Radiation transport experiments with high temperature, ~350 eV, large-scale hohlraums on the NIF

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Summary

- NIF makes it possible to reproducibly drive larger targets to higher radiation temperatures and study radiation flow in a new regime.
- Aerogel and foam samples enable such experiments to tailor the radiation flow from sub-sonic, to free-streaming, and to supersonic and diffusive flows
- This is important to not only our basic understanding of radiation transport but is also present in many astrophysical systems.
- As the range of radiation drives increases, it is increasingly important to understand the opacity and Equation of State (EOS) of the materials used in these new T and ρ regimes, with the primary quantity being the foam density and composition.
- We have designed a radiation flow experiment that can be used to validate the opacity and EOS for high radiation drives of ~350 eV
- The exceptionally reproducible drive delivered by NIF and sensitivity of radiation flow experiments, increases the necessity to make reproducible targets for shot-to-shot comparison. For these experiments, the key is gradient-free, well characterized aerogels and foams.

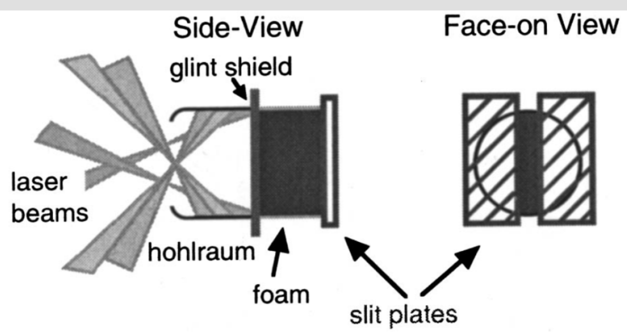
The available energy of NIF expands the range radiation drives and spatial scales for high energy density physics

Outline

- High-temperature, large-scale NIF half-hohlraums provide a high quality, reproducible x-ray source for studying radiation flow.
- Material properties are critical to be able to interpret results of radiation transport and other HED experiments.
- Experiments that study radiation flow in this new regime can be used to constrain our understanding of opacity and equation-of-state.
- How we understand the target materials to high accuracy, in order to be able to constrain the material properties.

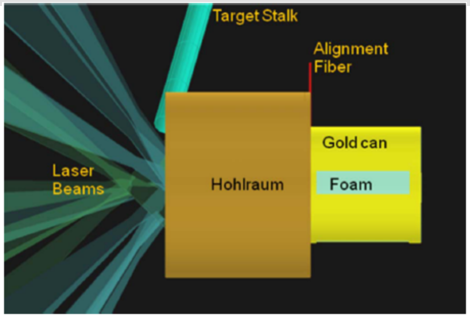
Hohlraum driven foams and aerogels enable the study of a wide range of radiation transport physics

Radiation transport in materials



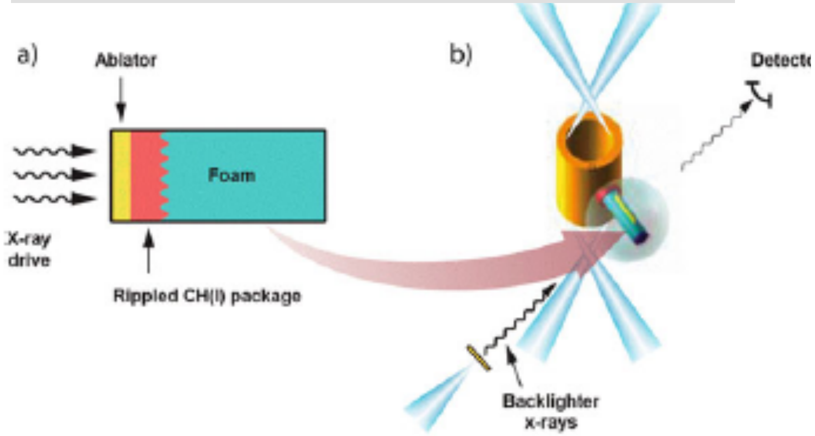
C. A. Back *et al.*, Phys. Plasmas 7, 2126 (2000)

Radiation transport in non-uniform materials



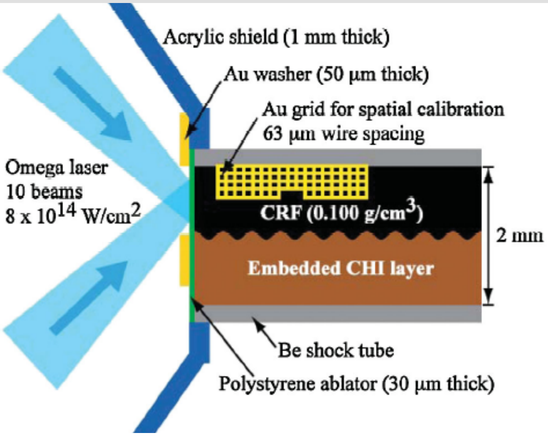
P. A. Keiter *et al.,* Phys. Plasmas 15, 056901 (2008)

Super nova core collapse



C.C. Kuranz*, et al*. Astrophys. Space Sci. 336, 207 (2011)

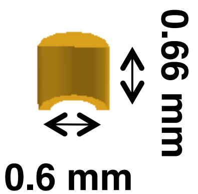
Kelvin-Helmholtz Instability



E. Hardin, et al. PRL 103, 045005 (2009)

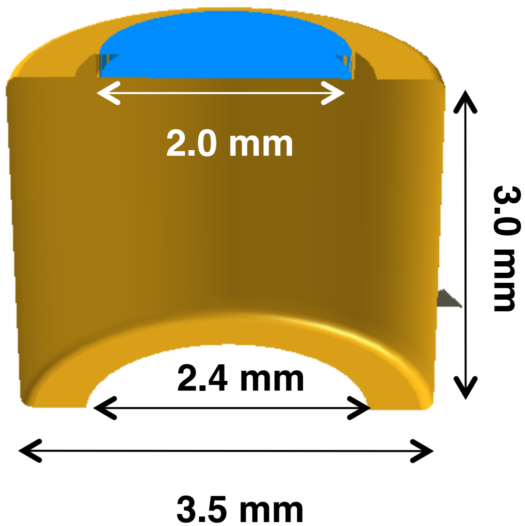
The available energy on NIF can drive larger targets to radiation drives only achievable in hohlraum 120x smaller in volume

Omega 340 eV hohlraums

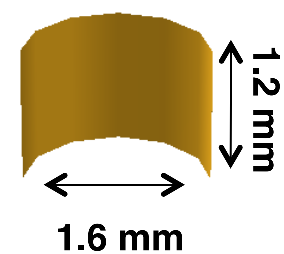


D. Hinkel *et al.*, Phys. Rev. Lett.

NIF half hohlraum ~349 eV radiation drive



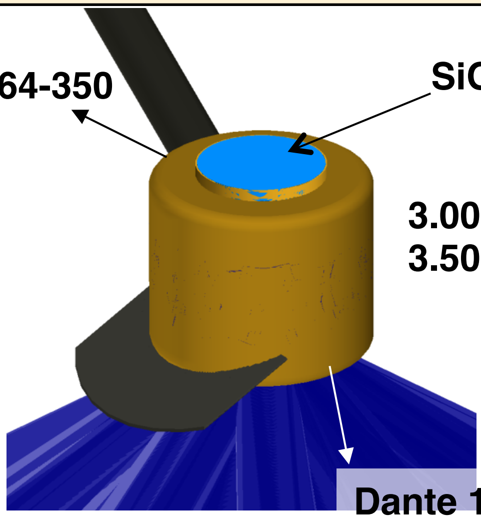
Omega radiation transport target ~ 190 eV



C. A. Back *et al.*, Phys. Plasmas 7, 2126 (2000);

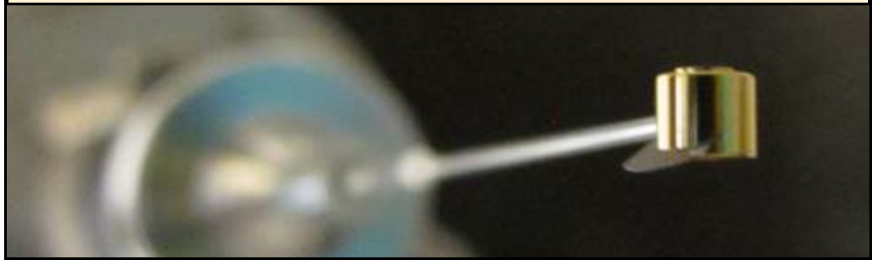
Half-hohlraums designed for the high-temperature radiation hydrodynamics experiments reached ~350 eV

Experimental Configuration

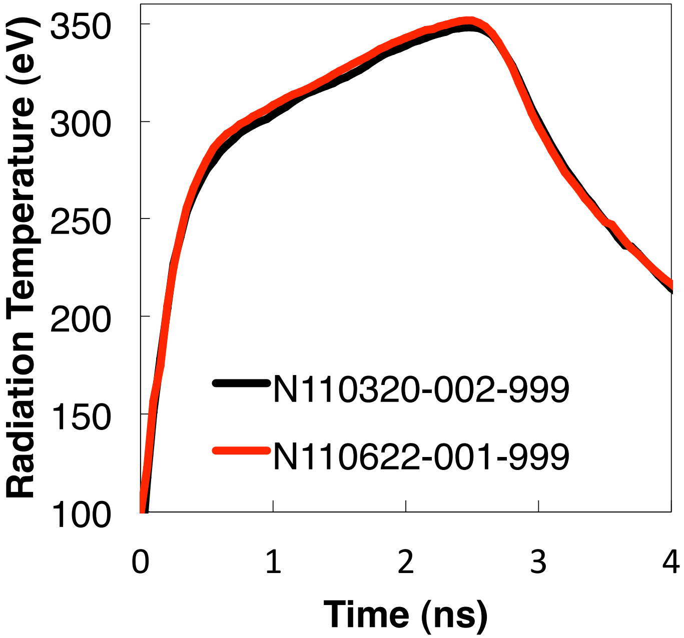


Same for up-side-down configuration without the shield and LEH facing 0-0

Target loaded for a shot



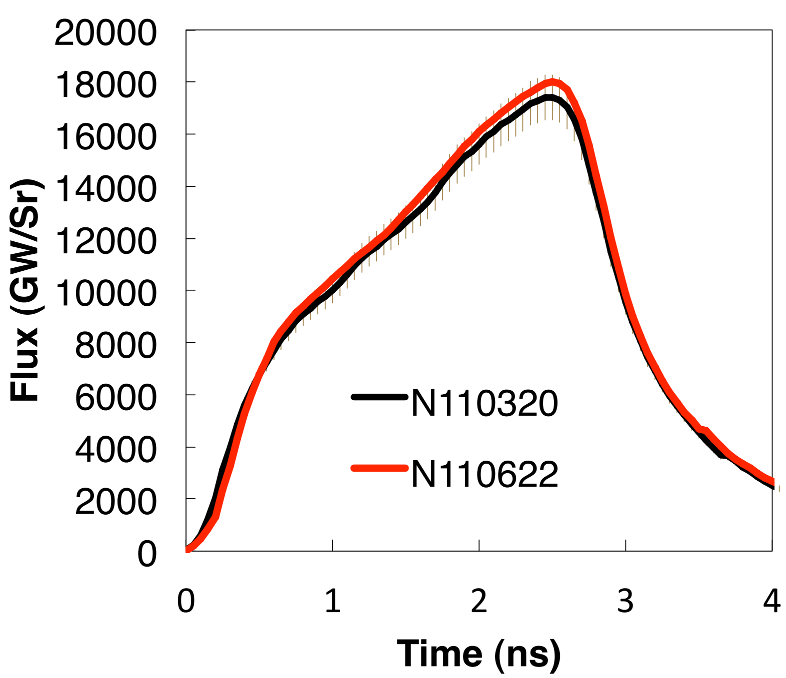
Dante-1 T_r vs time for N110320 & N110622



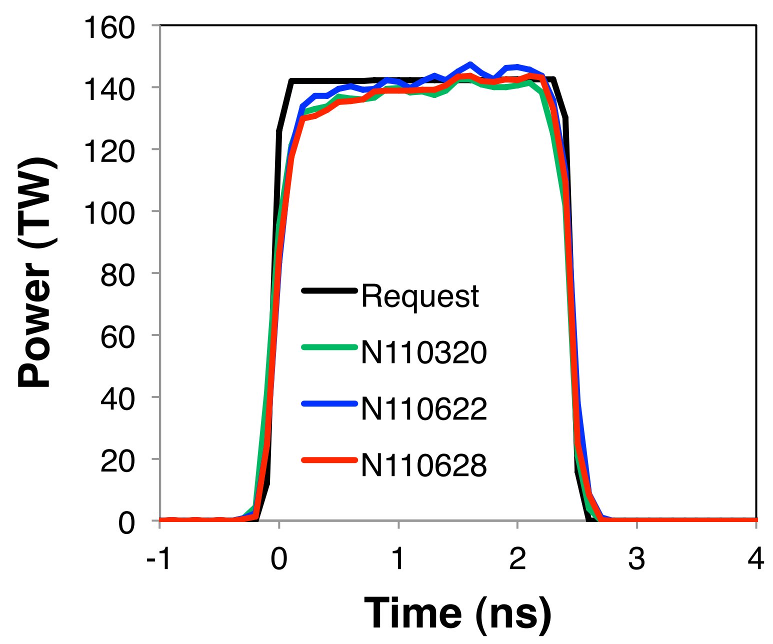
N110320 Peak Trad: 348 eV
N110622 Peak Trad: 351 eV

The reproducibility of NIF enables high quality shot-to-shot comparisons over several months

Radiation flux for two shots 3 months apart is within 5%

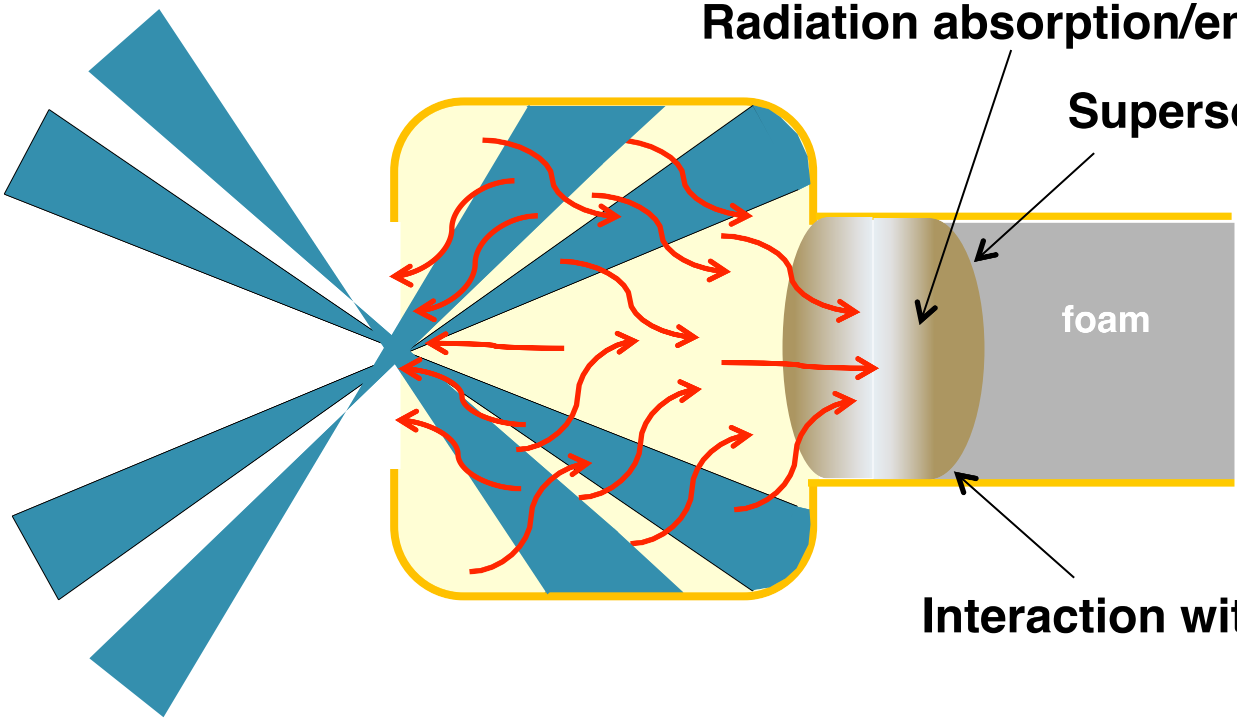


The laser reproducibility is better than 2% shot to shot



Laser pulse shape reproducibility has been demonstrated on multiple platforms including NIC and other experimental campaigns

Through careful design, the foam opacity and equation of state can be constrained by measuring the rad. transport

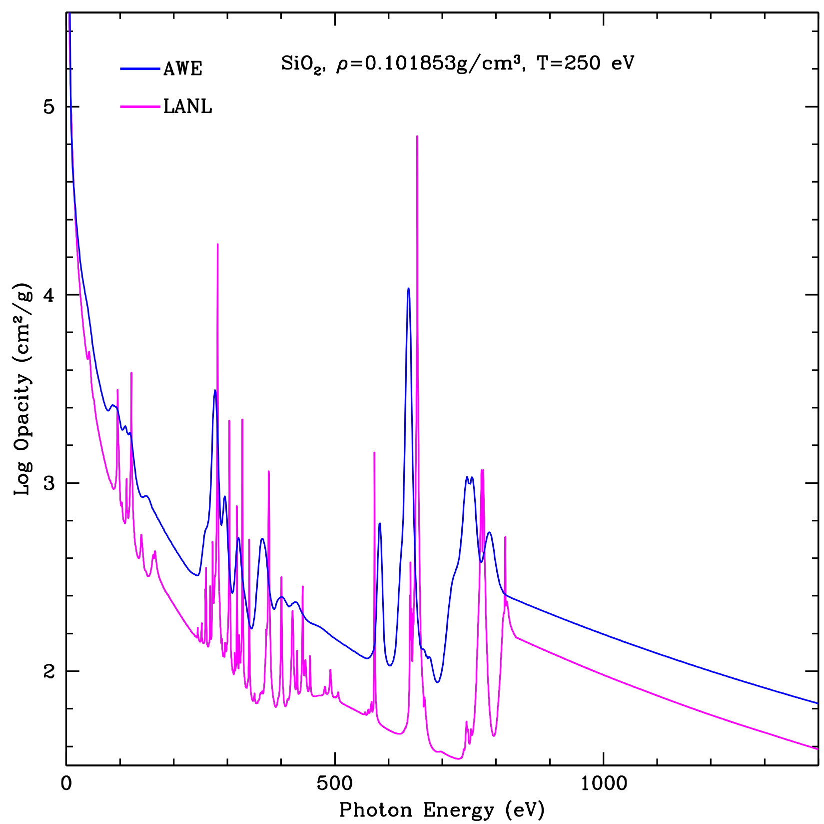


$$x = \sqrt{\frac{32}{3\left(n + 4 - \frac{3}{2} m\right)} \frac{\sigma T^4 t}{\kappa \rho^2 \varepsilon}} \qquad \varepsilon = \varepsilon_0 \left(\frac{T}{T_0}\right)^m \qquad \kappa = \kappa_0 \left(\frac{T}{T_0}\right)^{-n}$$

Opacity term, EOS terms

Opacity models for SiO_2 differ by approx. 65% between 300-600eV

SiO_2 Opacity (ρ=0.1g/cc, T=250eV)

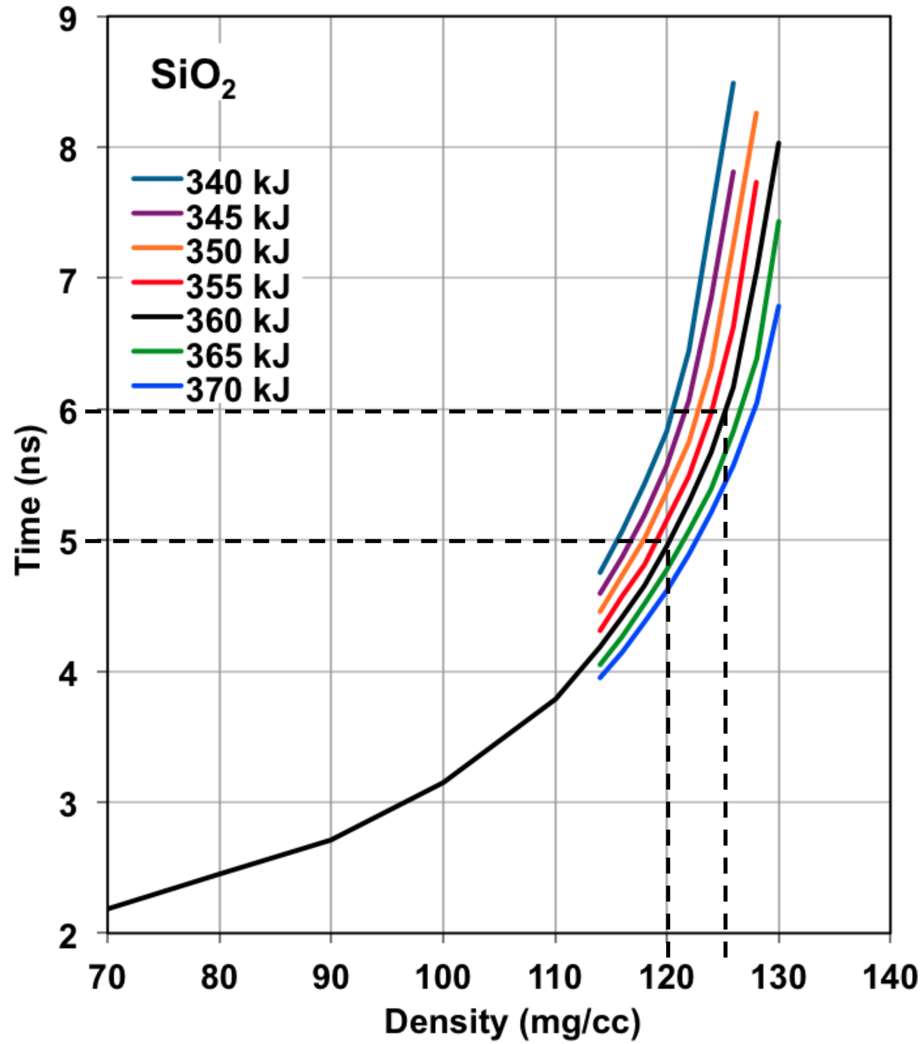


Opacity calculation from C. Fryer (LANL)

- **Difference between opacity models ➔ 300ps difference in radiation wave arrival**
- **Code-to-code comparisons between AWE and LANL, show ≈1ns uncertainty in predicting the arrival time.**
- **Using two densities of each material allows us to verify opacity/EoS change even if we have systematic uncertainties in the density.**

To constrain the opacity, the experiment is designed to be in a non-linear region of energy-density 'space'

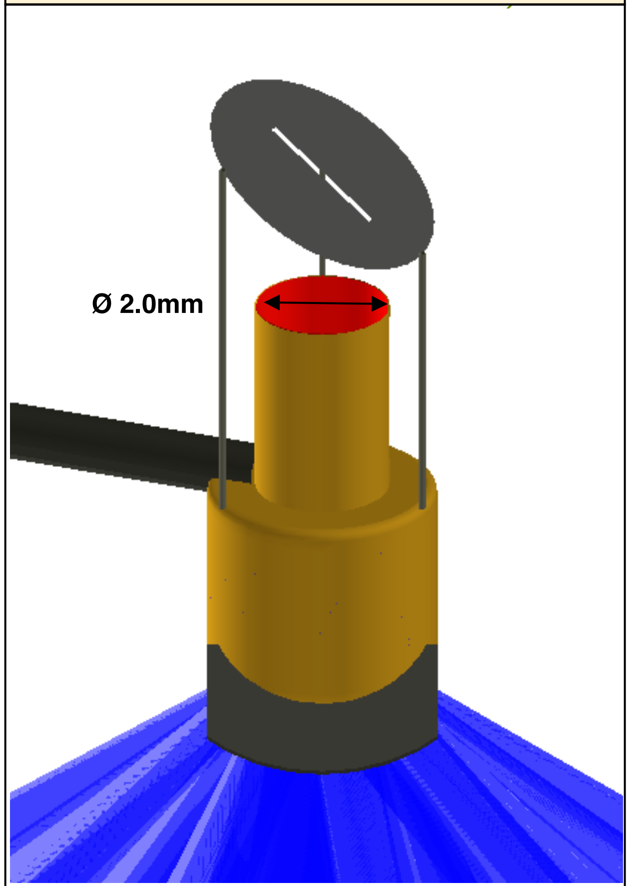
- **The foam-tube length was optimised to create the highest sensitivity to opacity and EOS while remaining super-sonic.**
- **This prevents hydrodynamic motion of the foam material from impacting the measurement.**
- **Simulations show the non-linear behaviour characteristic of the radiation wave approaching the transition from super- to sub-sonic at the end of the tube.**

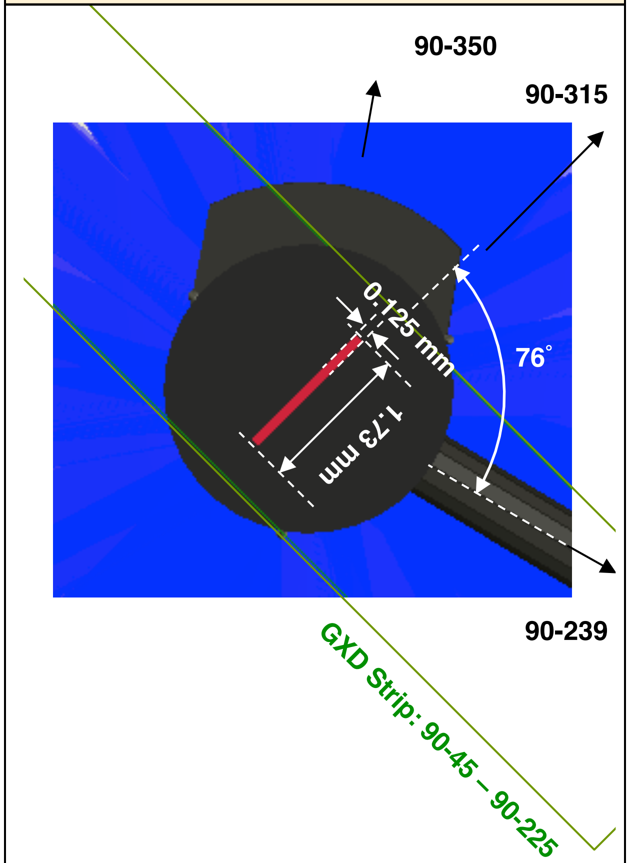


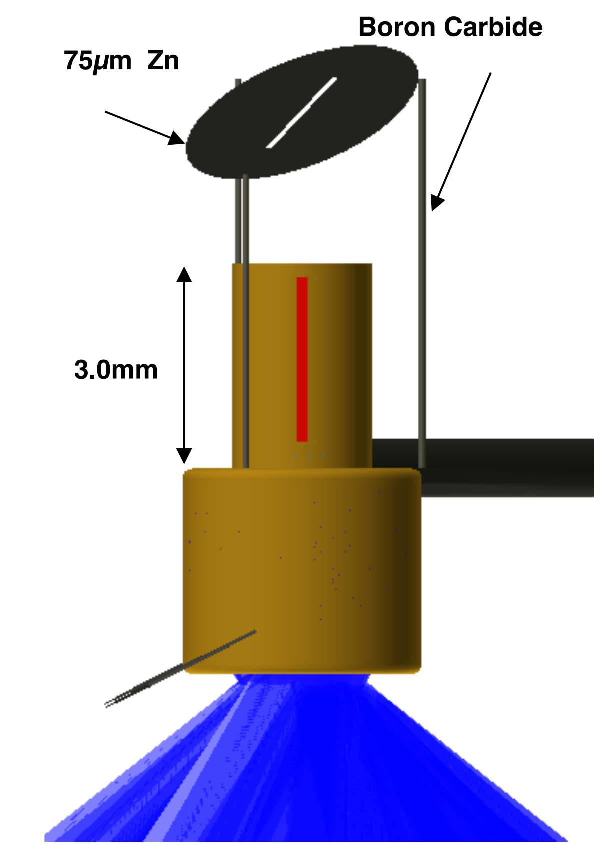
A 5mg/cc (4%) change in foam density results in a 1ns change in arrival time; this is equivalent to a 16% difference in opacity

We measure the propagation of the radiation front using multiple diagnostics to constrain the opacity and EOS

Soft x-ray power: Dante 64-350	Transmission grating spectrometer on GXD or streak camera in DIM 0-0	Soft x-ray imaging camera in DIM 90-78

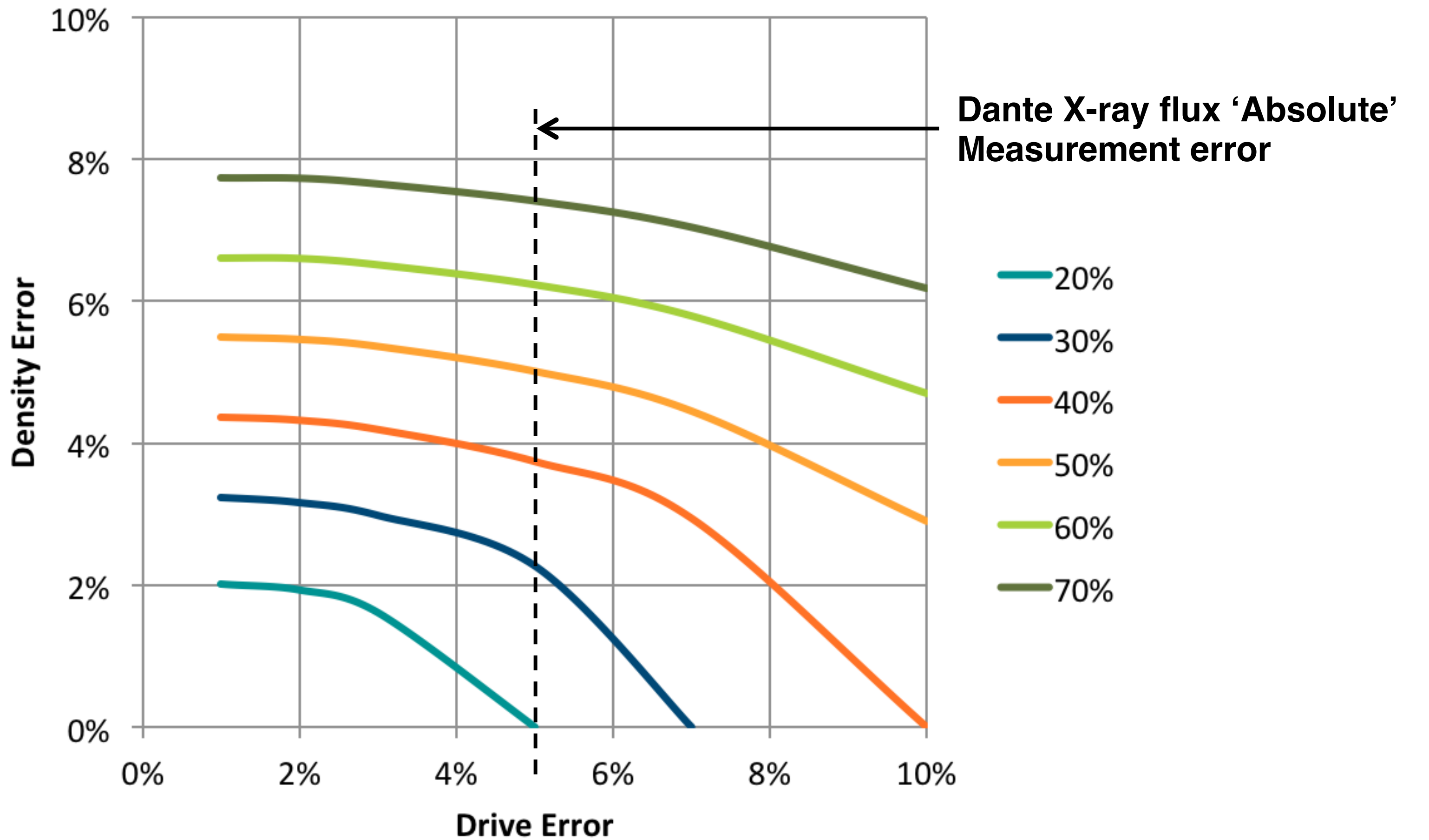






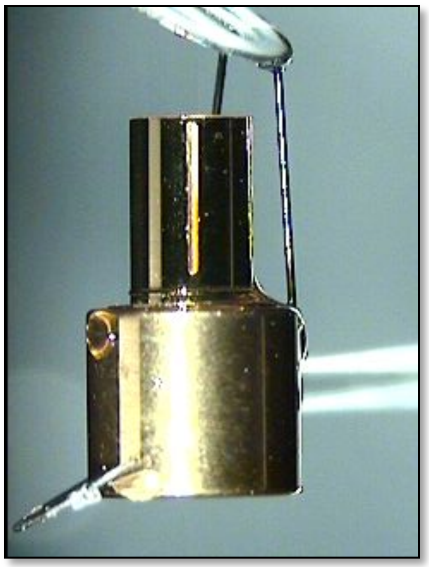
Absolute x-ray flux emitted from end of foam-tube vs. time	Spectral shape of radiation wave arrival at end of foam-tube	Radiation wave velocity and deceleration

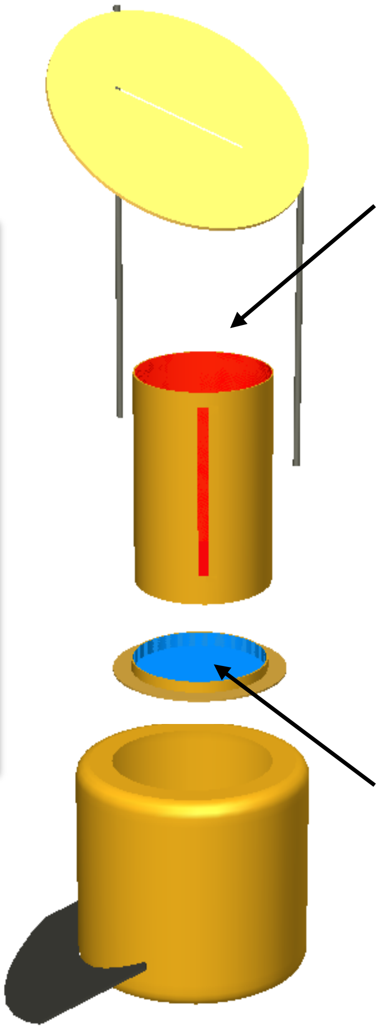
A ‘small-perturbation’ analysis reveals dependencies over a limited range of density-energy space.



Folding in the drive reproducibility, we need to know the foam density to < 2% to constrain the foam opacity to 30%

Target components need to be characterized and undergo 'process-control' from manufacture to assembly to time-of-shot.





120mg/cc SiO_2 aerogel or HiPE foam (C_8H_7Cl)
Dimensions: 2.8 x Ø 2.0mm

Manufacture process:
Cast and then machined-to-size at AWE

Total foam mass: 1.056mg

Characterisation Requirements:
Density, Uniformity and Composition

120mg/cc SiO_2 aerogel (hydrophobic)
Dimensions: 0.2 x Ø 2.0mm

Manufacture process: Cast to-size at LANL

Total foam mass: 75μg (not easily measured on a balance)

Characterisation Requirements:
Density, Uniformity and Composition

The most important target requirements are well-characterized, reproducible, gradient free foam densities

Quantity	Measurement Method	Requirement	Tolerance Required	
Bulk Density	• TGA Mass Analysis • Vacuum TGA Mass Analysis	115-120 mg/cc	1.0%	1.2 mg/cc
ρl (90% of area)	• NSLS • LANL Density Characterization Source (DCS)	2.5 mg/cm^2	5.0%	0.1 mg/cm^2
Density Gradient/ Non-uniformity	• LANL Density Characterization Source • NSLS	2%	< 1%	
Thickness	• Machining process • Mold depth	200 μm 2800 μm	1.0% 0.1%	3 μm 3 μm
Water content	• TGA vacuum analysis	< 1% wt	0.5%	

In addition to the foam density, we need to control other foam characteristics that could effect the experiment.

Quantity	Measurement Method	Requirement	Tolerance Required
Cell Size	SEM	Need to know	1 per batch
Composition	Combustion Analysis	<1% high Z contaminants	1 per batch
	X-ray Fluorescence	<1% high Z contaminants	1 per batch
	EDAX	<1% high Z contaminants	1 per batch
Foam-to-foam assembly	X-radia of assembled target	<10 μm	each assembly

To constrain the opacity measured in the experiment and to calculate the density from x-ray transmission measurements it is critical to know the foam composition is reproducible from batch-to-batch

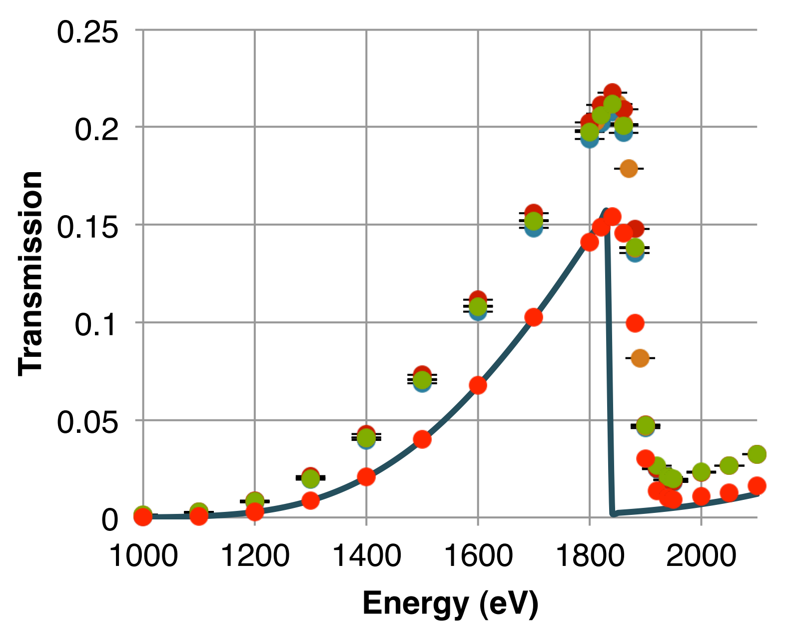
The SiO_2 “M-band absorbing” foams were characterized at NSLS

- **The small 200μm foam discs are too low-mass (75μg) to weigh accurately.**
- **A 3μm length uncertainty in volume determination and 6μg mass error, result in an 8% uncertainty in density.**
- **X-ray transmission measurements at NSLS were carried out to confirm bulk sample measurements and batch-to-batch uncertainties**

$$\left(\frac{d\rho}{\rho}\right)^2 = \left(\frac{d\kappa}{\kappa}\right)^2 + \left(\frac{dx}{x}\right)^2 + \left(\left|\frac{1}{\ln(T)}\right|\frac{dT}{T}\right)^2$$

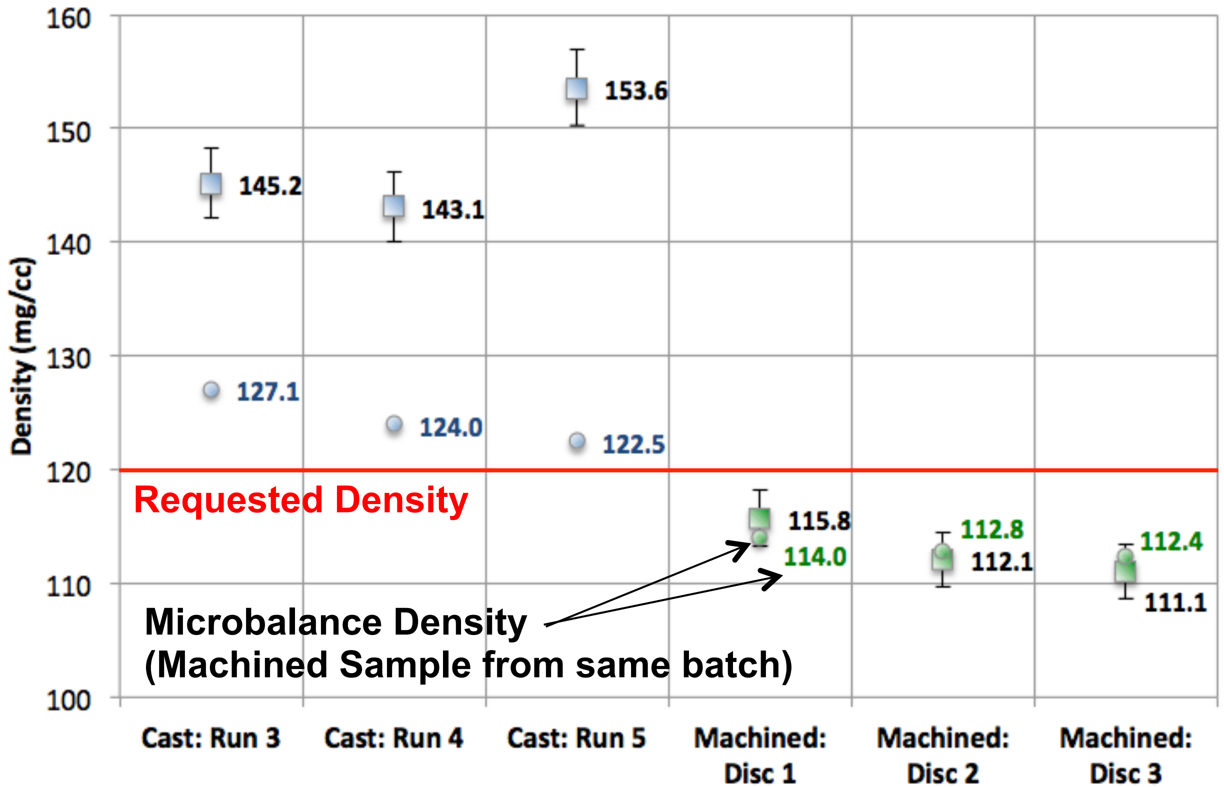
- **Uncertainty in the cold opacity is a small contributor to the total error:**
  ‘Absolute’ uncertainty = 2.1%
  ‘Relative’ uncertainty = 1.9%

The silicon edge was used to measure opacity



Assuming a 1% uncertainty in the cold opacity (κ), implies we could measure the density to 2.1%

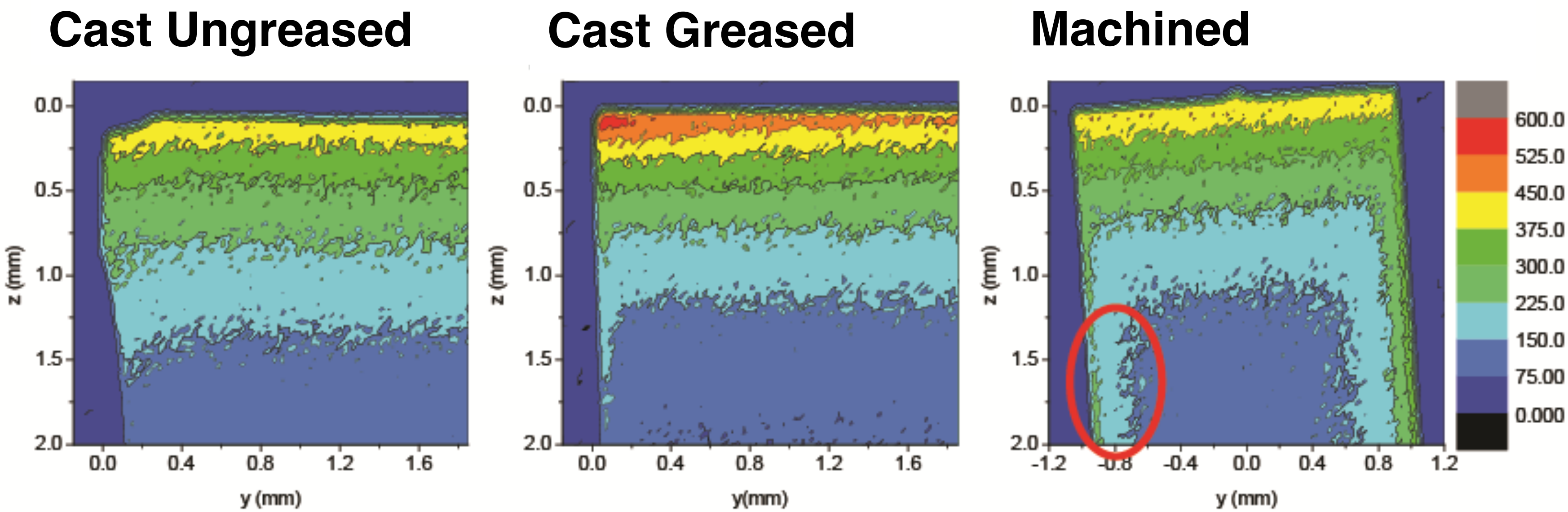
Cast foam measurements were more dense than the density measured on a bulk sample from the same batch



- 18 SiO_2 foams (3 per batch) were characterised at NSLS.
- Results show variation within a batch of between 1.9 and 4.2%.
- Batch-to-batch variation was 3.75%.

**Significant offset exists between the specified density and manufactured density.
Intra- and inter- batch variations are larger than relative measurement errors.
To meet 2% requirement on bulk density, foams must be selected from within a batch.**

Some of the difference cast and machined foams can be explained by the manufacture process.



Patterson, B. M., et. al; Journal of X-ray Spectrometry, submitted, Aug 2011

- Confocal Micro X-ray fluorescence† slices through aerogel components indicate that full density fumed silica residue, from silicon release agent comprised of short chained PDMS with fumed silica, is left behind at the surface upon supercritical drying.

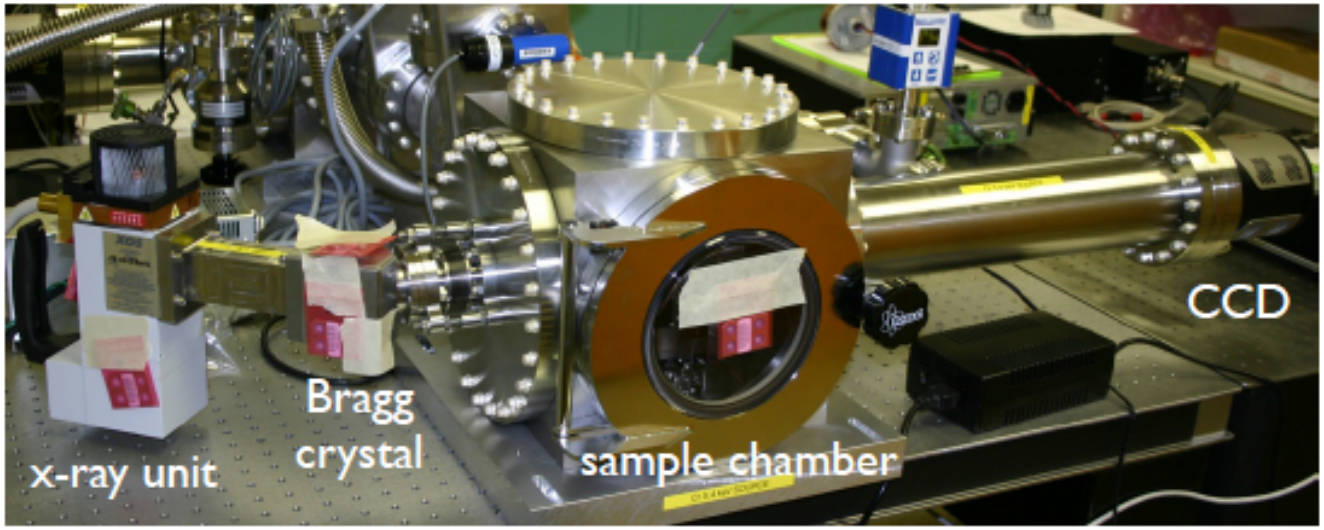
- Targets can use a mix of foams from different manufacture processes; 200μm foams – cast; 2800μm foams machined, but this must be maintained throughout all comparative experiments

Process-control is key to deliver required physics performance.

† See talk PM2-1 by B. Patterson on Tuesday

LANL Density Characterization Station† (DCS) has been used to characterise the 2.8mm foam samples.

DCS consists of two XOS™ *monochromatic* soft x-ray generating devices at 2.3 and 5.4 keV (one of them shown below)

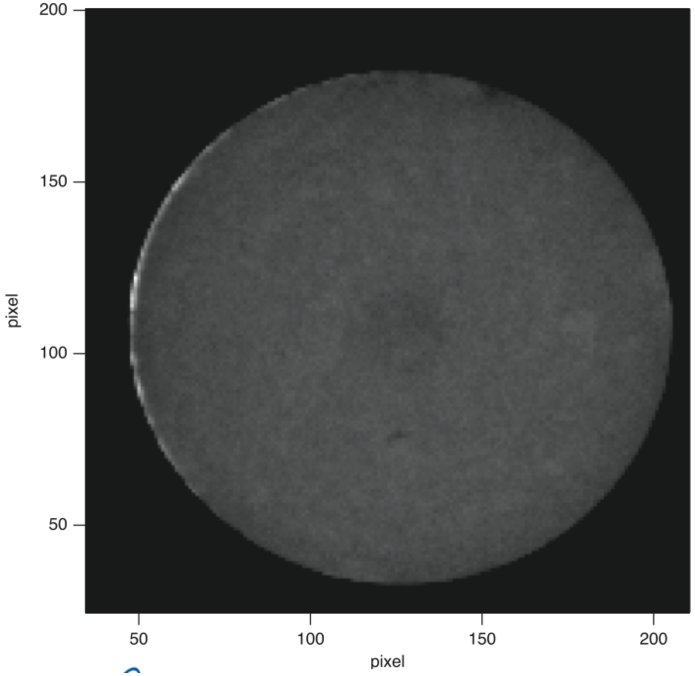


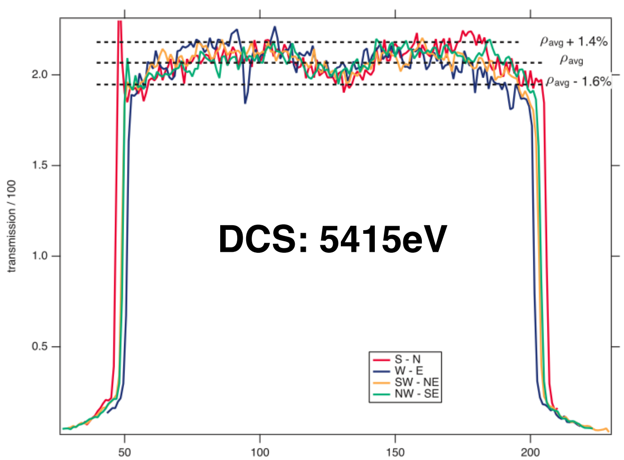
- Each device has a dedicated sample chamber and CCD camera
- X-rays are transmitted through the sample and imaged onto a CCD at 5-25x magnification, recording absorption as a function of density
- The soft x-rays are in the right regime to measure very small density variations in low-density C_8H_8 and SiO_2 foam targets

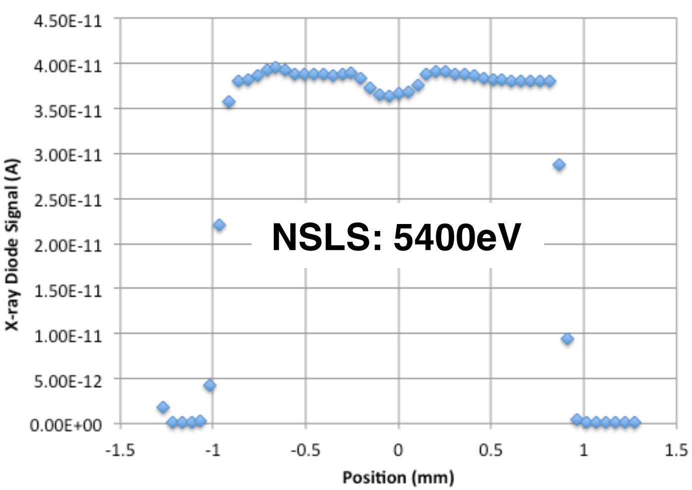
† See talk PM2-2 by M. Taccetti on Tuesday

High quality foam uniformity measurements have been using the DCS at 5.4keV and cross-compared to NSLS results.

- **Target C-06 (#22a) was characterized using the DCS at 5415eV (right) and at NSLS by raster scanning the Ø100μm apertured x-ray beam at 5400eV.**
- **The same decrease in transmission is seen at the centre of the foam as is present in the DCS measurement (below).**



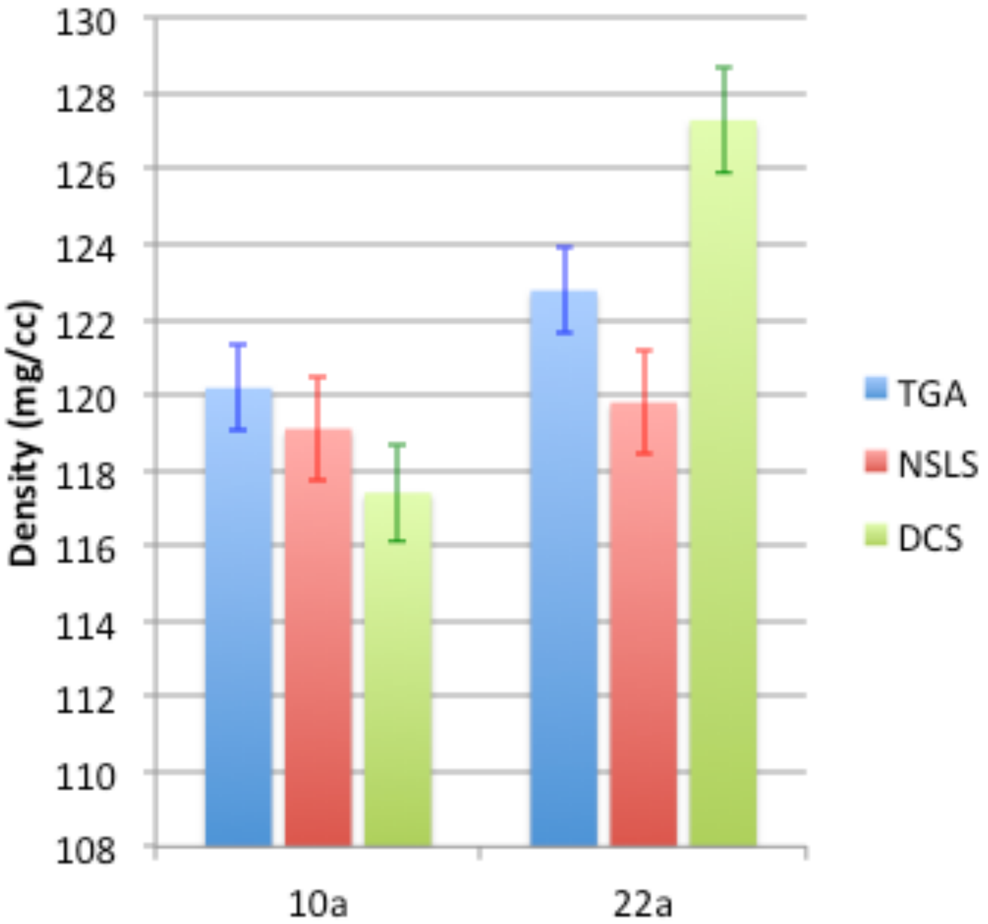




2.8mm foam cylinders have been characterised using multiple measurement techniques.

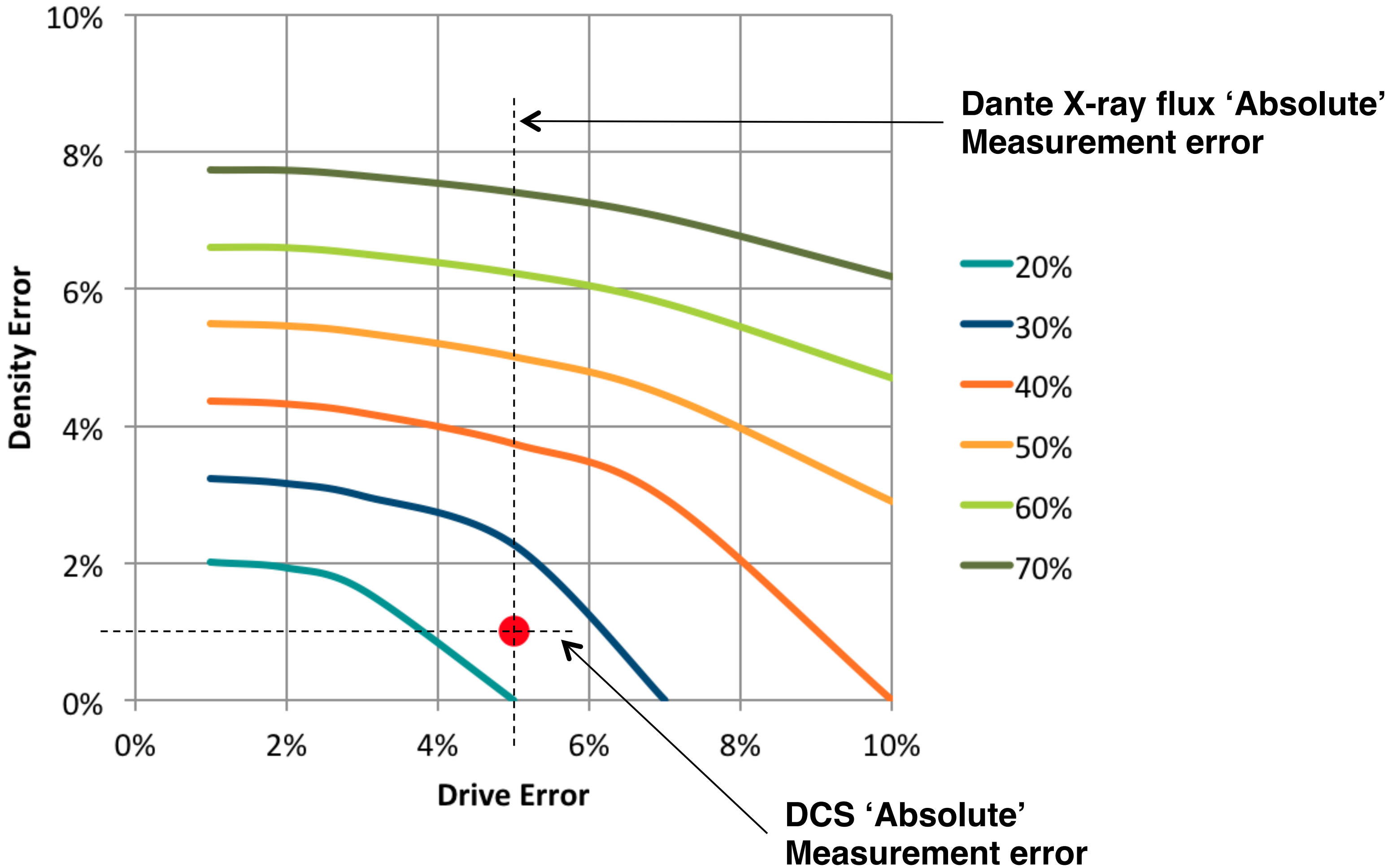
- ‘Large’ cylinders means that TGA mass analysis can be performed on actual component at an accurate level± 1%
- NSLS measurements are less than the TGA measurements for both samples – indicative of removal of H_2O when sample is put under vacuum.
- The high density of #22a measured on the DCS seems anomalous, but results taken on NIF indicate that the DCS result is correct.

	10a	22a	% error
TGA	120.2	122.8	0.94
NSLS	119.1	119.8	1.1
DCS	117.4	127.3	1.1



Process-control is key to deliver required physics performance.

Folding the uncertainties together means we should be able to constrain the opacity better than 30%



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