NSTX

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ORNL Oak Ridge National Laboratory

Application of fast dual-band infrared imaging on NSTX

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8 November, 2010

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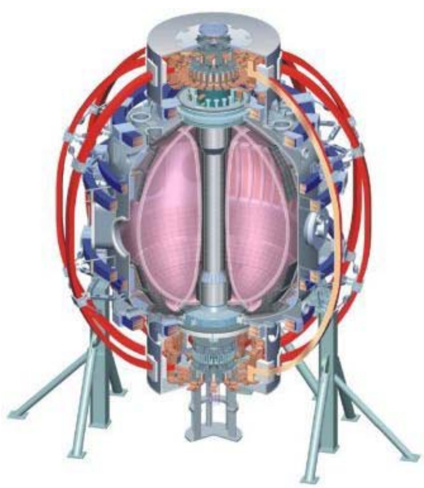
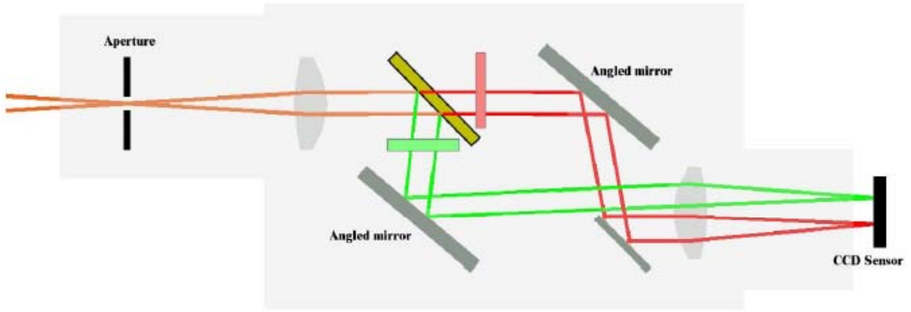


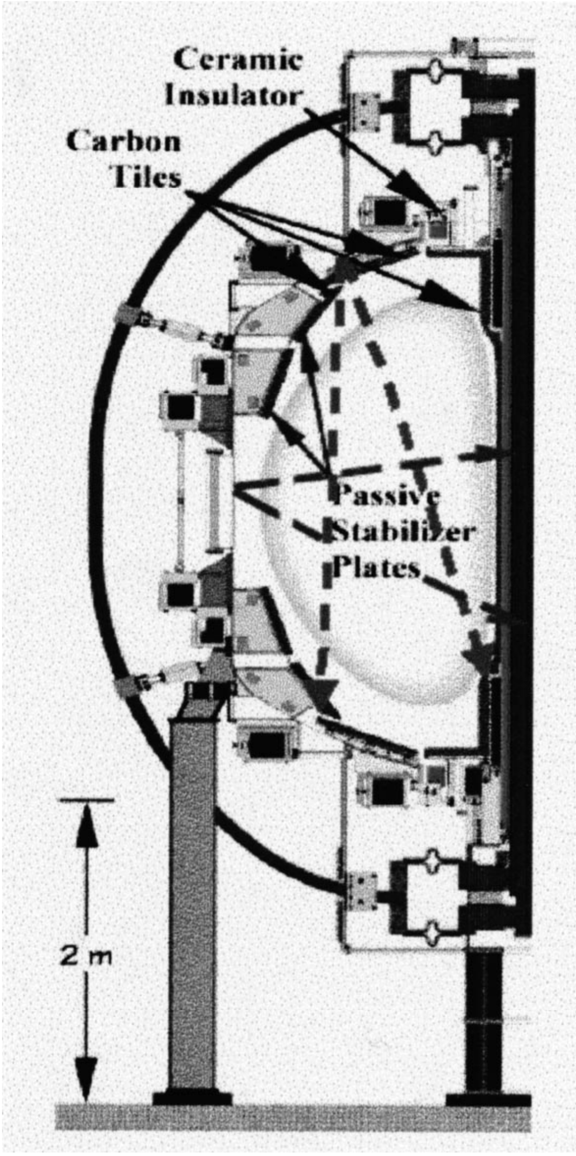
Infrared measurements on NSTX

- Essential for heat load measurement on plasma-facing components during plasma operation, especially in the divertor region
  - Heat flux calculated using 1-D conduction Carslaw and Yeager model into semi-infinite solid, and 2-D using THEODOR in collaboration with IPP Garching
  - Transient heat load can exceed 10 MW/m^2
  - Localize hot spots and significant impurity sources
- Use of lithium coatings in NSTX will make assumptions of high surface emissivity (applicable to graphite) inaccurate
  - Complications include: Surface coating changes in real time during plasma shots, emissivity changes due to H-absorption in Li, reflections from Li surface, deposition of Li on C surfaces, erosion/transport of Li and C
- Two-color camera measures temperature based on the ratio of integrated IR emission in two IR bands, not single band intensity
- Dual-band IR cameras now available from three companies worldwide
  - Limited to ≤300 Hz frame rate
  - $200+k cost, 3-6 month lead time
- Alternative: Optical image splitter



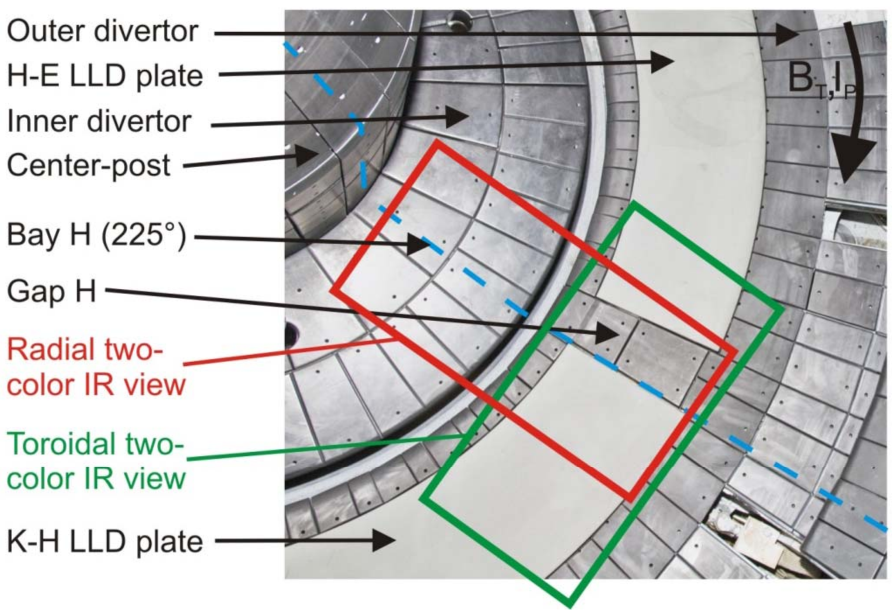
ORNL IR system currently on NSTX

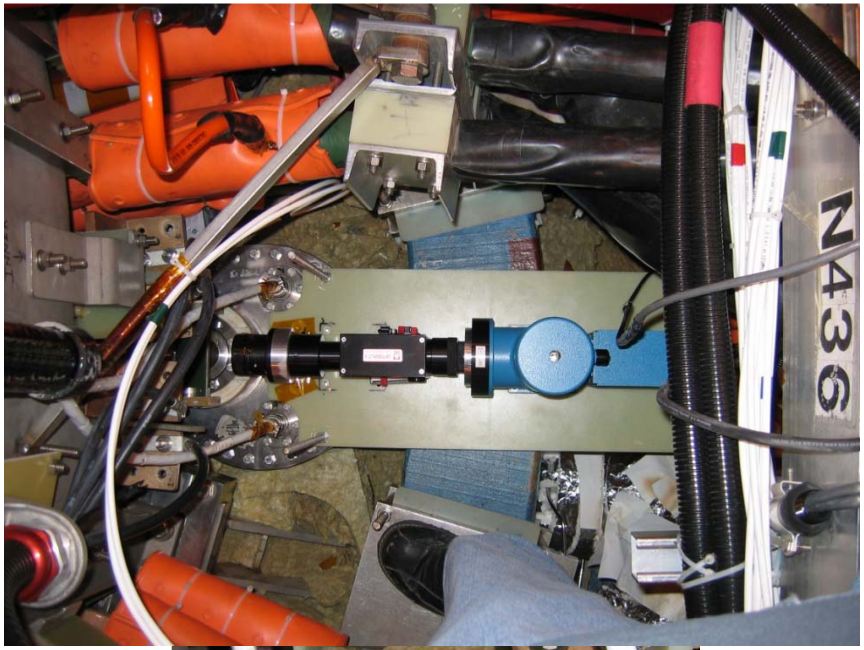
- Two slow (30 Hz) IR cameras
  - Indigo Alpha/Omega, 30 Hz, 160x128 pixel uncooled microbolometer FPA, 3.4 x 3.7 x 4.8 cm
  - 7-13 µm, 12-bit, 0-700°C range, ZnSe window
  - First camera: 15° FOV of lower divertor, ~0.7 cm/pixel resolution
  - Second camera: 15° FOV of upper divertor, ~0.6 cm/pixel resolution
- One fast (1.6-6.3 kHz) IR camera
  - Santa Barbara Focal Plane (Lockheed Martin) ImagIR 128x128, 40µm pixel HgCdTe FPA
  - QE>90% from 1.5-11 µm, 14-bit, <20 mK NETD
  - 25 mm *f*#2.3 Janos Varia (8-12 µm, T_{avg}=95%) and Ninox lenses (3-12 µm, T_{avg}=75%)
  - Bay H, 15.5° FOV of lower divertor, LN_2-cooled,
  - 8-12 µm AR-coated ZnSe window

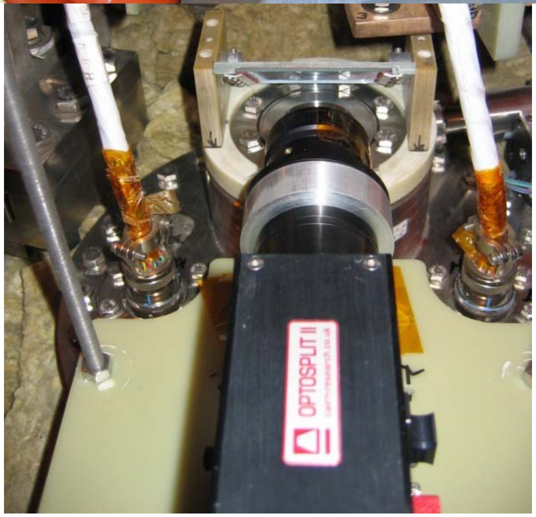


Modifications required for dual-band IR adaptor

- True-radial view into NSTX vessel
  - Adaptor able to be rotated to view 128x64 pixels in radial or toroidal direction
- Camera mount redesigned to include:
  - ~12” extension to accommodate length of image splitter
- Xeon-based PC operating camera moved outside of the test cell using fiber-optic Cablelink extender

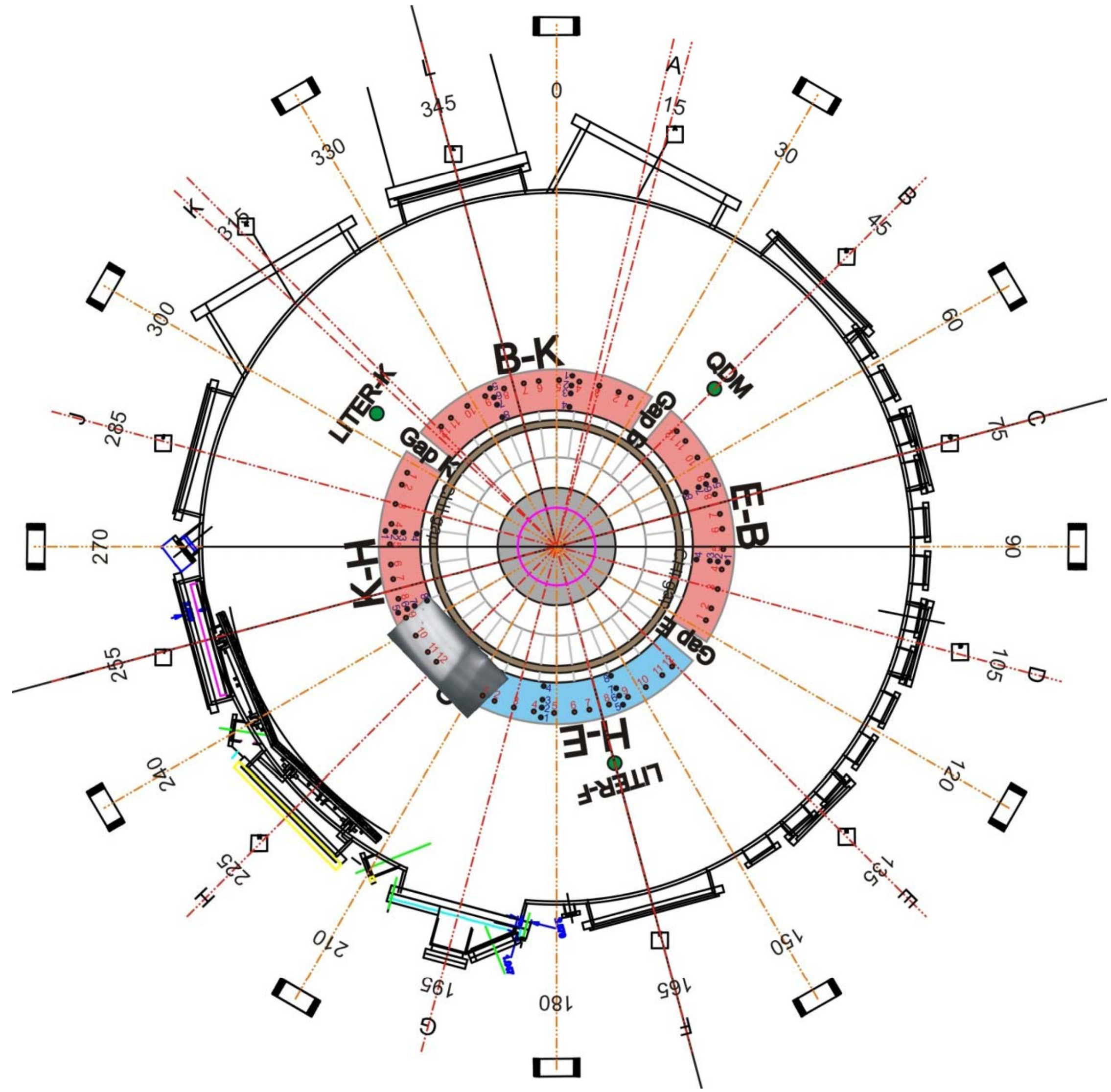






Fast IR camera view into NSTX

- IR view includes:
  - K-H LLD plate (operative)
  - H-E LLD plate (inoperative in early 2010)
  - Gap H bias tile (lithium-coated graphite, unheated)
  - CHI gap
  - Useful for study of LLD response to plasma
- For remainder of 2010
  - View rotated to include inner divertor, CHI gap, plus LLD plates
  - Better view of strike points in high-triangularity configuration

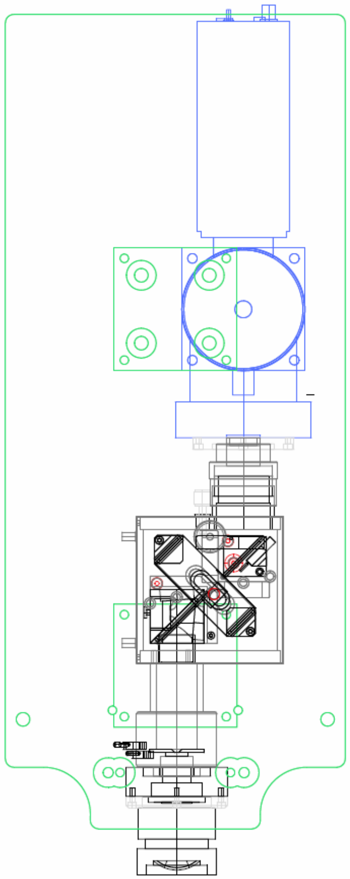


Primary dual-band IR adaptor components

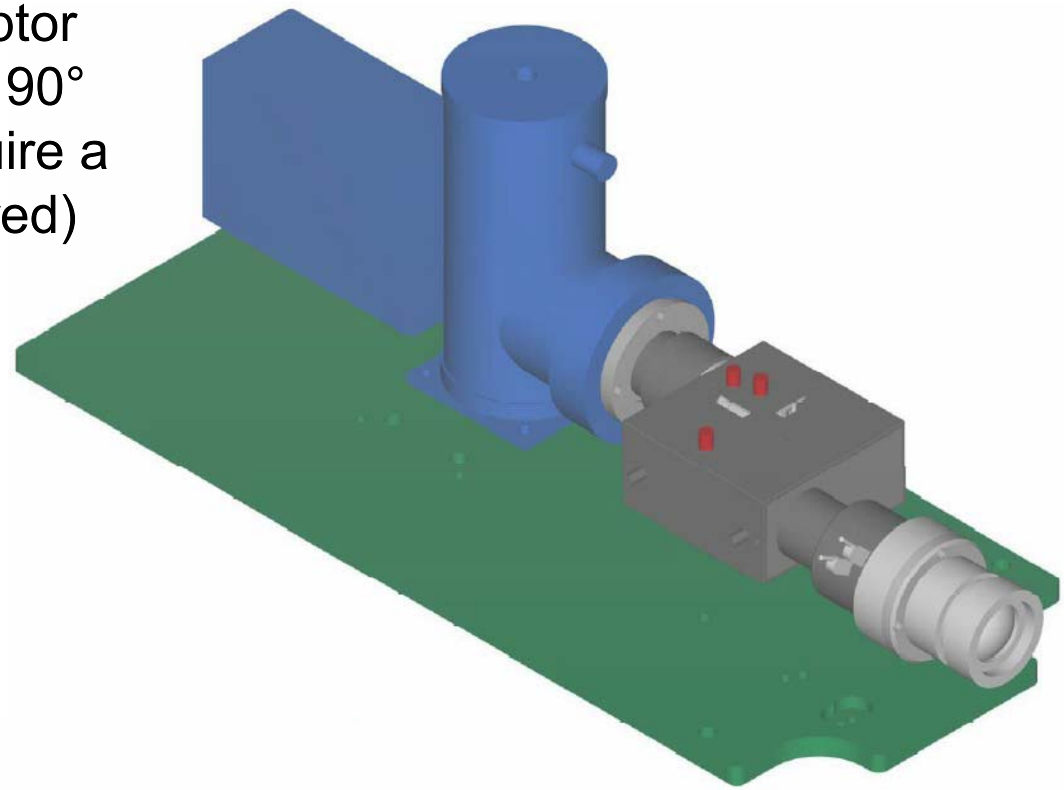
- Long-wave pass dichroic beamsplitter
  - Lambda Research Optics (CA, US)
  - Long-wave pass (7-10 µm transmit with T_{avg}~92%)
  - Medium-wave reflect (4-6 µm reflect with T_{avg}~99%)
- Image splitter optical platform
  - CAIRN Research OptoSplit II (UK)
  - Extensively modified for operation in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

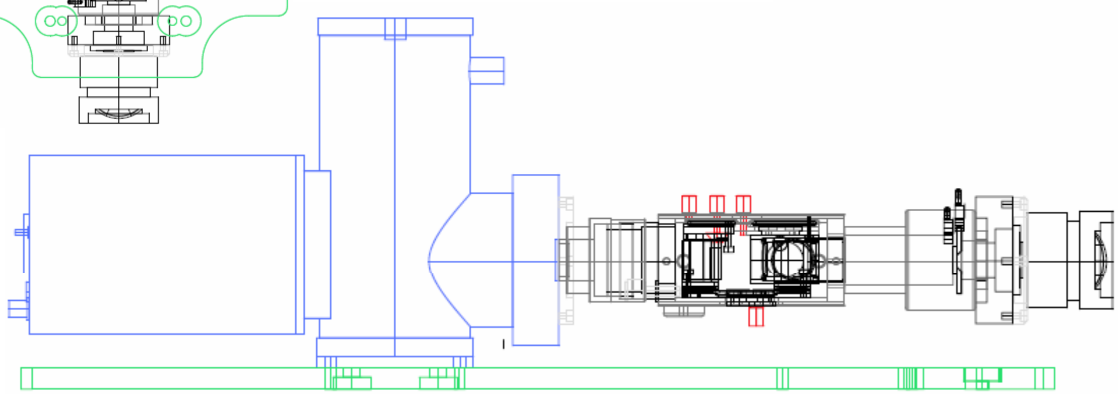
- Lenses
  - Uncoated ZnSe meniscus input/output lenses (T_{avg}~60-70%)
  - To be replaced with broadband AR-coated Diffractive Optical Element (DOE) hybrid singlet lenses
    - 10X reduction in chromatic aberration, reduced spherical aberration, improved SNR
  - II-VI Infrared (PA, US)
- Shortwave pass (SWP) and longwave pass (LWP) IR filters to limit spectral contamination in each channel
  - Reynard Corporation (CA, US)
- Custom designed lens adaptors/mounts

3D CAD model of fast IR camera and dual-band adapter



- Dual-band adaptor may be rotated 90° in order to acquire a radial (as pictured) or toroidal view





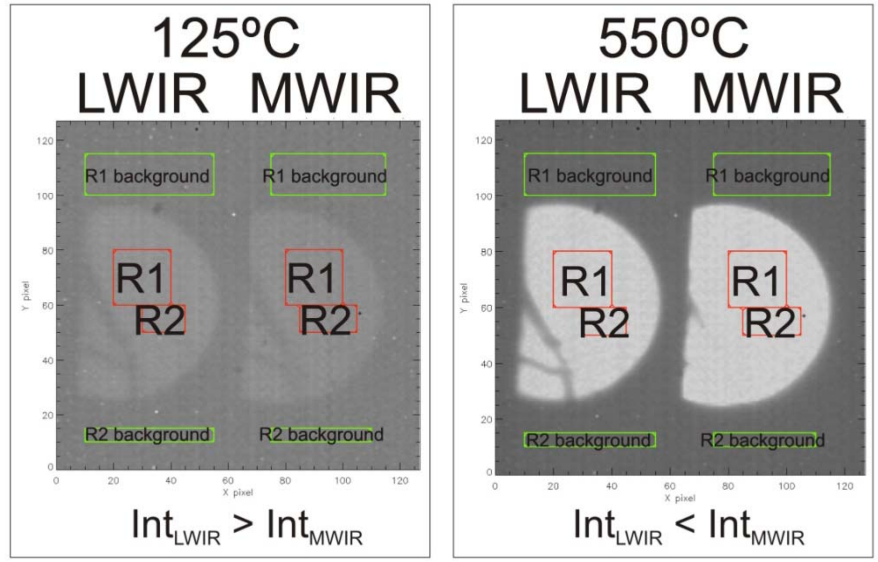
Spectral throughput comparison for IR camera assembly

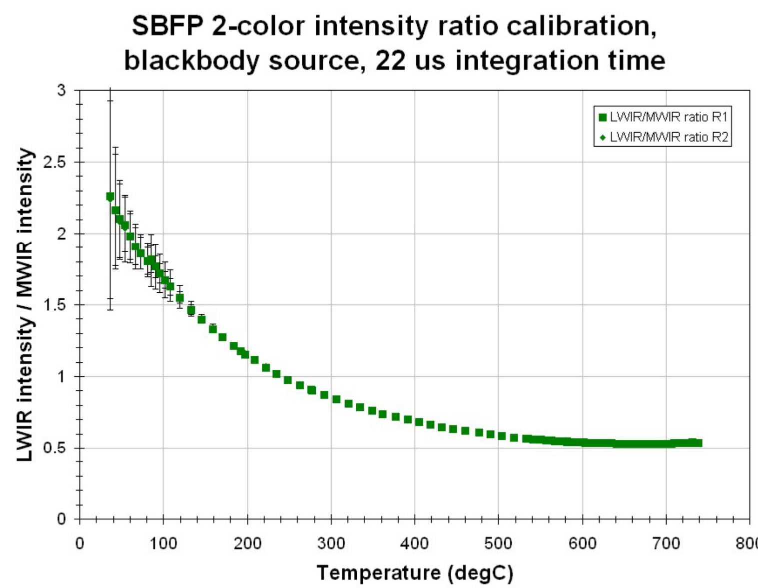
- Comparison of ideal throughput losses due to optical components in the dual-band adaptor
- Initial dual-band adaptor reduces throughput by ~4X compared to highest efficiency single-band mode
- Near-term improvements will reduce the difference to ~2X
- Significant margin is available in terms of integration time and dynamic range
  - Drop in transmission has no impact on required performance characteristics

Optical element		Wideband operation		Dual-band operation meniscus lenses		Dual-band operation DOE lenses	
		8–12 μm operation	3–12 μm operation	4–6 μm band	7–10 μm band	4–6 μm band	7–10 μm band
Observed bandwidth		4 μm	9 μm	2 μm	3 μm	2 μm	3 μm
Bay H port window		98%	83%	70%	96%	70%	96%
Perp. View mirror		98%					
IR primary lens		95%	75%				
Dual-band adapter	Input lens	N/A		70%	72%	95%	97%
	Mirror 1	N/A		98%			
	Dichroic	N/A		99%	92%	99%	92%
	Short pass filter	N/A		N/A	83%	N/A	83%
	Long pass filter	N/A		95%	90%	95%	90%
	Mirror 2	N/A		98%			
	Output lens	N/A		70%	72%	95%	97%
Camera window		95%	96%	97%	97%	97%	97%
Two-color adapter		N/A		**44%**	**34%**	**82%**	**62%**
Overall transmission		**87%**	**59%**	**22%**	**23%**	**41%**	**43%**

Demonstrated application of dual-band IR with extensive *ex-situ* calibration

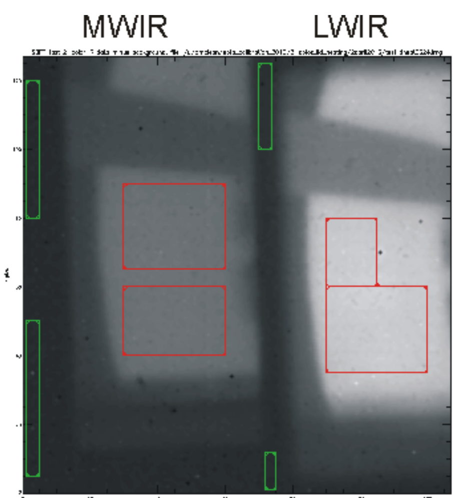
- Accomplished with fast camera + dual-band adaptor viewing a blackbody IR source
  - Electro Optical Industries WS162 capable of up to 750°C
  - 400+ frames of data taken with 10-75 µs integration time at 1610 Hz frame rate (1.6-12% duty cycle)
- Useful, low error LWIR/MWIR ratio from ~100-600˚C
  - Altering IR camera system gain will be explored to see if the useful range of the ratio can be extended up to ~1,000˚C





In-situ calibration accomplished during heating of the LLD

- Data captured with dual-band camera viewing LLD plates at 20-320˚C
  - Each LLD plate contains 20 thermocouples embedded in their copper substrate, 5 of which are in positions in the view of the fast IR camera
  - Nearly 500 frames of data taken with 10-75 μs integration time for complete comparison to *ex-situ* calibration data
  - Signal in MWIR band (4-6 μm) reduced by 35-45% due to lack of AR-coating for this spectral band on ZnSe port window, plus dust/dirt/deposits
  - Signal in LWIR band (7-10 μm) also reduced 20-25% likely due to dust/dirt/deposits
  - Overall ~20% increase in LWIR/MWIR ratio compared to *ex-situ* data



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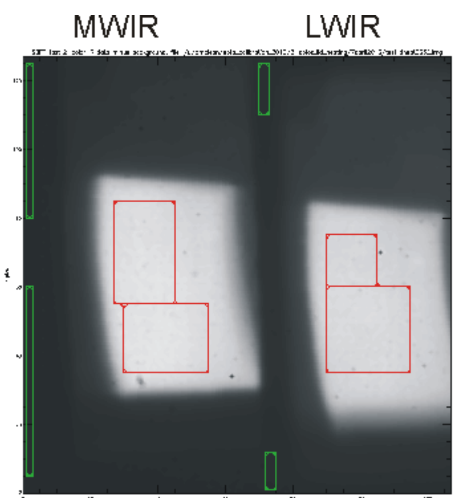
Both LLD plates at ~60°C, ratio=2.2



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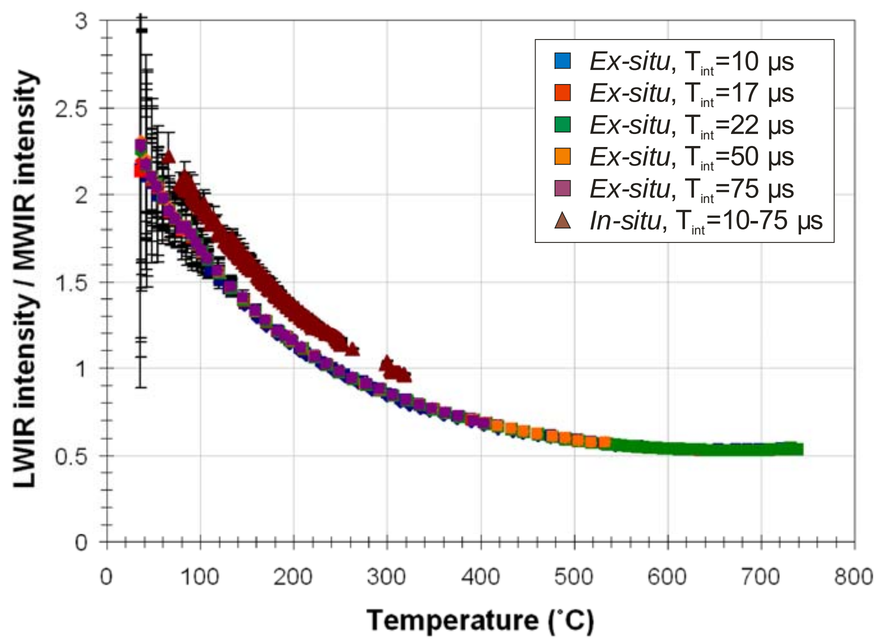
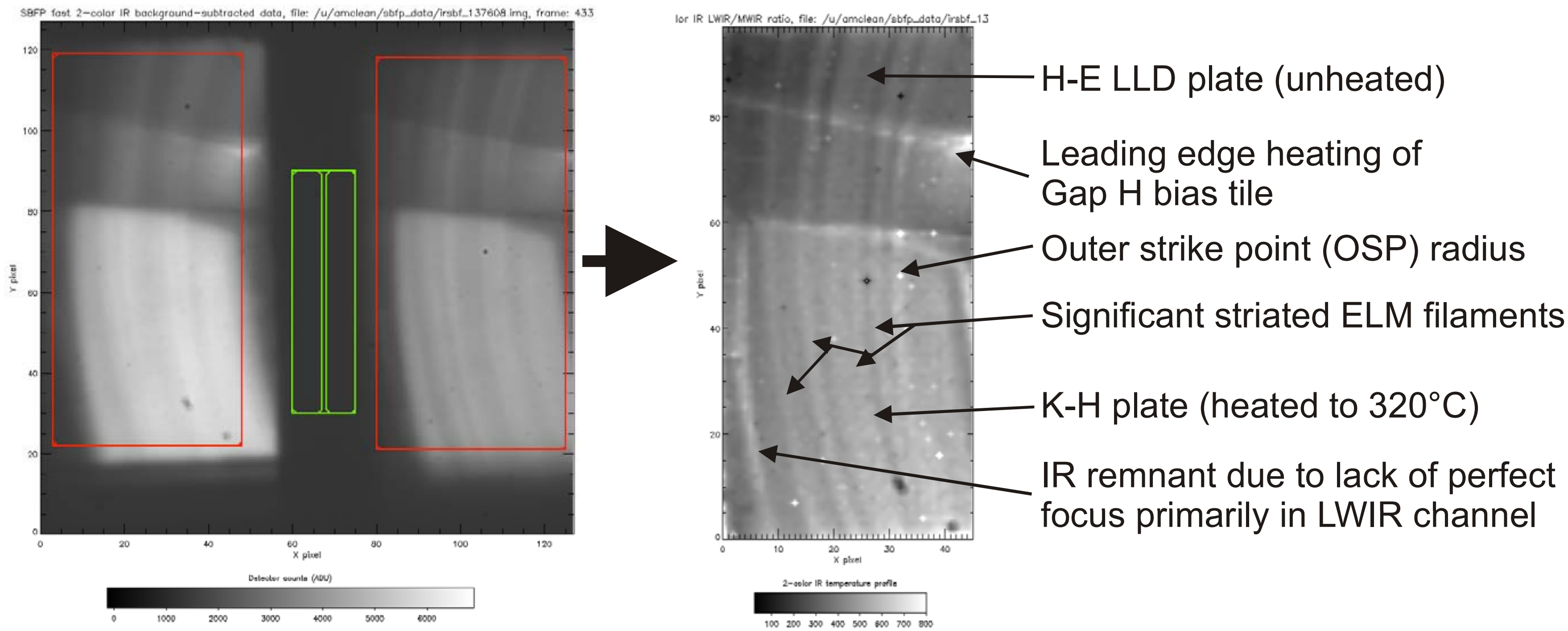
K-H LLD plate at ~320°C, ratio=1.0



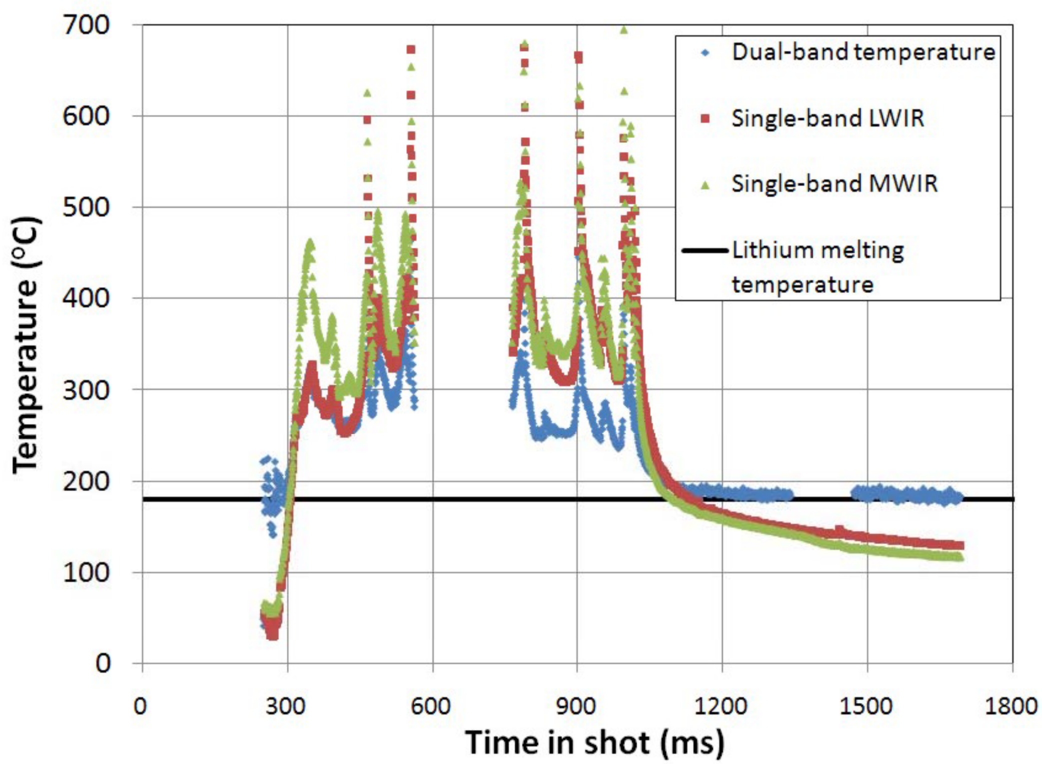
Dual-band IR technique demonstrated on images taken during plasma operation in NSTX with heated LLD

- *Ex-situ* calibration data of T vs. LWIR/MWIR ratio fitted polynomial function, then shifted for best fit to available *in-situ* data
- Data captured in ~1,000 shots in 2010, stored to NSTX data acquisition system
- Maximum 128x64 pixels on IR detector per channel (i.e., band), 1.6 kHz frame rate
- In practice, limited to ~55 x 110 pixels to prevent channel overlap, and allow adequate background for subtraction
- Data aligned, temperature calibration applied , 1-D and 2-D (THEODOR) heat flux calculated using custom-designed IDL-based software, FIRNACE



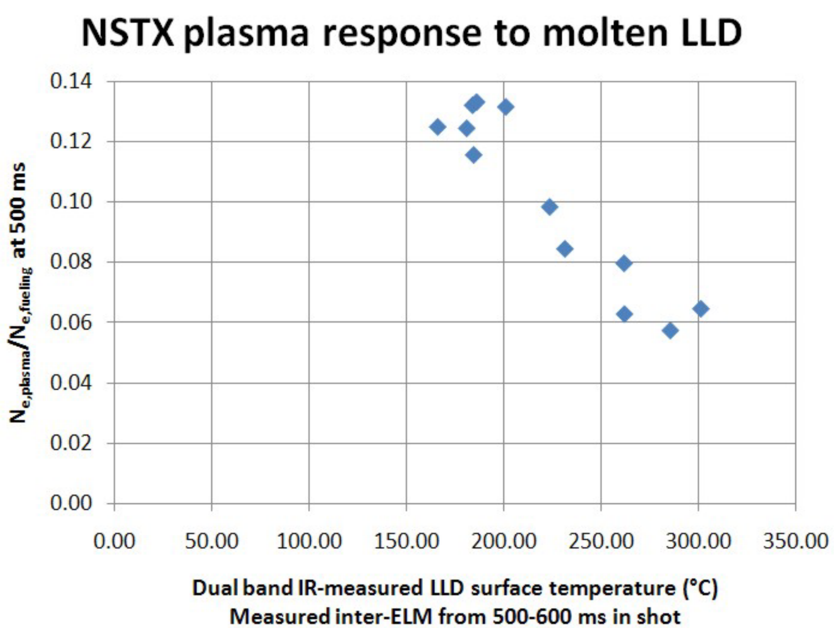
Post-shot LLD temperature measured by dual bands shows constant T_{surf} at enthalpy of solidification

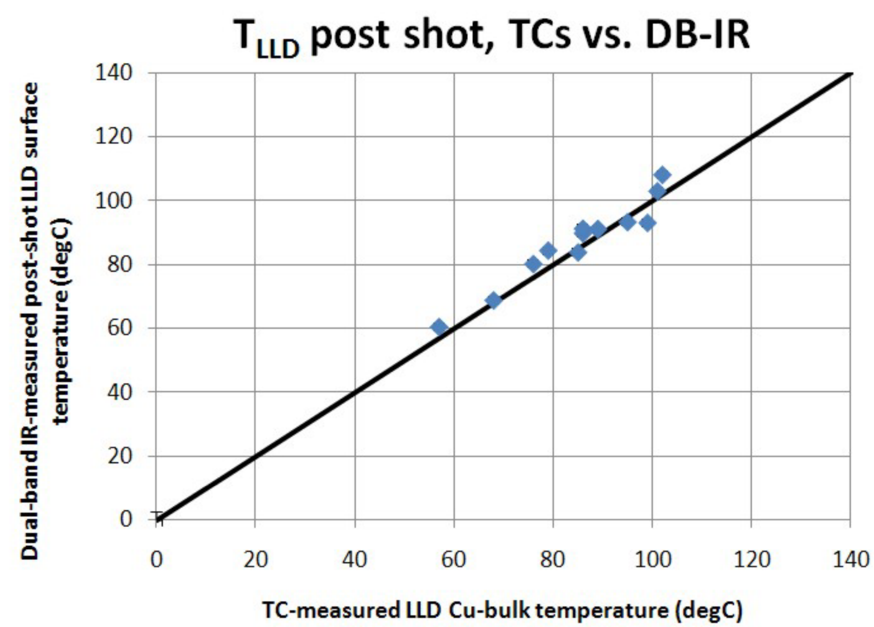
- Data on the LLD surface taken after a discharge
- Each of the LWIR and MWIR single band calibrated temperatures drop monotonically after a discharge is complete
- Dual-band calibrated data is found to remain at the melting temperature of Li (180 °C) for at least 700 ms due to its enthalpy during solidification
  - Key demonstration for validity, advantage of dual-band measurement



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

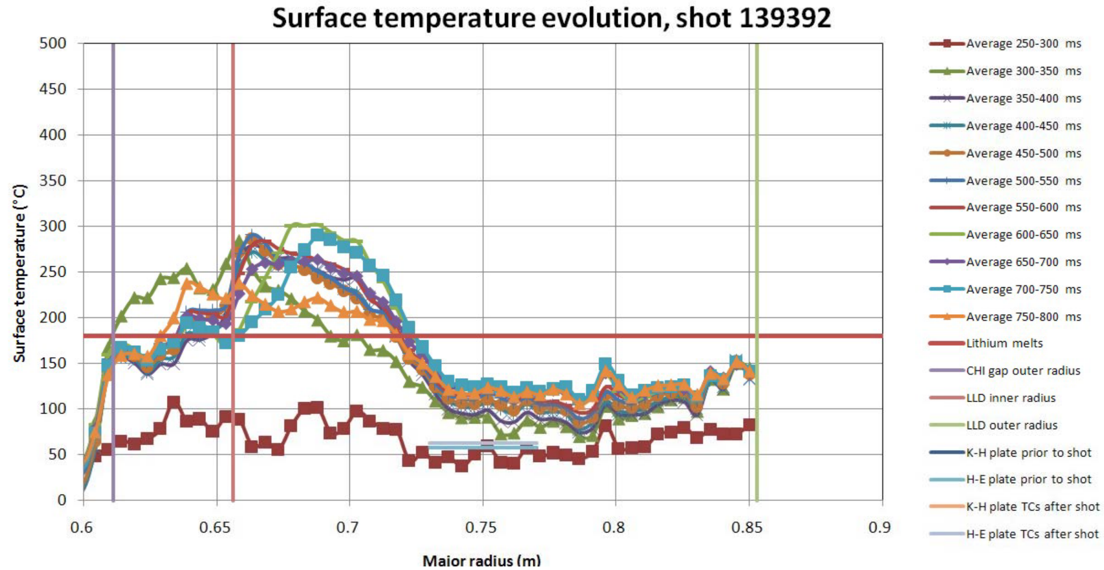
- Series of 20 shots with OSP on LLD, heating bulk Li up by 5-10 °C per shot
- Thomson and fueling used to measure ratio of $N_{e,plasma}$ over $N_{e,fueling}$ at 500 ms in each discharge (M. Bell)
- Average inter-ELM LLD surface temperature near the OSP from 500-600 ms measured by dual-band IR
- Ratio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

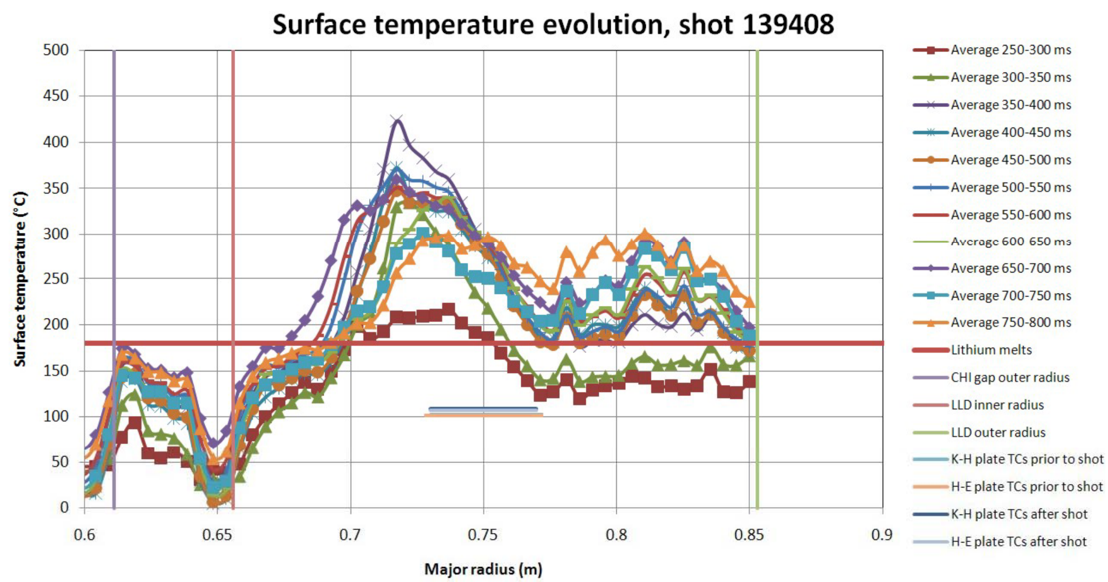




Fraction of LLD surface with T_{surf}>Li melting increases substantially over LLD heating series

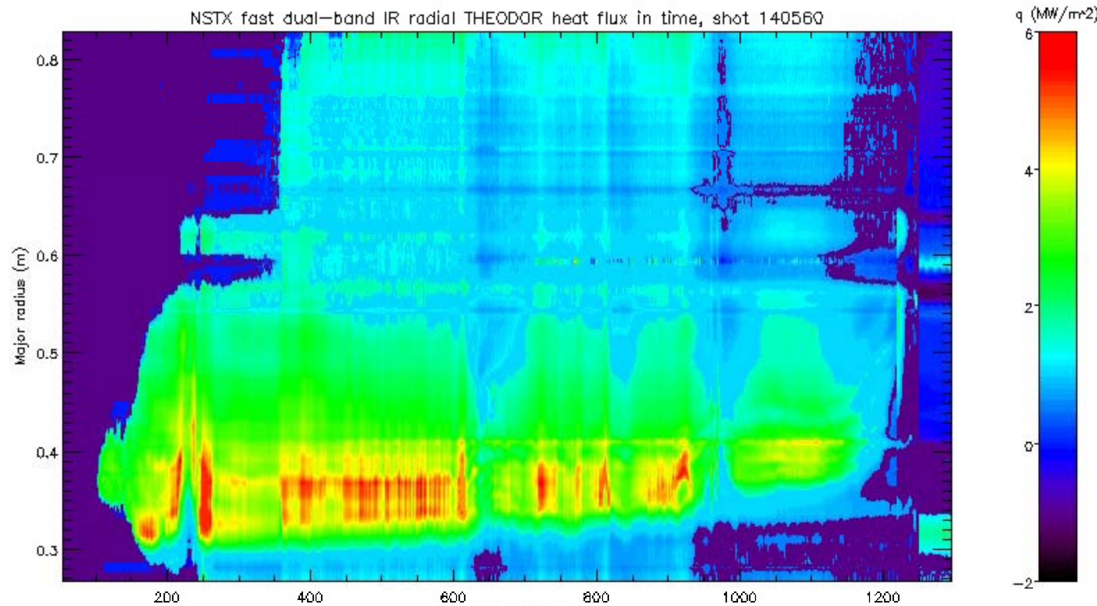
- Increases from ~28% in 139392, the first shot in the series, to ~86% in 139408, second last shot in series
- Surface temperature prior to shot well matched to embedded TCs in LLD
- Interesting heating trend through shot:
  - LLD quickly heats from pre-shot temperature to approx. steady state
  - No linear trend upwards
  - Suggests dynamic energy balance between heat flux and evaporative cooling / convective heat transport
  - Possibly of key importance for use of Li in future machines

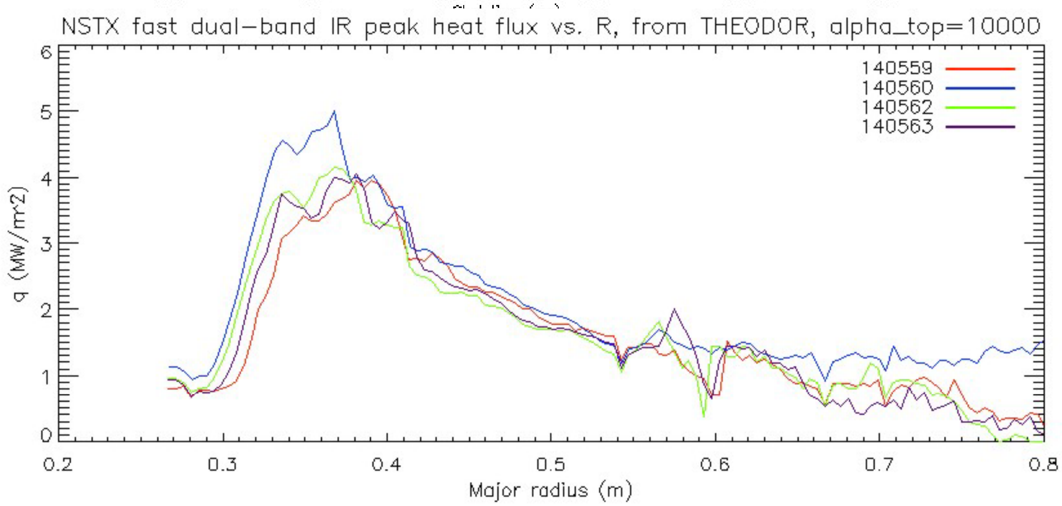




Dual-band IR data during ELMing H-mode

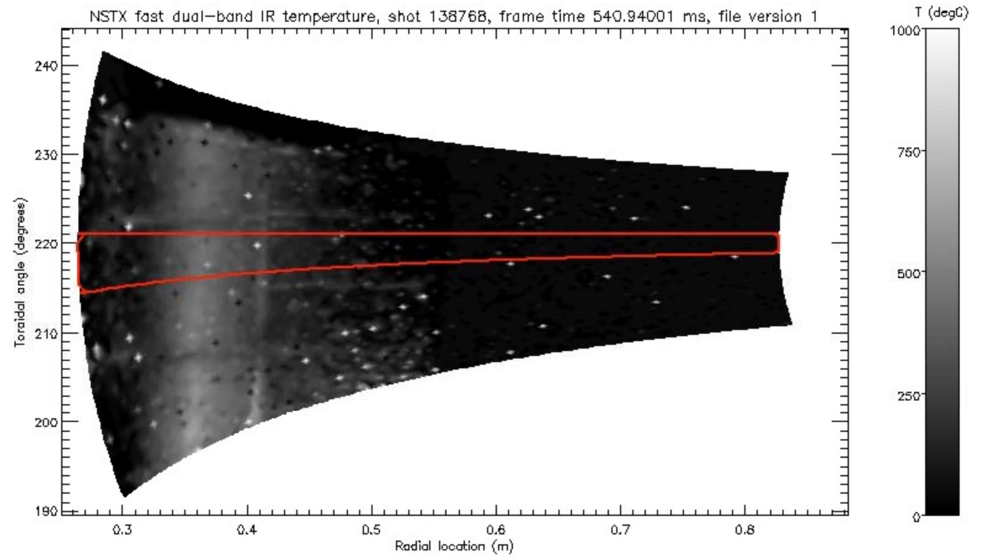
- T_{surf} and q (MW/m^2) calculated in 1-D and 2-D for available dual-band image view
- 1-D Carslaw and Yeager model, plus 2-D THEODOR model applied for heat flux
- Considerable improvement in data quality, accuracy using 2-D result
- Analyzed data to be mined for comparison to non-Li data and limited Li data from 2009

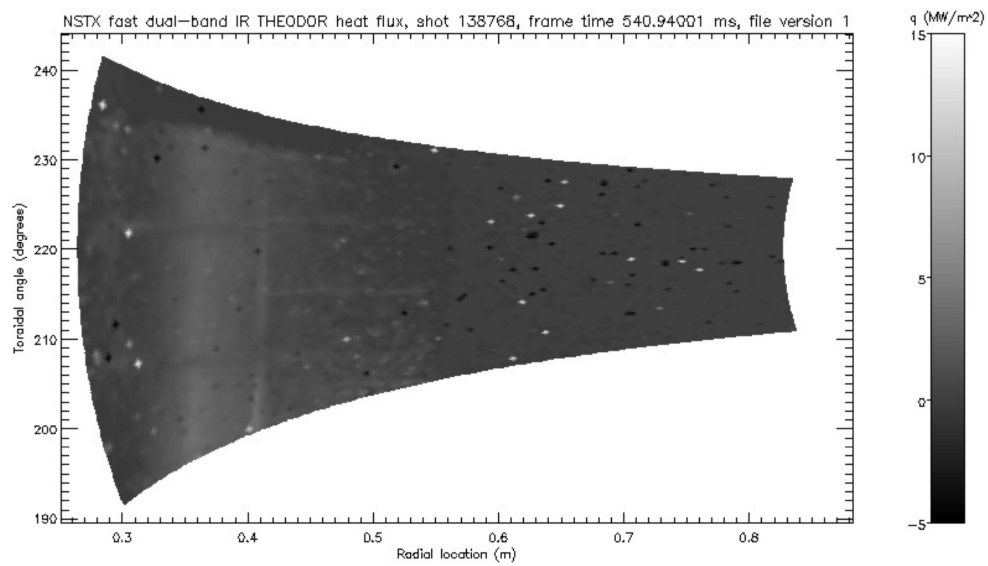




Dual-band IR data during ELMing H-mode

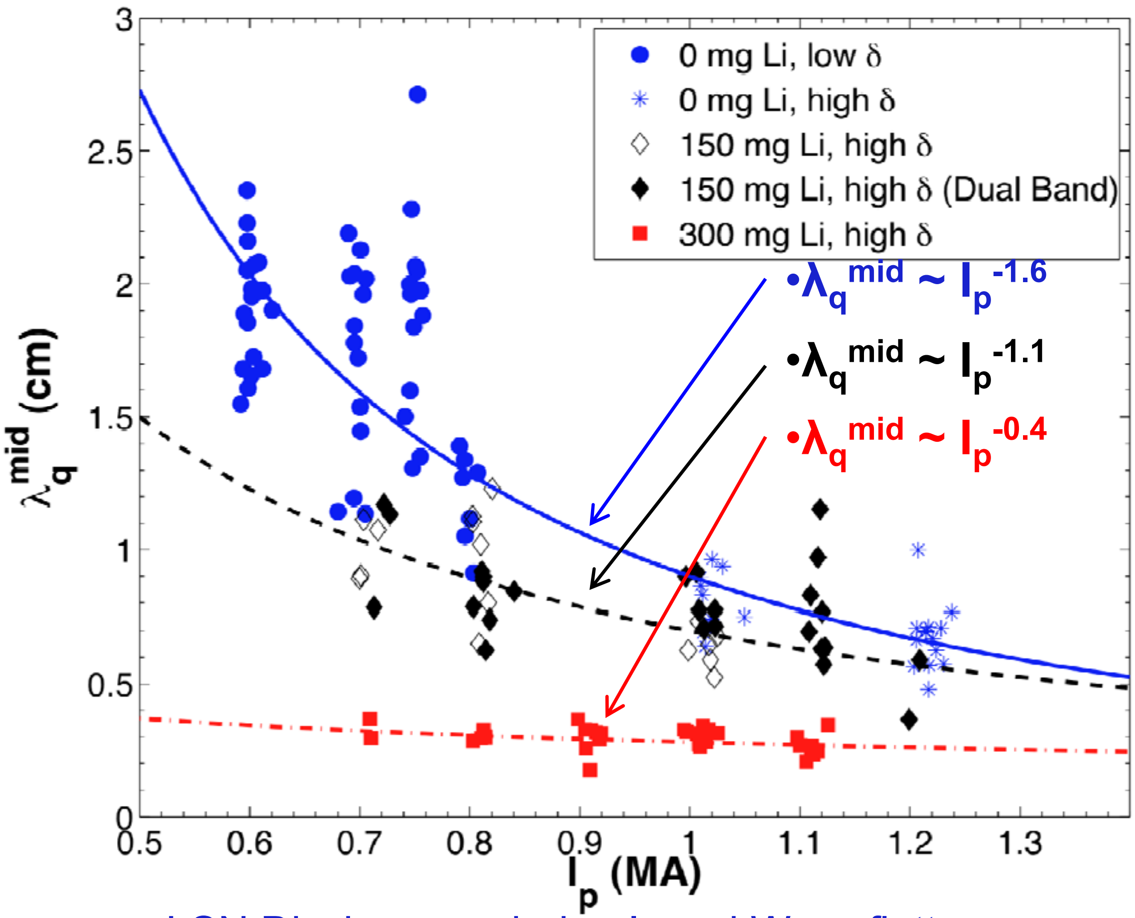
- Data processed with full 2-D spatial calibration to map results to R, phi, plus X,Y and R,t
- Location for radial cut shown
- Unfortunately noise can have significant effect on ratio calculated plus q calculation in time
  - Attempting to study impact of noise reduction techniques





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

- With out 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}

Future plans

- Mini IR source to allow alignment/focus of system at Bay H port
  - PCMCIA CameraLink card, W-filament and LED IR sources
- Broadband (BB) anti-reflection (AR) coated ZnSe window for port
  - >95% transmission from 3-11 μm would significantly improve dual-band SNR
- Optical relay
  - Makes shielding of the camera against EMF interference, and neutron/gamma radiation possible
  - Extremely challenging for broadband IR (4-10 μm) due to chromatic aberrations
  - Investigating use of reflective optic design similar to JET/ITER design
- Stepper-motor control of Bay H mirror orientation
  - Difficult to properly aim without *in-situ* IR source (heatable tile in 2011)
- Moveable in-vessel protected mirror or IR fiber for window calibration with ex-situ IR source
  - UHV rotary feedthrough bakeable to 350°C (Lesker)
  - IR optical fiber limited to ~300˚C before devitrification

Conclusions

- Dual-band infrared measurement works as expected
- Dual-band system for the ORNL fast IR camera on NSTX successfully designed, built, calibrated and demonstrated
  - Patent pending
- Components <15% of the cost of new dual-band IR camera, and does not limit the full frame-rate capability to $\leq$300 Hz
- Significant improvements in optical transmission and reduced chromatic aberrations have taken place in short term
- Used extensively for 1-D and 2-D heat flux measurements on LLD and lithium-coated graphite floor of NSTX
- Dual-band adaptor may be easily optimized for SWIR/MWIR, or dual-color operation within the MWIR or LWIR bands
  - System allows interchange of beamsplitter and IR filters
  - Direct application to existing IR cameras at other fusion facilities (e.g., InSb camera with 3-4 and 4.5-5 μm colors, microbolometer camera with 8-10 and 10.5-12 μm wavelengths)

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