



GENERAL ATOMICS
AND AFFILIATED COMPANIES

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Studies of Solid DT Layers in Foam

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Injection and Tracking**

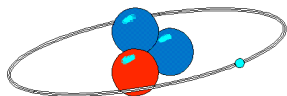
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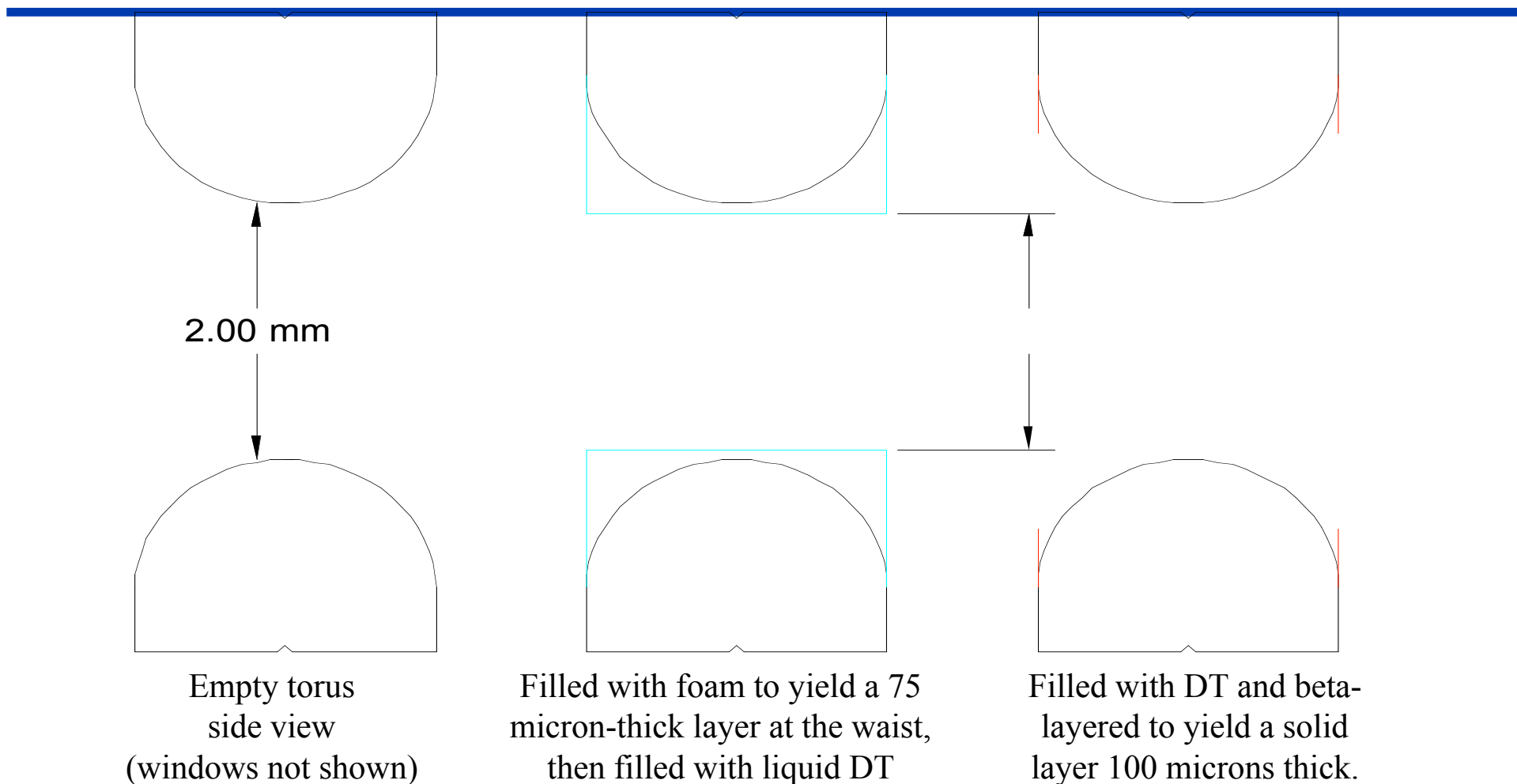
We have measured the effects of a foam-layered platinum torus on the beta-layered, Solid DT surface roughness

- Both the total RMS surface roughness as well as the I-mode spectral components were measured for several solid DT-in-foam layers that were equilibrated at 19.25 K
- The effects of cell cooling and warming on the solid DT-in-foam surface roughness were measured; cooling from 19.35 K down to 15 K and warming from 15 K to 19.55 K
- Our studies show an average smoothing of 50% for total RMS, and 60% for Σ (modes 10-100), compared to results from recent DT aging experiments done in our 2-mm beryllium torus. We also observed an average smoothing of 80% for Σ (modes 50-100) with DT-in-foam layers.

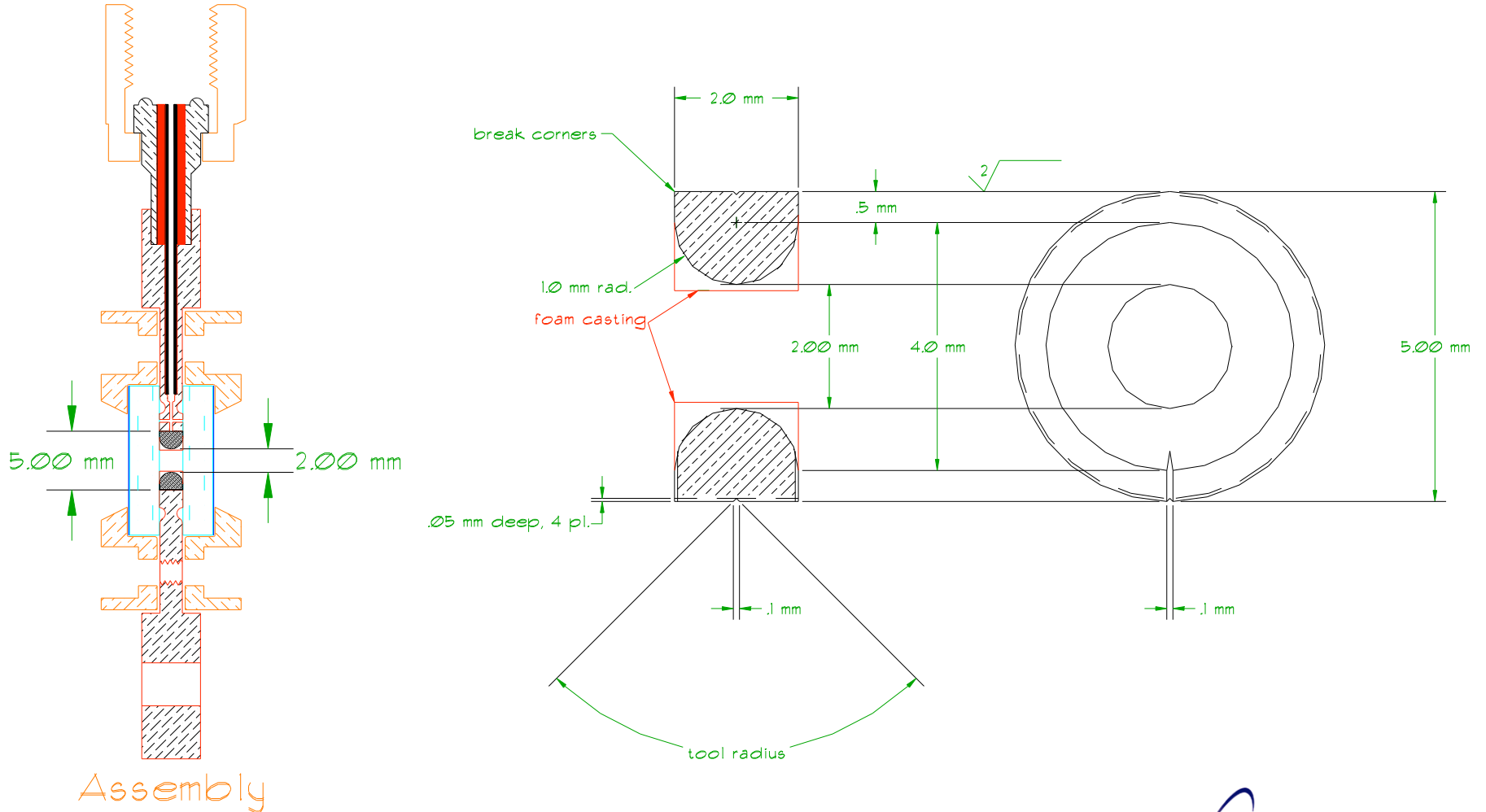
There are several hypotheses concerning the effects of an intermediate foam layer on the inner solid DT layer

- Beneficial effects:
 - **A smoother interior surface**
 - Because of the fine cell structure of the foam, freezing should begin with the formation of many small, randomly-oriented crystallites. These crystallites should propagate into the pure DT solid layer, hence there should be no tendency to form large crystalline facets at the solid-vapor boundary.
 - **Supercooling of the liquid should not occur**
 - With millions of nucleation sites presented by the foam, the liquid does not supercool as is observed in smooth plastic spheres without a foam layer.
- Detrimental effects:
 - **If irregular, the overall shape of the foam may affect the shape of the solid DT.**
 - But I'm guessing that the gross shape of the foam will not influence the shape of the solid DT layer, because the foam is a thermal insulator and will not disturb the isotherms defined by the isothermal boundary (i.e., the metallic cell boundary in my cylindrical experiments or the 'layering sphere' utilized for spherical targets at Omega.)
 - **The polymeric foam material may be damaged by beta activity and decompose.**
 - **DT voids in the foam cells may become trapped**
 - The solid DT is 12.5% denser than liquid. A void space (full of DT vapor) therefore develops whenever a cell full of liquid is frozen. (When symmetrized by beta-layering, the void in a single spherical shell will extend exactly half-way across the cell.) Voids first formed in the foam cells tend to propagate inwards to the central vapor space. If the inner edge of a foam cell is blocked by a cell wall (i.e., if the foam is not completely 'open-celled'), then the void may get 'stuck'. Stuck voids may not be too detrimental, because they are sub-micron in size. But a secondary effect might be a very slow approach to equilibrium wrt the DT layer thickness.

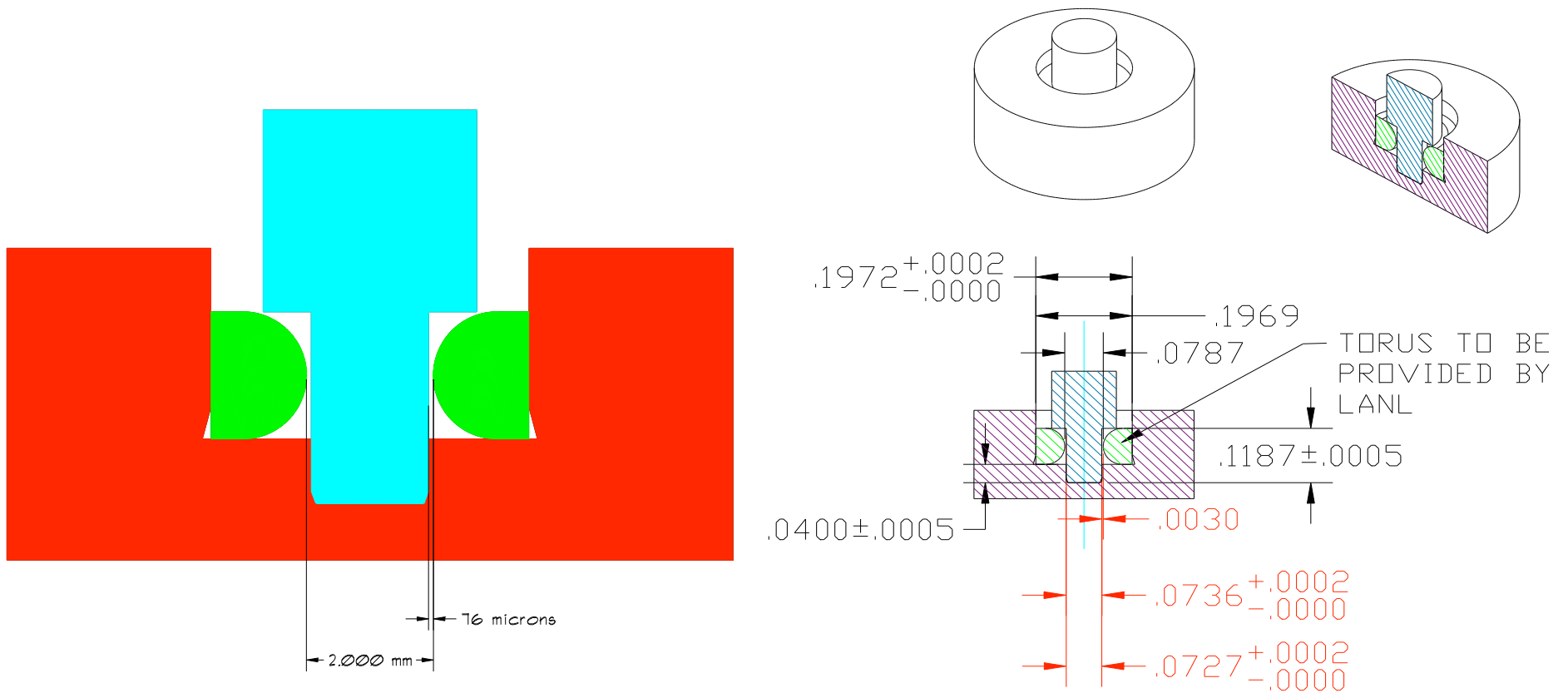
The foam-lined torus permits clear optical observations of the DT layer:



Several 2 mm tori were fabricated from pure Pt

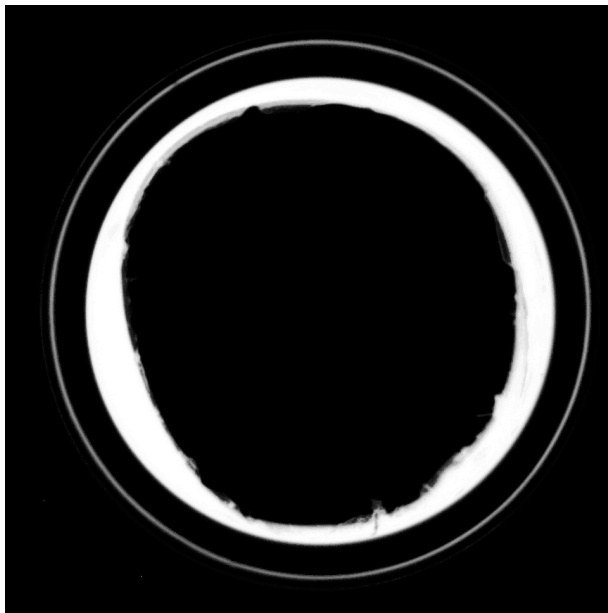


At Sandia, Diana Schroen & co-workers added ~70- μ m-thick RF foam layers to four tori:

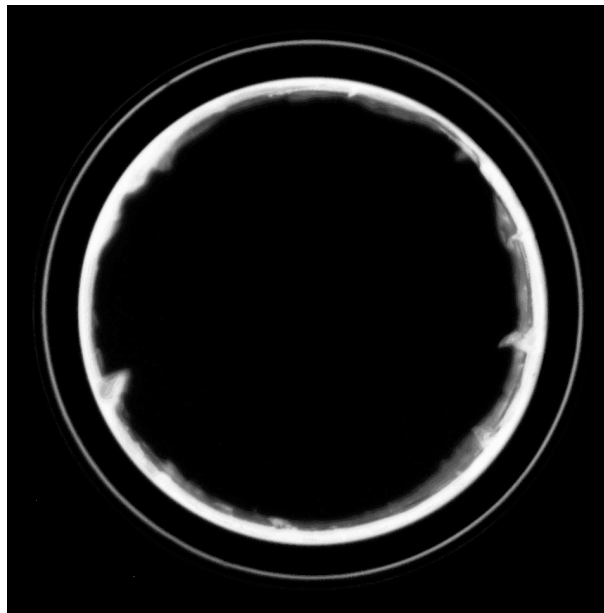


**We measured the foam thickness by ‘subtracting’
an image of the unfilled Pt torus.
We then chose cell ‘C’ based on:**

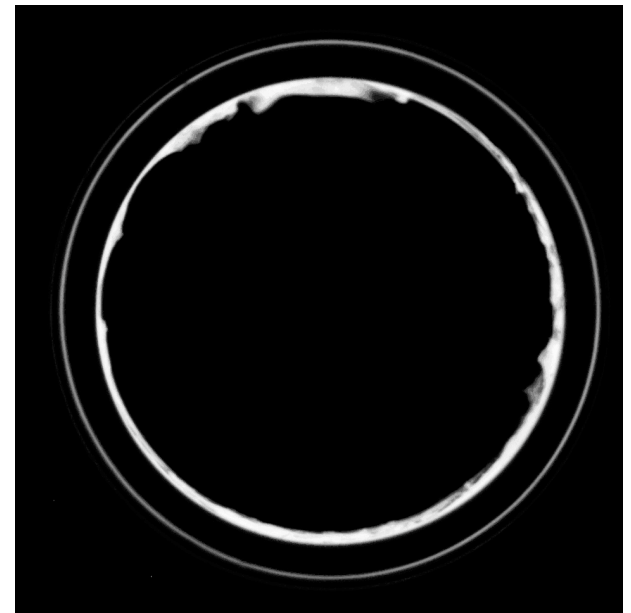
- overall symmetry,
- average foam layer thickness, and
- relative lack of defects at the toroidal waist



Cell ‘B’ - average $d = 125\mu\text{m}$



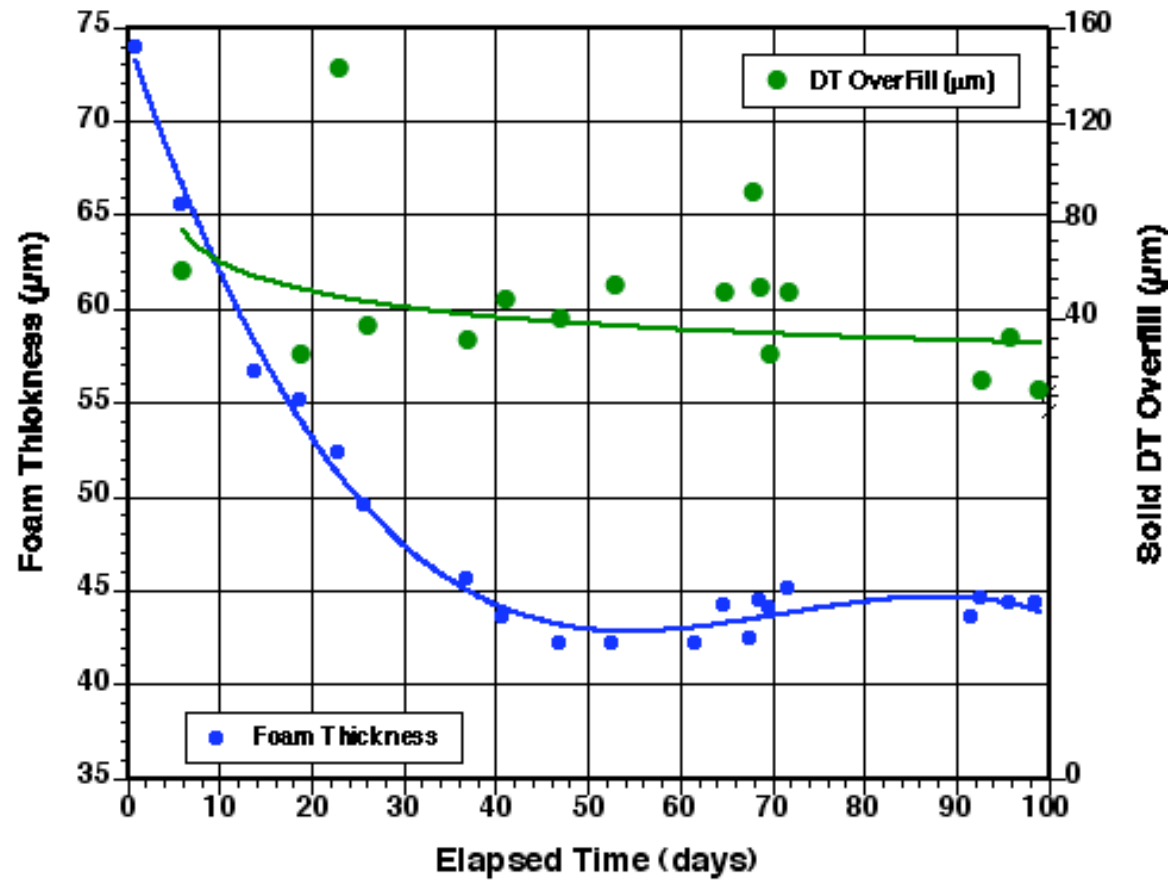
Cell ‘C’ - average $d = 74\mu\text{m}$



Cell ‘D’ - average $d = 47\mu\text{m}$

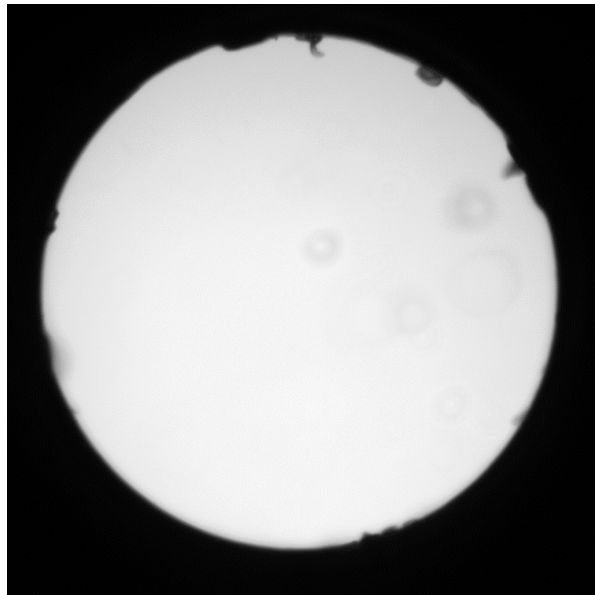
Foam Thickness Decreased from 74 μm over the course of several experiments, then stabilized at about 43 μm

Evolution of RF Foam Layer Thickness Coating 2 mm Diameter Pt Torus



Once the solid layer has equilibrated, we can show the pure DT layer by subtracting the empty foam image.

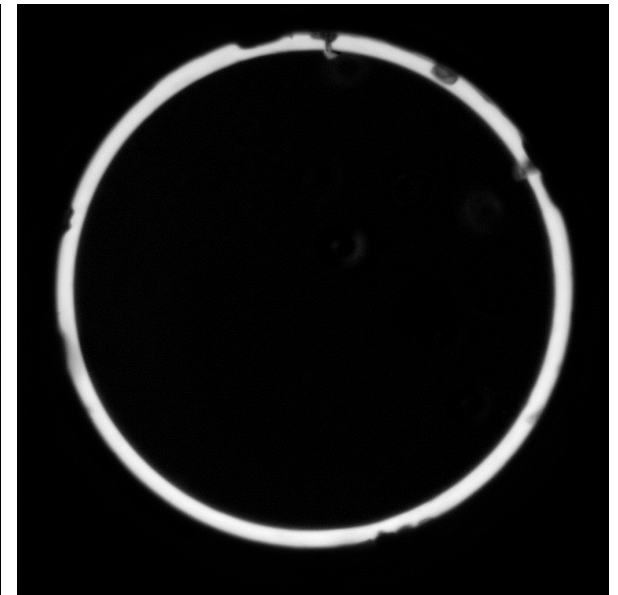
Note that the solid DT ignores the defects in the foam!!!



empty foam



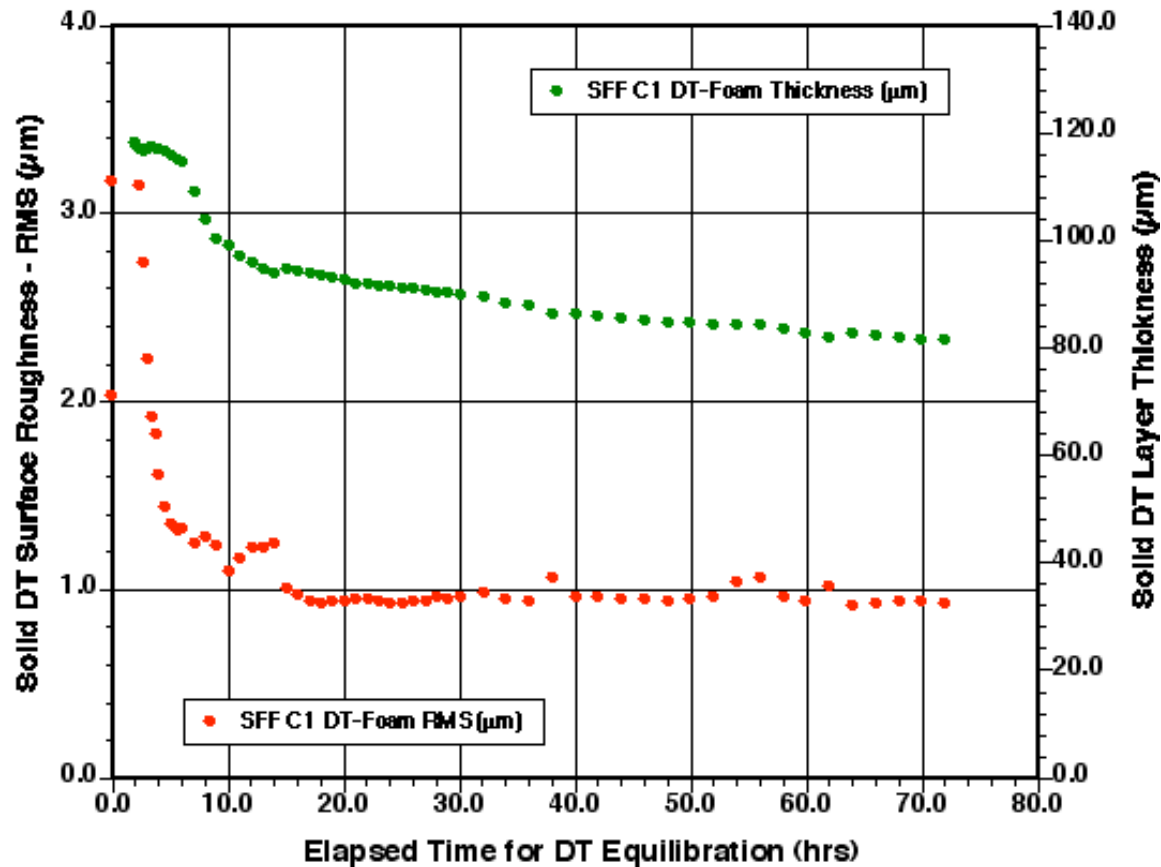
98 μm DT layer (total)
~50 μm is 'pure', while the rest resides in the foam



Empty foam – DT Layer

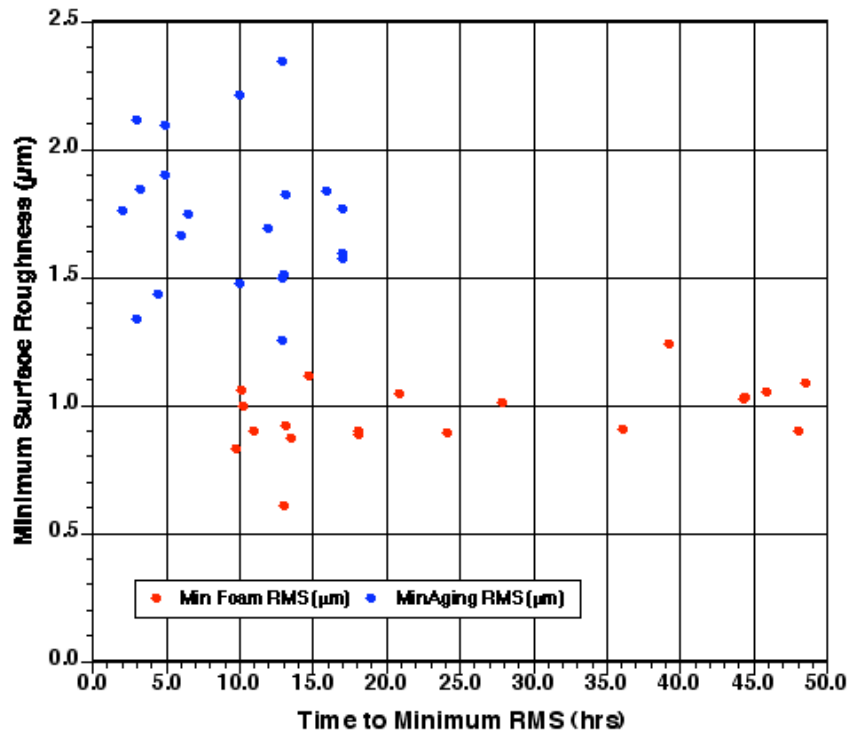
This is a typical solid DT layer equilibration at 19.25 K in the foam-layered Pt torus

DT Solid Layering in 2 mm Platinum Torus with 44 μm Foam Layer Equilibration 1 Starting 112002

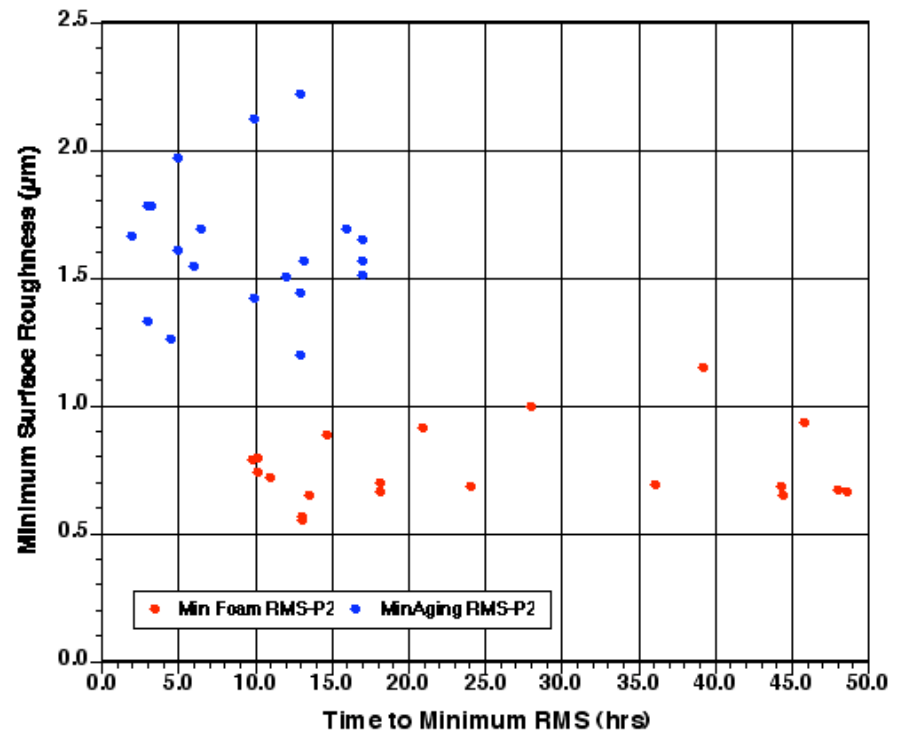


But the solid DT surface is much smoother than we have thus far observed in this geometry

Comparison of Total RMS Surface Roughness for DT Solid Layers Produced in DT Foam and DT Aging Experiments

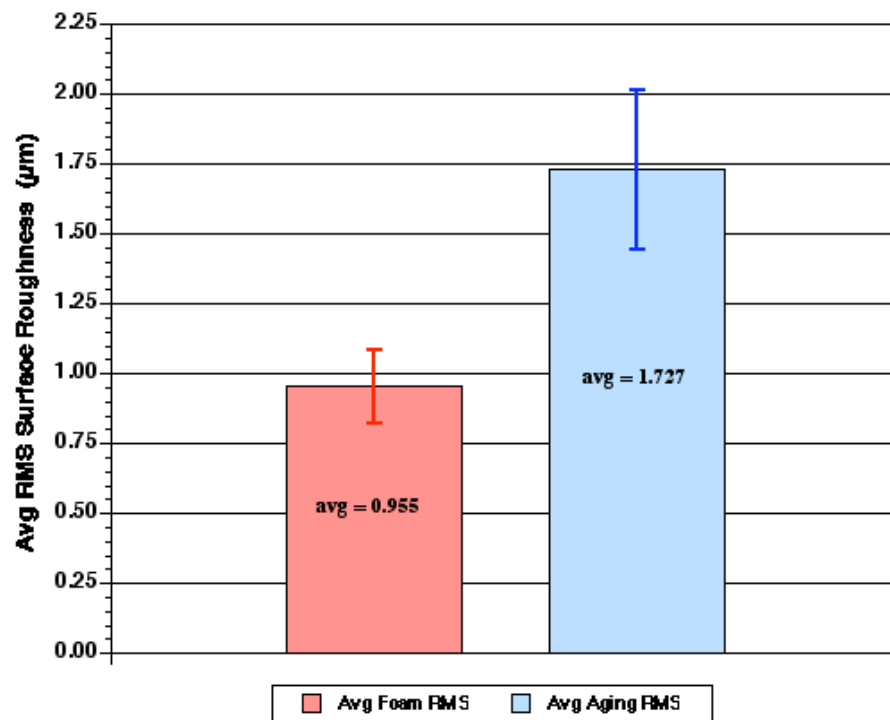


Comparison of Total RMS Surface Roughness After P2 Removal for DT Solid Layers Produced in DT Foam and DT Aging Experiments

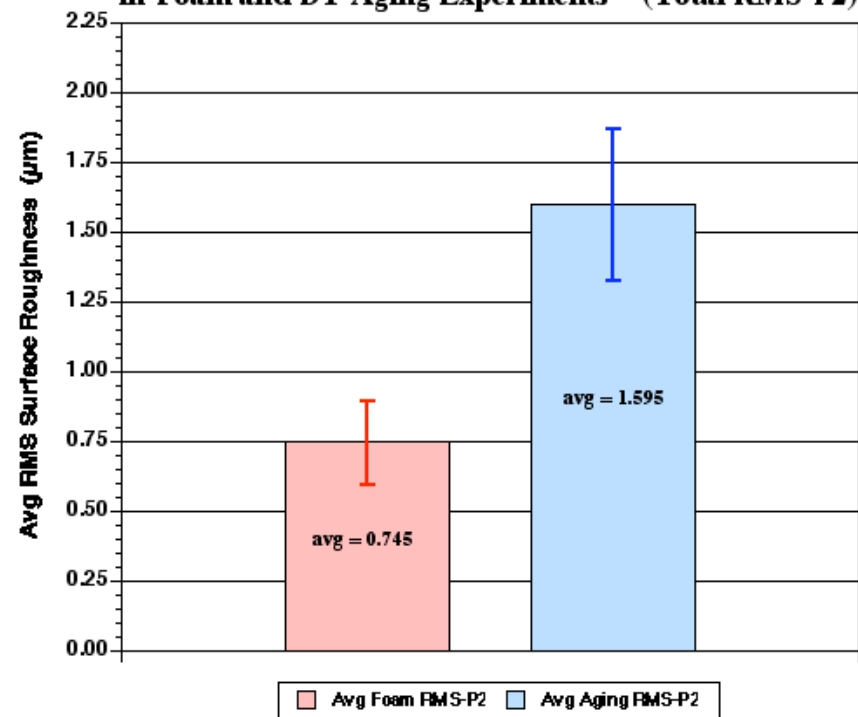


The mode 2 amplitude is responsible for about 20% of the total rms roughness. Some of this is due to the fact that we now cannot line up the empty torus 'on axis'.

Average Surface Roughness Comparison Between Solid DT-in-Foam and DT Aging Experiments - Total RMS

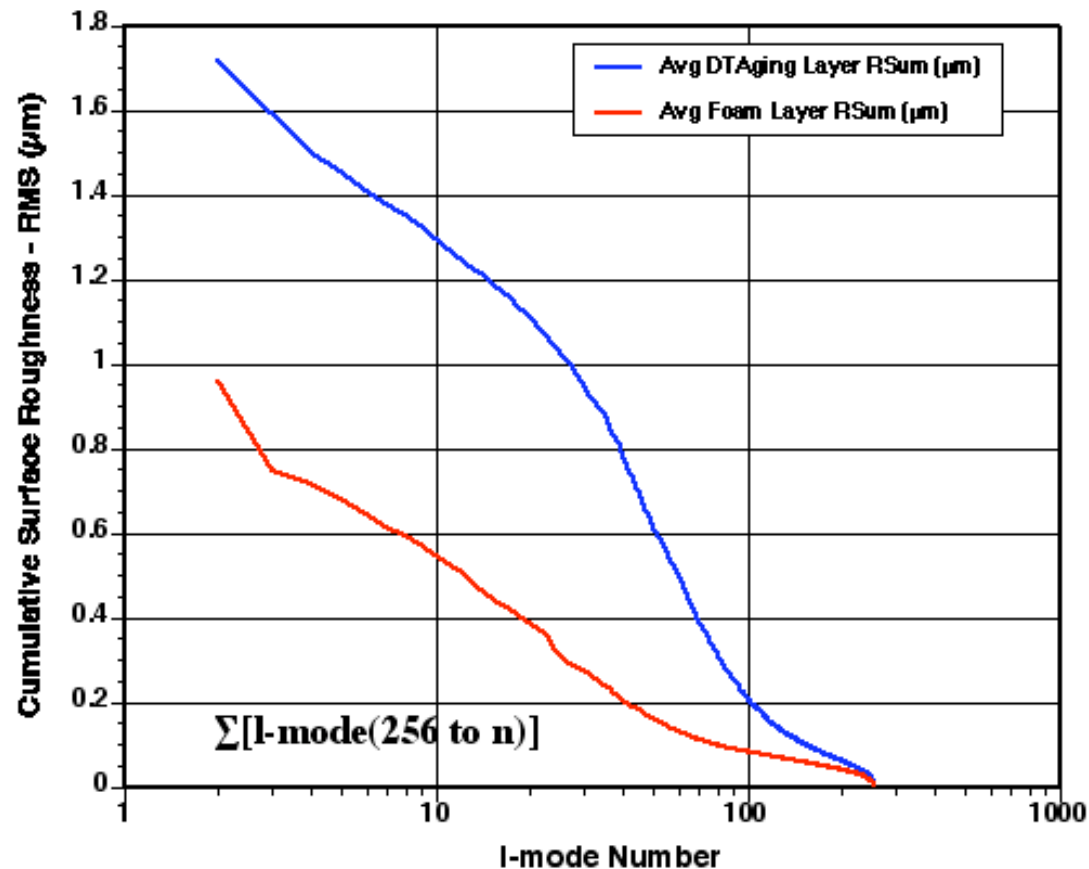


Average Surface Roughness Comparison Between Solid DT-in-Foam and DT Aging Experiments - (Total RMS-P2)



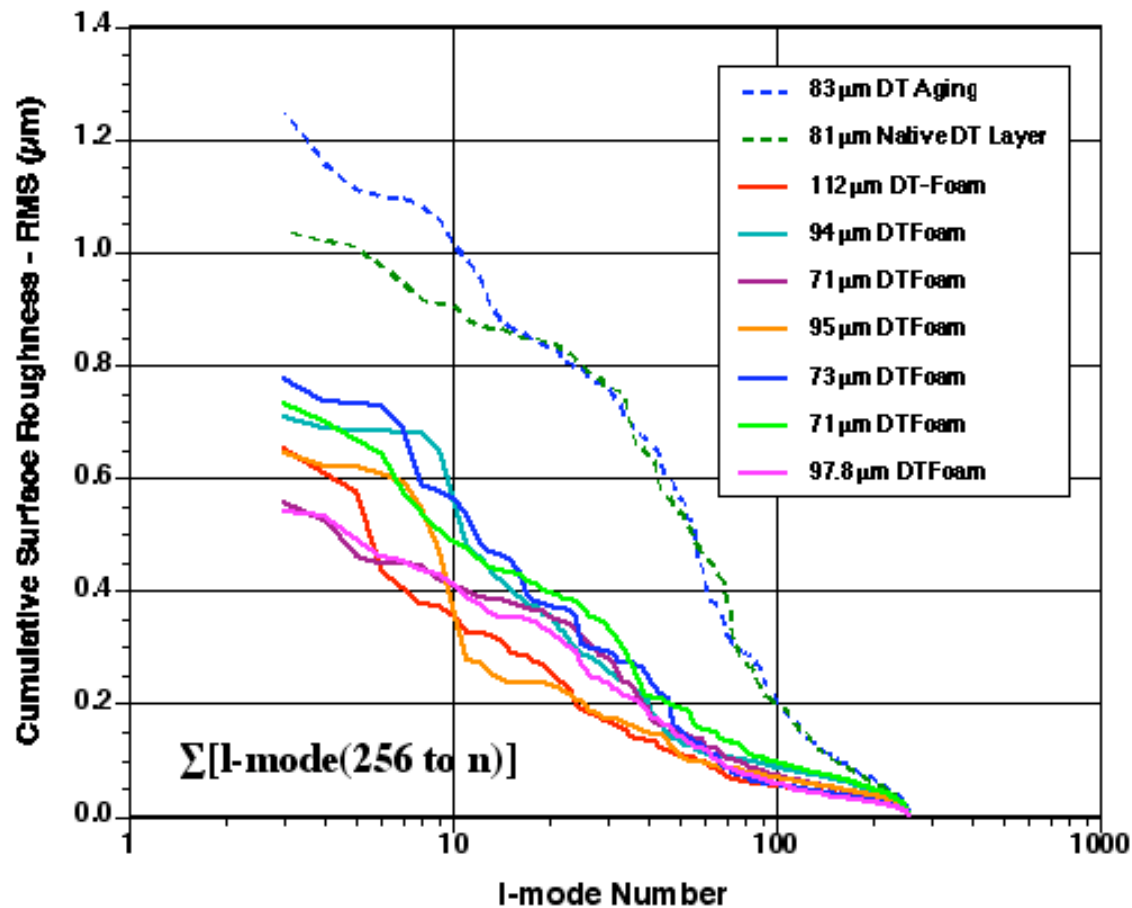
By plotting a 'reverse sum' of modes, the modal spectrum can be seen. The presence of the foam is dramatically reducing the roughness power at l-modes 10-100.

Comparison of Average Reversed Spectral RMS for Foam and Aging Experiments



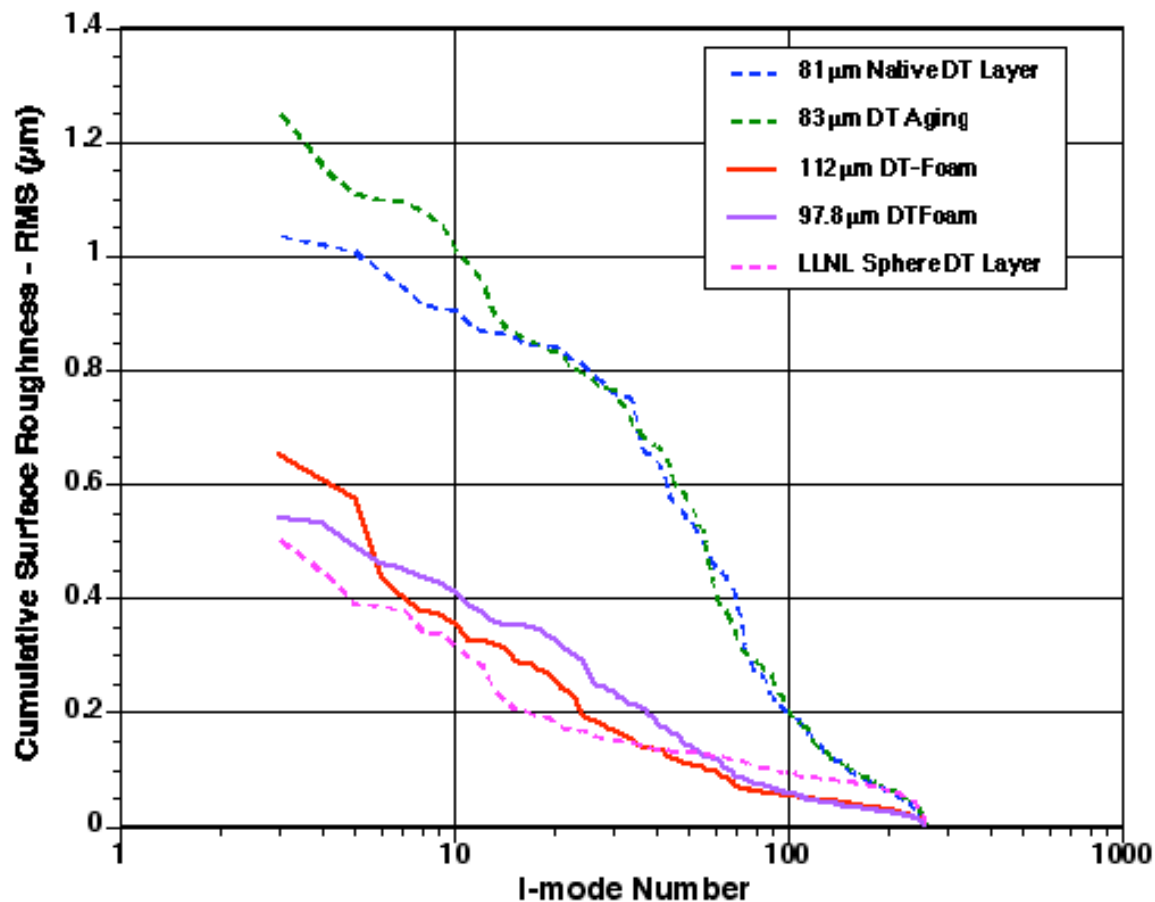
This compares the ‘best’ of our previous results with several of our results in foam. Simply put, **we have never seen such a smooth beta-layer!!**

Comparison of Minimum Reversed Spectral RMS Roughness Between DT-in-Foam and Previous DT Layering Experiments



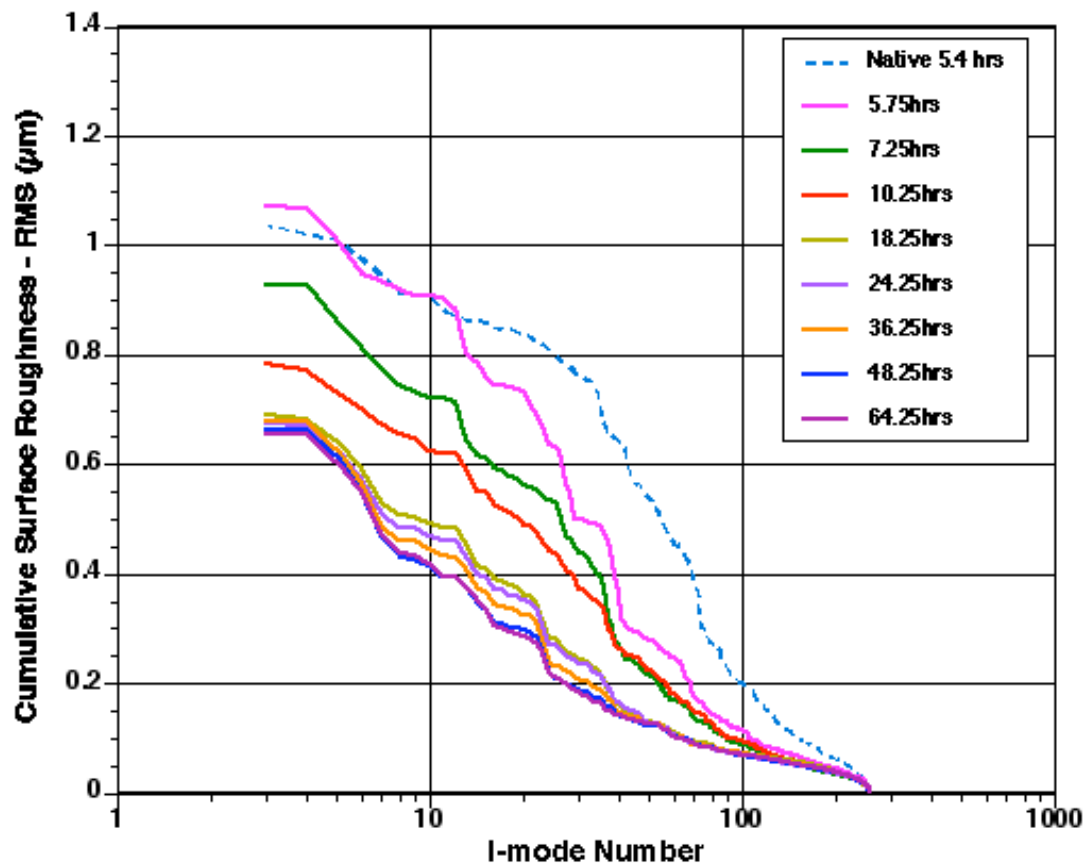
This compares the best two foam layers with the best of two previous experiments, and the LLNL data in spheres, where the solid DT layer is grown as a ‘single crystal.’

Comparison of Best Reversed Spectral RMS Roughness Between DT-in-Foam and Previous DT Layering Experiments



As a function of time, the ‘disappearance’ of mid and higher modes is precisely what we do not observe when no intermediate foam layer is present.

Time Evolution of Reverse Spectra for Local RMS Minima During DT-Foam Layering Equilibration 1 - 112002 Compared to Native 80 μm Layer Minimum RMS

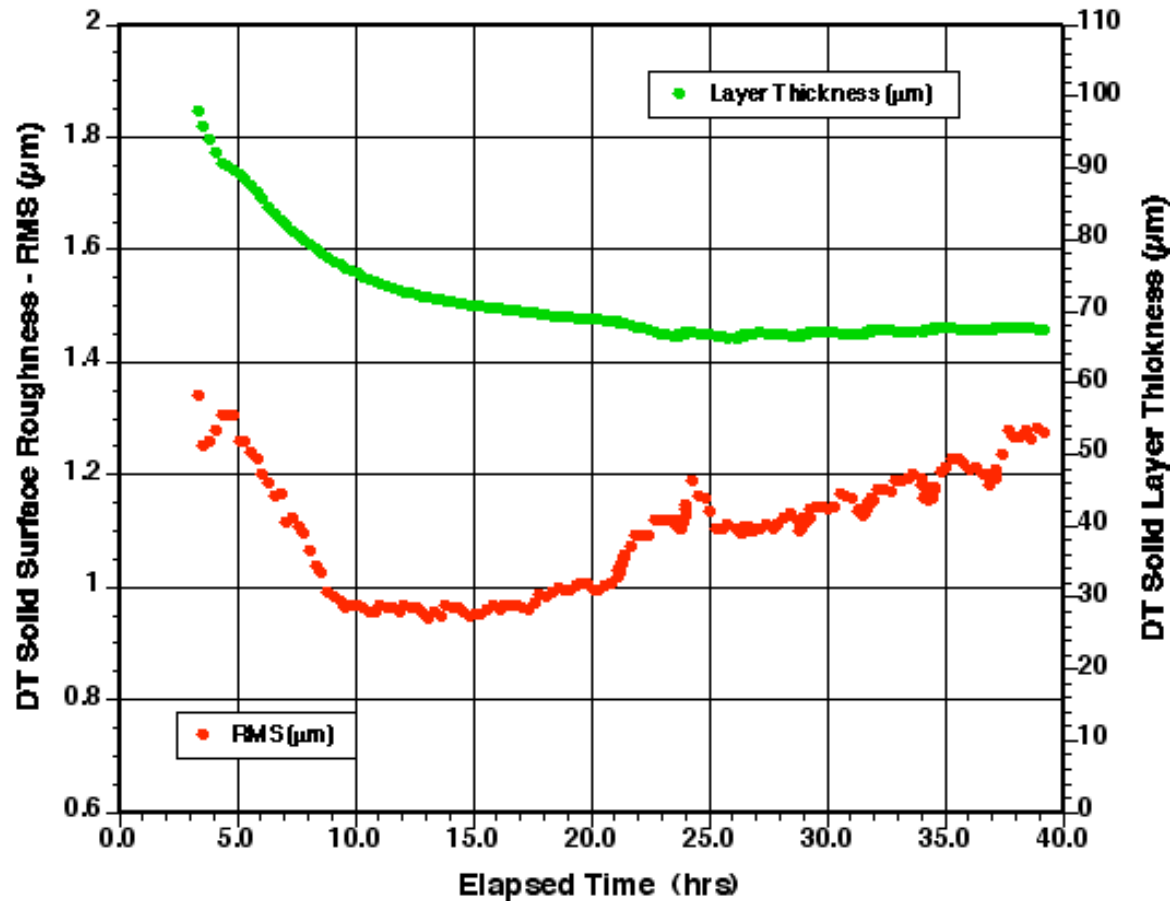


We also measured the effects of cooling the layer from initial equilibrations at 19.25 and 19.35 K down to 15 K

- Cooling an equilibrated DT solid layer from 19.25 to 16 K increased the average surface roughness 50-75% (using the same initial equilibration temperature); but on average the layers were still as smooth as, or smoother than those from our best previous experiments
- Warming the cooled DT solid layer back to 19.45 K does not reverse the roughening that was observed during the cooling process, although some smoothing is observed (~15%).
- Roughening appears to be dominated by I-modes 10 to 50 and P2; although \sum (I-modes 10-50) continue to roughen during re-warming, whereas P2 virtually disappears during re-warming

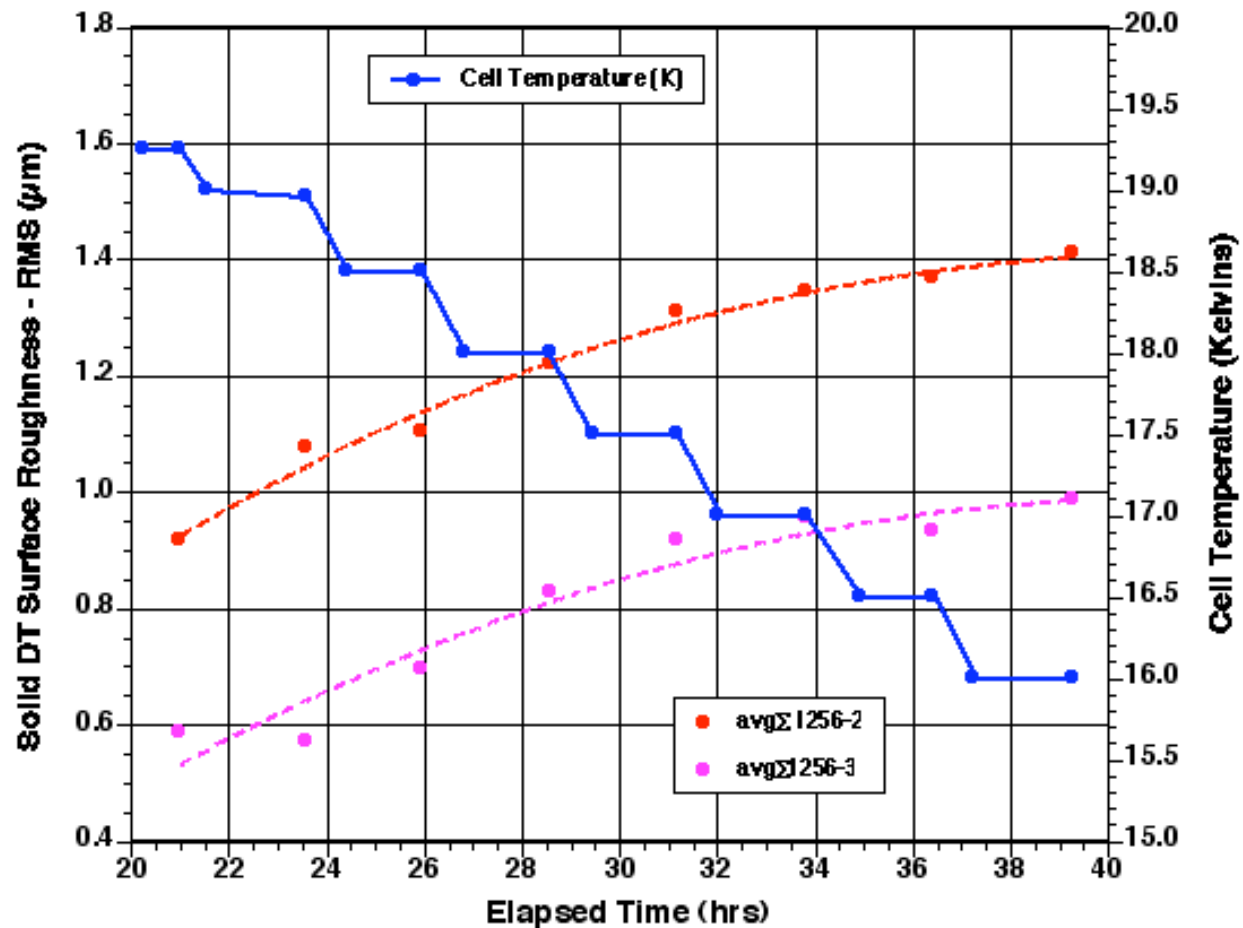
This is a typical solid DT layer equilibration at 19.25 K with decreasing stepped temperature ramping to 16 K

Surface Roughness Evolution of 66 μm Solid DT Layer in Foam, Equilibrated at 19.25 K Followed by Stepped Ramp Cooling to 16 K



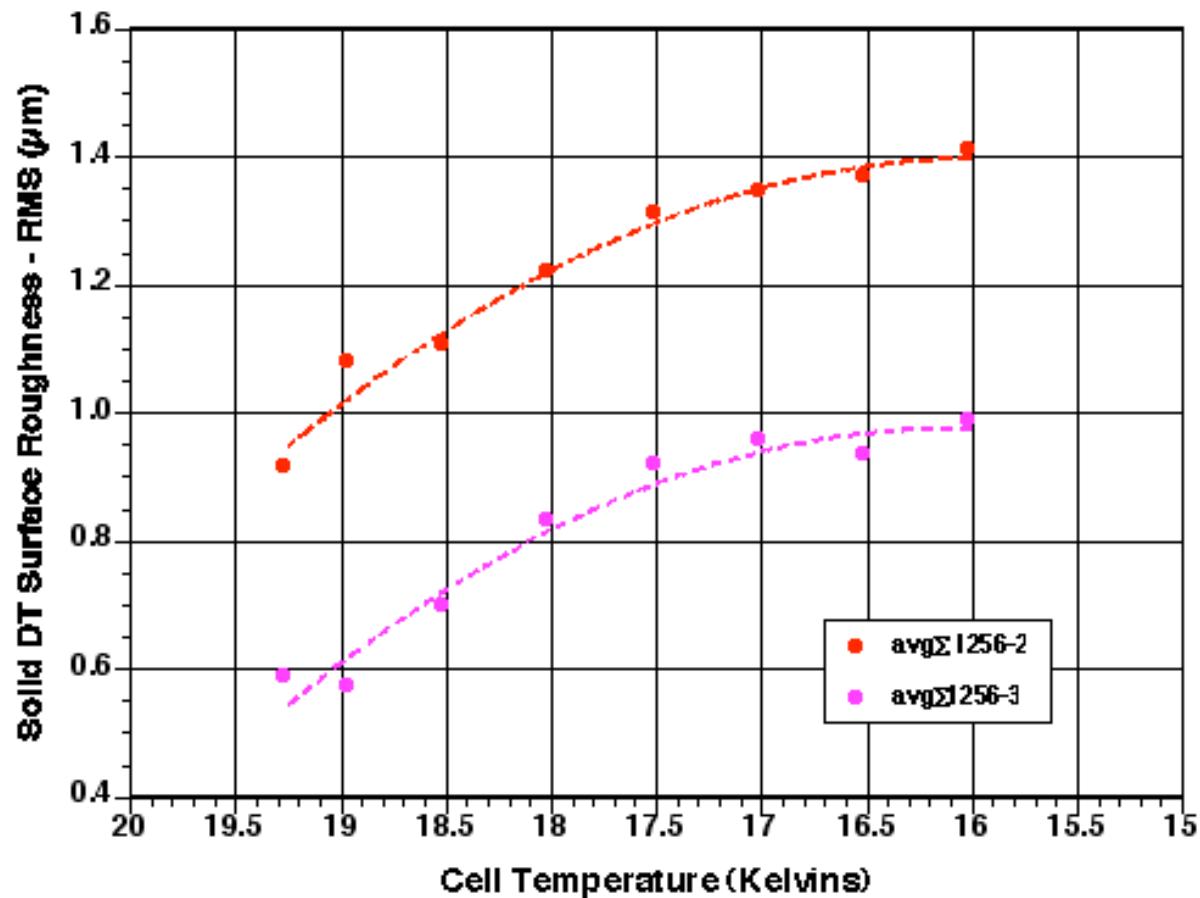
Stepped-ramp cooling to 16 K increased the surface roughness by about 50%, but RMS is still $\leq 1.4 \mu\text{m}$

Average Roughness Evolution of 66 & 95 μm Solid DT Layers in Foam, Equilibrated at 19.25 K Followed by Stepped Ramp Cooling to 16 K



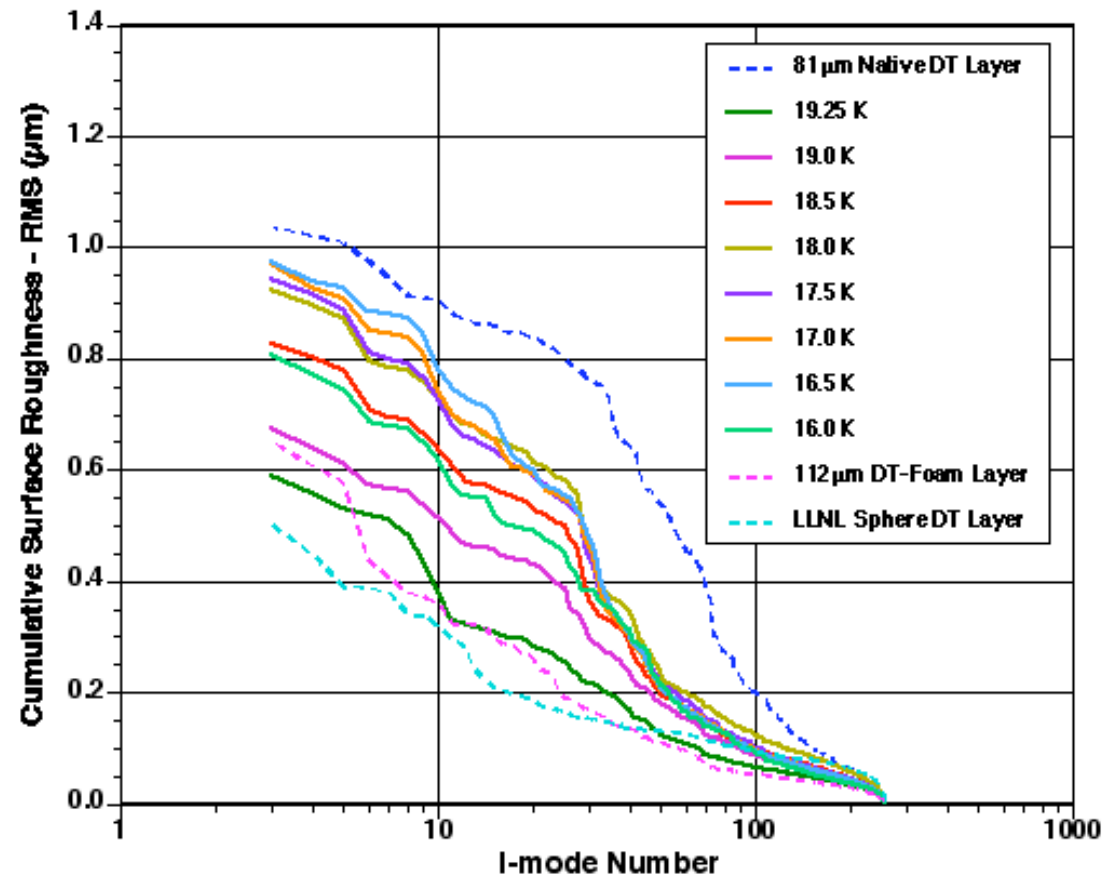
This is the solid surface total RMS roughness as a function of DT cell temperature

Average Surface Roughness vs Cell Temperature with and without I-mode 2 for a 66 & 95 μm DT Solid Layers



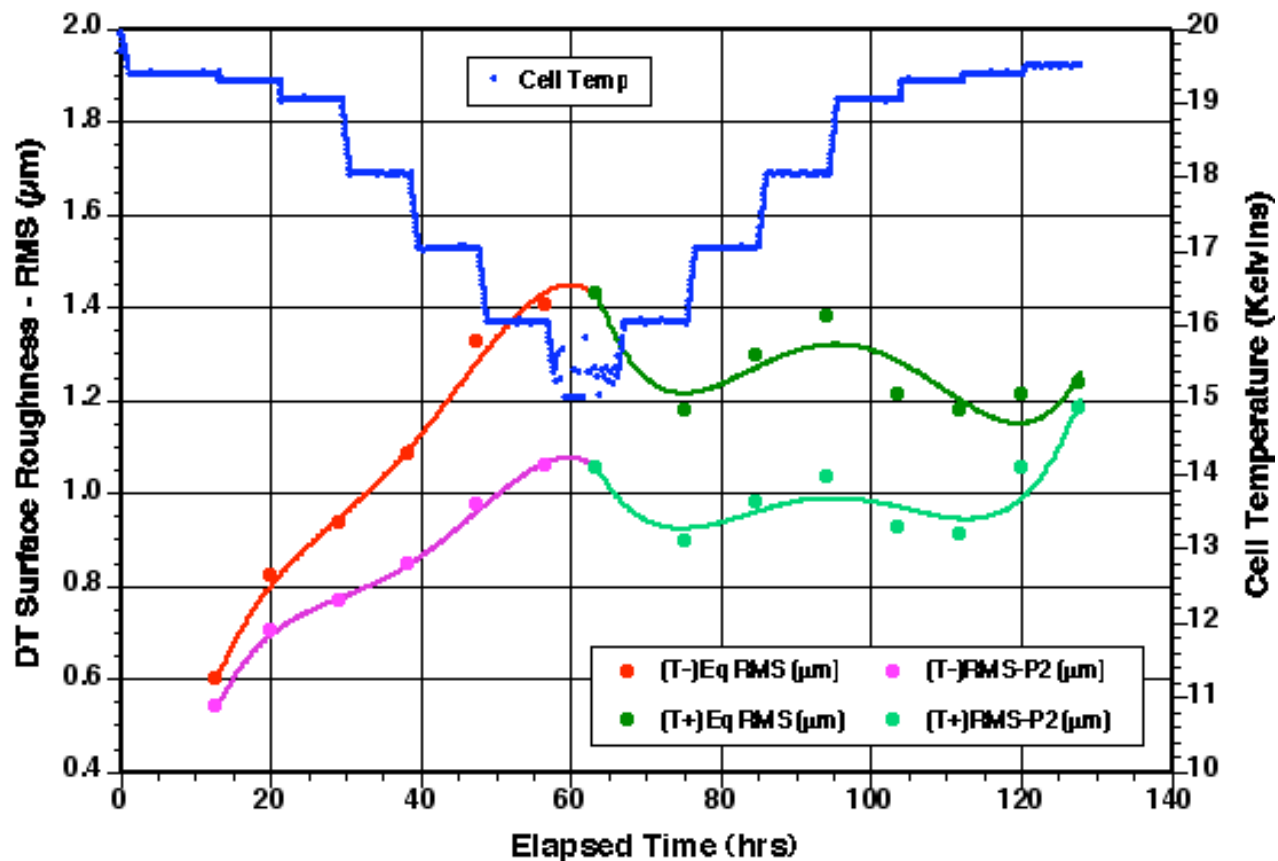
This 'reverse sum' of the l-mode roughness shows the DT-in-foam roughening process, excluding P2 contribution

Equilibration of 95 μm Solid DT Layer in Foam, Followed by Ramp Cooling to 16 K Compared with Previous Best Foam, Native DT, and LLNL Sphere Layers



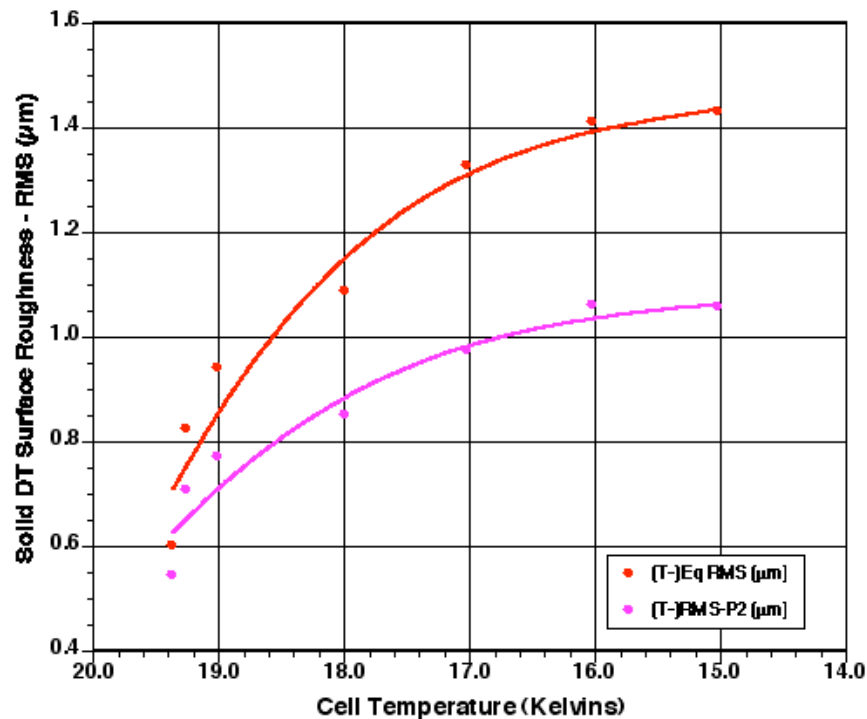
Solid DT roughening that is observed during the cooling process, smoothens some but does not 'heal' completely

Evolution of Surface Roughness and Cell Temperature for a 73 μm DT Solid Layer in Foam - With and Without I-mode 2

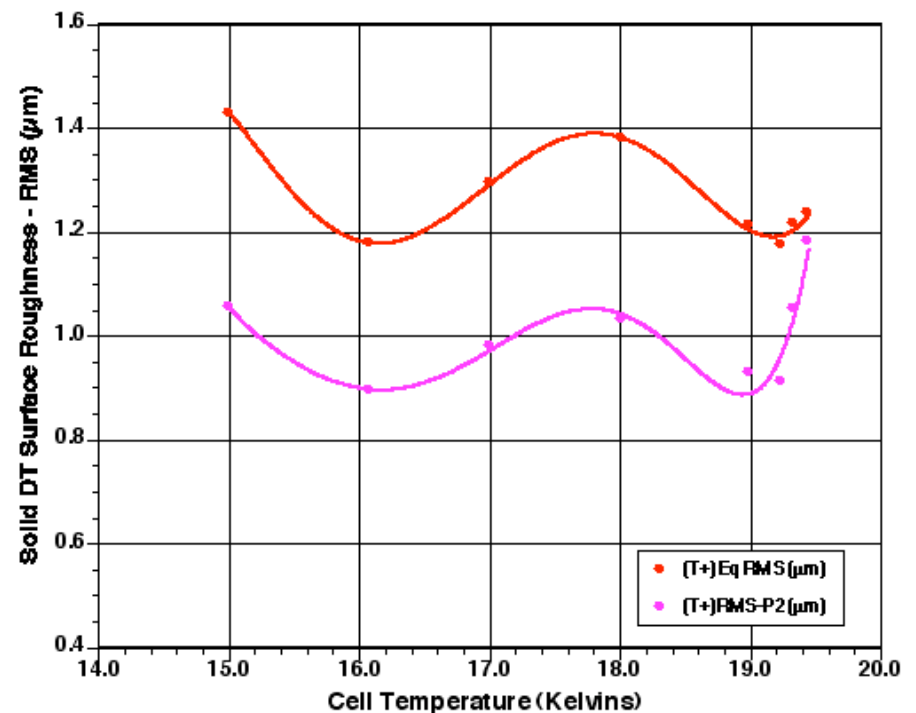


Roughening appears to be dominated by modes 10 to 50 & mode 2 (although P2 nearly vanishes during re-warming)

Solid DT Surface Roughness vs Temperature for a 73 μm DT Layer in Foam, with Stepped Ramp Cooling

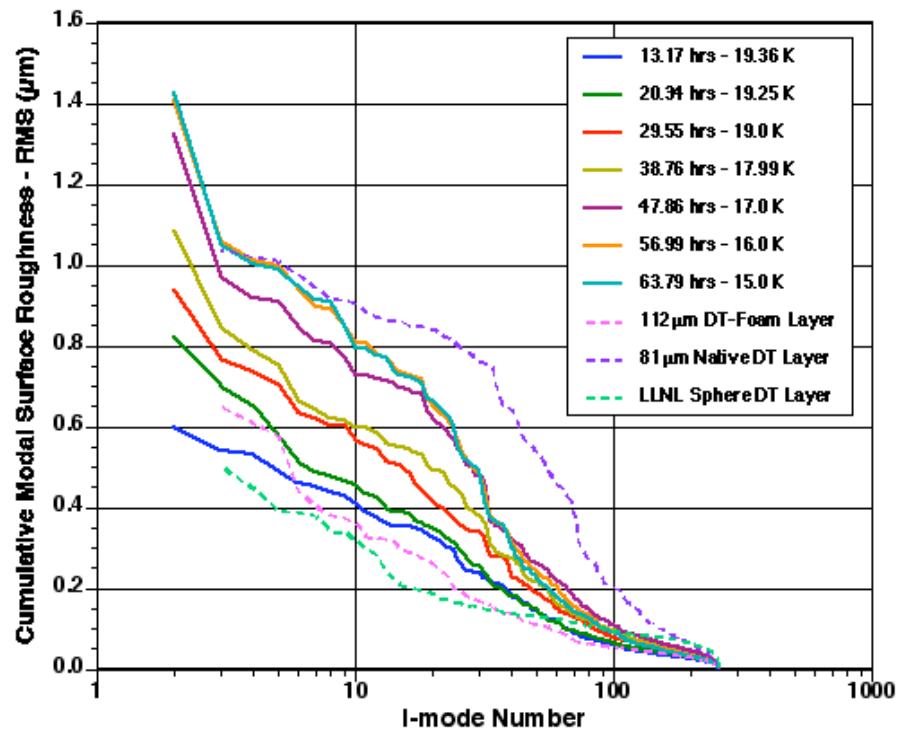


Solid DT Surface Roughness vs Temperature for a 73 μm DT Layer in Foam, with Stepped Ramp Warming

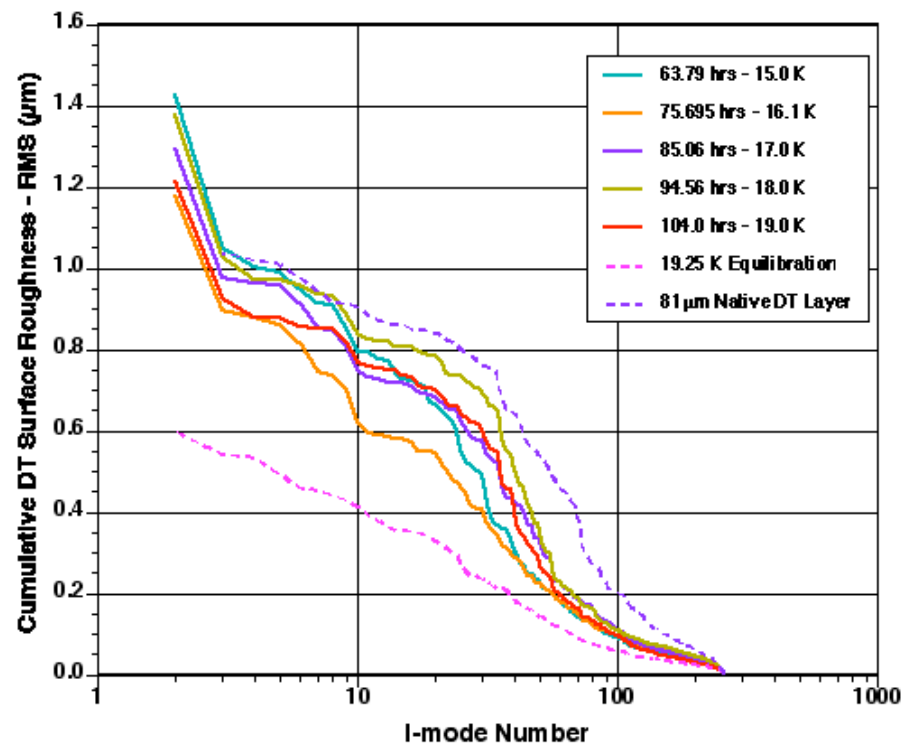


Solid Surfaces do roughen during cooling, and smoothen slightly when warming; yet the surface is as good as (or better) than those from our best previous experiments!

Time & Temperature Evolution of Cumulative Reverse Spectra for Local RMS Minima of 74 μm DT Solid Layer in Foam with Temperature Ramp Steps from 19.35 K to 15.0 K

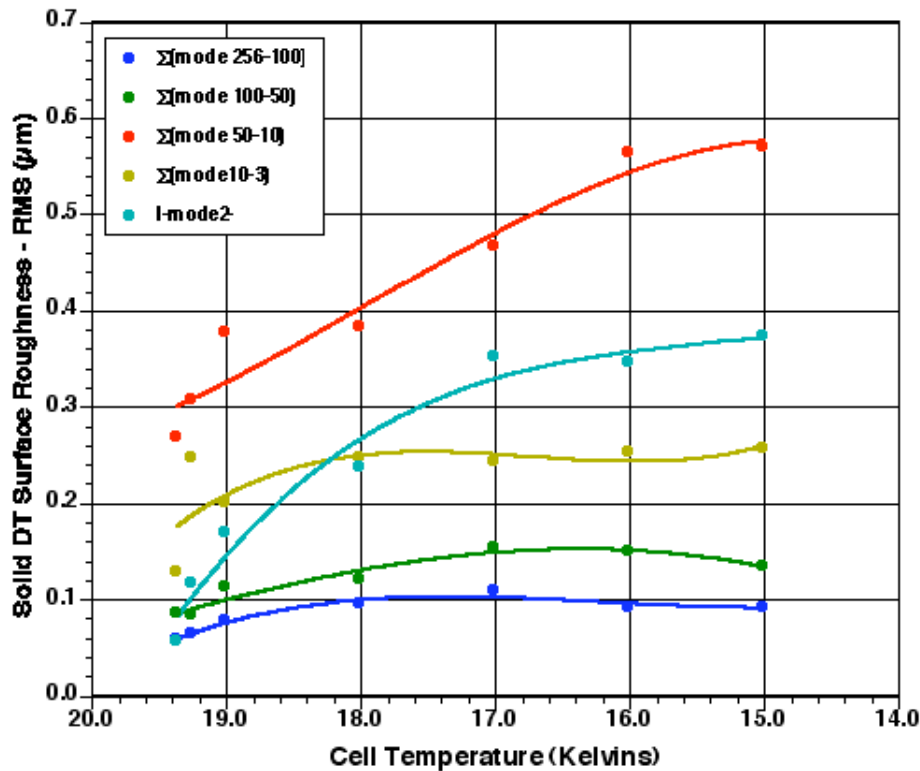


Time & Temperature Evolution of Cumulative Reverse Spectra for Local RMS Minima of 74 μm DT Solid Layer in Foam with Temperature Ramp Steps from 15.0 K to 19.35 K

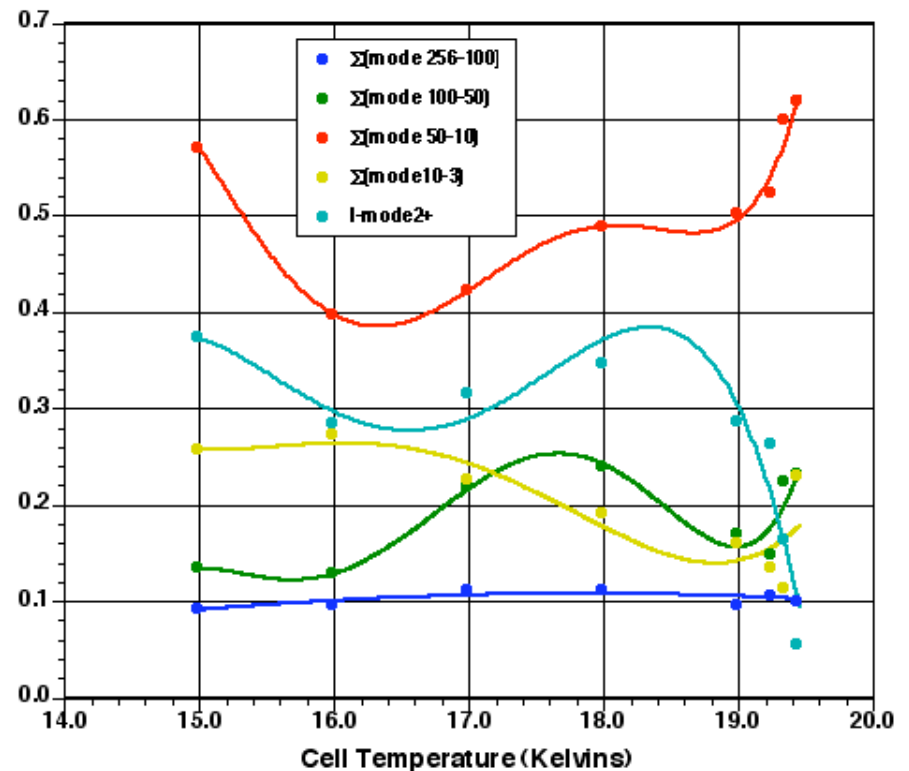


This shows the roughening effects of the cooling and re-warming process in terms of segmented l-modes $[\sum(l_u - l_l)]$

Segmented I-Mode Surface Roughness vs Decreasing Temperature for a 73 μm DT Solid Layer-in-Foam



Segmented I-Mode Surface Roughness vs Increasing Temperature for a 73 μm DT Solid Layer-in-Foam



Our Conclusions

- Layering solid DT in RF foam improves (smoothes) the overall surface roughness 50% or more, by dramatically suppressing mid-mode (10-100) roughness. (The fine foam cell structure causes freezing to begin with the formation of many small, randomly-oriented crystallites, which then propagate into the pure DT solid instead of forming large crystalline facets at the solid-vapor boundary)
- Stepped-ramp cooling of an equilibrated DT solid layer causes surface roughening (from 50-75% using same initial equilibration temperature) that is dominated by mode 2, and modes 10-50 (could re-crystallization be occurring?)
- Re-warming the solid layer smooths the surface slightly (~15%), but modes 10-50 continue to roughen and dominate (resulting large crystalline facets do not decrease in size?)