm illumination, the layer was observed to rotate while it was slumping.

Preliminary data – further work required

T1755

Current effort is to quantify the effect of low exchange gas pressure on the layering process. Earlier experiments overstated gas pressure and heat coupled into the target.

UR LLE

Background:

- Pressure of the He exchange gas was initially estimated to be 20 to 30 mtorr.
- Existence of a joint between the lower and upper shrouds makes for a large variable leak.
- At low gas pressure (scale length/mean free path <1), thermal transpiration causes the warm measured pressure and cold pressure to differ.
- At low gas pressures the analytical heat transfer equation for a sphere-in-a-sphere does not apply ($Q = k^* d_1 d_2 \Delta T / \Delta d$) — the original basis for determining the heat coupled into a target.
- Instead, $Q = \text{const}^*\text{pressure}^*\Delta T$: the constant accounts for different areas and includes accommodation coefficients.

→ Time scales for heat transport are dramatically longer, i.e., 90 min required to remove the latent heat for a 15-mK ΔT below T. P.

Disadvantage: Determining the temperature setting close to the triple point is very time consuming.

Advantage: Use pressure to establish a temperature gradient on the shell, to initially seed a crystal, and then to control the growth rate.

T1756

Summary and future plans for the CTHS

Current status:

- **Have completed 49 permeation-fill cycles using the CTHS**
- **Have provided targets with a wall thickness as low as 2 μm**
- **Production yield of targets (including all forms of attrition) ~ 70%**
- **Have shot 29 cryo targets**

Highest priorities are

1. **To provide targets for implosion experiments**
2. **To prepare system for use with tritium**

Layering studies will continue in parallel albeit at a lower priority:

1. **Routinely achieve ice layers with roughness of 5 to 8 μm**
2. **Infrequently achieve ice layers with roughness of 2 to 4 μm**
   Need to determine baseline smoothness
   Need to improve the reliability of achieving the smoothest layer
3. **Evaluate the ability to layer ice in foam**

If, and how, the CTHS can be used to perform IFE-relevant studies (in the near- and long-term future) should be decided soon. The system is currently oversubscribed, and engineering changes take time to implement. IFE work will require milestones that are integrated into the overall plan for the system.