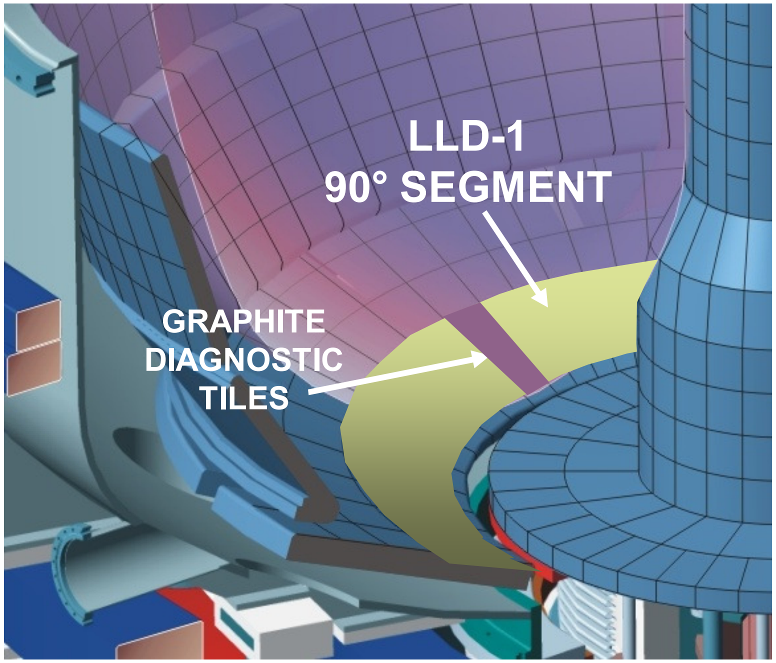
Abstract

A small prototype sample of the NSTX Liquid Lithium Divertor (LLD) was exposed to a MSE-LIF diagnostic neutral beam at a power of ~10 MW/m^2 for 1-3 seconds. Calibrated IR measurements of front face temperature and thermocouple measurements of bulk sample temperature were obtained. Predictions of temperature evolution were derived from a simple 1D heat flux model and compared with experimental data. These results demonstrated the effective heat load handling of a thin stainless steel liner with porous Mo coating on a copper heat sink, suggesting usefulness as NSTX-Upgrade PFCs. A novel method of measuring the resistance of the lithium films inside NSTX was also developed, the initial results of which will be presented.

Lithium experiments are ongoing on NSTX

- Three-phase approach:
  1. Lithium pellet injection (LPI)
  2. Lithium evaporation (LITER)
  3. Liquid lithium divertor (LLD)
     - Located on lower OD in four 82.5° segments
     - 152 μm porous Mo plasma-sprayed on 254 μm SS bonded to 1.9 cm Cu
     - “Filled” via evaporation from LITER probes



- Experiments with LITER probes have produced evidence of reduced edge density

H. Kugel.

LLD also provides greater power handling capabilities

- Mo has advantages over C
  - Higher thermal conductivity -> expanded distribution of heat
  - Higher Z -> lower sputtering yields
- **Additional offline testing of porous Mo required**
  - Determine extent of physical damage to the substrate
    - Will the LLD melt or suffer significant erosion?
  - Measure spatial & temporal thermal evolution of front face
    - How is thermal conductivity affected by the porosity?
  - Quantify the effects of solid/liquid Li
    - What are the erosion and sputtering yields vs. temperature?
    - Does Li protect the Mo?

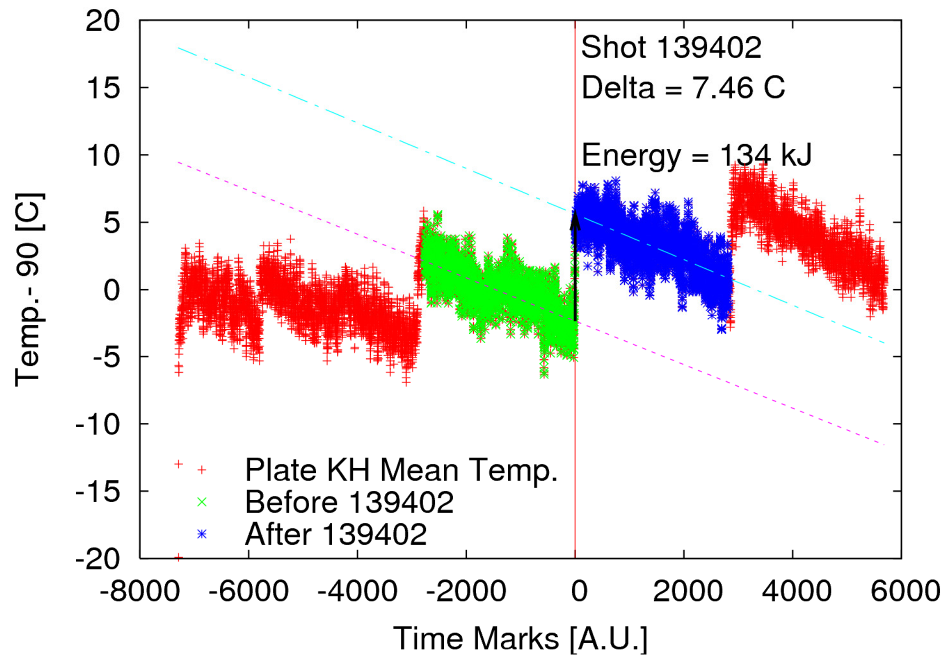
Heat flux constrained by thermocouple measurements

- Thermocouples measure LLD plate temperatures
- Treat LLD plate as a 90lb. calorimeter
- Rise in mean temperature yields energy deposited
- Energy into KH for shot 139402 is 134 kJ
  - Geometric conversion to 360 degrees yields ~590 kJ
  - NBI input into tank is ~4 **MJ**
  - Mean plate power for 1.1s discharge is 530 kW

$$E = V_{plate} \rho_{Cu} C_{p,Cu} \Delta T$$

$$E = 5222\, cm^3 \cdot 8.94\, g / cm^3 \cdot 0.384\, J / (gm\, K) \cdot \Delta T$$

$$E = \Delta T \cdot 17.9\, kJ / K$$



M.A. Jaworski.

Integral heat flux obtained from two-color IR data

- Time varying function f(t) taken from IR data waveform
  - f(t) is normalized and assumed proportional to heat flux q(r,t)
  - 2cm decay length λ taken from shot 120755 (similar shape as original plasma)
- Resulting heat flux integral set equal to energy
  - 3.7 MW/m^2 mean heat flux obtained
  - “true” mean flux is lower (missing IR data)

$$q(r,t) = q_0 f(t)\exp\left[\frac{-(r-r_{sep})^2}{\lambda^2}\right]$$

$$E = \iiint q(r,t)\, r\, d\theta\, dr\, dt$$

$$q_0 = \frac{E}{2\pi\, 0.025\, m^2} = 3.73\ MW/m^2$$

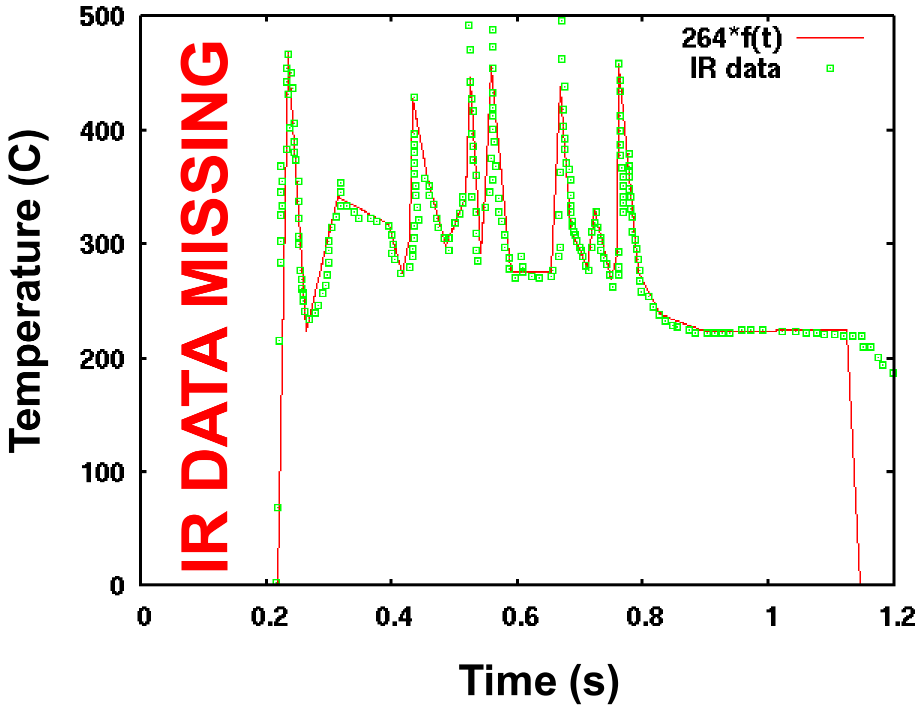


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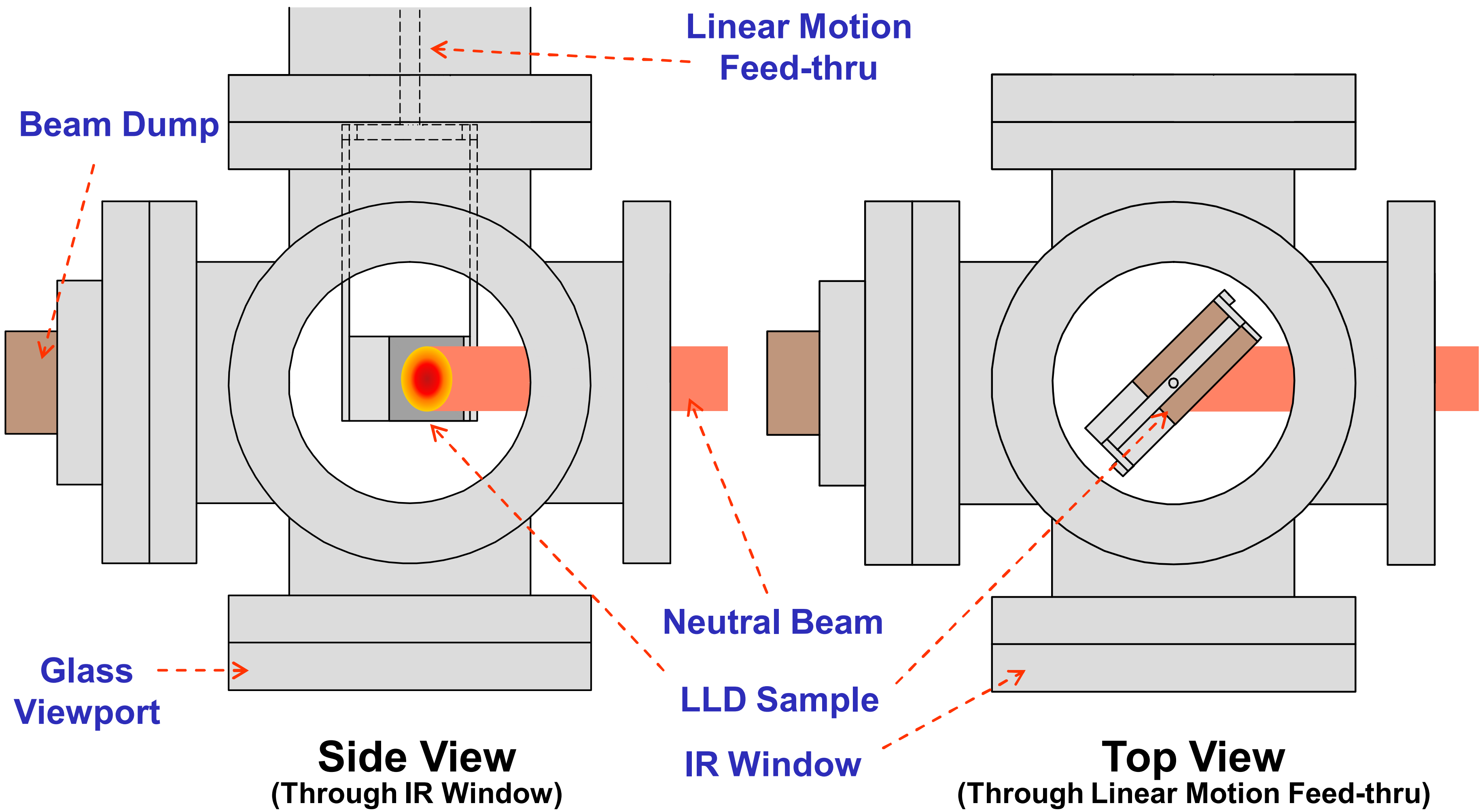
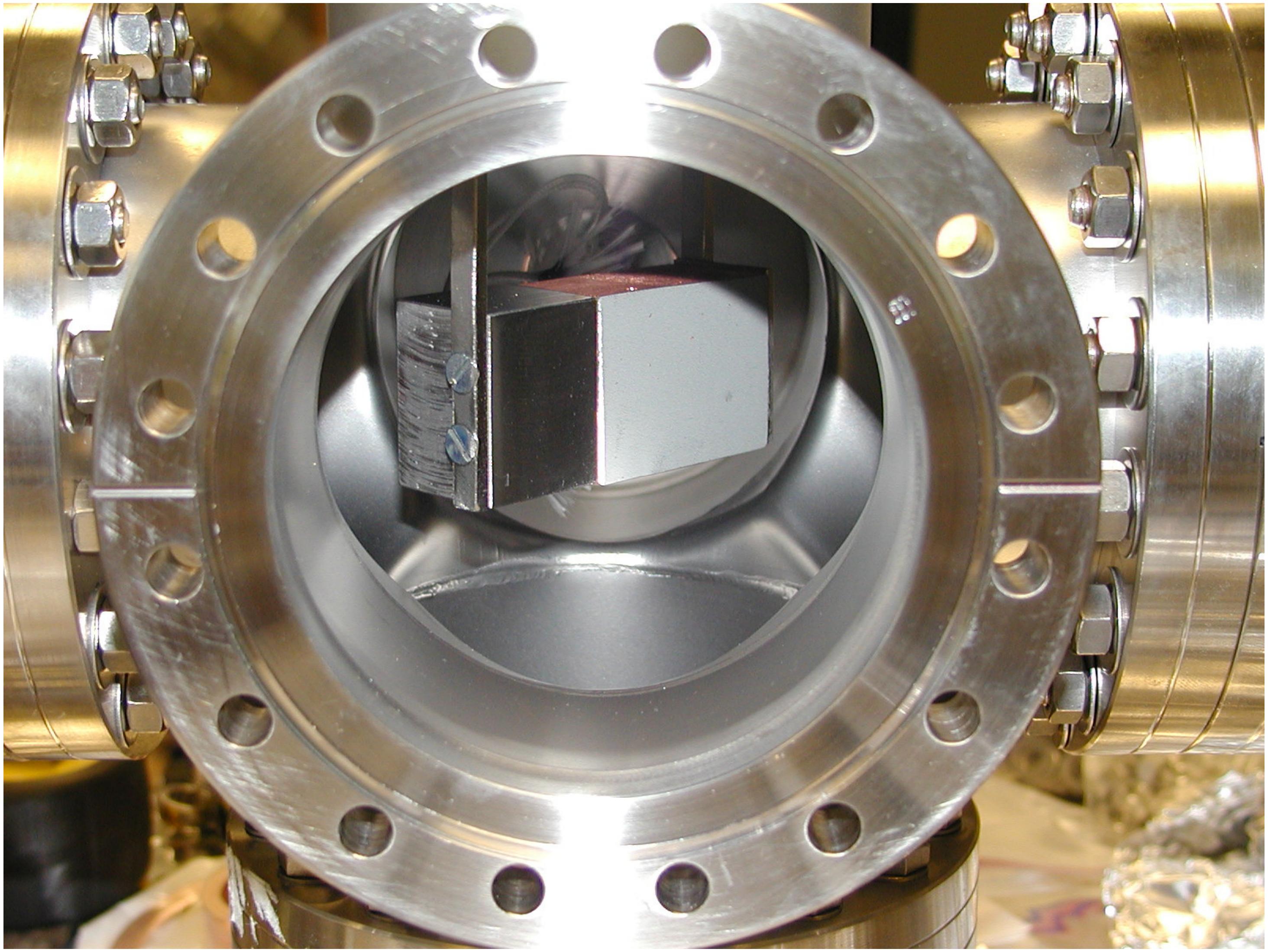
Diagram of Experimental Setup

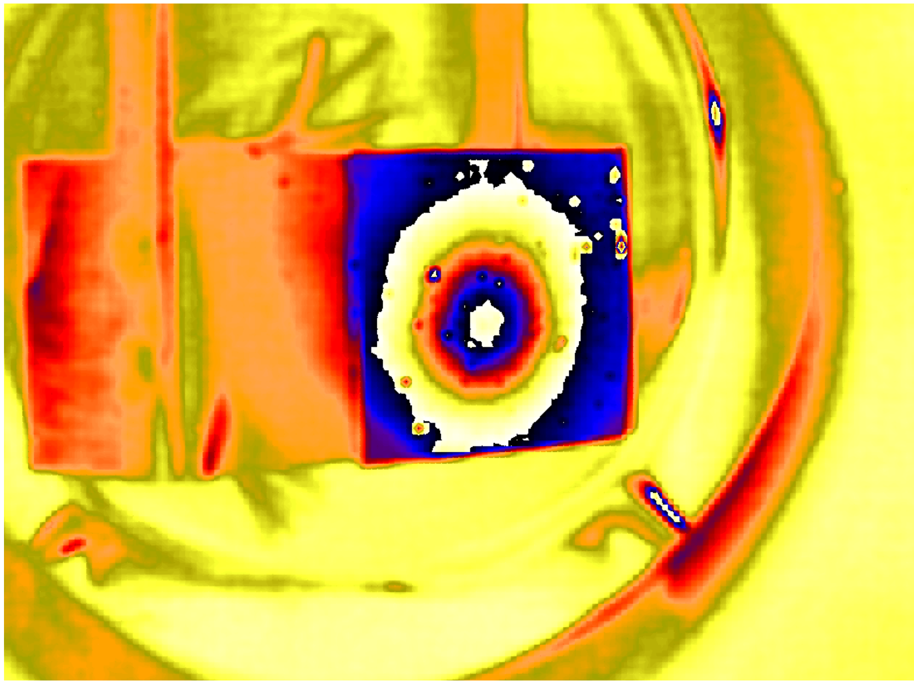


Side View of Experimental Setup



IR Camera provides Time-Resolved 2D Temperature Data

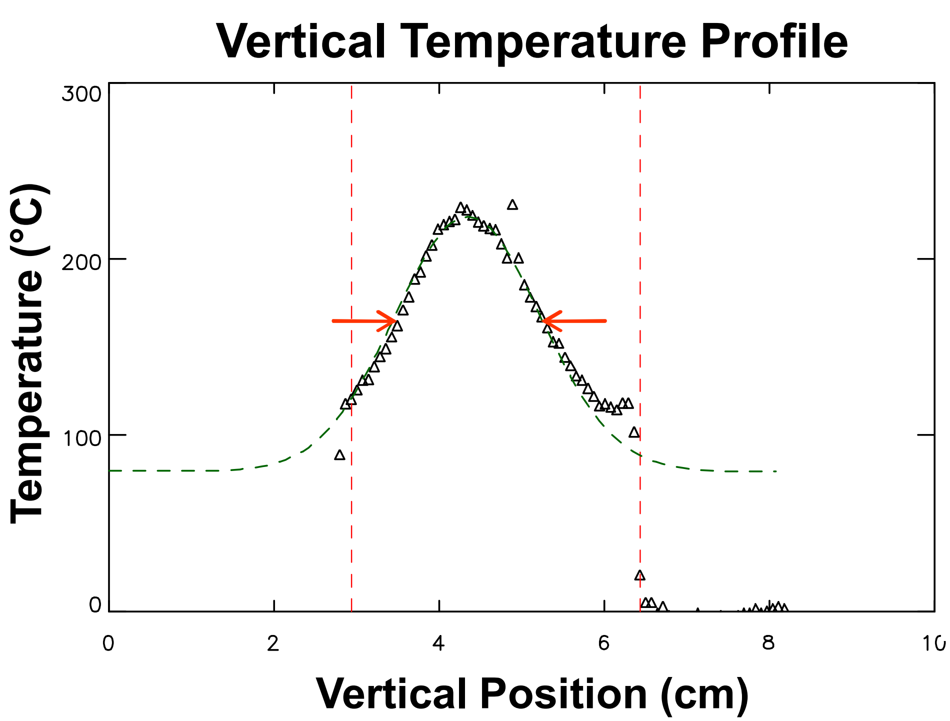
- Camera resolution:
  - ~1mm spatial
  - 33.3 ms temporal
- LLD sample “plunged” in front of DNB for 1-3 s
- Front face temperature recorded by IR camera
  - Absolute temperatures determined via calibration
  - Performed with replicated experimental conditions, matches TC data to within 10° C
- Back face temperature recorded by TCs

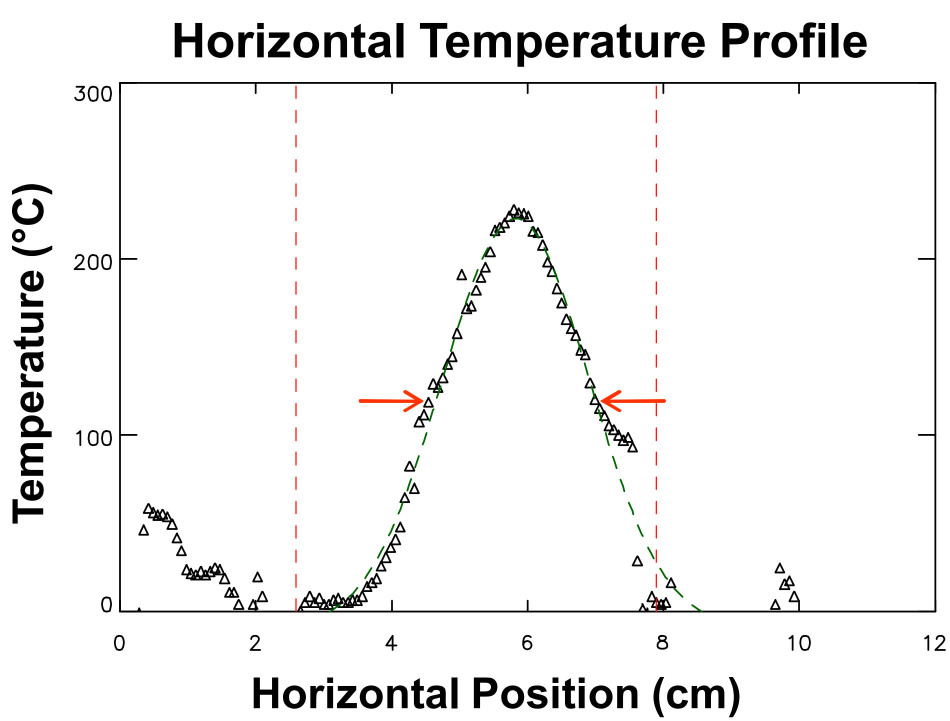


False color image of LLD sample during neutral beam exposure

Beam profile determined from Temperature data

- Beam profile assumed Gaussian
- Again assume q proportional to T

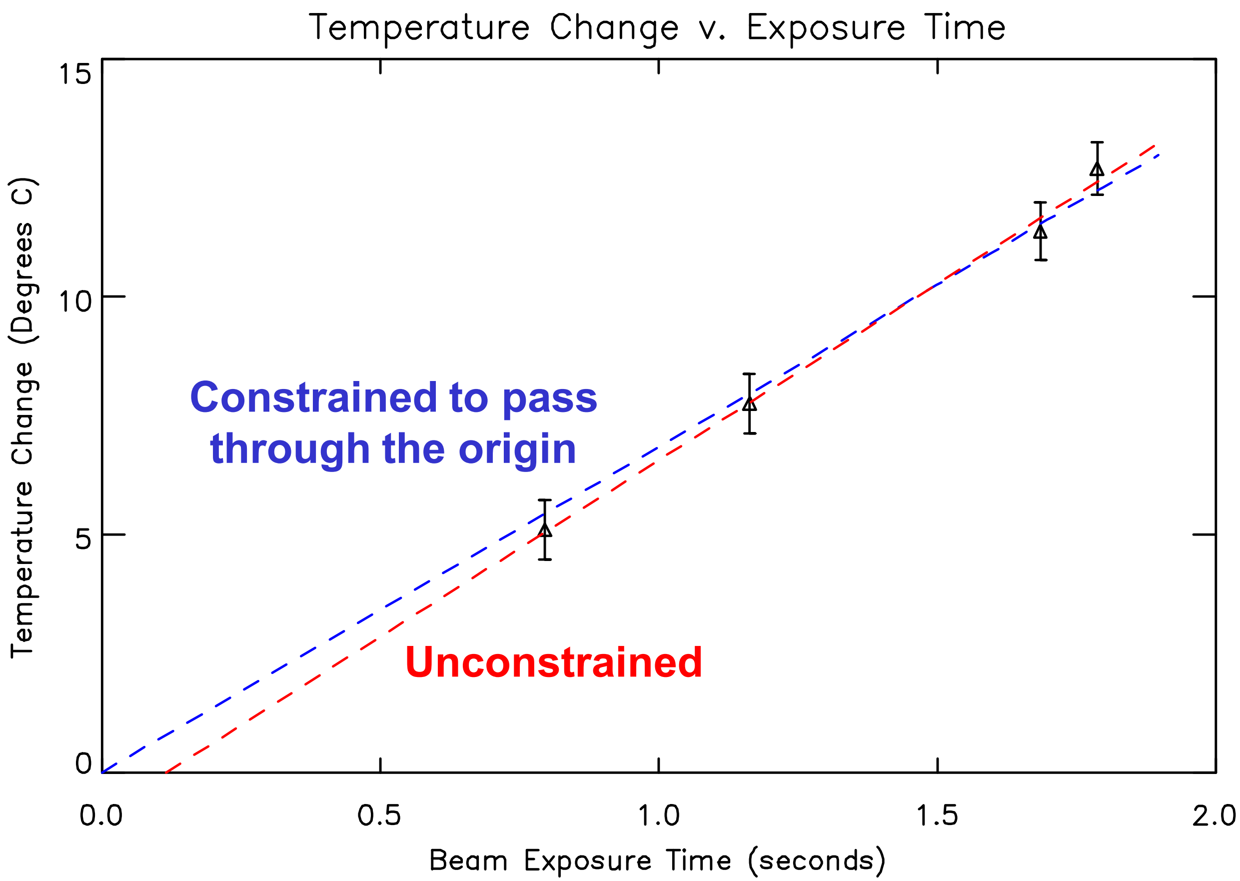




$$\sigma_y = \sigma_V = 0.89\ cm$$

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

Copper Sample can be used as Calorimeter



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

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

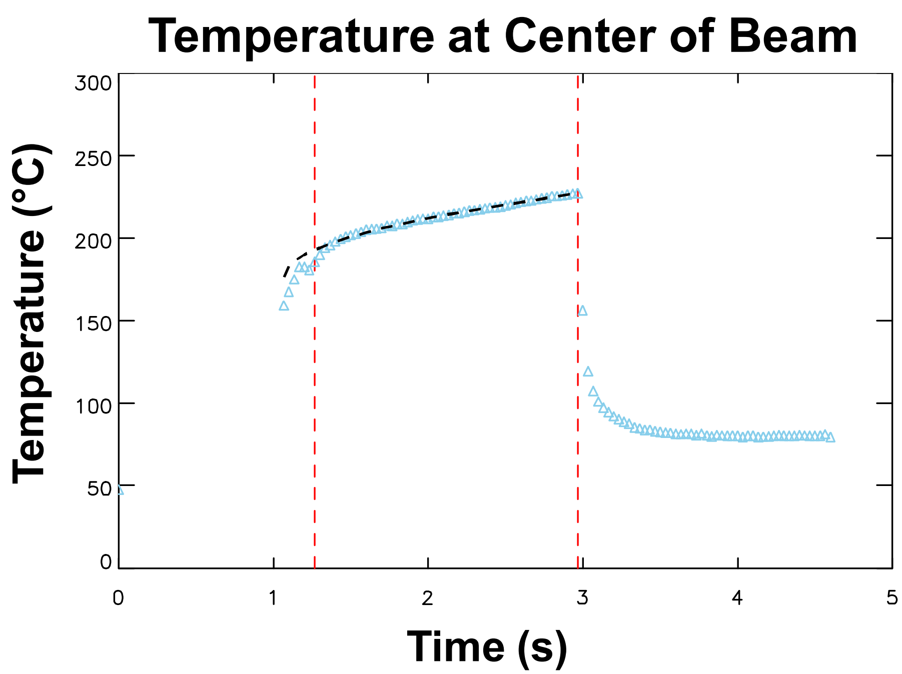
$$q_{\max} = q(0,0) = \frac{\langle J \rangle}{2\pi\sigma_x\sigma_y}$$

- 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)

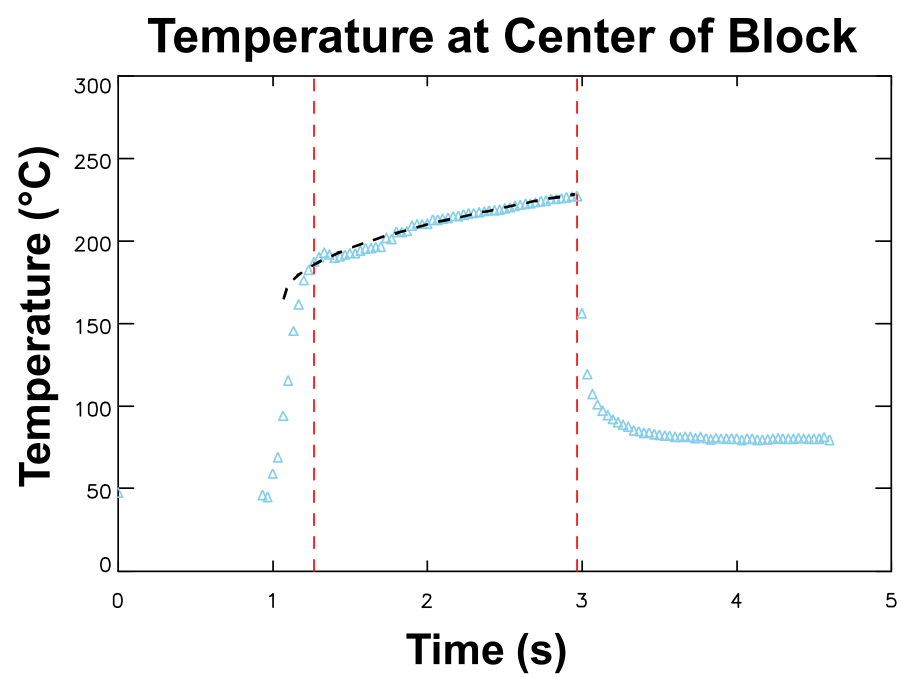
IR Data can be fit analytically, but with arbitrary T_0

- Assume 1D problem, 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**

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:

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

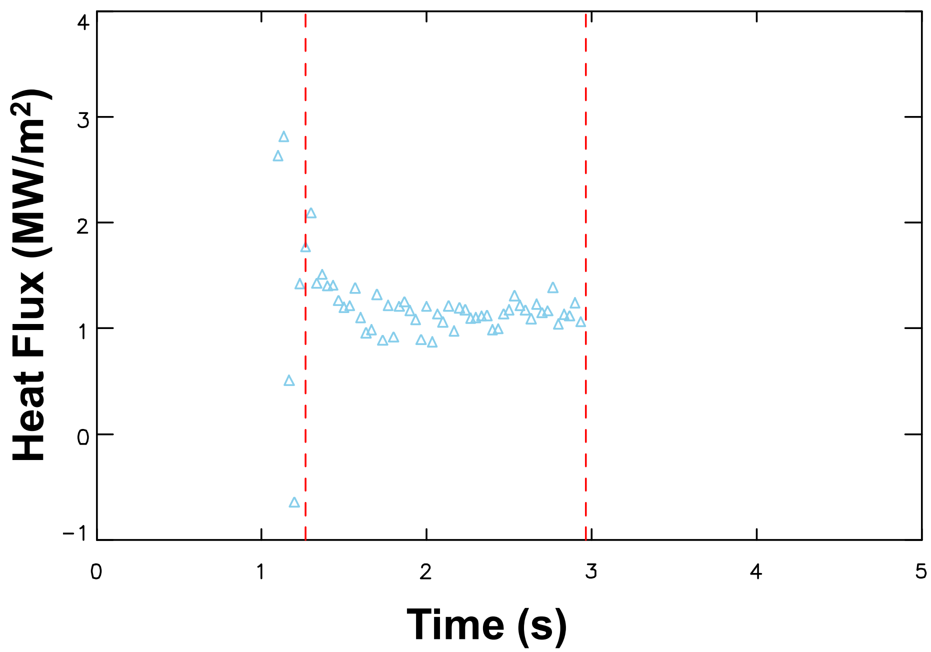
- T_1^n, T_j^0 known for all n,j respectively. Solve for q:

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

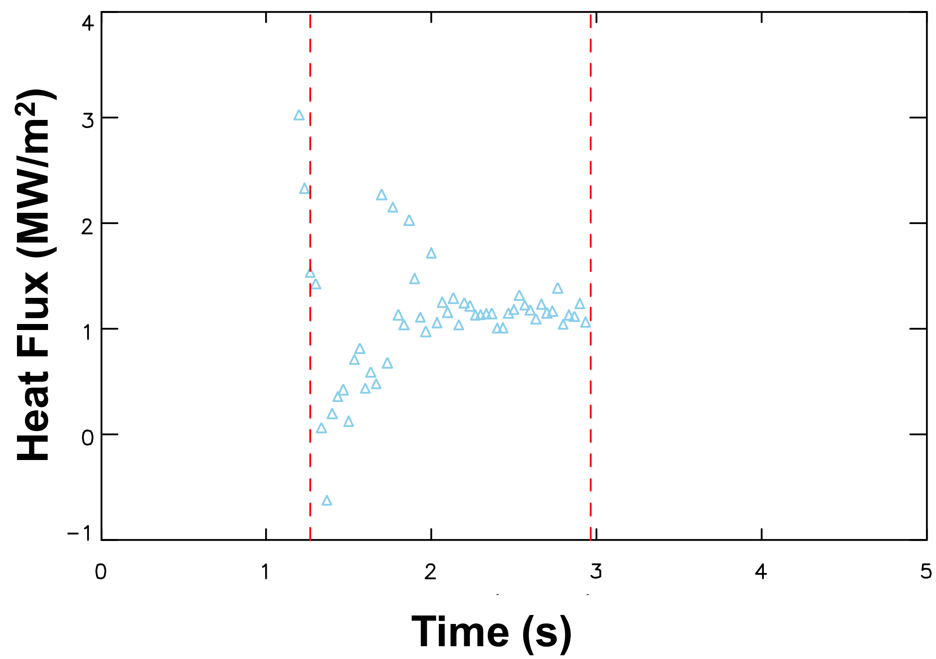
IR Data can also be fit numerically

- 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

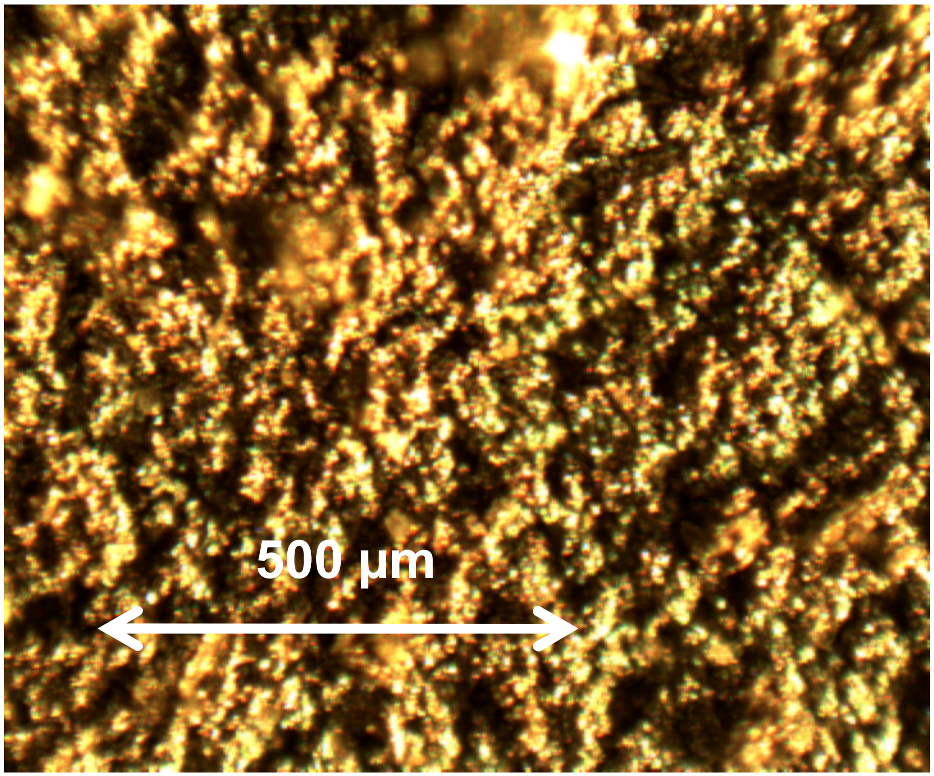
Heat Flux at Center of Beam



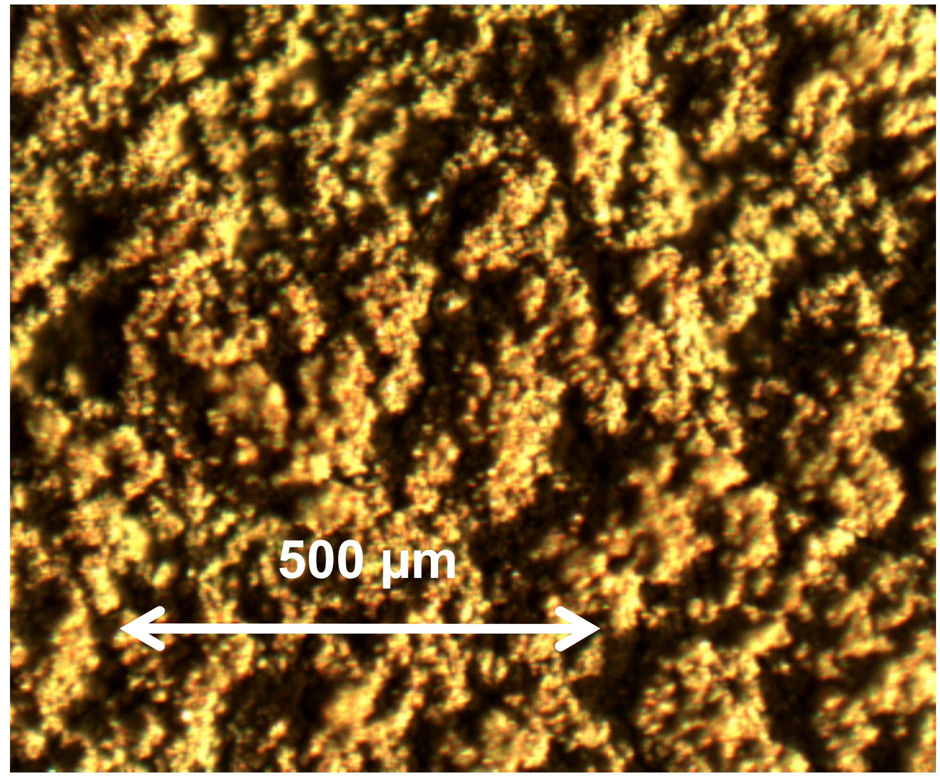
Heat Flux at Center of Block



Optical Microscope provides micron-level spatial resolution

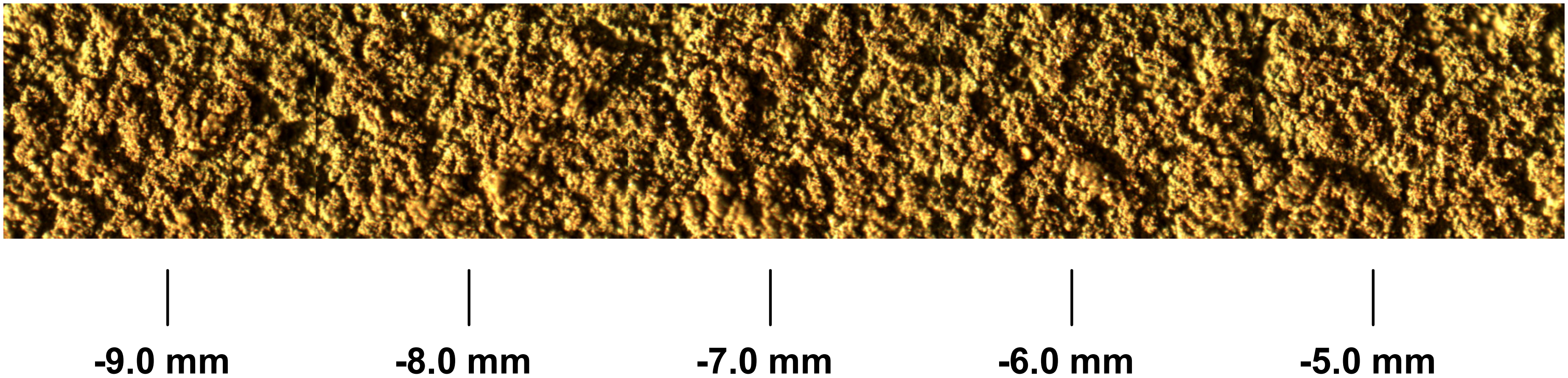


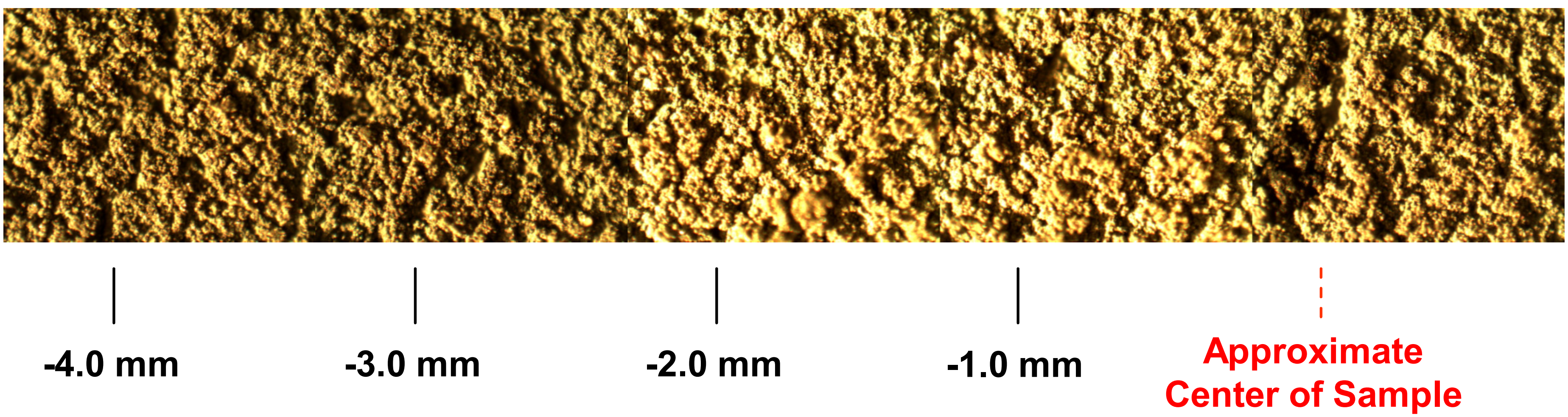
No Beam Exposure



With Beam Exposure

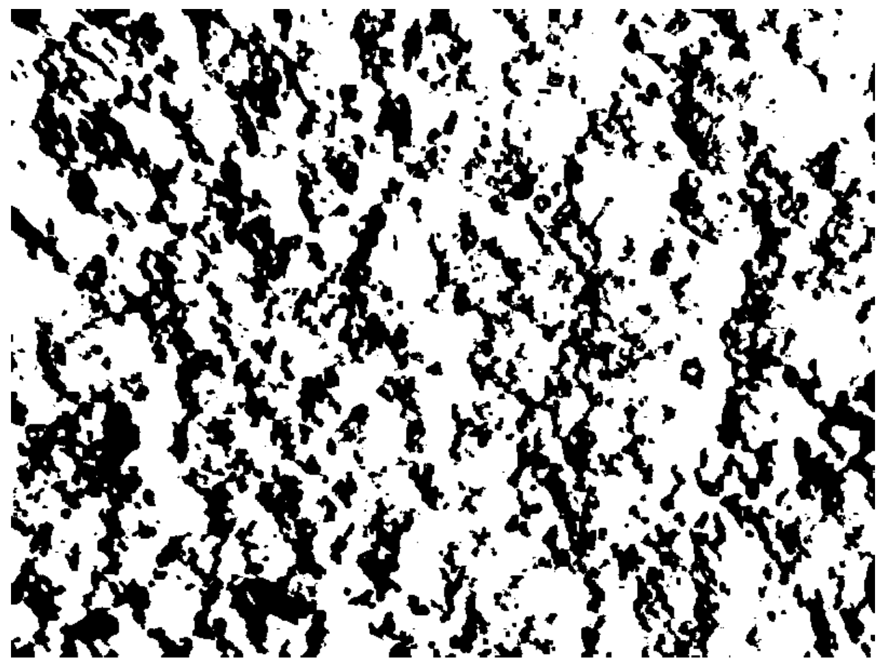
No Apparent Spatial Dependence of Damage



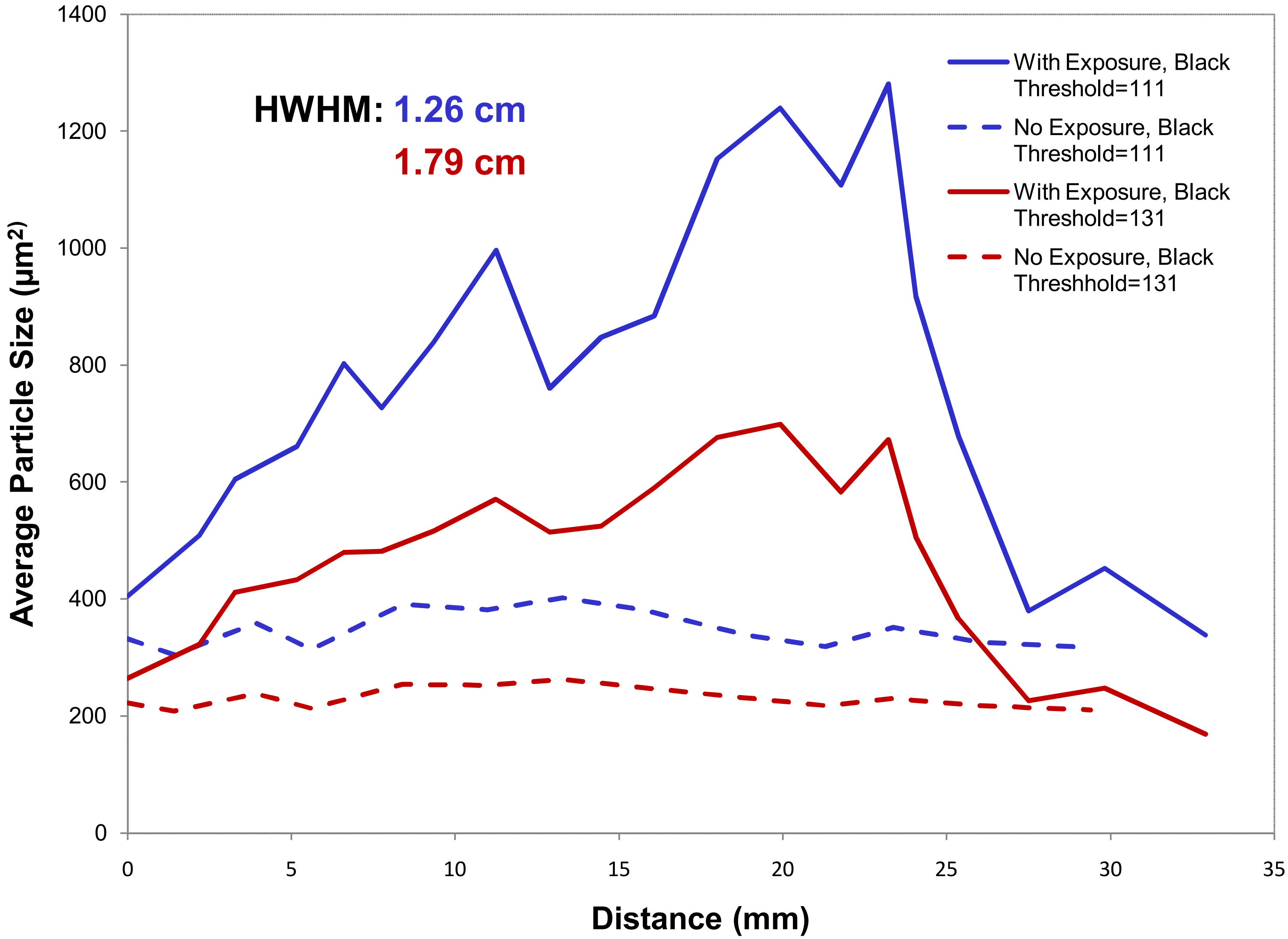


ImageJ software provides quantitative analysis methods

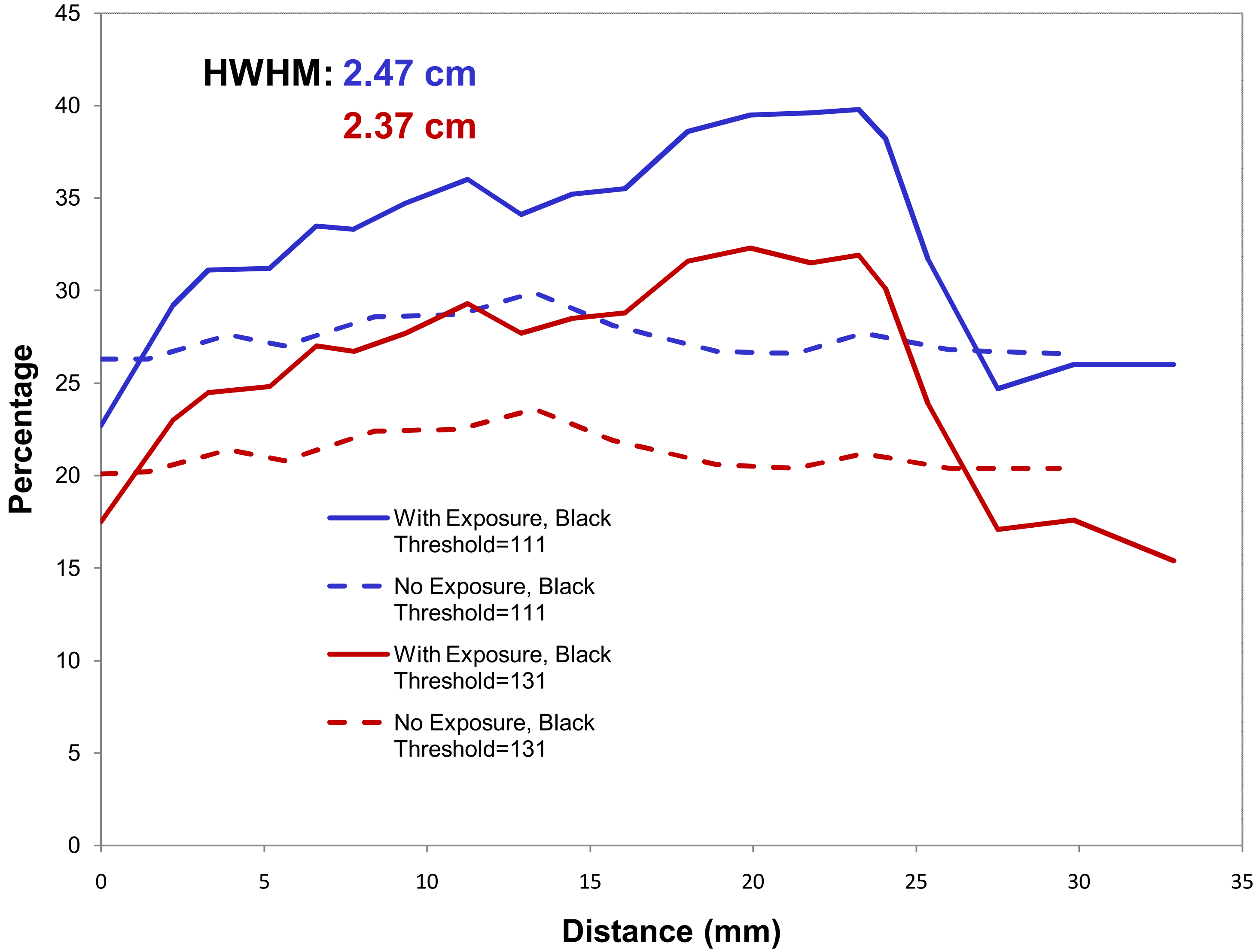
1. Start with full-color images
2. Convert to grayscale
3. Set black threshold (131 or 111) to convert to B&W
4. As a function of position, measure:
   - Fraction of black area
   - Number of “particles”
   - Average size of “particle”



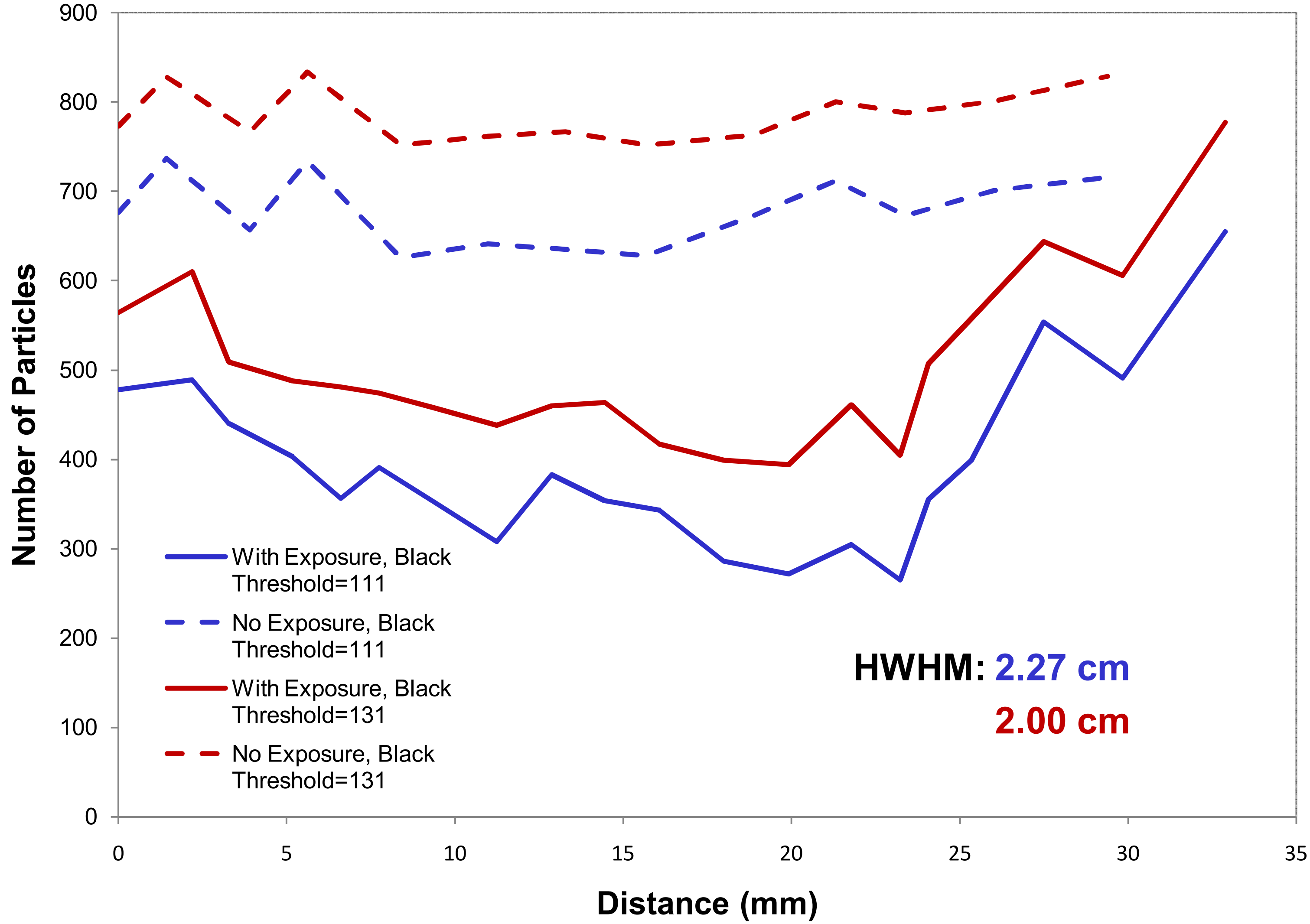
Average Size of Particle per Image



Percentage of Black Area per Image



Number of Particles per Image



Discussion

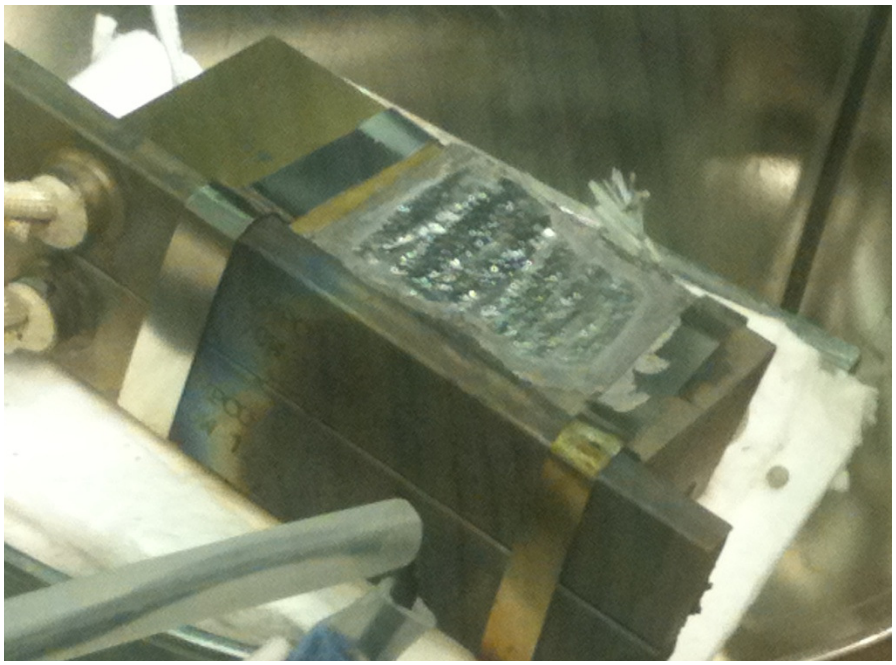
- Heat flux confirmed to be on the order of strike-point fluxes
  - ~ 1.5 MW/m^2 on sample, 3 MW/m^2 for NSTX shot analyzed (139402)
- Outstanding issues:
  - Unknown error introduced by IR calibration
  - Arbitrary temperature offset in analytic heat flux determination
    - Needed correction to k_{Mo} would be a factor of ~20
  - Finite "stroke time" results in non-uniform heat flux
    - Frame-by-frame "time weighting" introduces additional error

Future Work

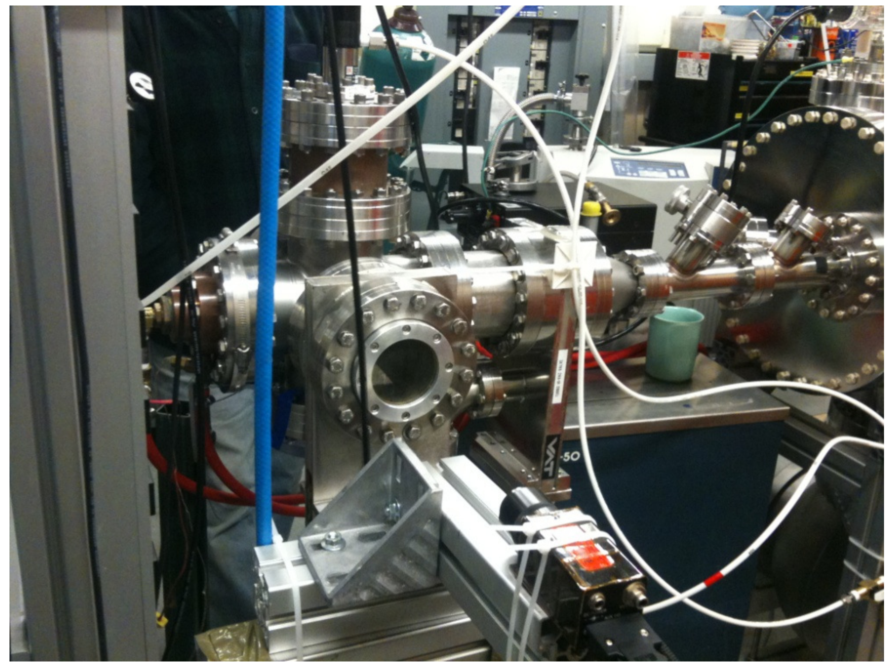
- Additional beam exposure tests:
  - Li-coated LLD sample
    - Strip heaters attached to sample
      - Enables in-situ (vacuum) calibration
      - Explore both solid & liquid Li regimes
    - Pneumatic feed-thru provides faster stroke time
      - Temporally uniform heat flux
      - MSE group also exploring “pulsed mode” beam operation
    - Longer pulse length
      - Test to failure!
  - Carbon sample (bare, Li-coated)
- 3-D Thermal Modeling (M. Jaworski)
- Possible collaboration with UIUC on surface modification by sputtering (VFTRIM)

Tests with Li-Coated LLD Sample are Imminent

- Li has been loaded on to a new LLD sample that has not been exposed to the DNB



New LLD sample coated with a fresh layer of Li



New experimental setup has been completed and Li sample will be installed as soon as next week

Summary/Conclusions

1. Will the LLD melt or suffer significant erosion?
   – No obvious macroscopic erosion or melting
   – Microscopic damage matches beam profile
     • HWHMs show sub-linear damage scaling with heat flux
     • Suggests "peaks" on LLD sample are eroded due to bombardment

2. How is thermal conductivity affected by the porosity?
   – Large correction needed (~20) suggests poor thermal contact between Mo and SS
   – Possible subject for future offline experiments

3. What are the Li erosion/sputtering yields? Does Li protect the Mo?
   – To be determined through further exposure tests.

Acknowledgements

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

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