Dual-band infrared observations of temperature dynamics on the NSTX liquid lithium divertor (LLD)

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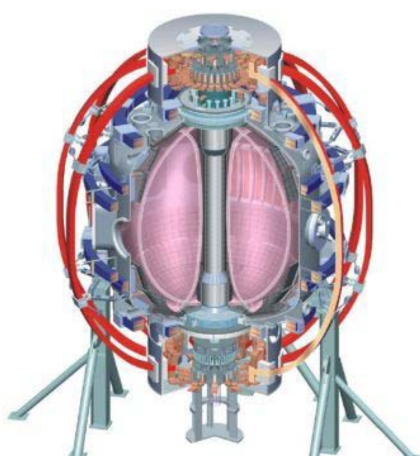
16 November, 2011



Outline

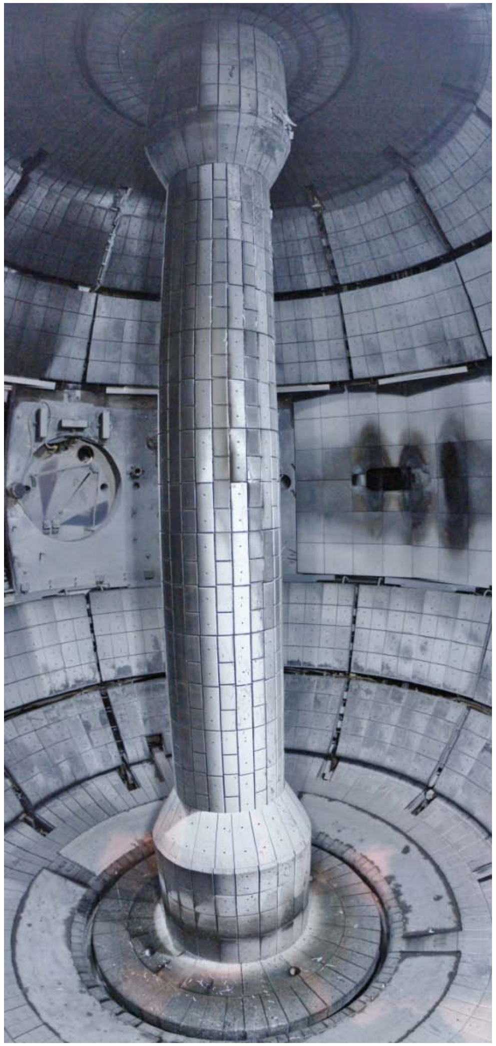
- Dual-band infrared technique demonstrated in NSTX in 2010
  - Also see J. Kallman, *et al*., PP9.00038 Wed. 2:00 PM
  - Also see J. Nichols, *et al*., PP9.00070 Wed. 2:00 PM
- Li melt dynamics on the LLD
  - Also see H.W. Kugel, *et al*., BO4.00009 Mon. 9:30 AM
  - Also see C.H. Skinner, *et al*., PP9.00025 Wed. 2:00 PM
- LLD vs. graphite tile surface heating
  - Also see K. Gan, *et al*., PP9.00027 Wed. 2:00 PM
  - Also see V. Surla, *et al*., PP9.00043 Wed. 2:00 PM
- Edge plasma modification with and without Li deposition
  - Also see J-W. Ahn, *et al*., NO4.00004 Wed. 9:30 AM
  - Also see M.A. Makowski, *et al*., PI2.00005 Wed. 4:00 PM
  - Also see R.Q. Maingi, *et al*., PP9.00044 Wed. 2:00 PM
  - Also see M. Segall, *et al*., JP9.00034 Tues. 2:00 PM
- Thermal diagnostic improvements on NSTX for 2014
  - Also see J. Nichols, *et al*., PP9.00070 Wed. 2:00 PM

The IR system on NSTX is designed to overcome limitations inherent in a complex Tokamak environment

- Accurate IR measurements are essential for heat load analysis on plasma-facing components (PFCs) during plasma operation, especially in the divertor region
  - Transient heat load can exceed 10 MW/m^2
  - Localized hot spots and significant impurity sources

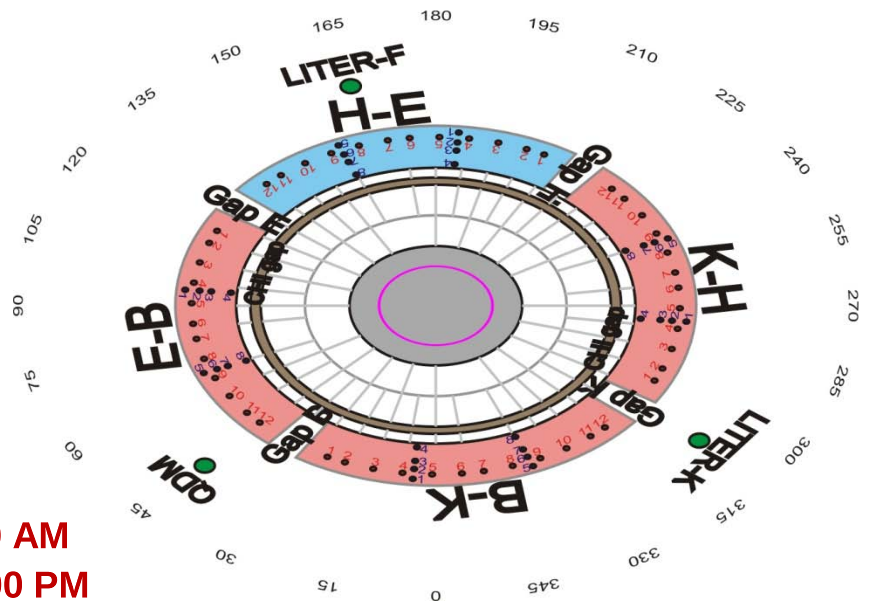
- Use of lithium coatings in NSTX make assumptions of high surface emissivity inaccurate
  - e.g., ε of graphite >0.85, ε of molten lithium <0.1

- Primary diagnostic effort to move from single-band to dual-band infrared observations
  - Technique measures temperature based on the ratio of integrated IR emission in two IR bands, not single band intensity → Less dependent on emissivity



The Liquid Lithium Divertor (LLD) was used extensively in the 2010 NSTX campaign

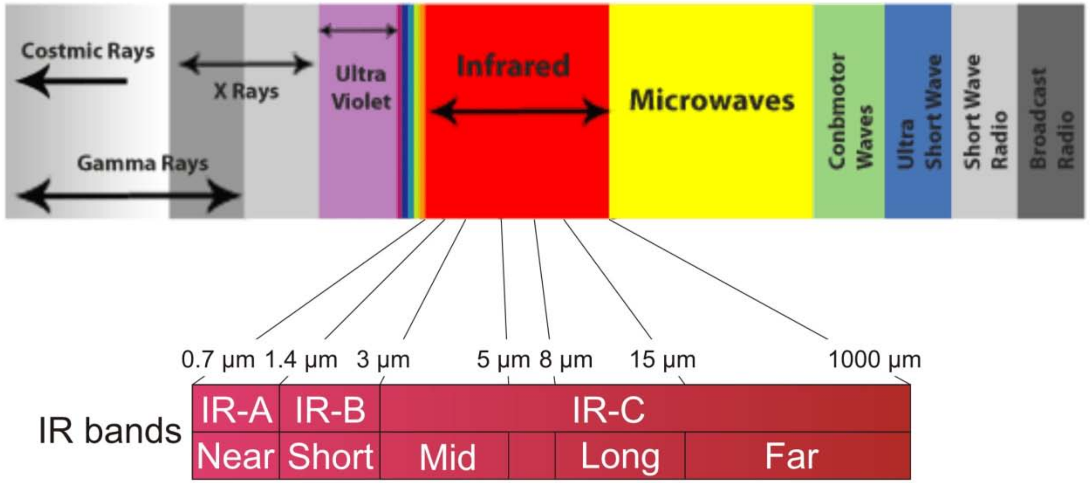
- Four plates extending toroidally around the outer divertor
- 12, 500W cartridge heaters and 44 type K thermocouples provide active control of each plate's temperature
- Electrically heated to
  - 100-199°C in 7 runs days
  - 200-299°C in 9 run days
  - Up to 320°C in 3 run days
- Heated by repeated plasma discharge exposure to
  - 100-130°C in 3 run days
- Heated by hot forced air to
  - 150-180°C in 2 run days
- Only heating to ≥ 180°C maintained Li as liquid between discharges



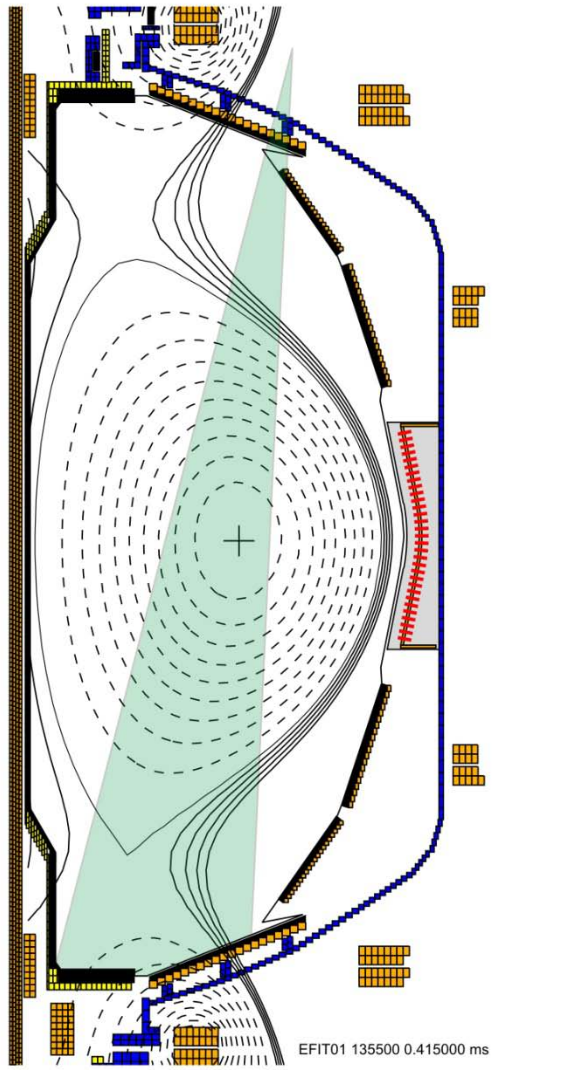
- **Also see H.W. Kugel, *et al*., BO4.00009 Mon. 9:30 AM**
- **Also see C.H. Skinner, *et al*., PP9.00025 Wed. 2:00 PM**

NSTX has extensive infrared coverage for surface temperature and heat flux diagnosis

- Two slow (30 Hz) single-band IR cameras
  - Indigo Omega, 30 Hz, 160x128 pixel uncooled microbolometer FPA, 3.4 x 3.7 x 4.8 cm
  - 7-13 μm, 12-bit, 0-700°C range, ZnSe window
  - 15° FOV of lower divertor, ~0.7 cm/pixel resolution
- One fast (1.6-6.3 kHz) dual-band IR camera
  - Santa Barbara Focal Plane (Lockheed Martin) ImagIR 128x128, 40μm pixel HgCdTe FPA, LN_2-cooled
  - QE>90% from 1.5-11 μm, 14-bit, <20 mK NETD
- 2011 addition of dual-color, wide angle IR camera



NSTX fast IR camera field of view



Primary dual-band IR adaptor components

- Long-wave pass dichroic beamsplitter
  - Lambda Research Optics (CA, US)
  - Long-wave pass (7-10 μm transmit with T_{avg}~92%)
  - Medium-wave reflect (4-6 μm reflect with T_{avg}~99%)
- Image splitter optical platform
  - CAIRN Research OptoSplit II (UK)
  - Extensively modified for operation in IR
  - Precision multi-axis optical alignment, focusing, flexibility

- Lenses
  - Broadband AR-coated Diffractive Optical Element (DOE) hybrid singlet lenses
    - 10X reduction in chromatic aberration, reduced spherical aberration, improved SNR compared to meniscus lenses
  - II-VI Infrared (PA, US)
- Shortwave pass (SWP) and longwave pass (LWP) IR filters to limit spectral contamination in each channel
  - Reynard Corporation (CA, US)
- Custom designed lens adaptors/mounts

Calibration of the ratio of emission intensities to temperature removes emissivity as a variable

- Two-color camera measures temperature based on the ratio of integrated IR emission in two IR regions, not single band intensity
- Mathematically
  - Planck's law for photon emittance [ph/s/cm^2/μm]
  - Radiant emittance from source some fraction of that from a blackbody source [W/cm^2/μm]
- If emissivity, ε, in both wavelengths regions is equal, first term in denominator falls out

$$Q_{BB}(\lambda,T) = \frac{2\pi c}{\lambda^4 \cdot \left[exp\left(\frac{hc}{\lambda kT}\right) - 1\right]} \qquad W(\lambda,T) = \frac{hc}{\lambda} Q(\lambda,T)$$

$$I_{\lambda,surf}(\lambda,\theta,\phi,T) = \varepsilon_{\lambda,\theta}(\lambda,\theta,\phi,T) \cdot I_{\lambda,BB}(\lambda,T)$$

$$\frac{I_{\lambda_1,surf}}{I_{\lambda_2,surf}} = \frac{\varepsilon_{\lambda_1,\theta}}{\varepsilon_{\lambda_2,\theta}} \cdot \frac{I_{\lambda_1,BB}}{I_{\lambda_2,BB}}$$

$$I_{\lambda,BB}(\lambda,T) = \frac{2\pi hc^2}{\lambda^5 \cdot \left[exp\left(\frac{hc}{\lambda kT}\right) - 1\right]} \cong \frac{2\pi hc^2}{\lambda^5 \cdot \left[exp\left(\frac{hc}{\lambda kT}\right)\right]}, \text{since } exp(hc/\lambda kT) \gg 1$$

$$\vdots$$

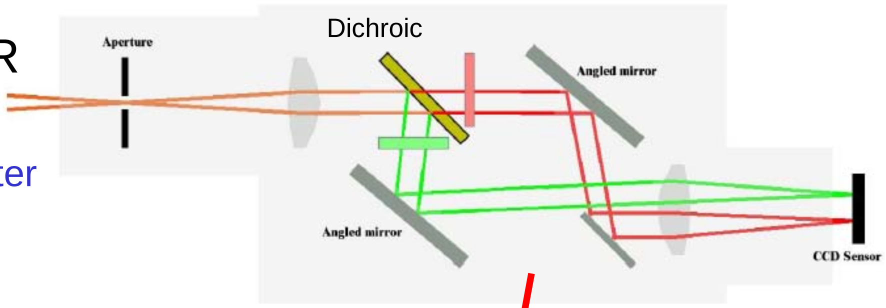
$$T = \frac{hc}{k} \cdot \frac{\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right)}{\left[ln\left(\frac{\varepsilon_{\lambda_2,\theta}}{\varepsilon_{\lambda_1,\theta}}\right) + ln\left(\frac{I_{\lambda_1,surf}}{I_{\lambda_2,surf}}\right) + ln\left(\frac{{\lambda_1}^5}{{\lambda_2}^5}\right)\right]}$$

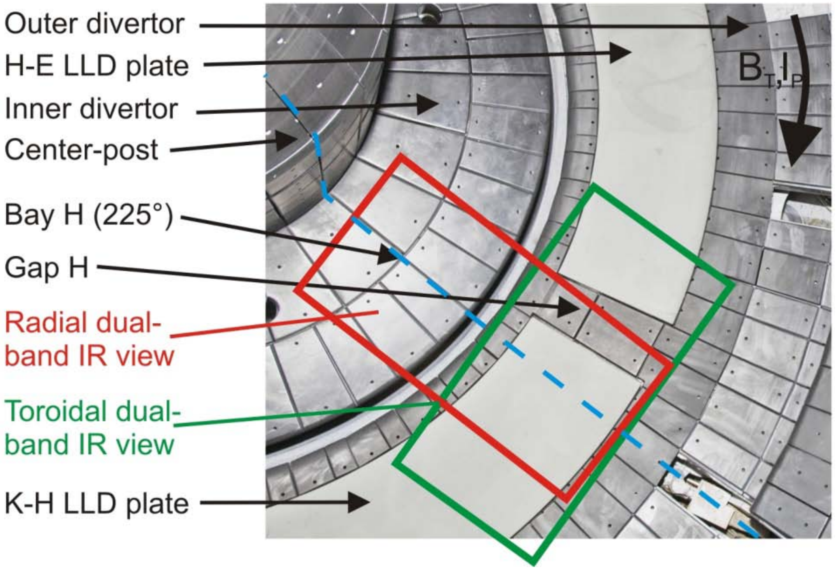
0

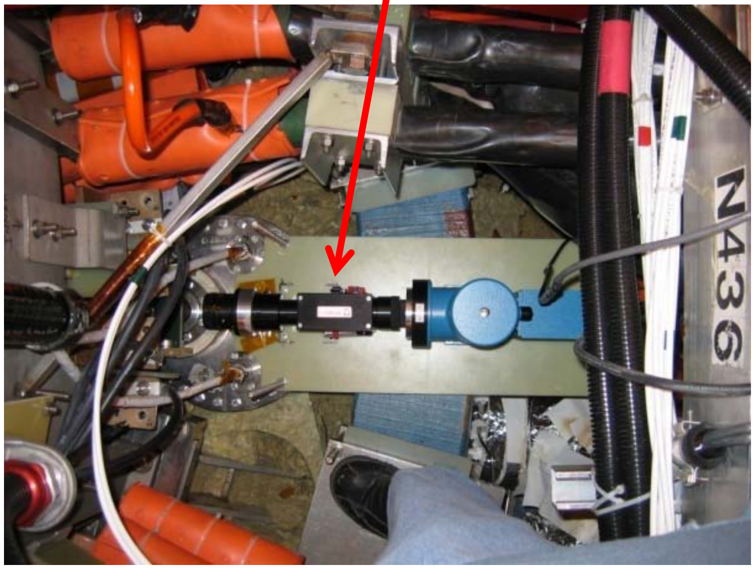
NSTX operates with a first-of-its-kind optical dual-band-capable fast IR camera

- Pioneering adaptor based on new commercial IR optical capabilities
- An optical splitter is inserted between the IR camera and lens
  - Contains an IR-specific custom dichroic beamsplitter
  - Diffractive optical element (DOE) hybrid singlet lenses for low chromatic aberration
  - Projects separate IR wavelengths side-by-side on the camera's detector

Dual-band IR adaptor layout







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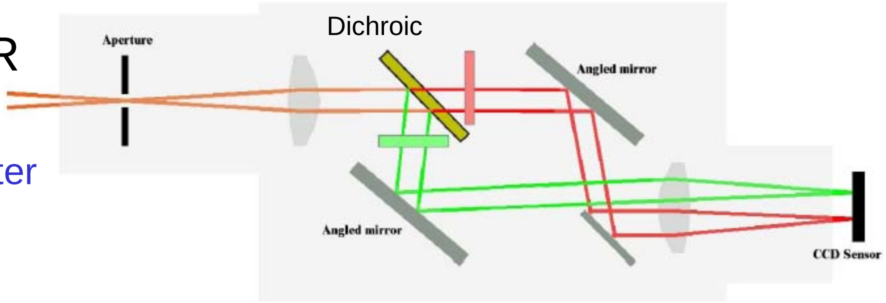
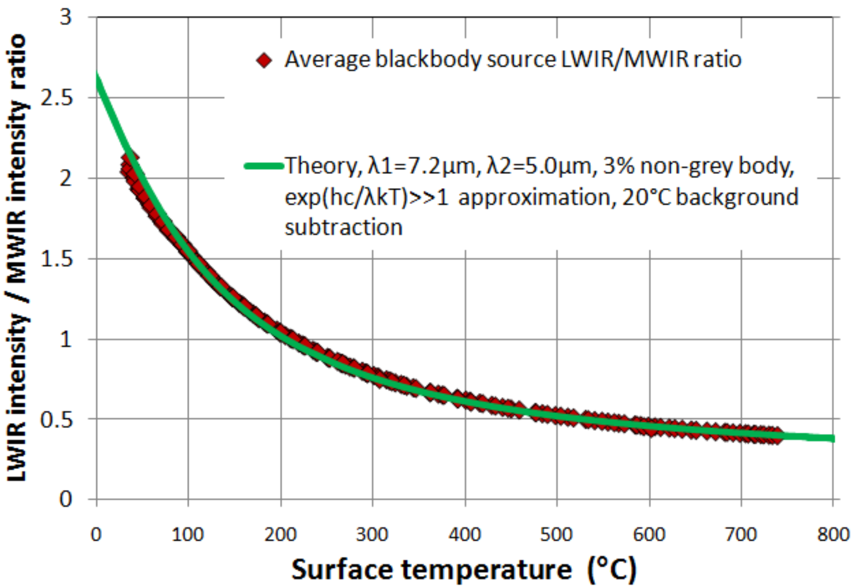
  - Diffractive optical element (DOE) hybrid singlet lenses for low chromatic aberration
  - Projects separate IR wavelengths side-by-side on the camera's detector
- Intensity ratio calibrated vs. temperature *ex-situ* using a blackbody source, and *in-situ* by artificially heating the LLD
- Dual-band IR cameras now available from three companies worldwide
  - Integrate two detecting elements into each pixel
  - However, all limited to ≤300 Hz frame rate
  - $200+k cost, 3-6 month lead time
- Optical image splitter: $20k total cost, adaptable to any IR camera

Dual-band IR adaptor layout



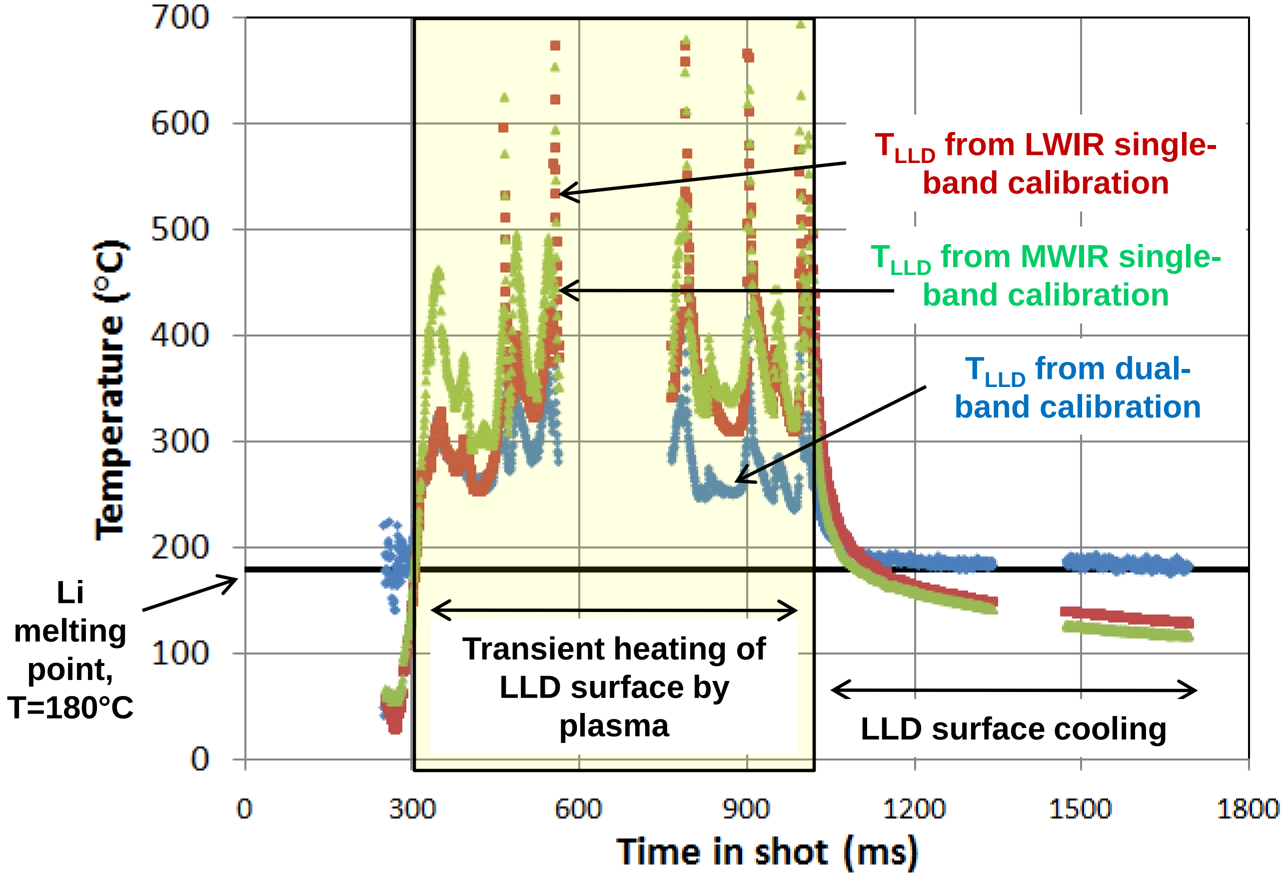
Dual-band intensity ratio calibration



Interpretation of NSTX data viewing the LLD in single-band intensity vs. dual-band ratio demonstrates the technique

- Independent calibrations in both single-bands (MWIR and LWIR), and calibration using the **dual-band ratio** are performed

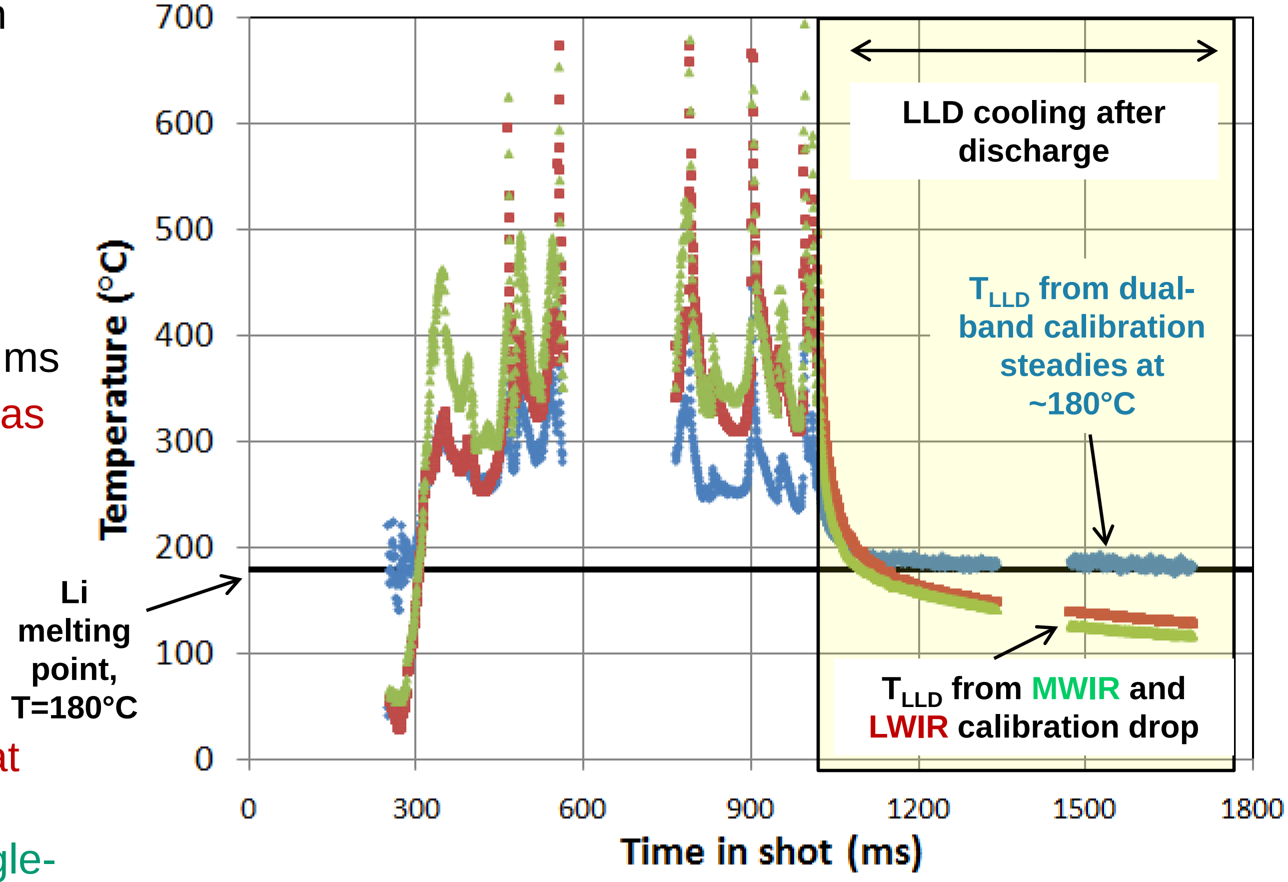
Surface temperature measured by the fast IR camera at the outer strike point in an NSTX plasma discharge



Interpretation of data in single-band intensity vs. the dual-band ratio demonstrates that the technique works

- Independent calibrations in both single-bands (MWIR and LWIR), and calibration using the **dual-band ratio** are performed
- In single-band results, apparent LLD surface temperature reduces monotonically after ~1000 ms
  - Change in emissivity as Li solidifies not accounted for
- **However, dual-band calibrated temperature steadies at Li melting temperature**
  - Indicator of latent heat of solidification
- Bonus: Ratio between single-band and dual-band temperature is a measure of surface emissivity

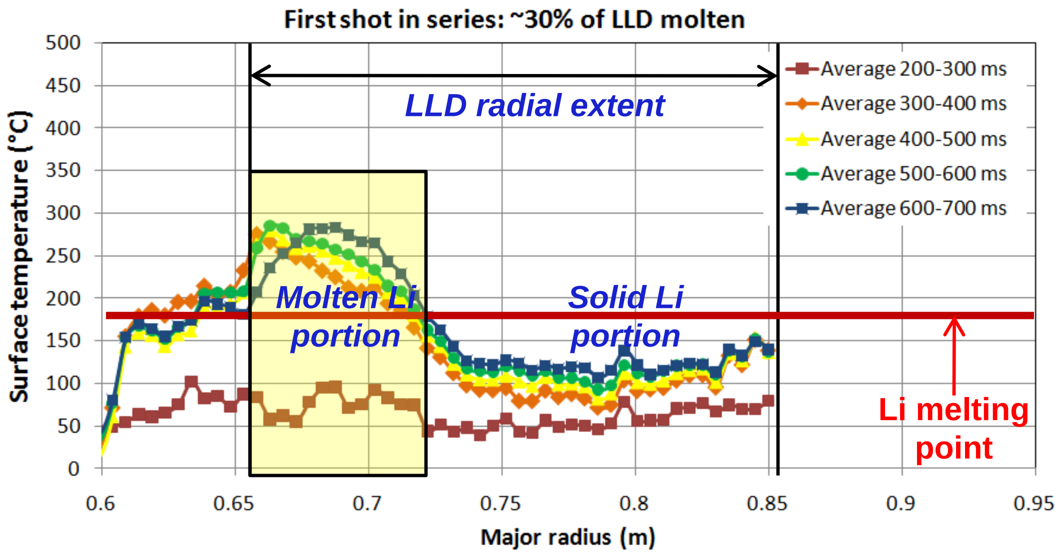
Surface temperature measured by the fast IR camera at the outer strike point in an NSTX plasma discharge

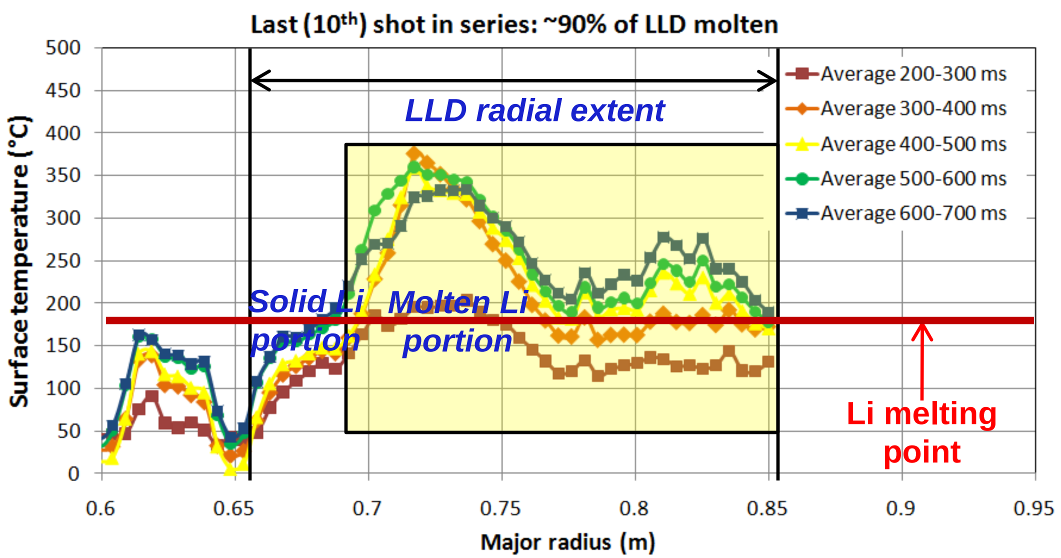


**** All subsequent data shown is dual-band***

Incremental plasma exposure in discharge series on the LLD causes the melted area to increase

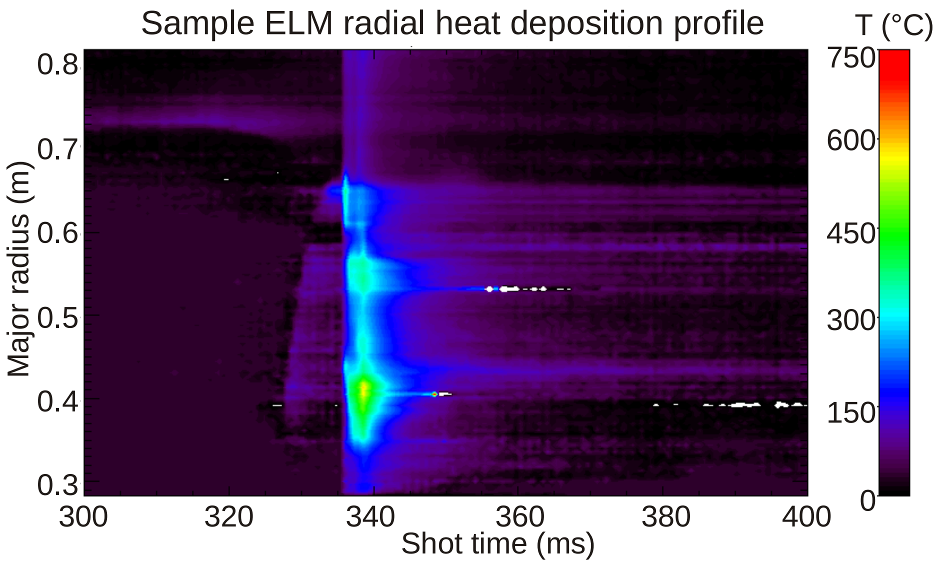
- Heating of the LLD surface over a series of repeat discharges demonstrates how the Li surface is heated
  - ~30% of total LLD surface at > Li melting at beginning of series
  - Melted fraction does not change significantly in one discharge
- Melted area increases to ~90% of LLD surface by end of discharge series

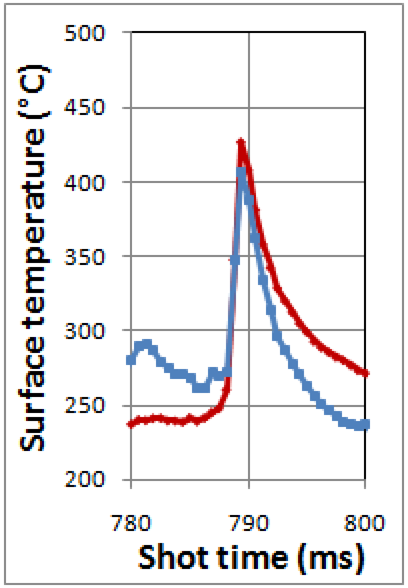


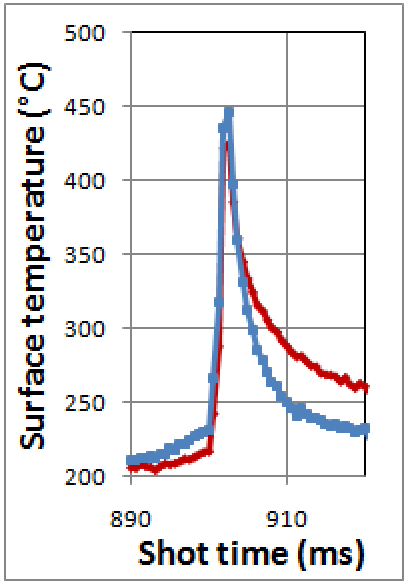


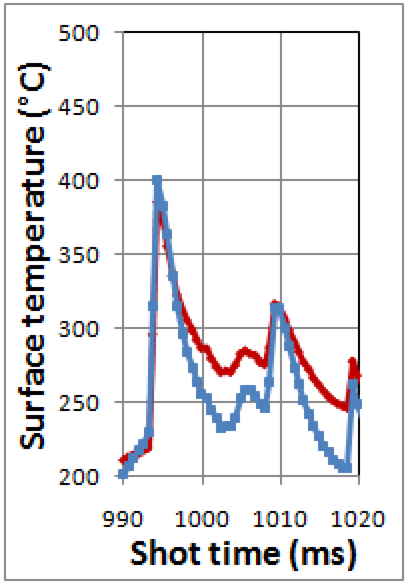
Transient power excursions (ELMs) on the LLD cause brief heating of surface to >500°C

- ELMs can occur frequently on the LLD, depending on plasma geometry and conditions
- Temperature during ELMs briefly (<5 ms) reach >400°C
- Further study required to determine whether this may be a significant Li evaporation loss mechanism





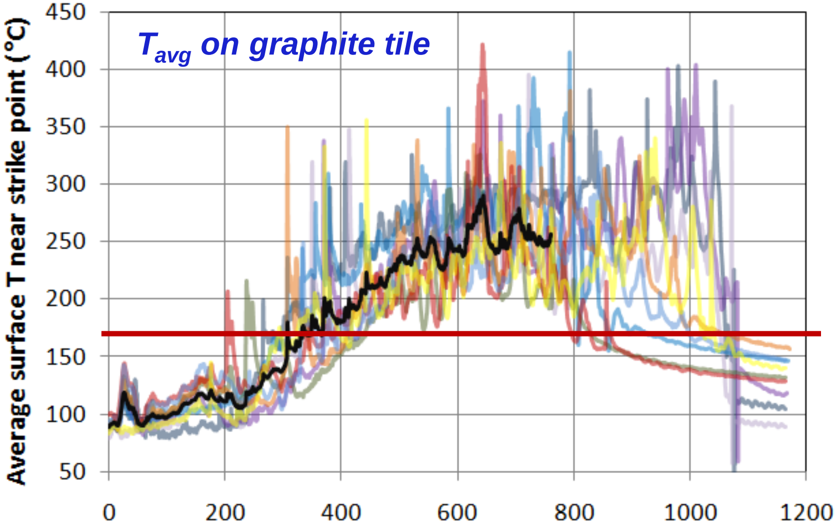


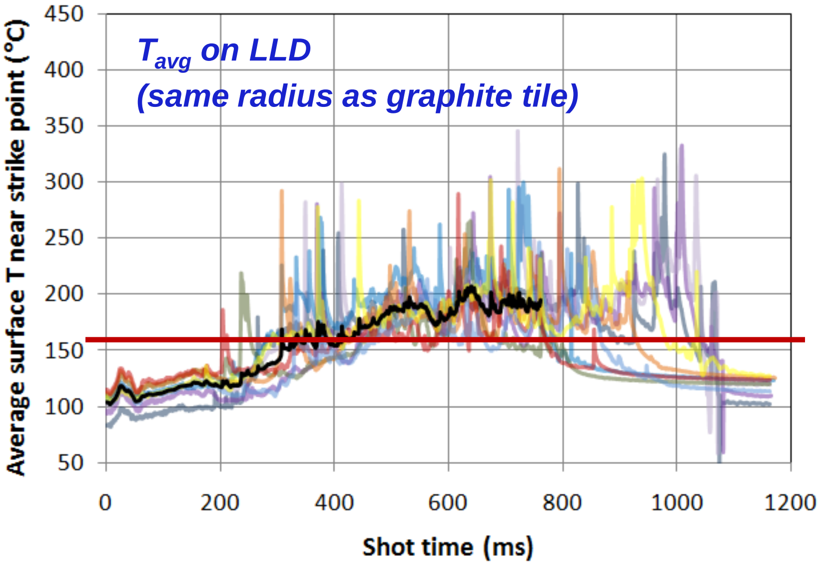


Also see V. Surla, *et al.*, PP9.00043 Wed. 2:00 PM

T_{avg} near OSP on LLD and graphite tile at equal radii suggests that Li in the LLD is causing clamping of the temperature

- Series of 10 repeat discharges with outer strike point on the LLD
- Graphite and LLD in this case begins with T_{Li}~70°C
- T_{avg} on graphite gap tile increases through all shots in SQRT(t) fashion
  - Average $T_{surface}$ of ~250°C
- Falls back to ambient post-discharge
- T_{avg} plotted at same radius, but on LLD
- T_{avg} on LLD surface gravitates at $T_{melt,Li}$ (average $T_{surface}$ of ~180°C) throughout discharges, increases with ELMs
  - Efficient heat removal through LLD depth?
  - Li radiation, vapor shielding playing a role?
- Insufficient energy to maintain Li 'bulk' at Li melting temperature
  - Measured response dominated by thin upper surface

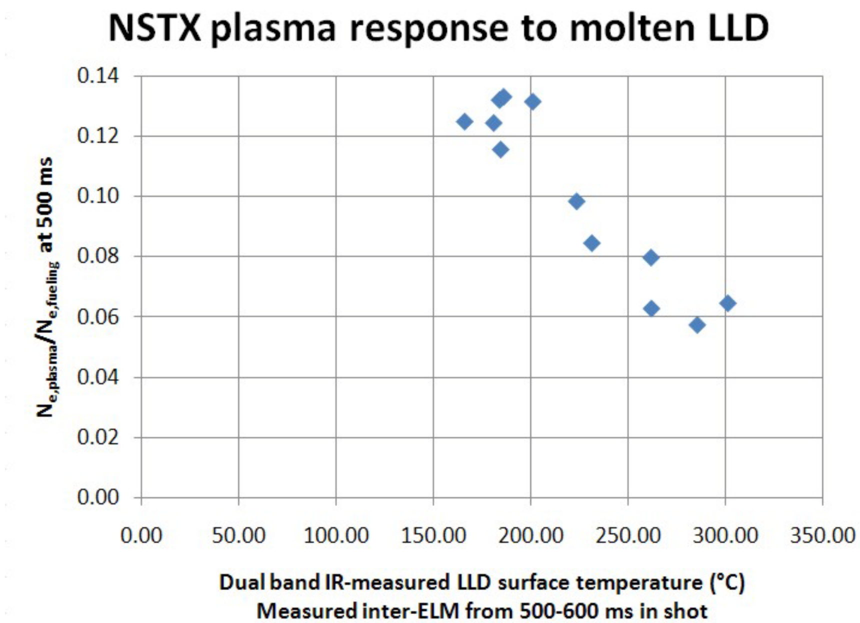


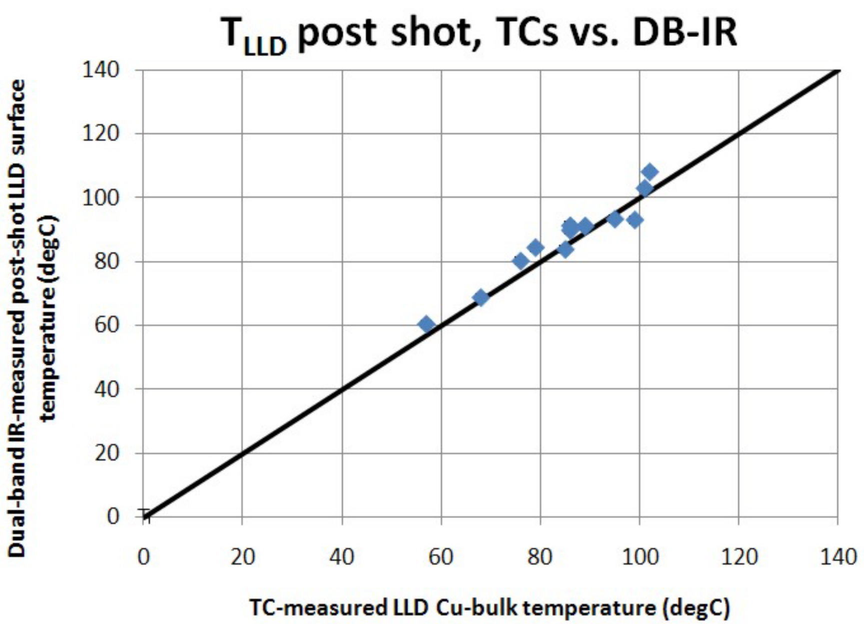


- **Also see K. Gan, *et al*., PP9.00027 Wed. 2:00 PM**

Dual-band IR data shows possible D pumping effect by LLD in NSTX

- Series of 20 shots with OSP on LLD, heating bulk Li up by 5-10 °C per shot
- Thomson and fueling used to measure ratio of $N_{e,plasma}$ over $N_{e,fueling}$ at 500 ms in each discharge (M. Bell)
- Average inter-ELM LLD surface temperature near the OSP from 500-600 ms measured by dual-band IR
- Ratio found to decrease significantly as T_{surf} increases
- T_{surf} post-shot found to match well between dual-band IR and LLD TCs



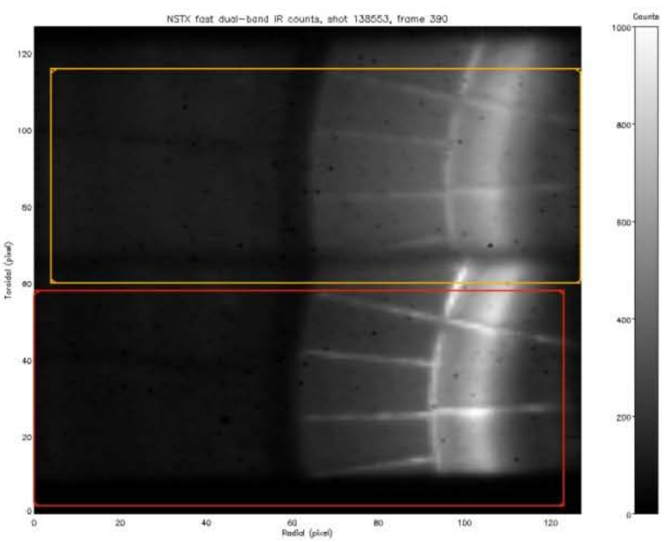


- **Also see H.W. Kugel, *et al.*, BO4.00009 Mon. 9:30 AM**

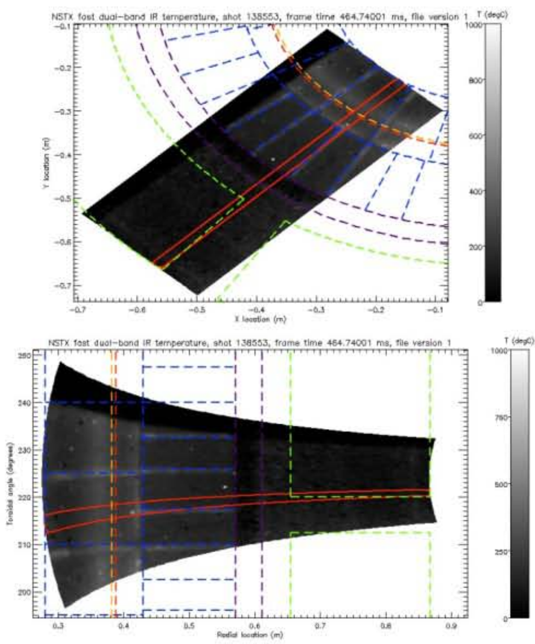
The IDL-based FURNACE analysis suite integrates dual-band IR calibration and analysis for NSTX database

- Semi-automated image alignment, (spatial/temporal/temperature) calibration, and heat flux calculation for any shot in the 2010 NSTX database
  - Ratio profile highly dependent on accurate band image alignment
- Incorporation of 1-D Carslaw & Jaeger heat flux calculation and THEODOR (A. Herrmann) for determination of 2-D heat flux (q)
  - Adds thin layer with poor thermal contact, artificially high heat transmission coefficient, α
  - Value of α estimated based on power balance through the shot
- 1-D vs. radius, 1-D vs. time, 2-D output for ease of visualization

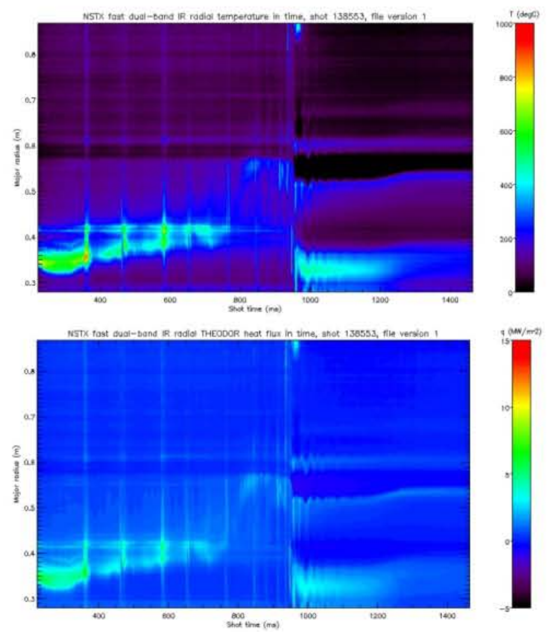
Raw dual-band data



Aligned, calibrated

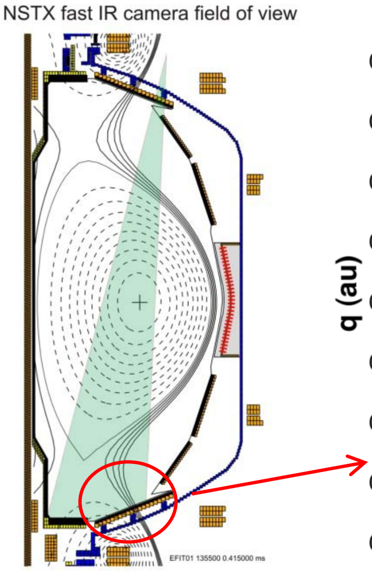


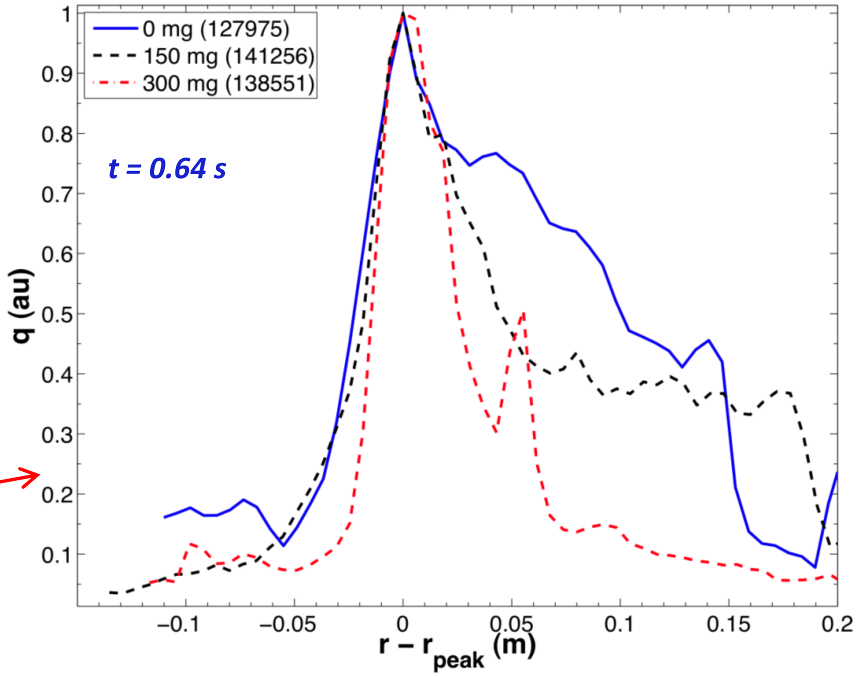
T(R,t), q(R,t)



Divertor λ_q contracts with increasing lithium deposition

- Type V ELMs eliminated from discharges with Li deposition
  - Some sporadic type I ELMs are still present
  - Responsible for some of the contraction in IR profiles
- λ_q^{div} contracts further with increasing lithium deposition
- This effect is confirmed by dual-band IR measurements



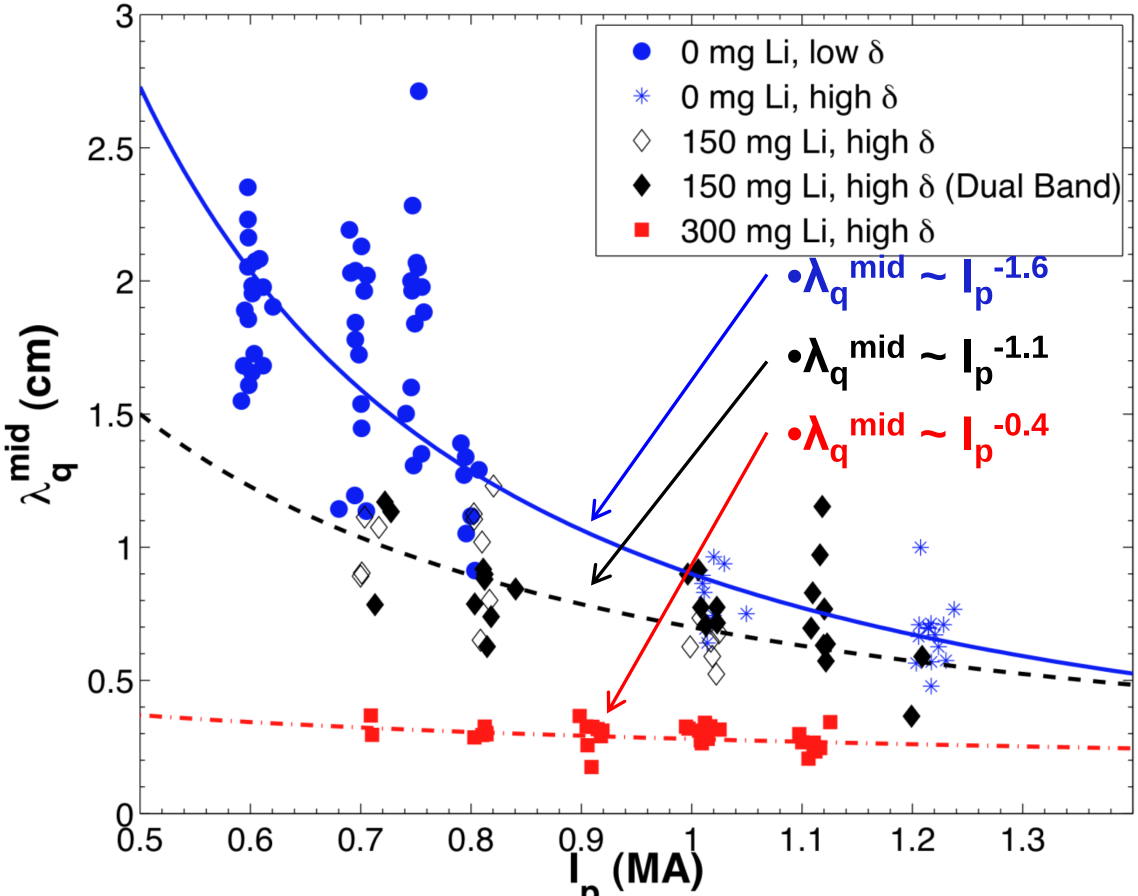


	0 mg	150 mg	300 mg
λ_q^{div} (cm)	14.1	13	7
λ_q^{mid} (cm)	0.98	0.74	0.37

- **Also see R.Q. Maingi, *et al*., PP9.00044 Wed. 2:00 PM**
- **Also see M. Segall, *et al*., JP9.00034 Tues. 2:00 PM**

Dual-band IR data agrees with previous results: Scaling of λ_q^{mid} with I_p Relaxes with Increased Lithium Deposition

- Without lithium, λ_q^{mid} has shown a strong contraction with I_p
- As increasing amounts of lithium are deposited, this trend relaxes
  - $\lambda_q^{mid} \sim I_p^{-0.4}$ at 300 mg
- Suggests reduced perpendicular transport in the SOL
  - Modeling with XGC0 suggests $\lambda_q^{mid} \sim I_p^{-1}$ with neoclassical transport [JRM 2010 Final Report]



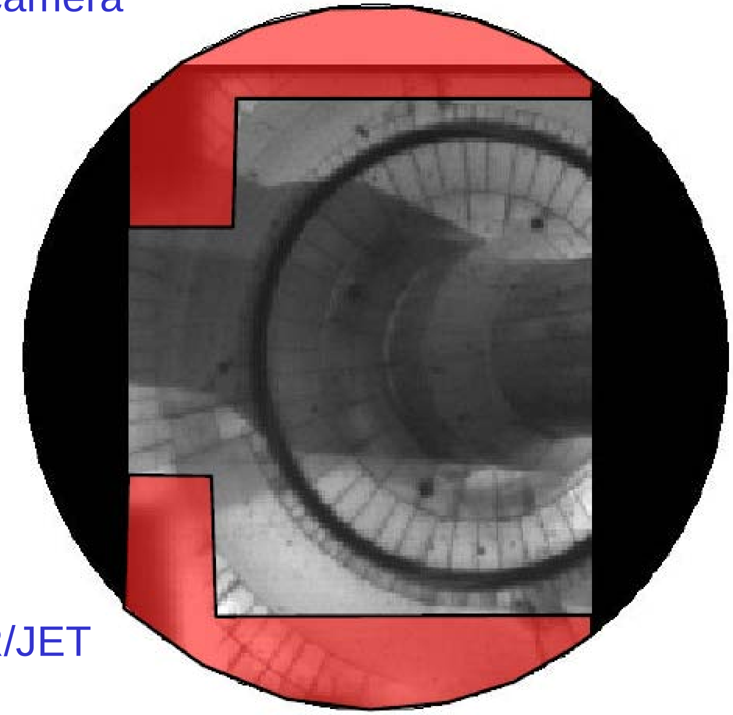
- LSN Discharges, during I_p and W_{MHD} flattops
- P_{NBI} = 4 MW (some 6 MW data in 0 mg discharges)
- $4 < n_e^{LD} < 7(10)^{19}$ m^{-3}

- **Also see M.A. Makowski, *et al*., PI2.00005 Wed. 4:00 PM**

Wide-angle two-color IR camera on NSTX

J. Nichols, A. McLean, J. Ahn, K. Gan, R. Maingi, L. Roquemore, B. Stratton, T. Gray

- Wide-angle, high-resolution temperature and heat flux measurements
  - Dynamic range similar to existing dual-band camera
  - Straightforward observation of non-axisymmetric phenomenon
- Two color: 8-10 µm and 10.5-13 µm in the LWIR band
  - FLIR Tau 640x480, 30 Hz, LWIR microbolometer camera
- Radial/toroidal configurations
  - Diagnosis of Moly tiles
  - High-res radial profile out to R=120 cm
  - 180° coverage of OSP
  - 4 mm spatial resolution
- Optical relay to locate camera outside of magnetic field
  - Re-entrant tube with CVD diamond window
    - Allows 450°C bake uncooled
  - Reflective ellipsoidal light collection (based on ITER/JET design)
  - BBAR coated ZnSe optics, Au-coating reflective surfaces

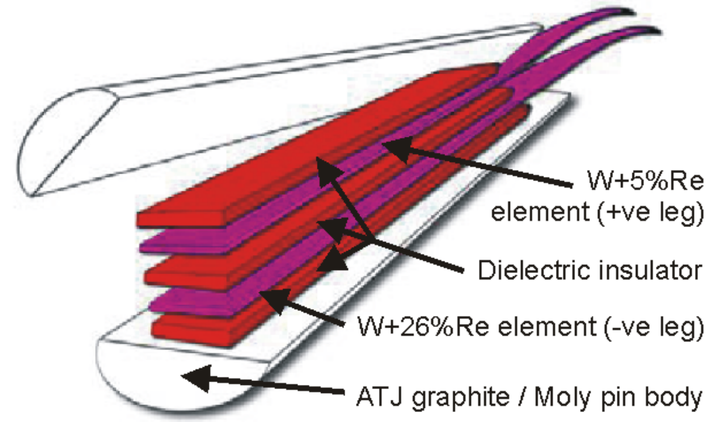


- **Also see J. Nichols, *et al.*, PP9.00070 Wed. 2:00 PM**

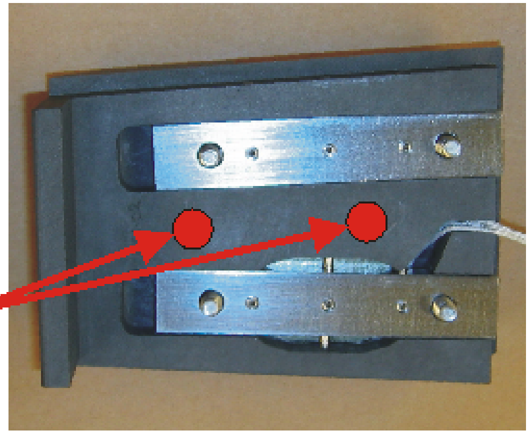
Fast 'eroding' thermocouples (TCs) for NSTX

A. McLean, J. Ahn, T. Gray, H. Kugel, R. Maingi, L. Roquemore

- Standard TC junctions have ~100 ms response time due to thermal mass
  - Existing array of TCs in NSTX not active during plasma discharges
- Junction in 'eroding' or 'self-renewing' thermocouples forms dynamically between ribbons (0.0015" thick) separated by thin (0.0002") dielectric insulator layers
  - Used in transient high heat-flux environments (rockets, gun barrels, recently on C-Mod)
  - ~1 ms response time, in direct plasma contact to provide direct benchmark of heat flux measured by infrared cameras
- Strong collaboration with patent holder, Nanmac (Ma. US, www.nanmac.com)
- High temperature Type C design
  - Tungsten (W) / Rhenium (Re), 0-2320°C range

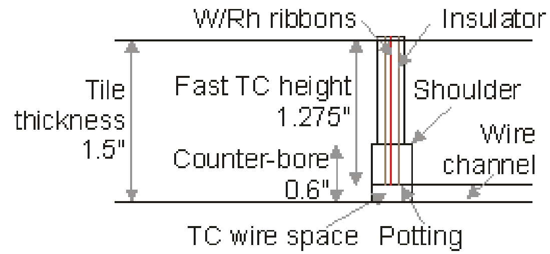


Tile #1 underside



Fast TC locations penetrating the surface

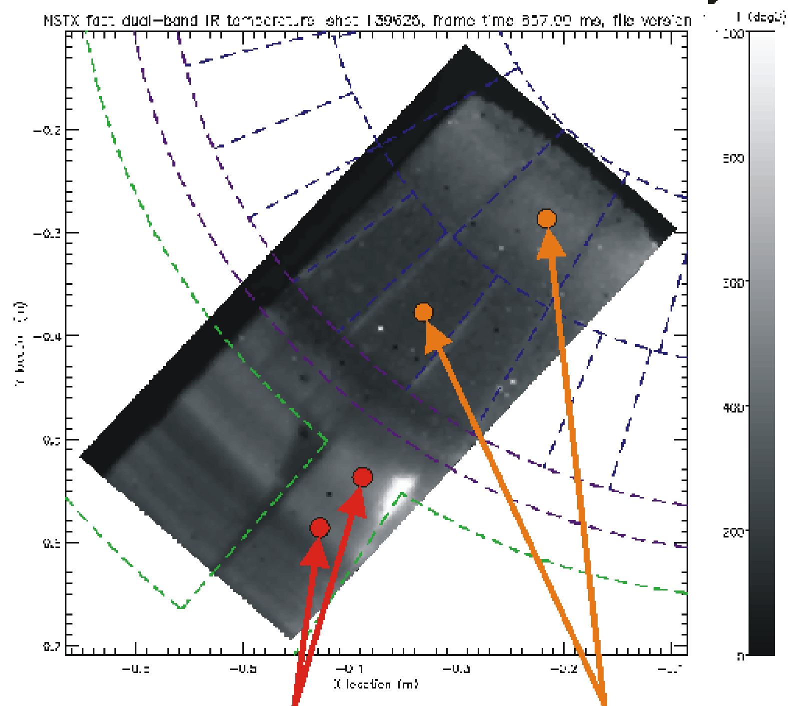
Poloidal cross section



Two fast thermocouple have been installed for use in 2014

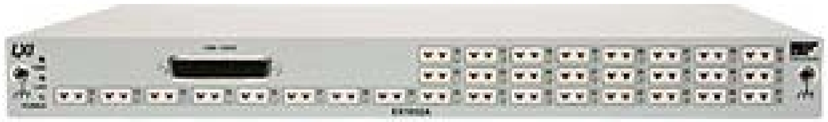
- Initially, single pair of self-renewing TCs with graphite body installed in this vent
  - Units in Gap H tile 1
  - Optimal observation by IR cameras
  - Overlaps radial extent of Langmuir probe array
- Additional pair of Mo-body TCs
  - Installation in Mo tile row next vent
- High temperature twisted Type C wire
  - Omega EXGG-C glass braided (max 427°C)
  - Twisted for low noise, covered with fiberglass sleeving (Markel Thermoflex-1200, max 650°C)
  - Assembly baked to 400°C for 16 hours (Jurczynski)
- High-speed (1 kHz) integrated signal conditioning, cold-junction compensation, plus isolation and self calibration
  - VTI EX1000A series controller (32 channels)
  - Ethernet for post-shot upload to MDSplus

Fast dual-band IR view from Bay H



Proposed graphite fast TC locations (2011)

Proposed moly fast TC locations (2012)



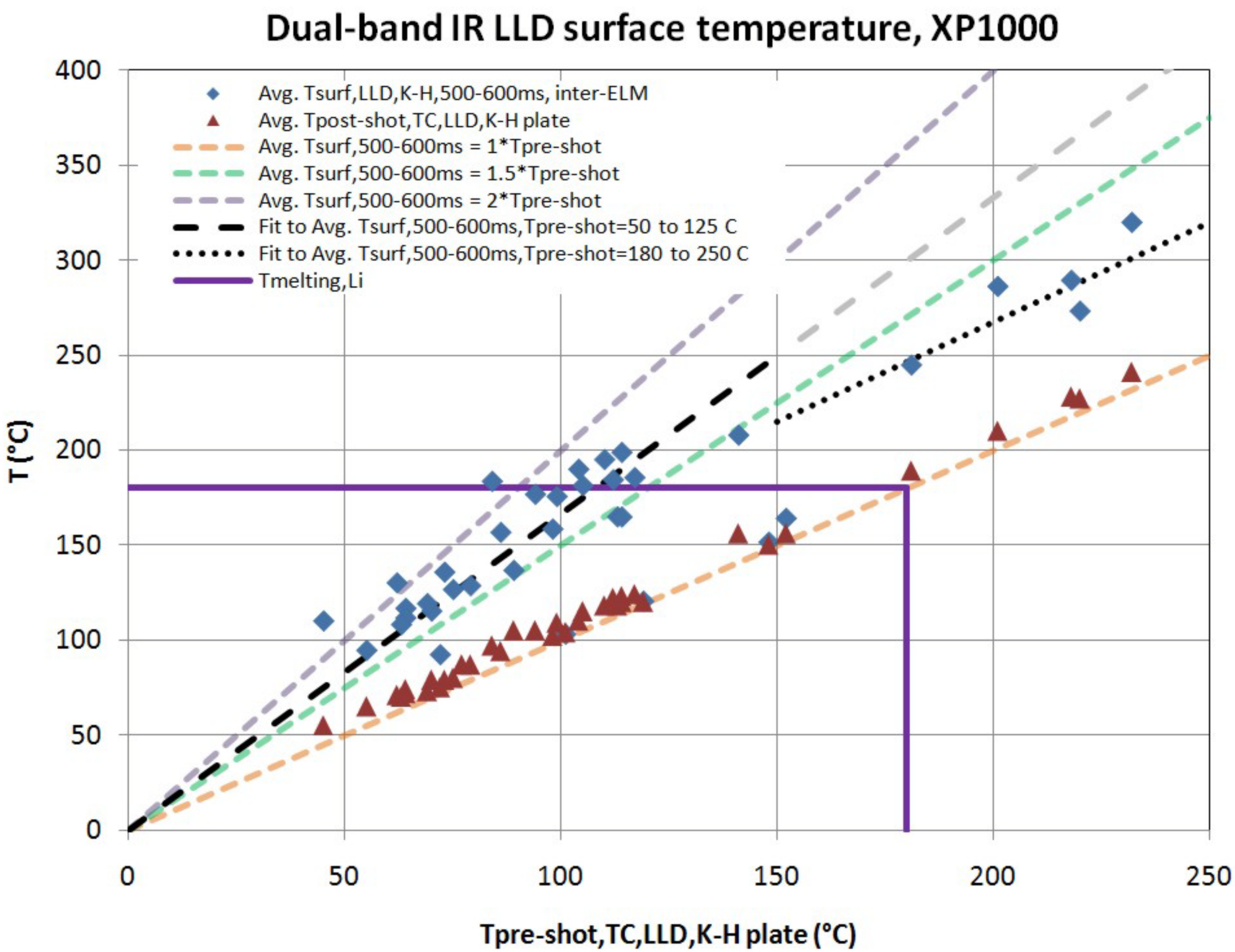
LLD temperature dynamics provide a glimpse of an operating regime for Li as a Tokamak first-wall material

- Dual-band IR measurement of LLD surface proven effective
- Front face thermal properties of the LLD are dominated by the Cu substrate → See the poster on Friday
- Surface temperature dynamics heavily dependent on total surface area with $T>T_{melt,Li}$
- LLD surface shows significant signs of clamping in peak and radially averaged temperature compared to graphite where no clamping occurs
- Deposition of increasing amounts of Li leads to contraction of the heat flux profile, but with lower peak values

Emails for poster copies

Backup slides

- T_{avg} of LLD surface at equal points in repeat shots as LLD heats up
- Suggests that thermal capacity of Li layer does not substantially change with LLD bulk temperature



Bulk temperatures in the LLD plates show expected heating and cooling rate characteristics

- Thermocouples measure the bulk temperature in the copper plates beneath SS and porous Mo layers
- Cooling depends on whether previous plasma discharge exposed the LLD to significant heat flux
  - When exposed to the OSP, heat pulse through Li, Mo and SS leads to slower average cooling rate
- Higher LLD starting temperature leads to
  - Faster cooling rate when unheated
  - Slower heating rate when heated