NSTX

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Investigation of LLD Test Sample Performance Under High Heat Loads

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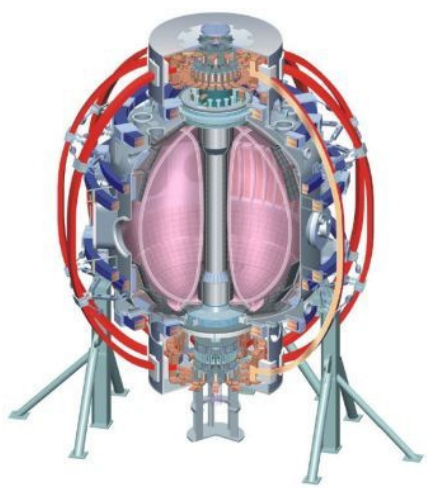
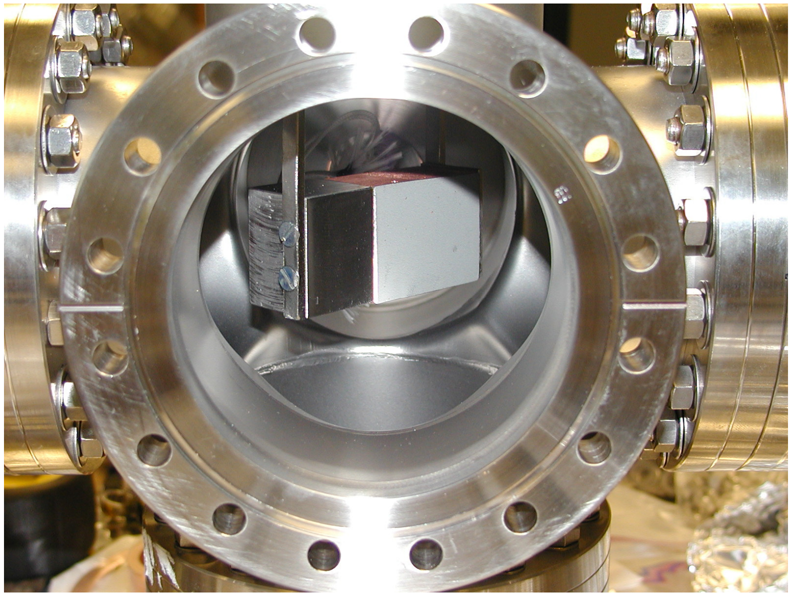


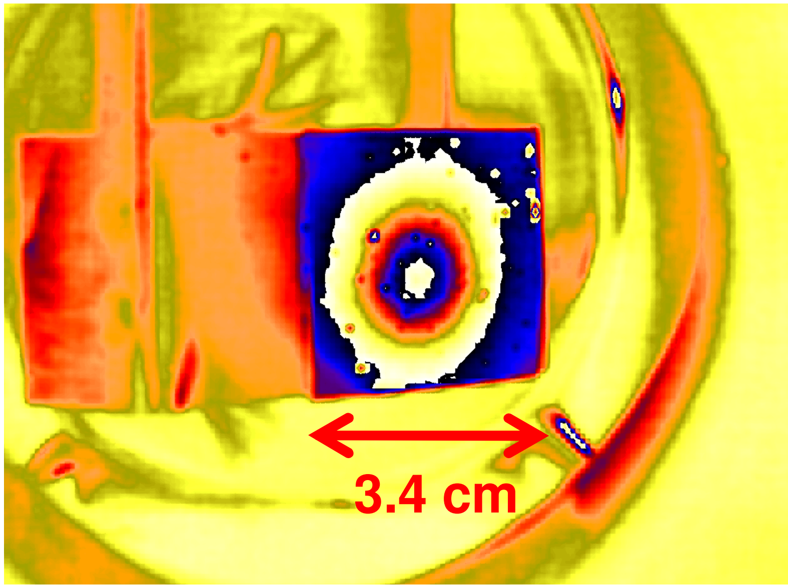
Offline testing of porous Mo motivated by concerns over power handling capabilities of LLD

- In-situ heat load testing of LLD is difficult on NSTX
- Offline experiment provides greater flexibility and control
- **Controlled heat load testing necessary to:**
  - Determine extent of physical damage to a porous Mo surface
    - Verify that the "bare" LLD will not melt or suffer significant erosion
  - Quantify the effects of high heat flux on a Li-coated Mo substrate
    - Measure the magnitude of Li melting/sputtering
    - Determine the degree of Li interaction with Mo substrate
  - Examine the extent and effects of Li passivation on the LLD
    - Determine the power handling capabilities of this LiOH layer

LLD sample exposed to neutral beam on test stand to investigate effect of high heat load



Test chamber showing LLD sample (non-Li case)



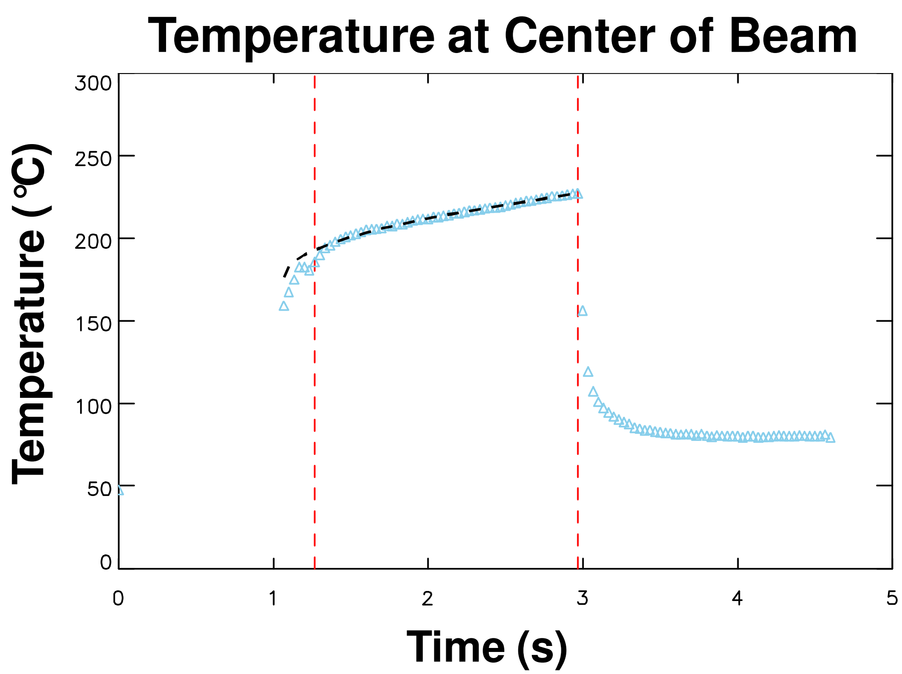
False color image of “bare” LLD sample during neutral beam exposure

- **Diagnostic neutral beam (DNB) strikes LLD sample from right**
- **Beam energy of ~30 keV, peak power density of > 1 MW/m^2**
- **LLD sample “plunged” in front of DNB for 1-5 s**
  - First tests done with a bare sample. Subsequent tests used Li-coated sample.
- **Front face temperature recorded by IR camera, TCs on back face**

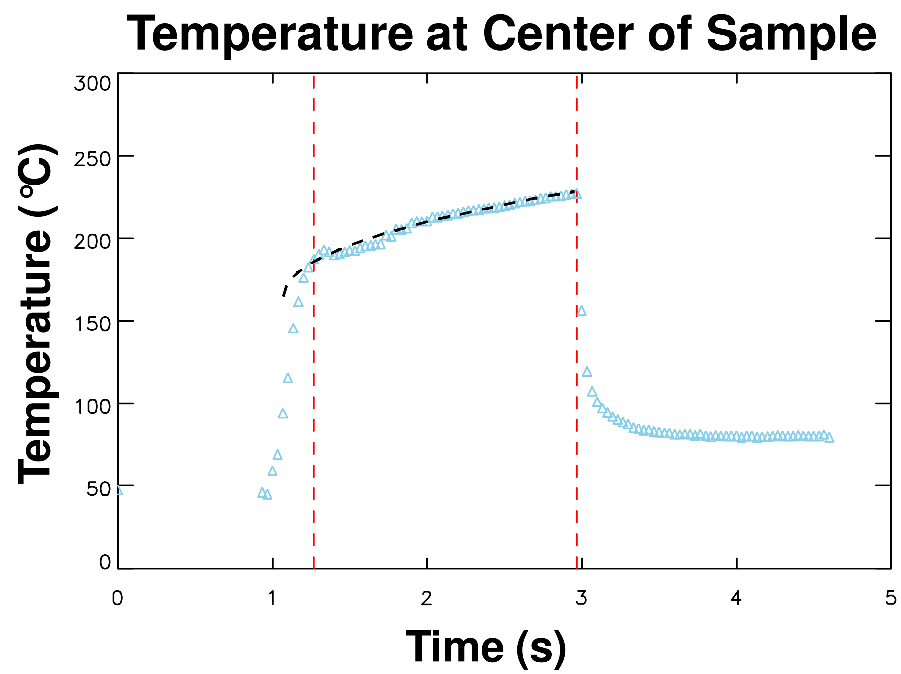
Heat flux determined using 1-D analytic model

- Assume time-constant heat flux q_s
- Using $\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$ and $q_s = -k \left. \frac{\partial T}{\partial x} \right|_{x=0}$ one obtains:

$$T(x,t)\big|_{x=0} = q_s \left[\left(\frac{4\alpha_{Cu} t}{\pi k_{Cu}^2} \right)^{1/2} + \frac{\Delta x_{Mo}}{k_{Mo}} + \frac{\Delta x_{SS}}{k_{SS}} \right] + T_0$$



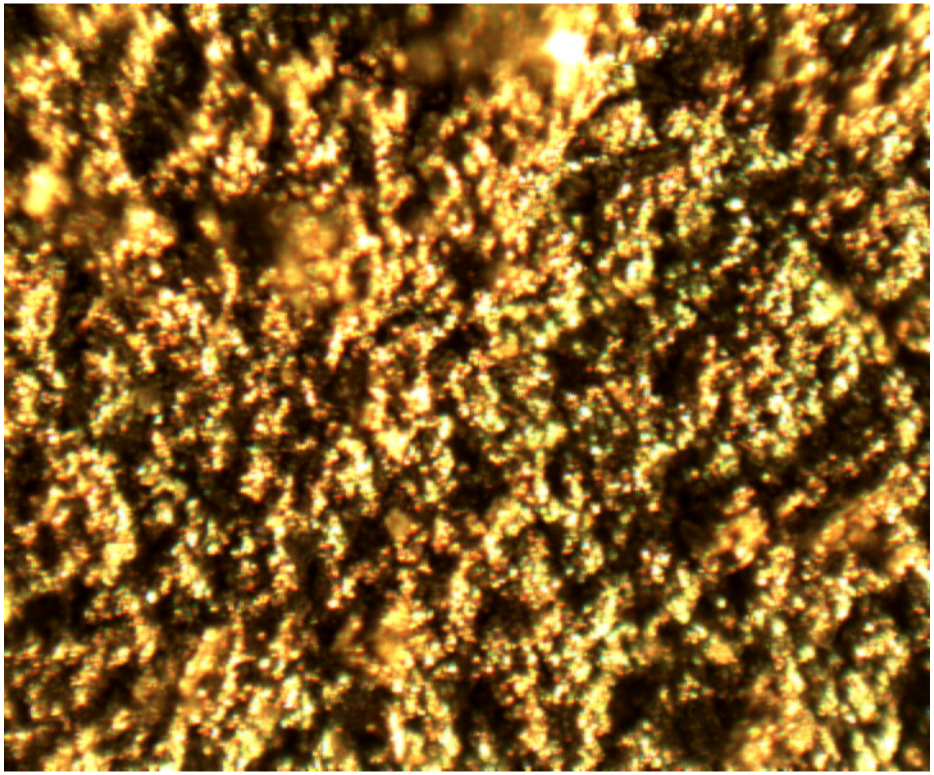
- **Heat flux: 1.22 ± 0.02 MW/m²**



- **Heat flux: 1.53 ± 0.03 MW/m²**

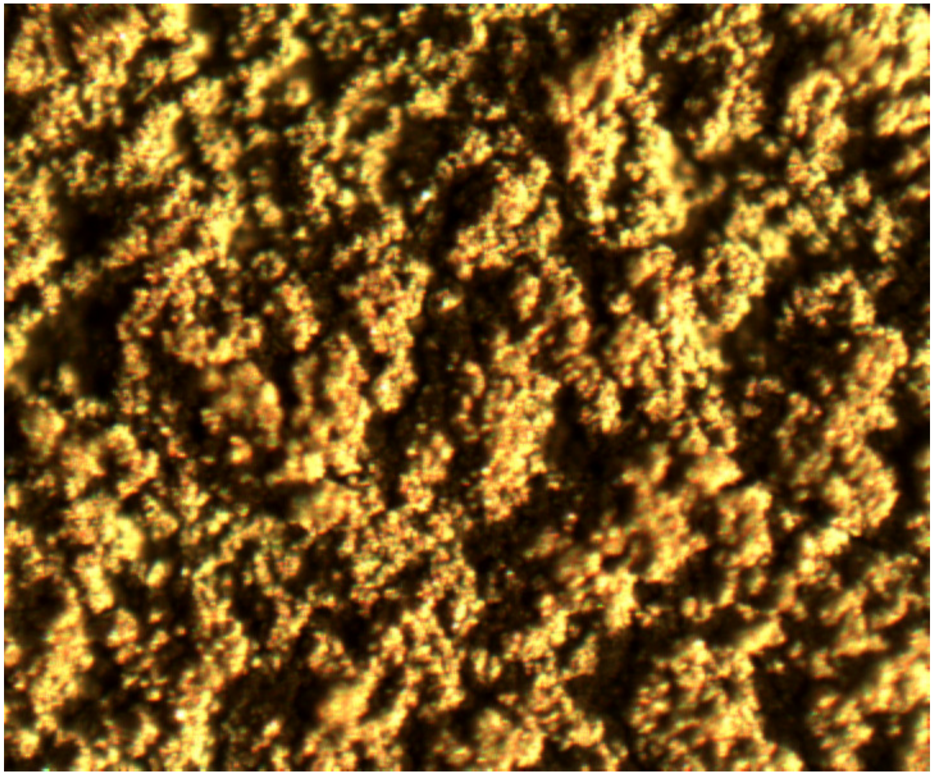
Observation of microscopic images of surface indicates no apparent damage to bare sample surface

No Beam Exposure



500 µm

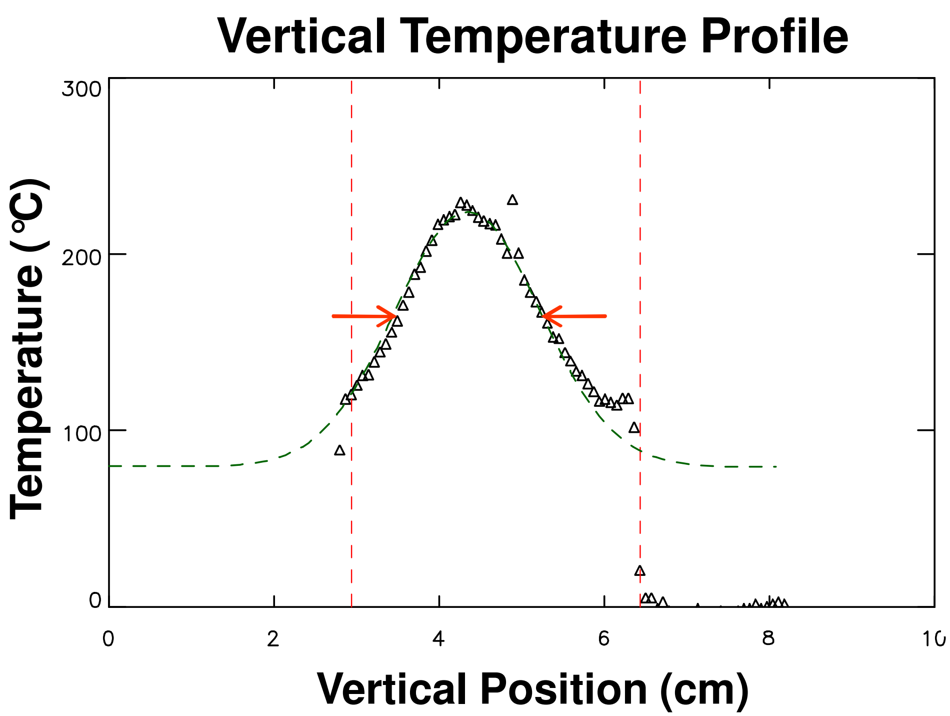
With Beam Exposure

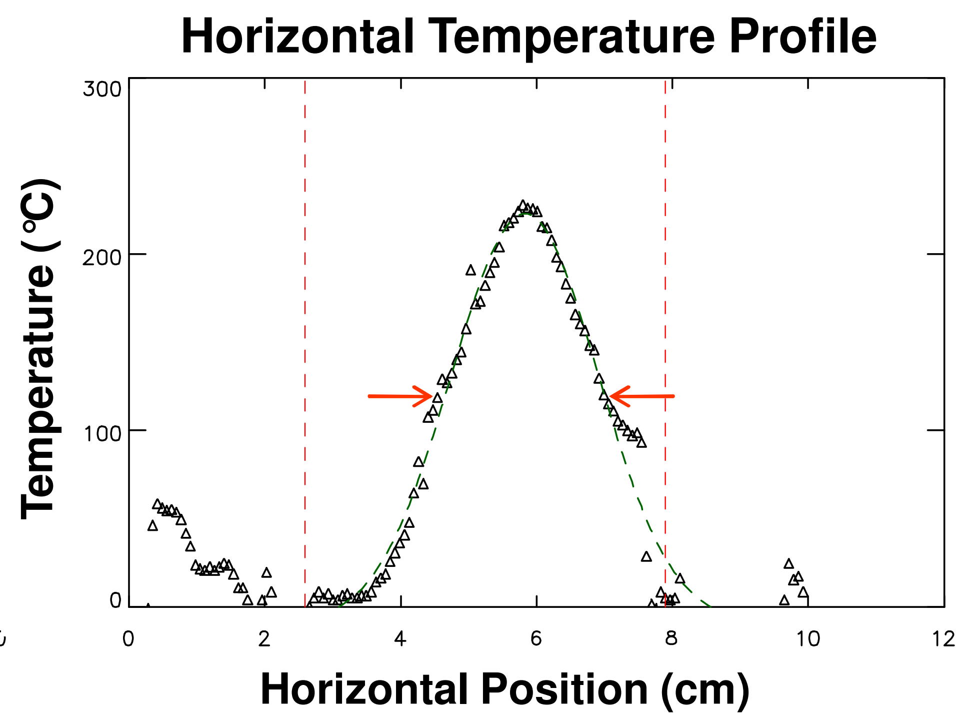


500 µm

Gaussian beam profile motivates a search for spatially varying morphology of exposed sample

- Sample temperature profile fit to a Gaussian
- Assume heat flux proportional to temperature

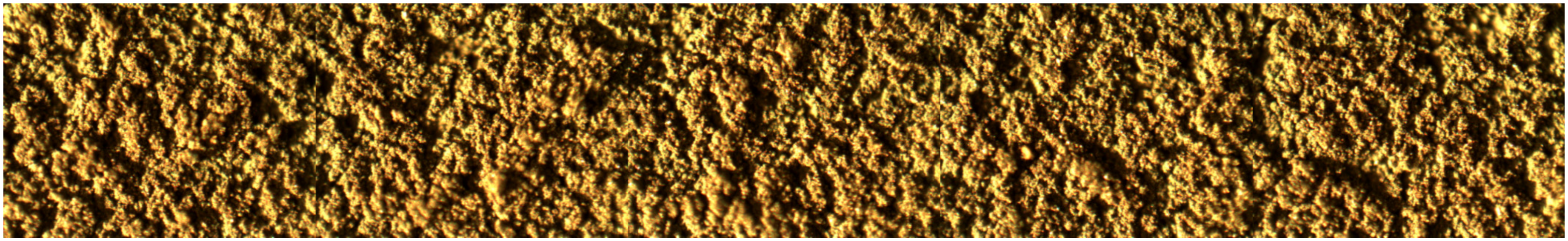




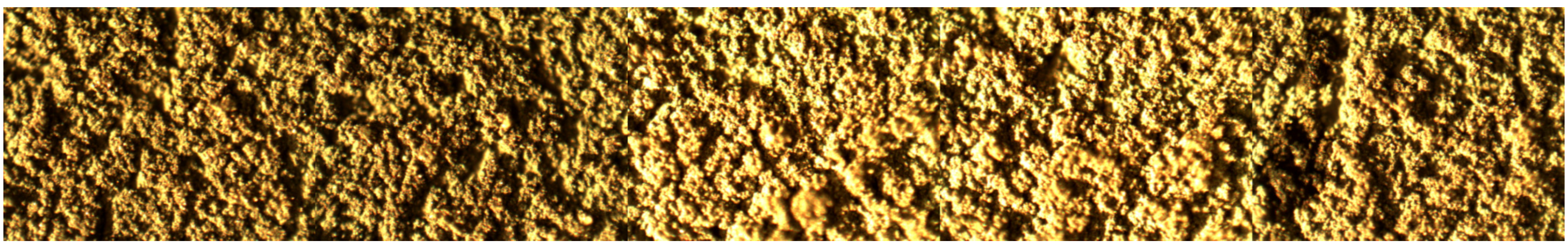
$$\sigma_y = \sigma_V = 0.89\ cm$$

$$\sigma_x = \sqrt{\sigma_v^2 + \sigma_h^2} = 1.40\ cm$$

Microscopic analysis indicates no apparent spatially varying morphology of exposed sample surface



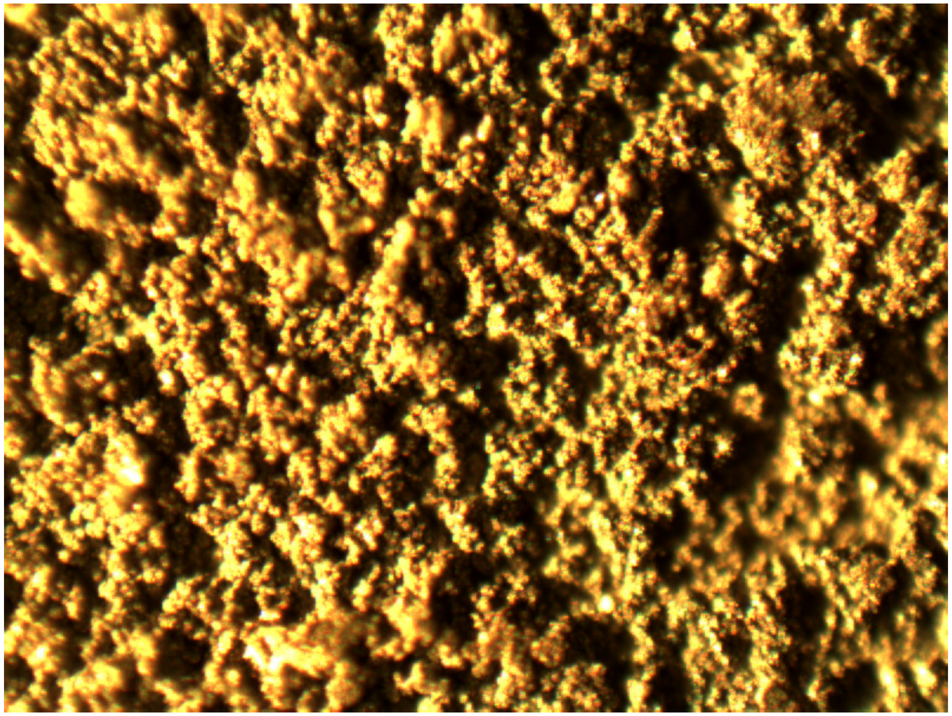
-9.0 mm   -8.0 mm   -7.0 mm   -6.0 mm   -5.0 mm



-4.0 mm   -3.0 mm   -2.0 mm   -1.0 mm   Approximate Center of Sample

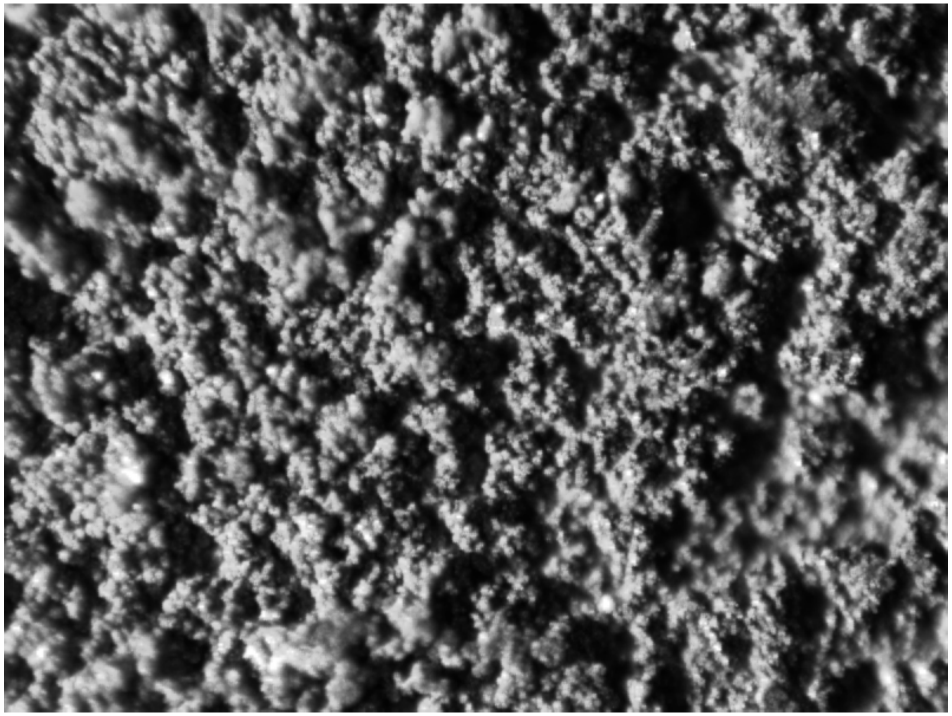
Quantitative analysis of surface morphology possible using image processing software

1. Start with full-color images



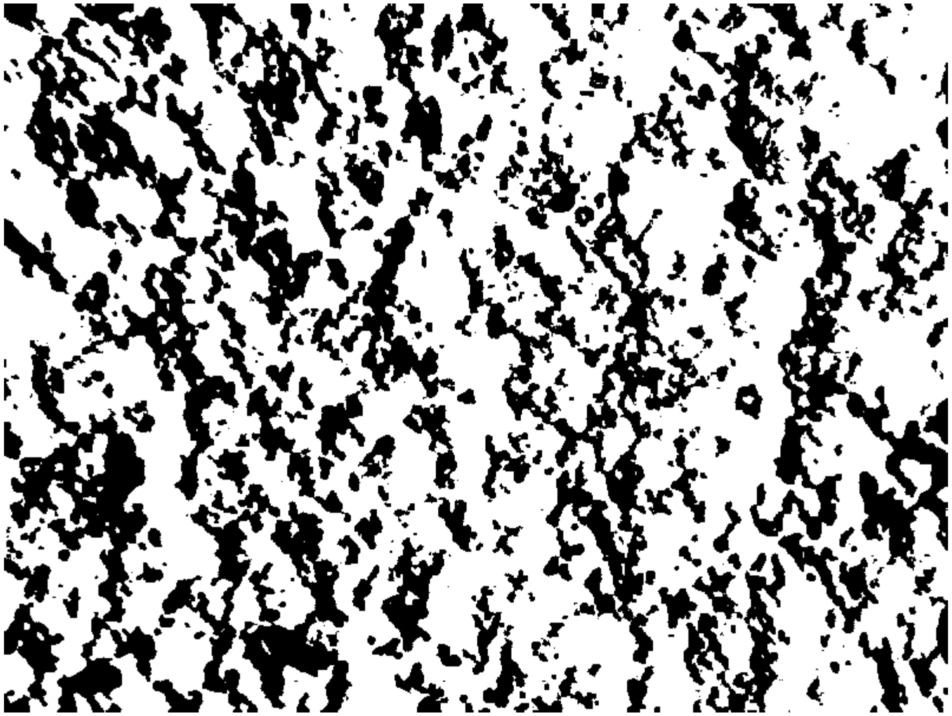
Quantitative analysis of surface morphology possible using image processing software

1. Start with full-color images
2. **Convert to grayscale**



Quantitative analysis of surface morphology possible using image processing software

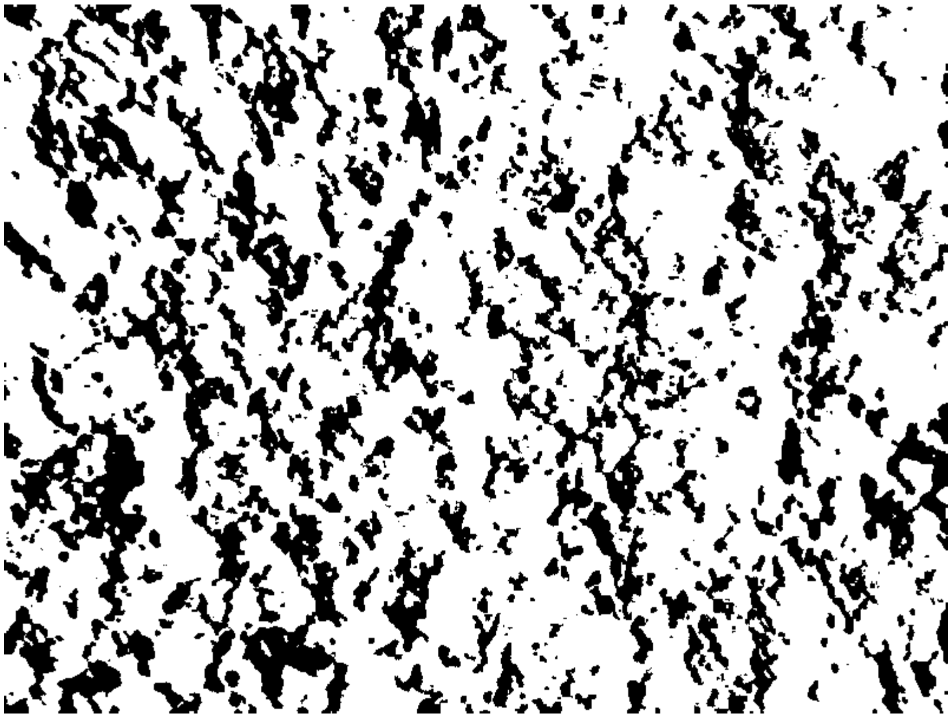
1. Start with full-color images
2. Convert to grayscale
3. **Set pixel threshold (131 or 111) to convert to B&W**



Threshold = 131

Quantitative analysis of surface morphology possible using image processing software

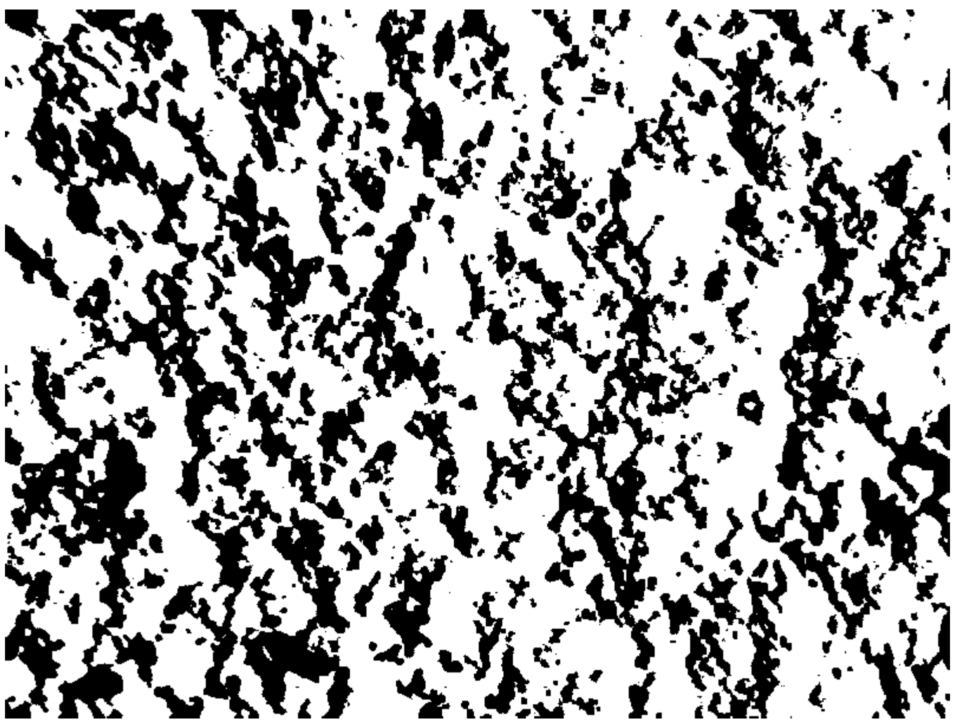
1. Start with full-color images
2. Convert to grayscale
3. **Set black threshold (131 or 111) to convert to B&W**



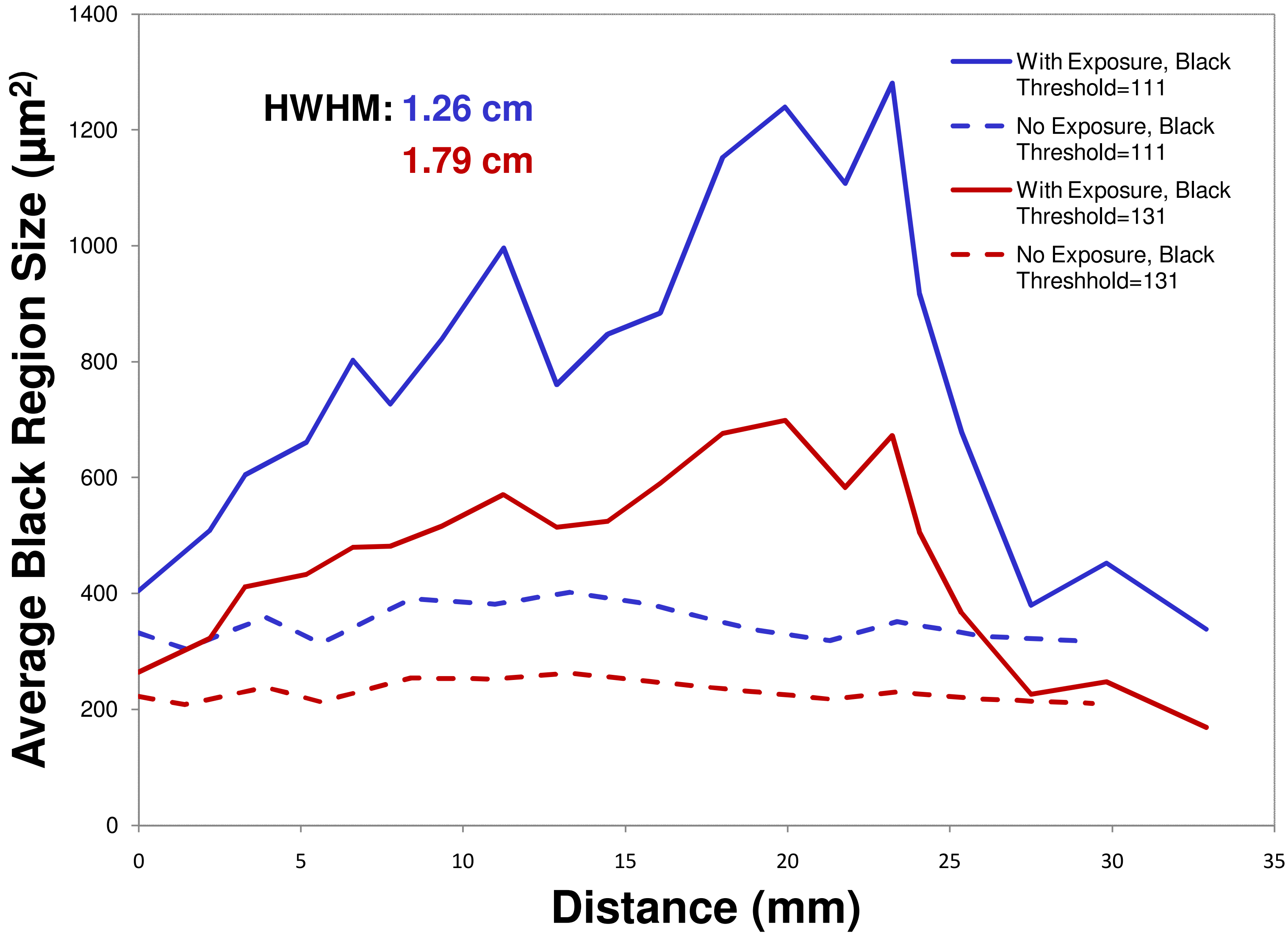
Threshold = 111

Quantitative analysis of surface morphology possible using image processing software

1. Start with full-color images
2. Convert to grayscale
3. Set pixel threshold (131 or 111) to convert to B&W
4. **Calculate average area of black regions**

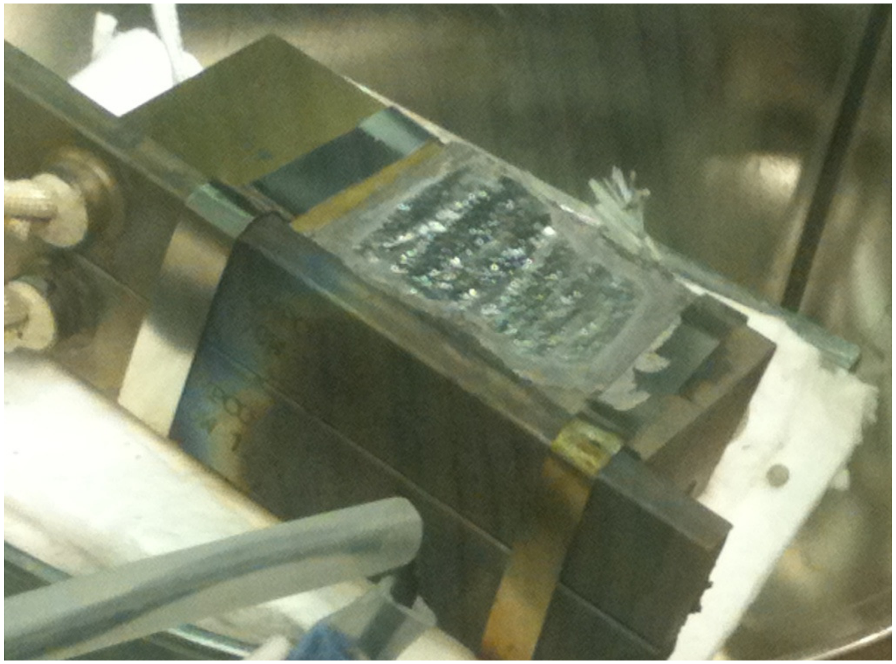


Microscopic spatially-varying sample damage evident using image processing software



Experiment repeated with a Li-coated LLD sample

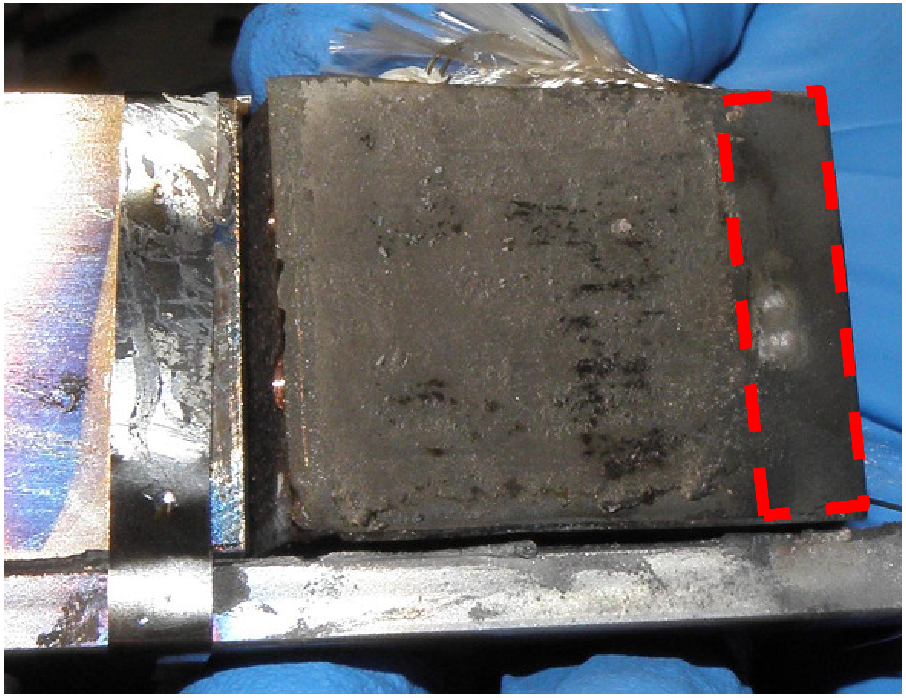
- ~150 mg (150 µm) of Li loaded on to a new LLD sample that had not been exposed to the beam
- LiOH layer developed on sample despite storage in Argon and vacuum
- Heaters added to sample
- Beam exposures were performed with initial sample temperature of 50˚C to 300˚C



New LLD sample coated with a fresh layer of Li

Analysis of images "by eye" indicates no large-scale modifications to lithiated sample surface

False color image of Li-coated sample exposure



Photograph of post-exposure Li-coated sample surface

- No beam "imprint" observed on sample surface
  - LiOH layer did not melt at 300 ˚C
- Note: boxed region covered with SS shim stock

Summary/Conclusions

1. Bare LLD surface does not melt or suffer significant erosion
   – No macroscopic damage apparent on visual inspection.
   – Only microscopic changes in surface morphology appear
   – LLD design withstands NSTX divertor-level heat fluxes

2. Mo layer exhibits large reduction (~20) to thermal conductivity
   – Suggests poor thermal contact between Mo and SS layers

3. LiOH layer forms on LLD surface, even in Argon/vacuum
   – Varying emissivity of LiOH may be an issue (in-situ calibration)

4. LiOH layer is unaffected by high heat loads
   – LiOH has a melting point of 462 ˚C, and thus did not melt
   – Consistent with the LLD results on NSTX

Future Work

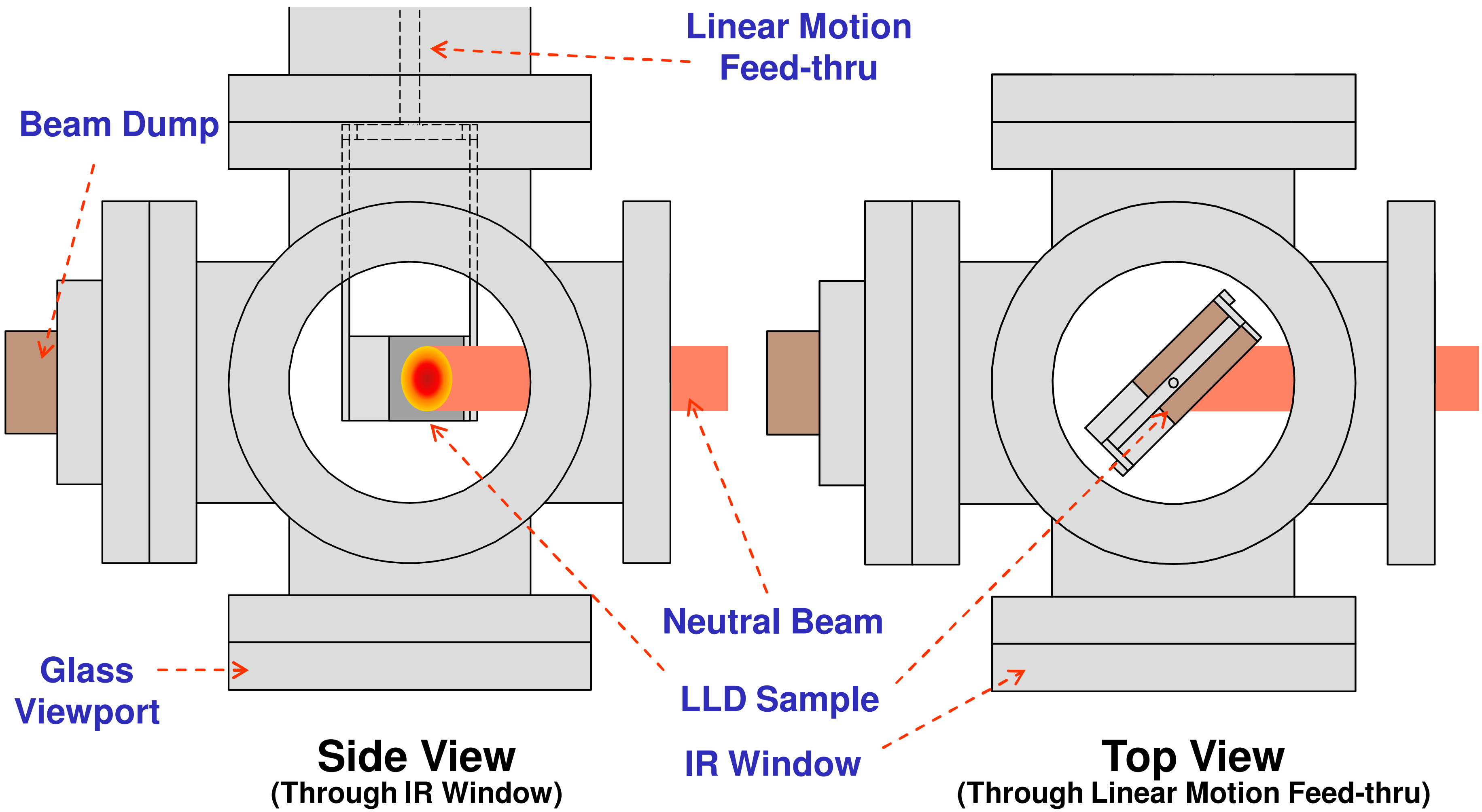
- Microscopic analysis of Li-coated sample using image processing software
  - Examine morphology of LiOH surface
    - Microscopic spatial variation in surface morphology is expected due to bombardment by the neutral beam
  - Clean the LLD sample and examine the surface morphology of the Mo substrate
    - No change in morphology expected due to protection by Li layer
- 3-D Thermal Modeling (M. Jaworski)
- Possible collaboration with UIUC on surface modification by sputtering (VFTRIM)

Acknowledgements

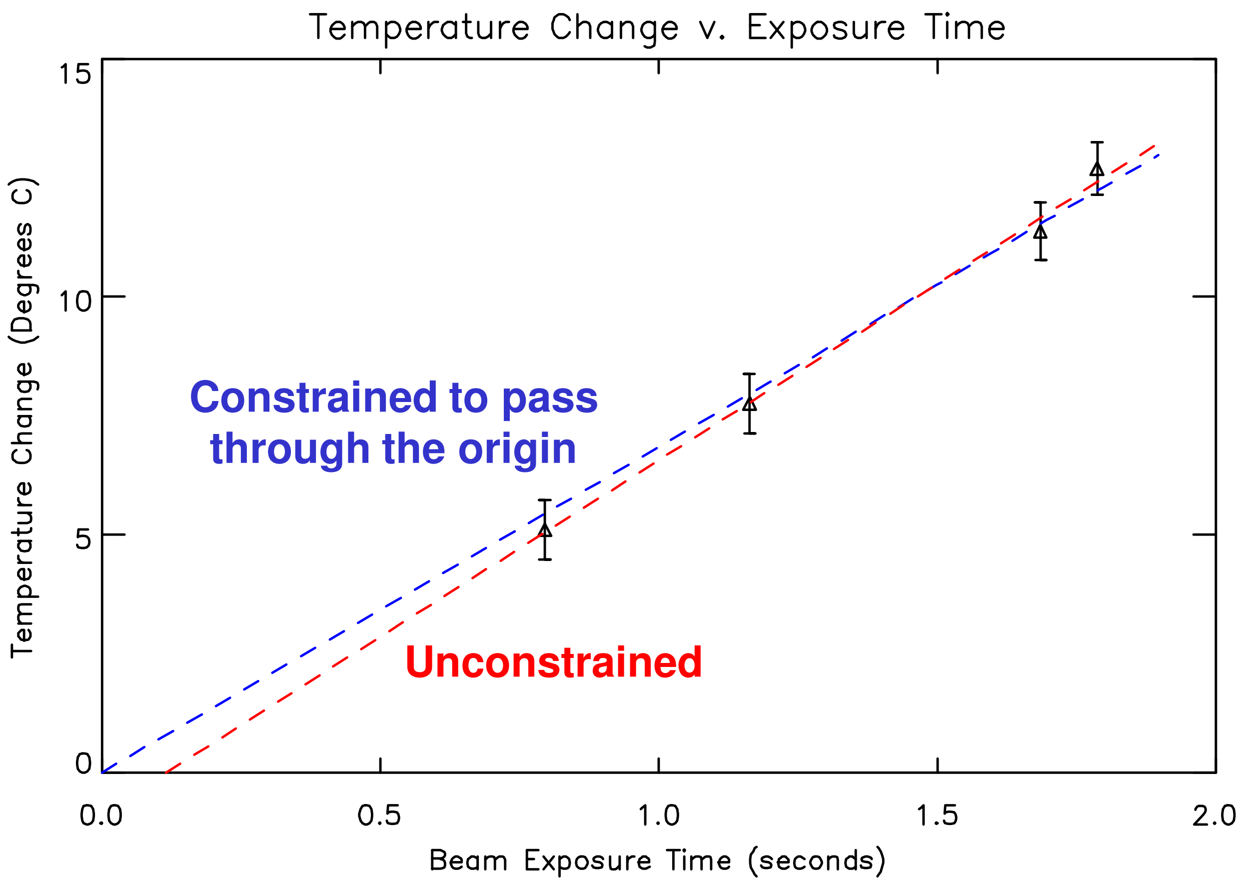
- Equipment:
  - Nova Photonics (E. Foley, F. Levinton) for use of DNB
  - Oak Ridge (T.K. Gray, R. Maingi) for use of IR camera
  - C. Skinner for use of optical microscope
  - LTX for various flanges and feed-throughs
- M.A. Jaworski, J. Kallman, R. Kaita (advisor) and the rest of the LLD team for constant advice/feedback

- Supported by US DOE contracts DE-AC02-09CH11466 and DE-FG02-01ER54616, and partially performed under appointment to the Fusion Energy Sciences Fellowship Program administered by Oak Ridge Institute for Science and Education.

Diagram of Experimental Setup



Copper Sample can be used as Calorimeter



$$\Delta E = mC_p \Delta T = \langle J \rangle \cdot t + E_0$$

$$q(x,y) = \frac{\langle J \rangle}{2\pi\sigma_x\sigma_y} \exp\left[\frac{-x^2}{2\sigma_x^2} + \frac{-y^2}{2\sigma_y^2}\right]$$

$$q_{\max} = q(0,0) = \frac{\langle J \rangle}{2\pi\sigma_x\sigma_y}$$

- Temperature change varies linearly with exposure time
- Corresponds to peak heat flux of:
  - 1.13 ± 0.03 MW/m^2 (blue), 1.22 ± 0.07 MW/m^2 (red)

IR Data can also be fit numerically

- Again in 1D, but variable q
- Finite difference the diffusion equation:

$$\frac{T_j^{n+1} - T_j^n}{\Delta t} = \alpha \left[\frac{T_{j+1}^n - 2T_j^n + T_{j-1}^n}{(\Delta x)^2} \right]$$

- Boundary Conditions:

$$q^n = -k \frac{T_1^n - T_0^n}{\Delta x} \qquad\qquad T_J^n = T_{J-1}^n$$

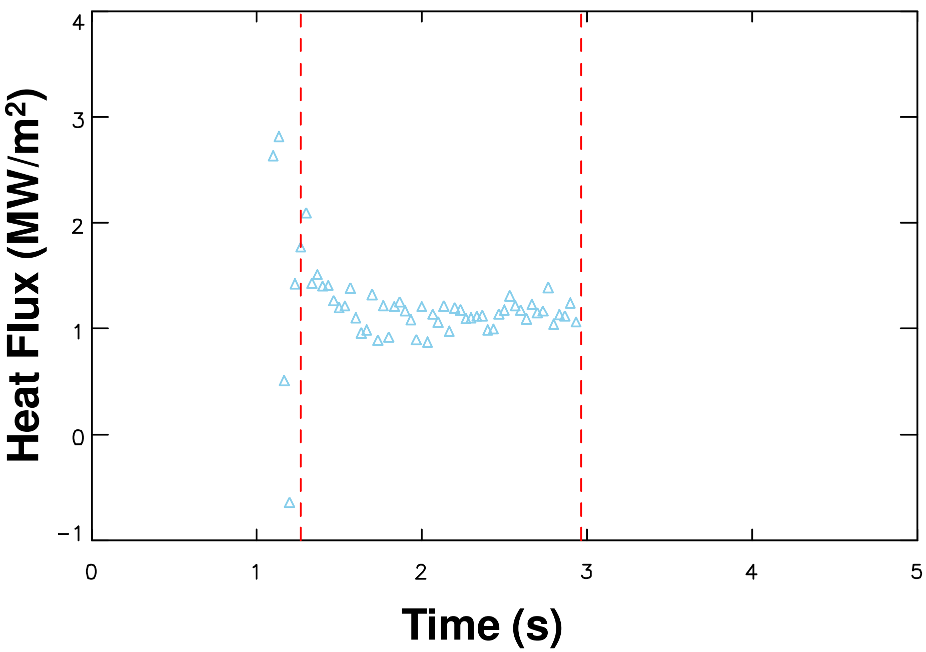
- T_1^n, T_j^0 known for all n,j respectively. Solve for q:

$$q^n = \frac{k}{\Delta x} \left\{ \left[\frac{T_1^{n+1} - T_1^n}{\Delta t} \right] \frac{(\Delta x)^2}{\alpha} - T_2^n + T_1^n \right\}$$

IR Data can also be fit numerically

- T_1^n, T_j^0 known for all n,j respectively. For each n:
  1. Calculate temperatures other than at boundaries
  2. Determine the heat flux
  3. Find temperatures at boundaries using BCs

Heat Flux at Center of Beam



Heat Flux at Center of Block