Update on high-speed infrared imaging of the NSTX divertor

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May 10, 2010

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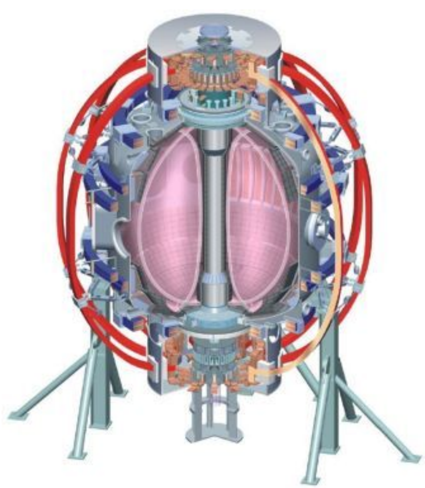

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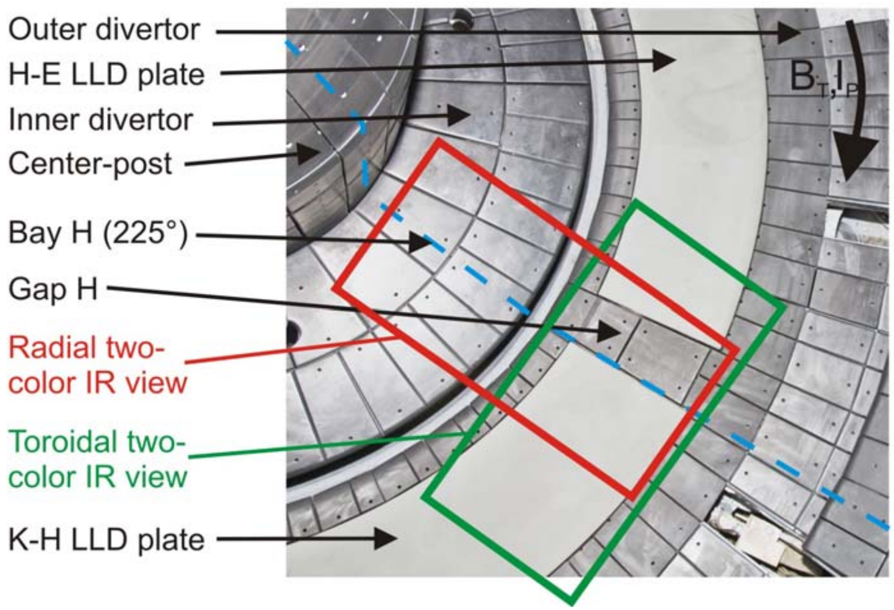
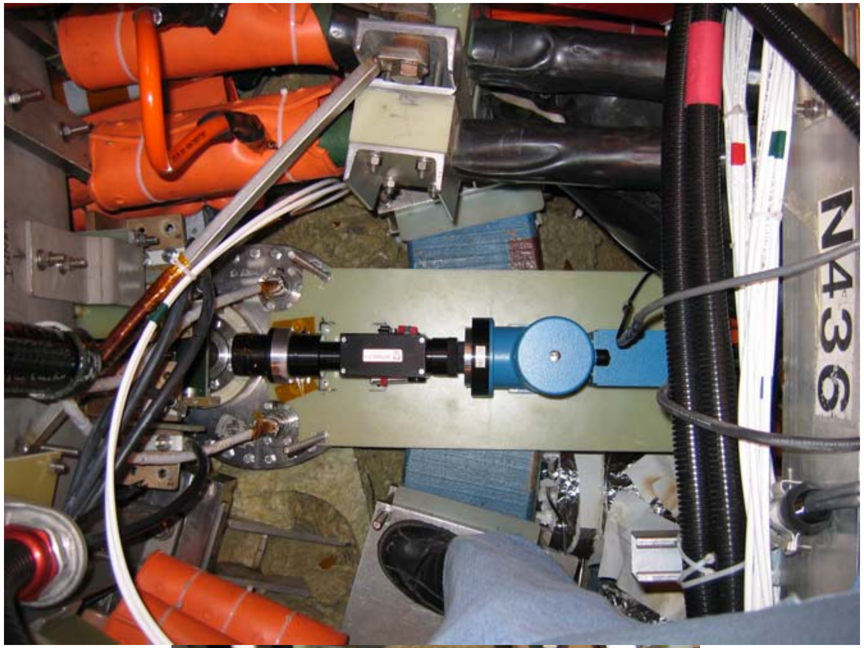
Infrared measurements on NSTX

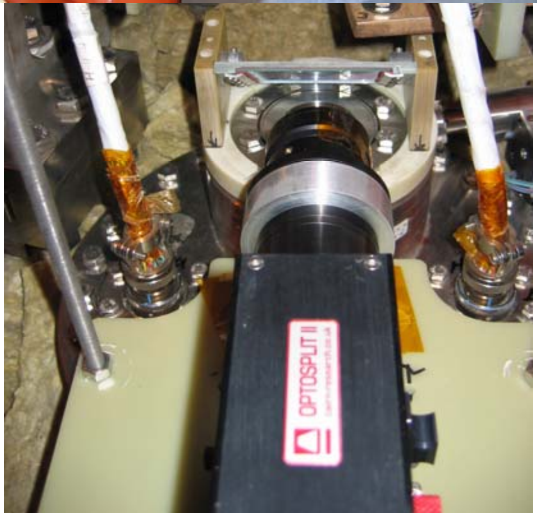
- Essential for heat load measurement on plasma-facing components during plasma operation, especially in the divertor region
  - Heat flux calculated using 1-D conduction model into semi-infinite solid (2-D in collaboration with IPP Garching)
  - Transient heat load can exceed 10 MW/m^2
  - Localize hot spots and significant impurity sources
- Use of the LLD 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

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

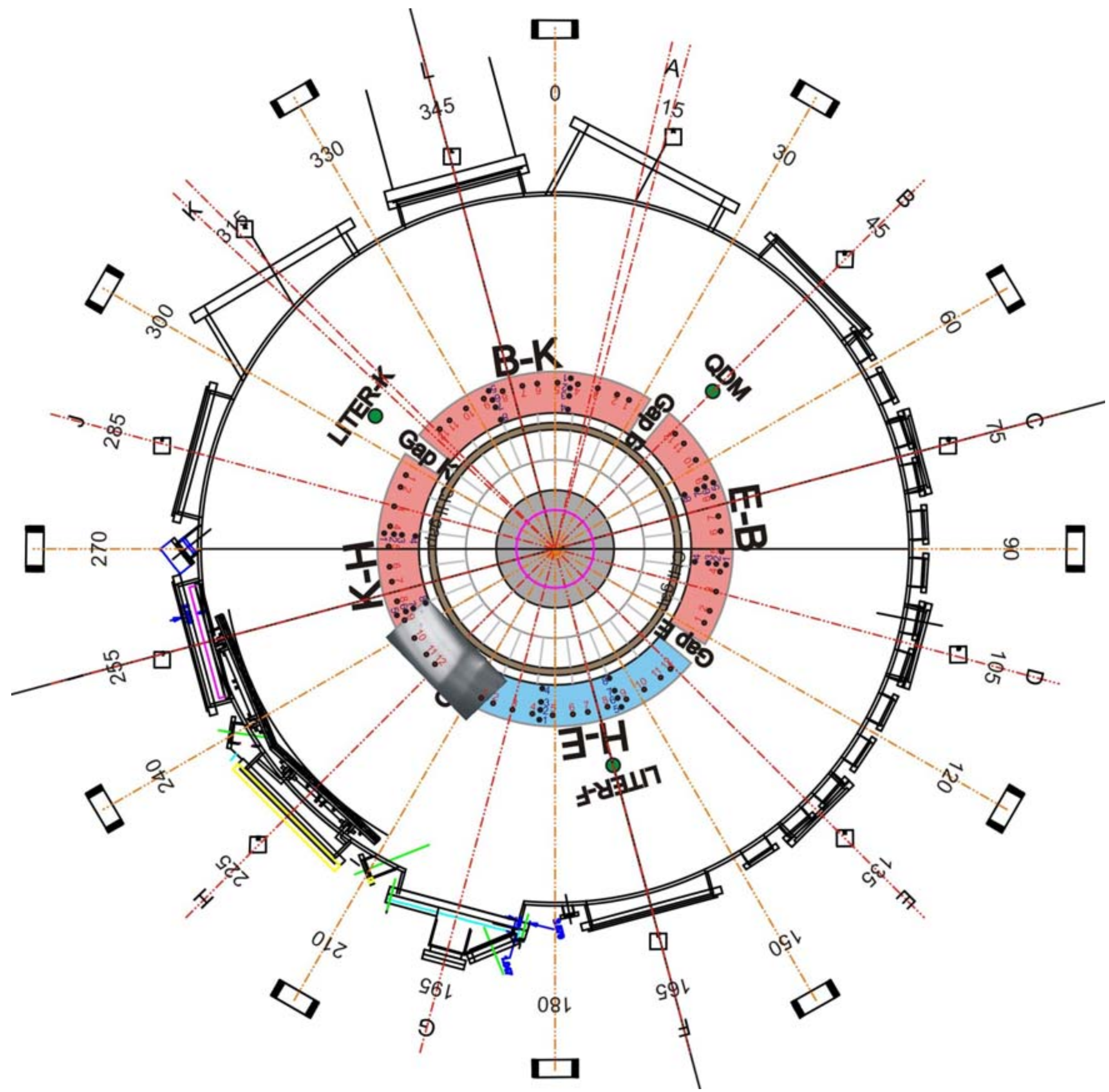






Fast IR camera view into NSTX

- IR view currently 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 elements (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

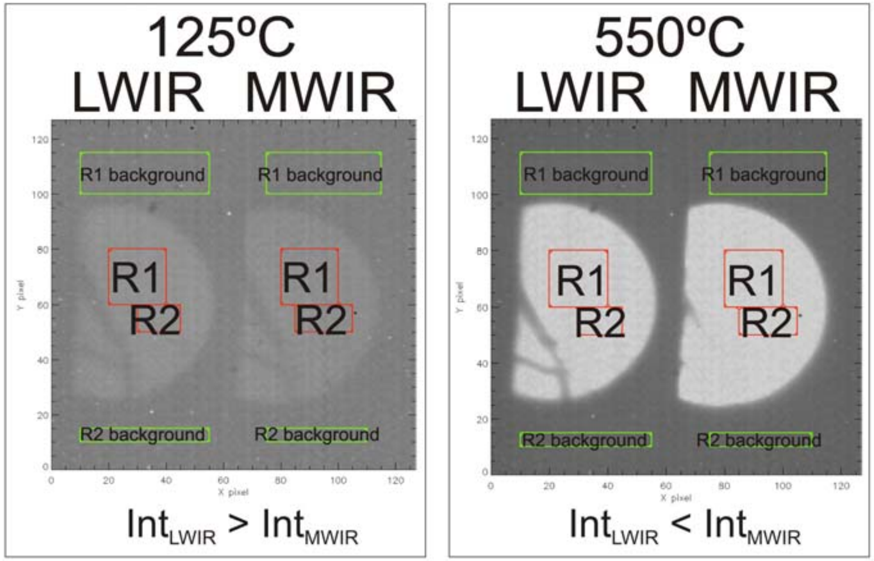
Spectral throughput comparison for IR camera assembly

- Comparison of static 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

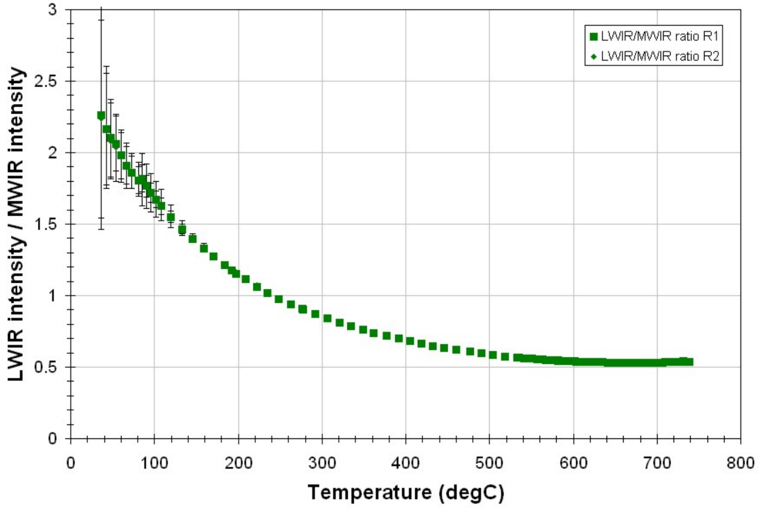
Optical element		Wideband operation		Dual-band operation meniscus lenses		Dual-band operation DOE lenses	
		8–12 μm operation	3–12 μm operation	4–6 μm band	7–10 μm band	4–6 μm band	7–10 μm band
Observed bandwidth		4 μm	9 μm	2 μm	3 μm	2 μm	3 μm
Bay H port window		98%	83%	70%	96%	70%	96%
Perp. View mirror		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 SBFP 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 ~1000˚C

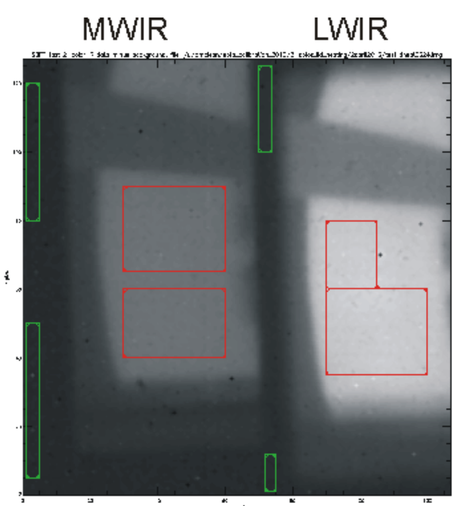


SBFP 2-color intensity ratio calibration, blackbody source, 22 us integration time



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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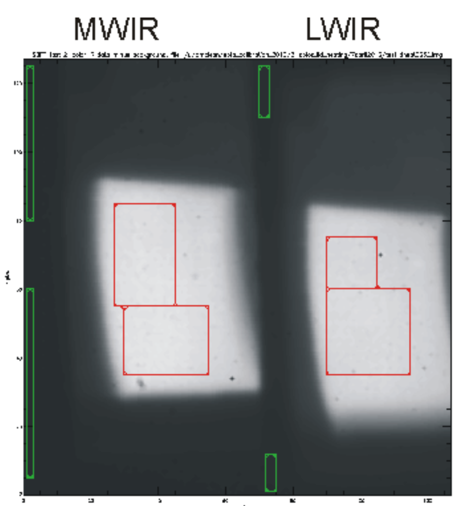
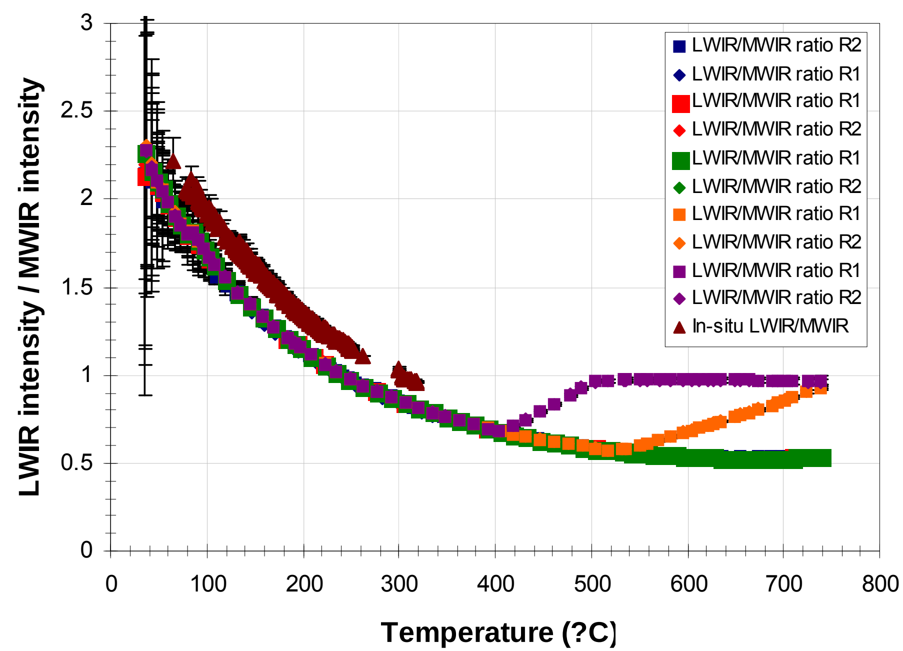
Both LLD plates at ~60°C, ratio=2.2

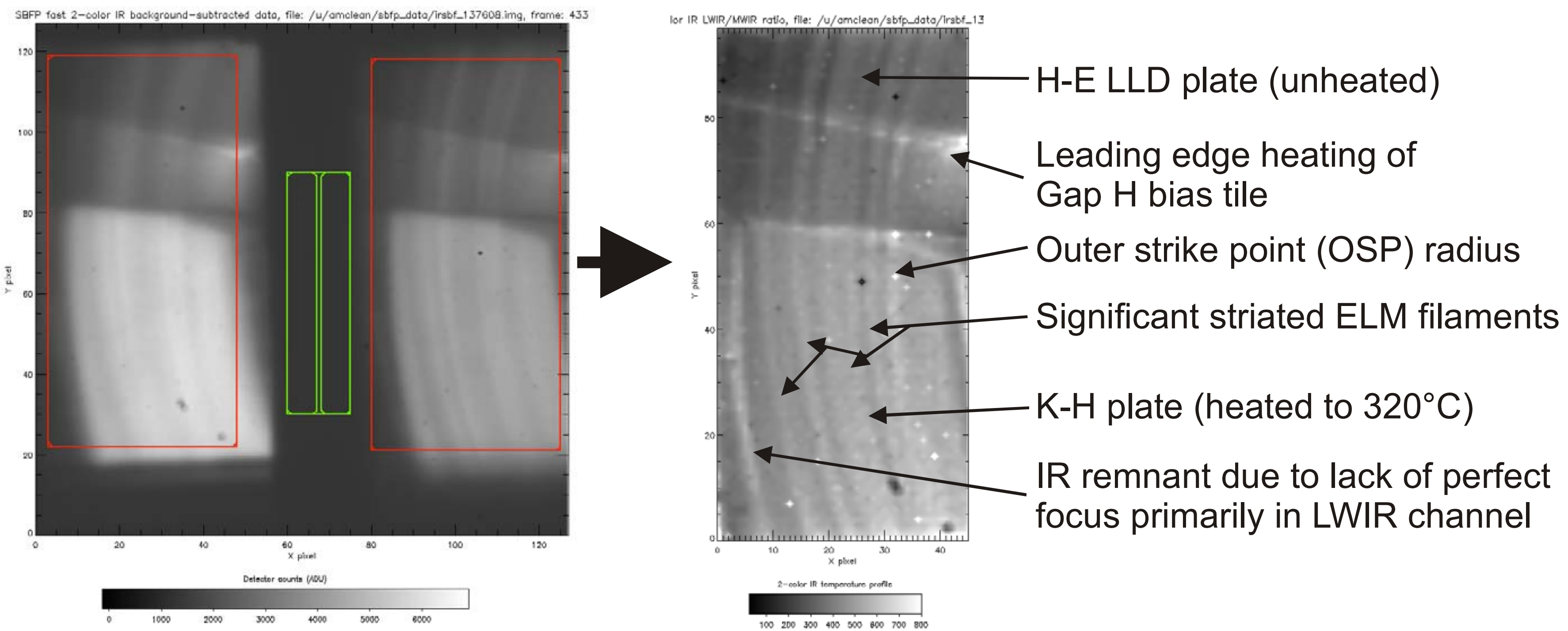


April 7, 2010 3:25.26 PM
K-H LLD plate at ~320°C, ratio=1.0



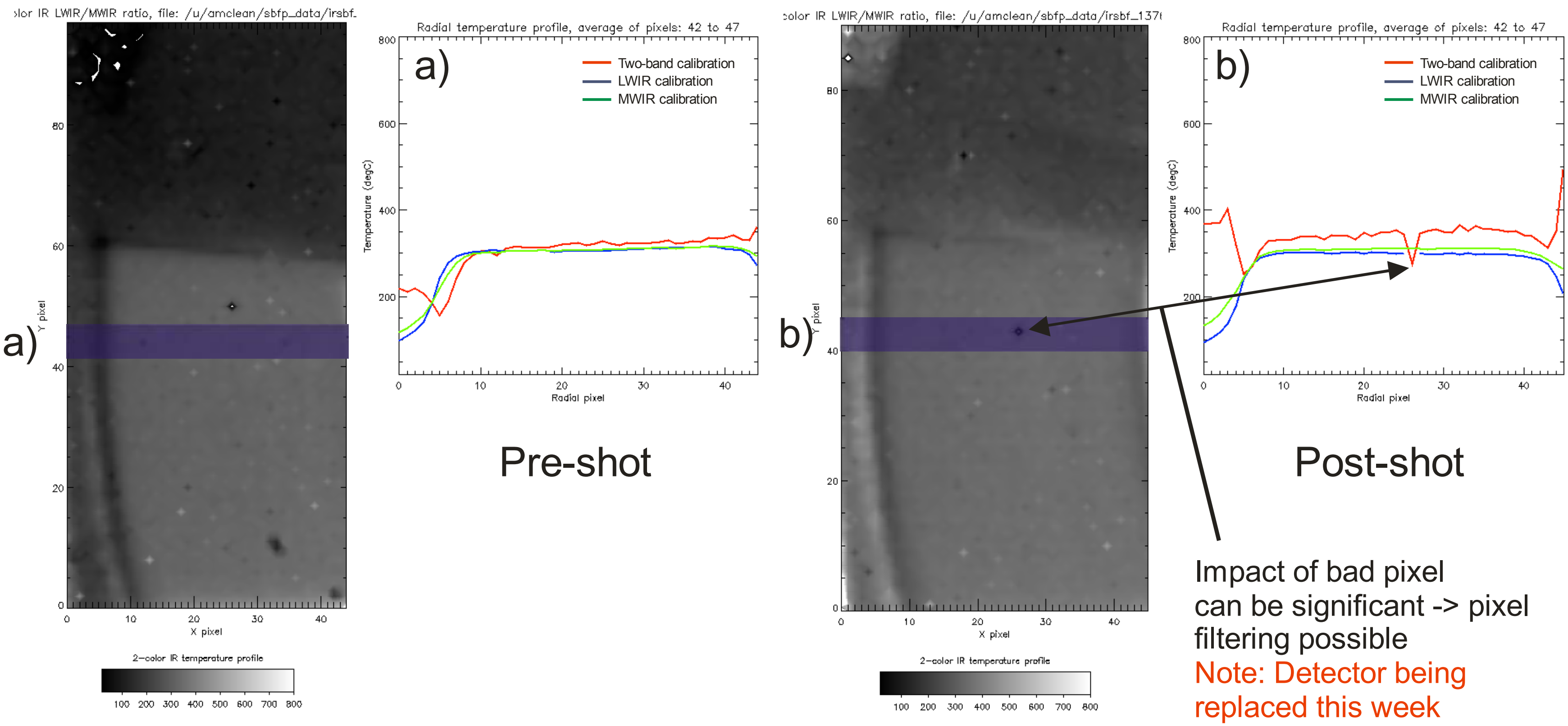
Dual-band IR technique demonstrated on images taken during plasma operation in NSTX with heated LLD

- *Ex-situ* calibration data of T vs. LWIR/MWIR ratio fitted to functional form, then shifted for best fit to available *in-situ* data
- Data captured in ~350 shots so far, stored to MDSplus
- Maximum 128x64 pixels on IR detector per channel (i.e., band), 1.6 kHz frame rate
- In practice, limited to ~45-55 x 100-110 pixels to prevent channel overlap, and allow adequate background for subtraction
- Data analyzed, temperature calibration applied using custom-designed IDL-based software



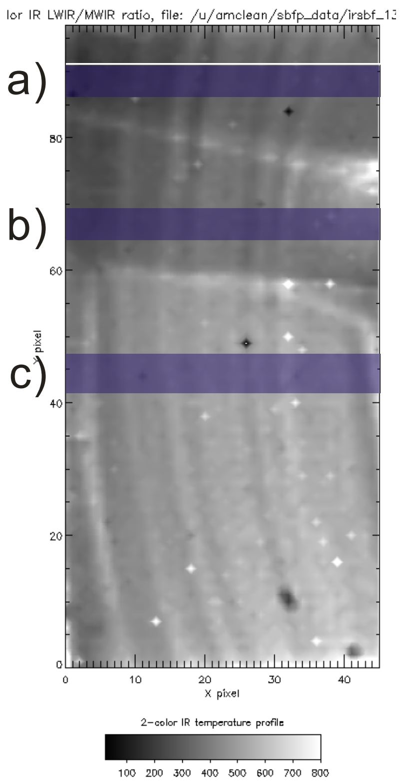
Pre- and post-shot sample data from April 7, 2010

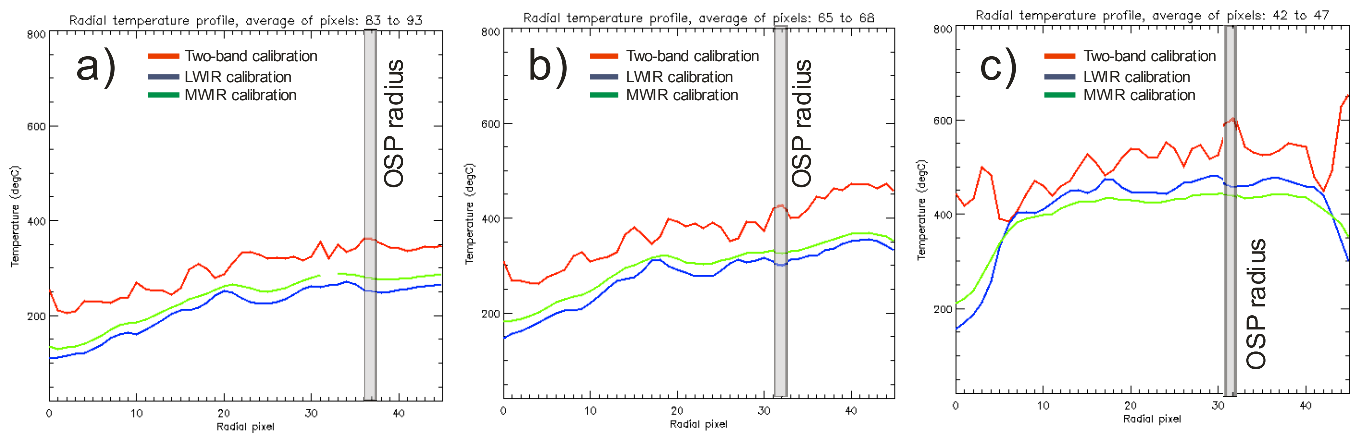
- Data taken before plasma operation shows dual-band IR calibration is well matched to individual single-band calibrations
  - All three calibrations give proper temperature across K-H LLD plate, ~320˚C
- Post-shot data shows dual-band indicates slightly higher temperature profile
  - Implies emissivity of lithium/lithium coated surface after a discharge is lower than during calibrations, possibly due to contamination of lithium by oxygen/carbon



Dual-band IR data during ELMing H-mode

- Data taken during plasma operation shows consistently higher temperature from dual-band IR calibration compared to individual single-band calibrations
  - Implies emissivity of lithium/lithium coated surface is lower than during calibrations
- LLD surface temperature reached ~600˚C during plasma exposure (K-H plate at 320˚C)
- Filament structure from small ELMs (note: not turbulence filaments) clearly resolved, even better than either single-band





- Analysis of frame-to-frame temporal continuity with limited/damaged detector in progress
- Detailed analysis of temperature vs. time and heat flux to LLD (1-D and 2-D) can now proceed

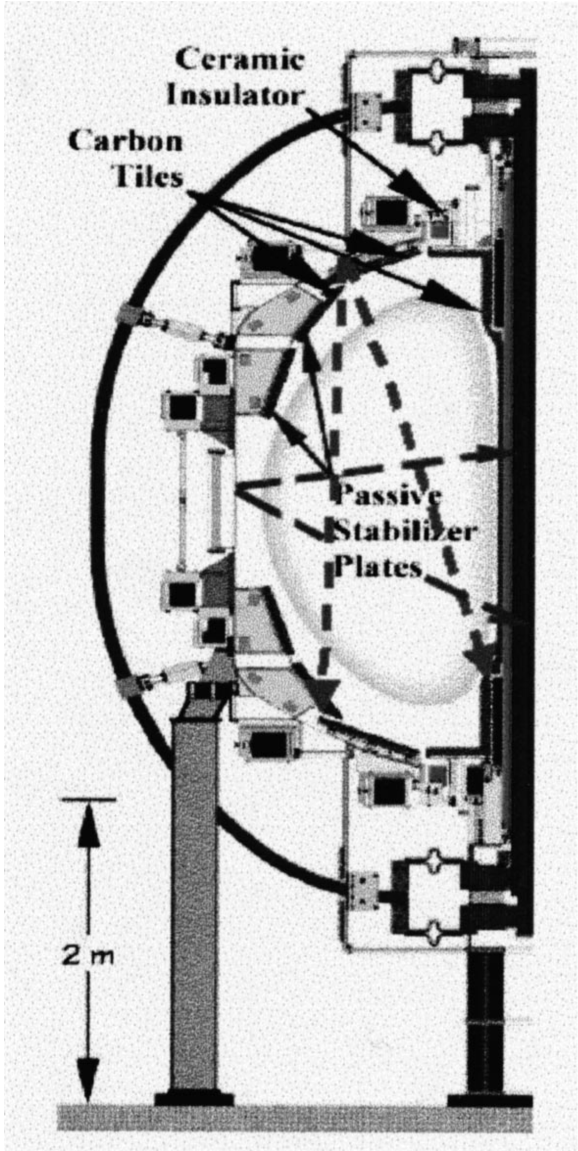
Conclusions

- Dual-band adaptor for the ORNL fast IR camera on NSTX successfully designed, built, calibrated and demonstrated
- Components <15% of the cost of new dual-band IR camera, and does not limit the full frame-rate capability
- Significant improvements in optical transmission and reduced chromatic aberrations will take place in short term
- Will be 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
  - Platform 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, VO-based microbolometer camera with 8-10 and 10.5-12 μm colors)

Backup slides

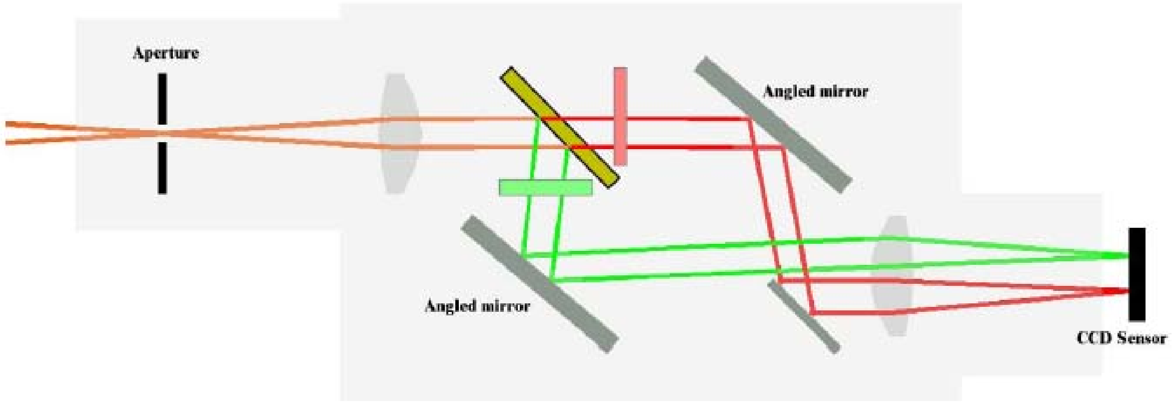
ORNL IR system currently on NSTX

- 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

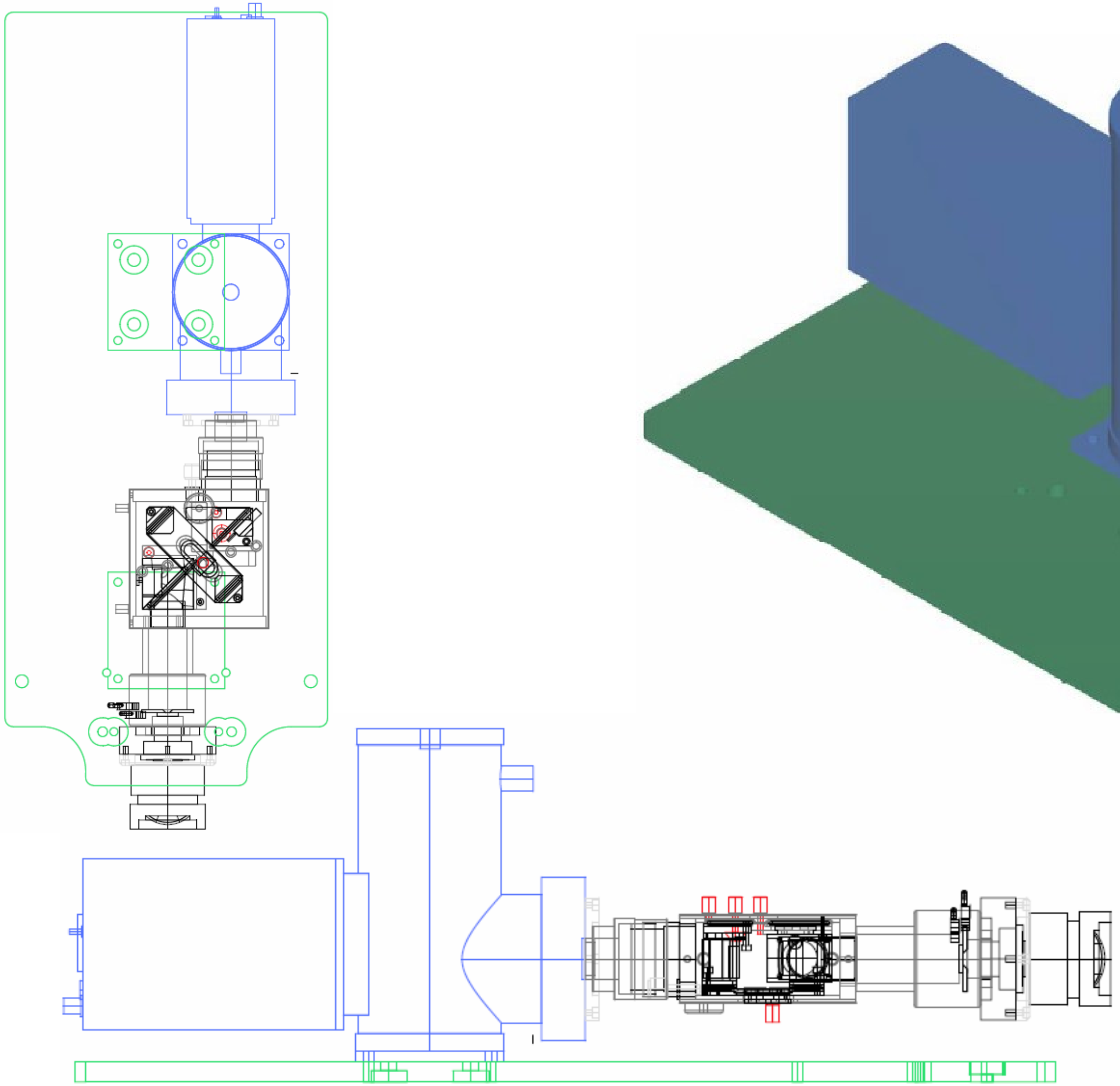


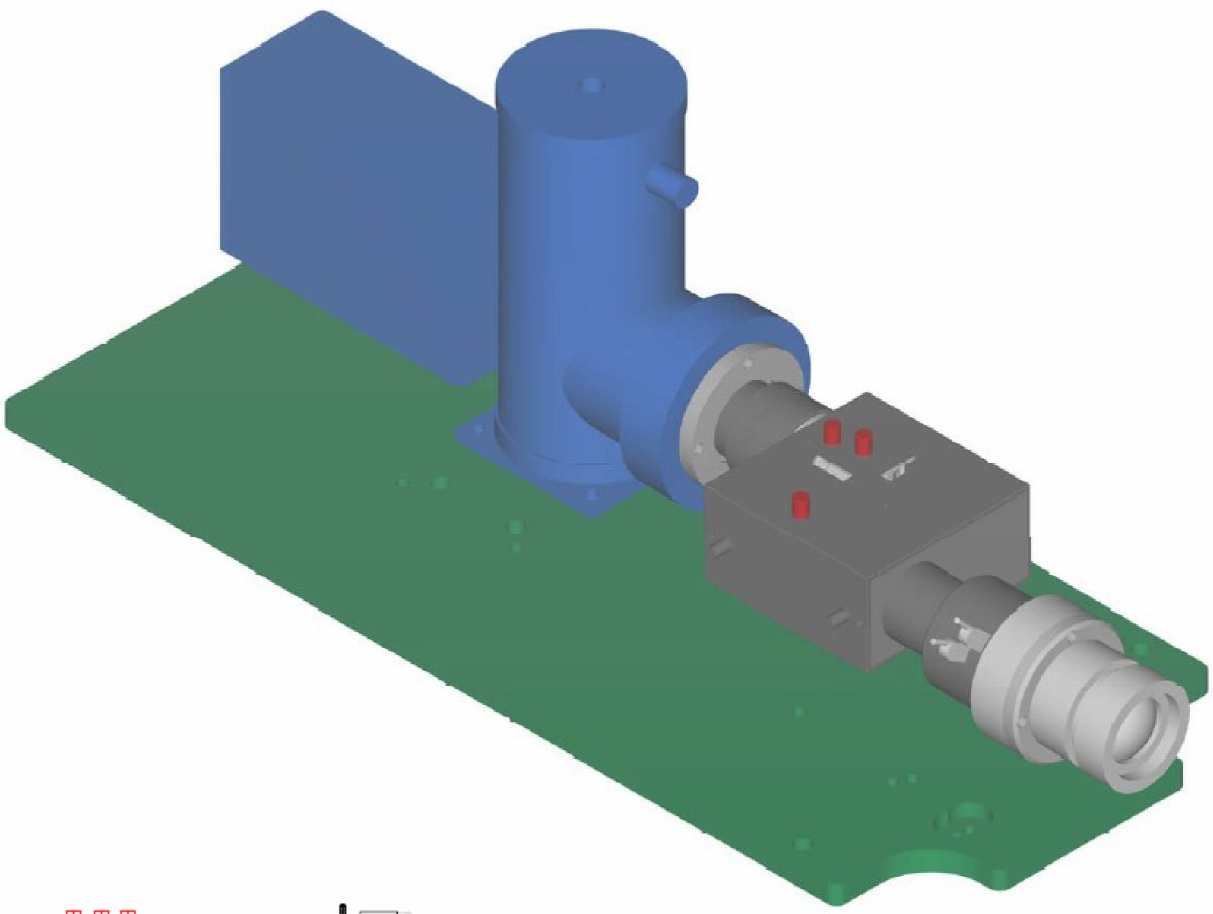
Two-color infrared camera

- Installation of the LLD will make assumptions of low surface emissivity (applicable to graphite) inaccurate
  - Surface coating changes in real time during plasma shots, emissivity changes due to H-absorption in Li, reflections from Li surface
- Two-color camera measures temperature based on the ratio of integrated IR emission in two IR bands, not on intensity of a single band
- Image split into medium wavelength IR (4-6 μm) and long-wavelength IR (7-10 μm) using a dichroic beamsplitter, filtered with bandpass filters, projected side-by-side into the IR camera



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





Future plans for dual-band IR measurement on NSTX

- 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