NSTX

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# High-speed dual-band infrared imaging of the LLD and NSTX divertor


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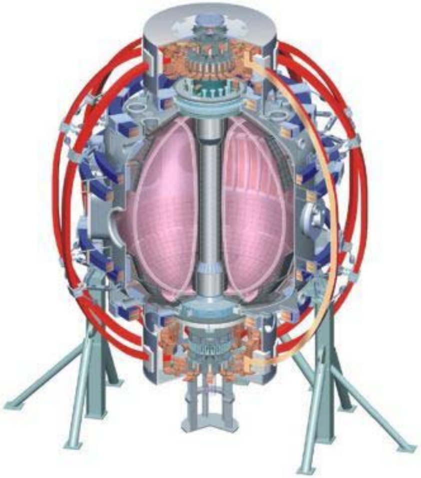

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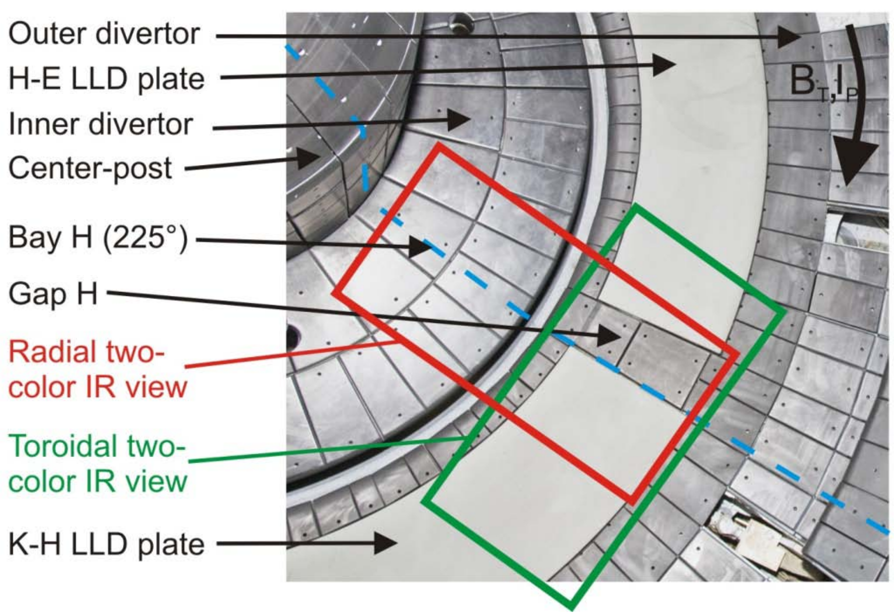
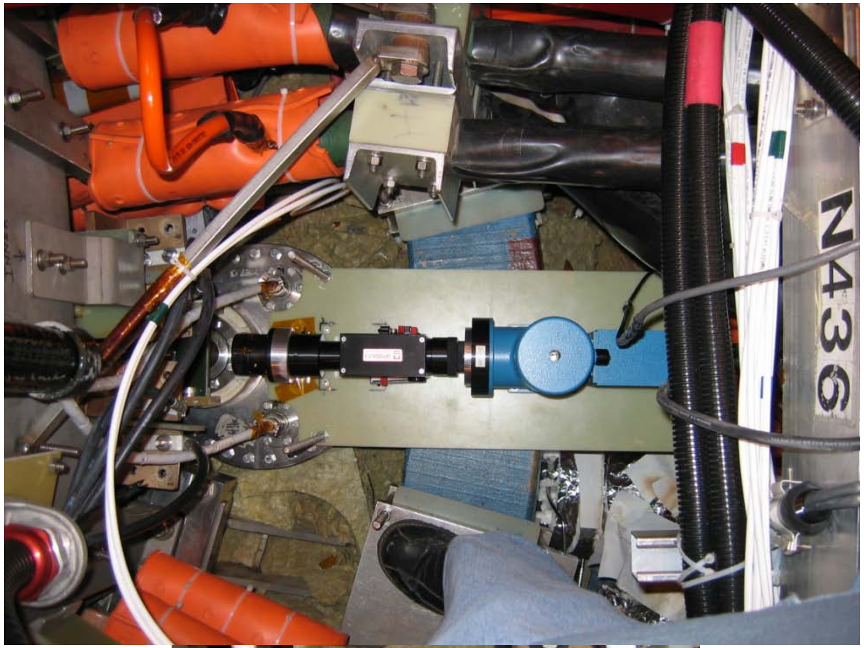
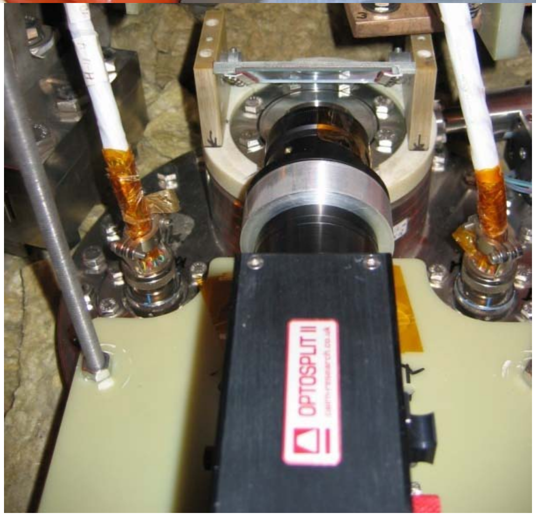
# Modifications required for dual-band IR adaptor

- 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 being moved outside of the test cell



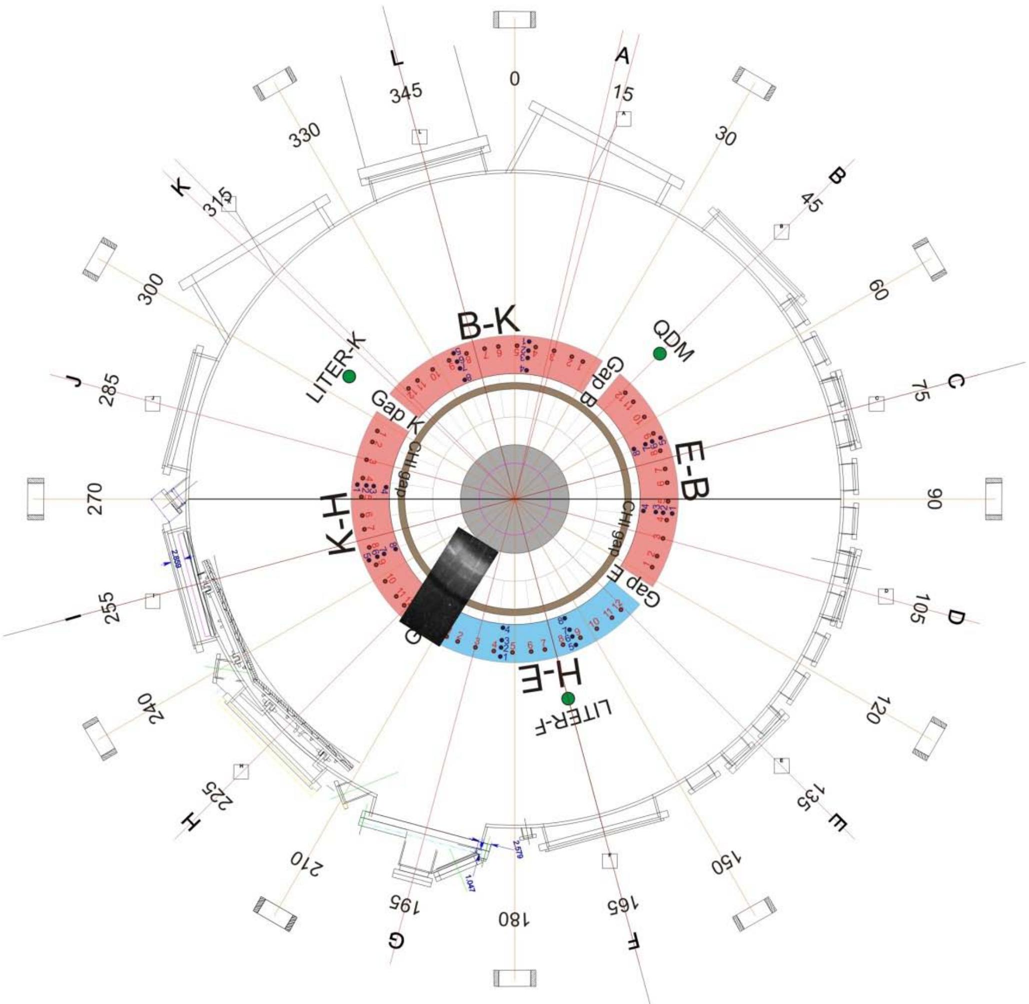



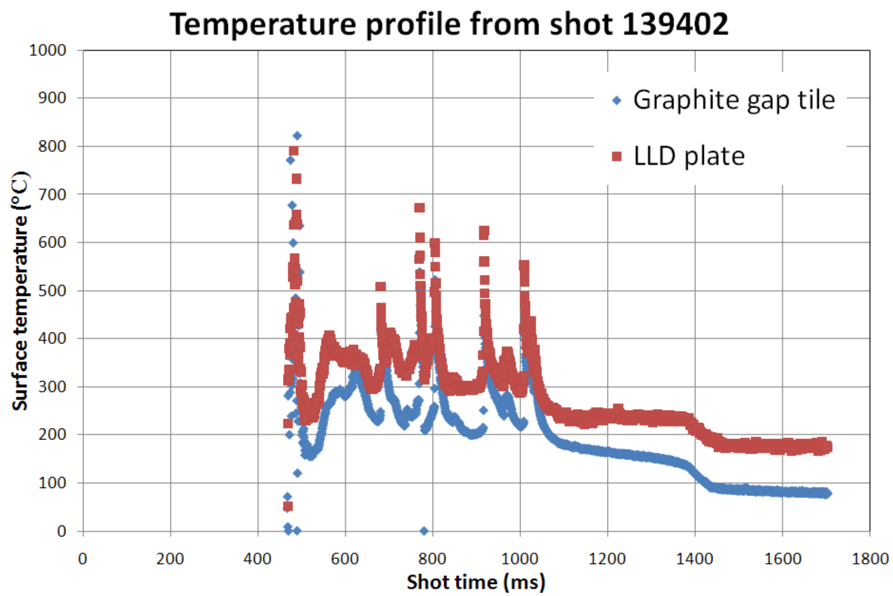
# Fast IR camera view into NSTX

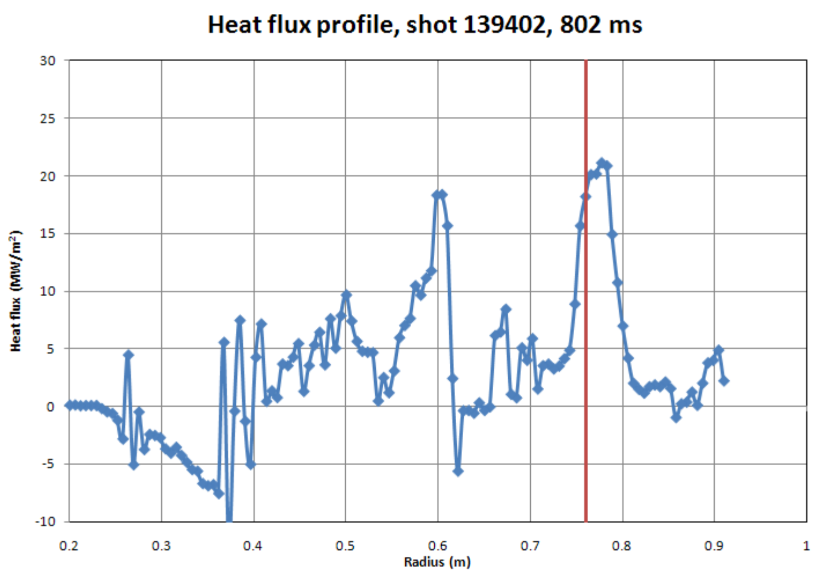
- IR view currently includes:
  - Toroidal orientation
  - K-H LLD plate (operative)
  - H-E LLD plate (inoperative in early 2010)
  - Gap H bias tile (lithium-coated graphite, unheated)
  - CHI gap
  - Useful for study of LLD response to plasma
  - Better view of strike points in high-triangularity configuration

ORNL NSTX Fast Infrared Camera View
Dual-band, radial configuration



# NSTX dual-band IR measurements on 7/30/2010

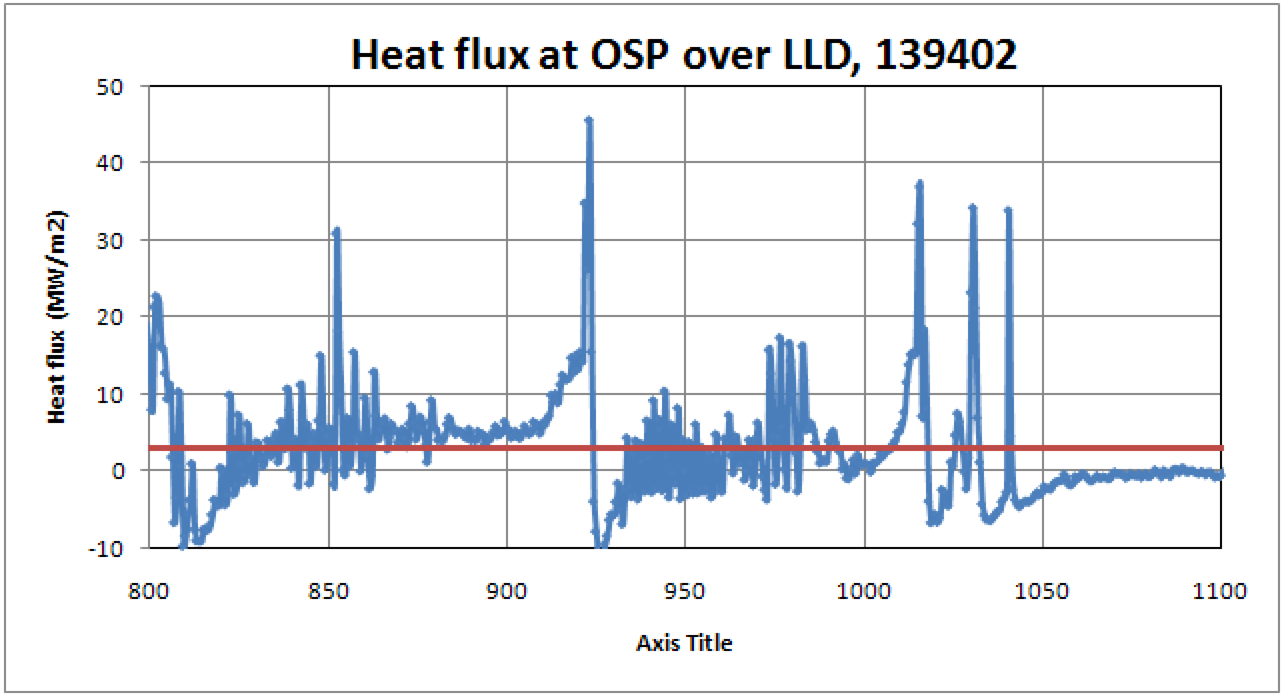



- Similar heating of LLD and graphite tiles surfaces during shot
  - Some significant differences, especially after ELMs
- Temperature during ELMs reach ~500 degC
- Trend after plasma diverts upwards, then plasma terminates (~1100 ms) most interesting
  - LLD first settles at ~230 degC, then quickly (in ~80 ms) reduces to ~180 degC after end of shot
  - Graphite cools from 1100-1400 ms, then also drops ~50 degC at 1400-1500 ms where the cooling trend continues
  - The drop is likely not due to reflections; something physical?

# Heat flux measurements, 139402

- Steady state heat flux of ~3-4 $MW/m^2$
- Peak heat flux in ELMs of ~40-50 $MW/m^2$ common
- Peak heat flux of 100-200 $MW/m^2$ found in disruptions

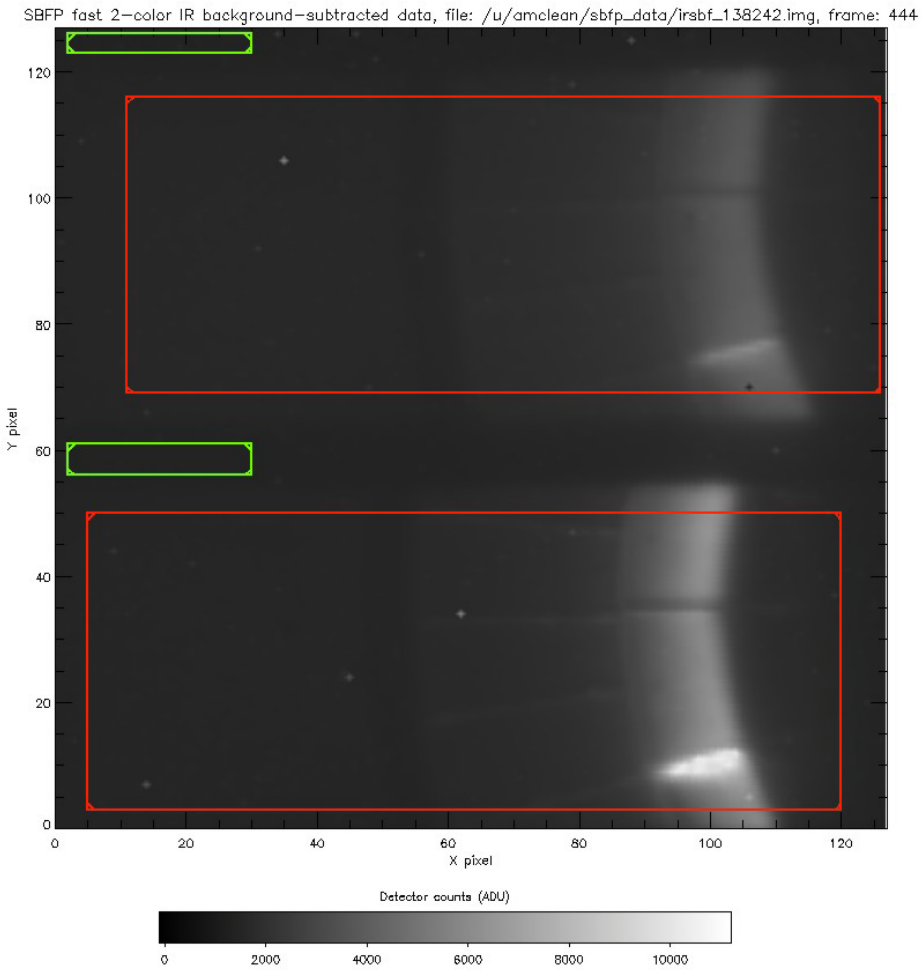


# Challenges to fast IR operation

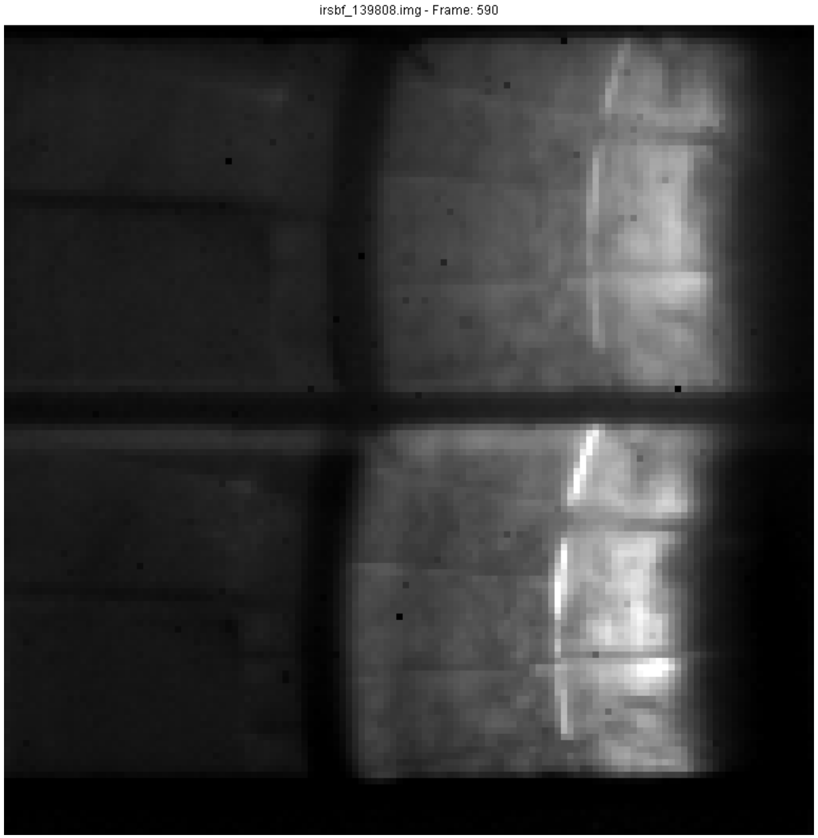
- First: Port window transmission
  - ZnSe IR-transparent LWIR-AR coated window (MFP)
  - Design: Transmission ~75% from 4-6 um, ~95% from 8-12 um (ratio: 1.27)
  - Practice:
    - Start of 2010 campaign (April 2-9): 58.3% MWIR, 66.4% LWIR (ratio: 1.14)
    - LLD Liter fill/heat up (August 5): 32.0% MWIR, 29.2% LWIR (ratio: 0.91)
  - Transmission ratio, April to August: 0.55 MWIR, 0.44 LWIR
  - Transmission ratio, theoretical to August: 0.43 MWIR, 0.31 LWIR
  - Significant loss in SNR, dynamic range
  - Li coating believed to be the cause
    - High absorption of MWIR and LWIR wavelengths (not necessarily so at visible wavelengths)
- Hope for the future
  - Possible 4” gate valve for 2011
  - Jake Nichols (PU graduate student) working on integrating this into the Bay H upper port design

# Bay H upper port window has suffered…

Shot 138242

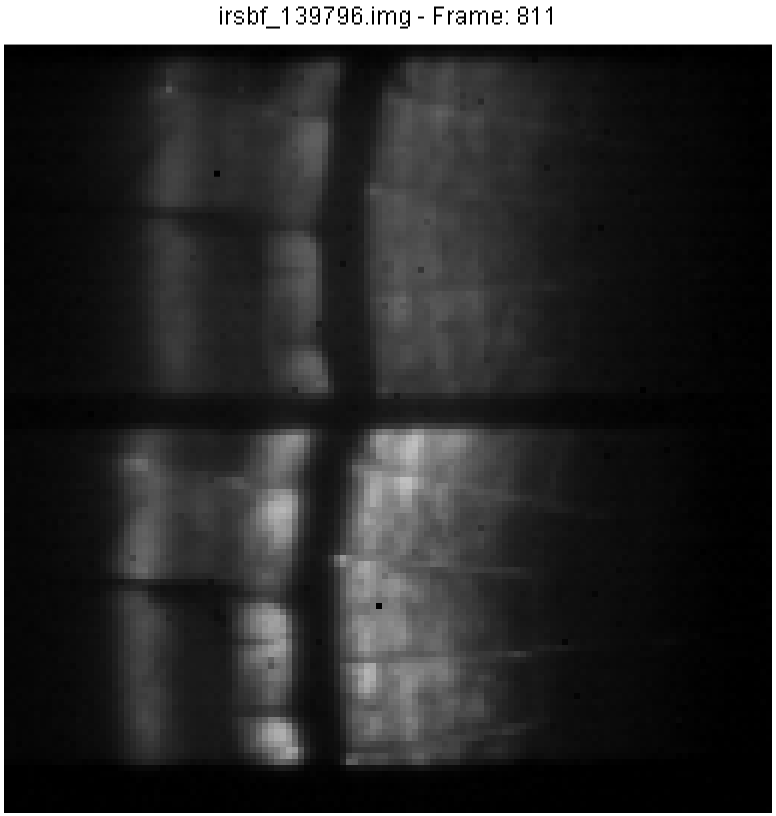



Shot 139808

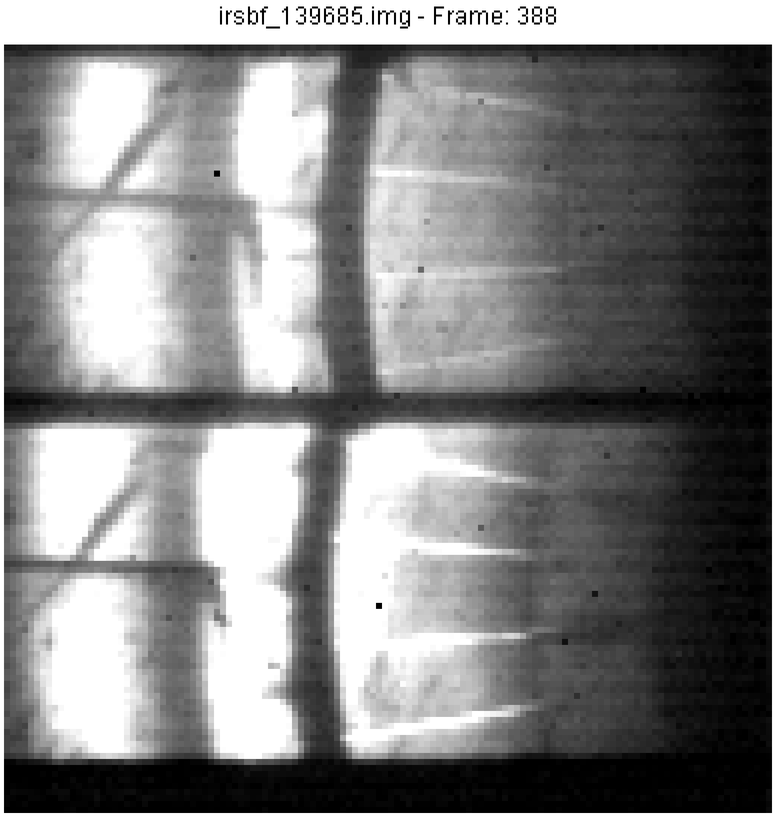


# ‘Blotching’ apparent everywhere, splatter over outboard divertor

Shot 139796

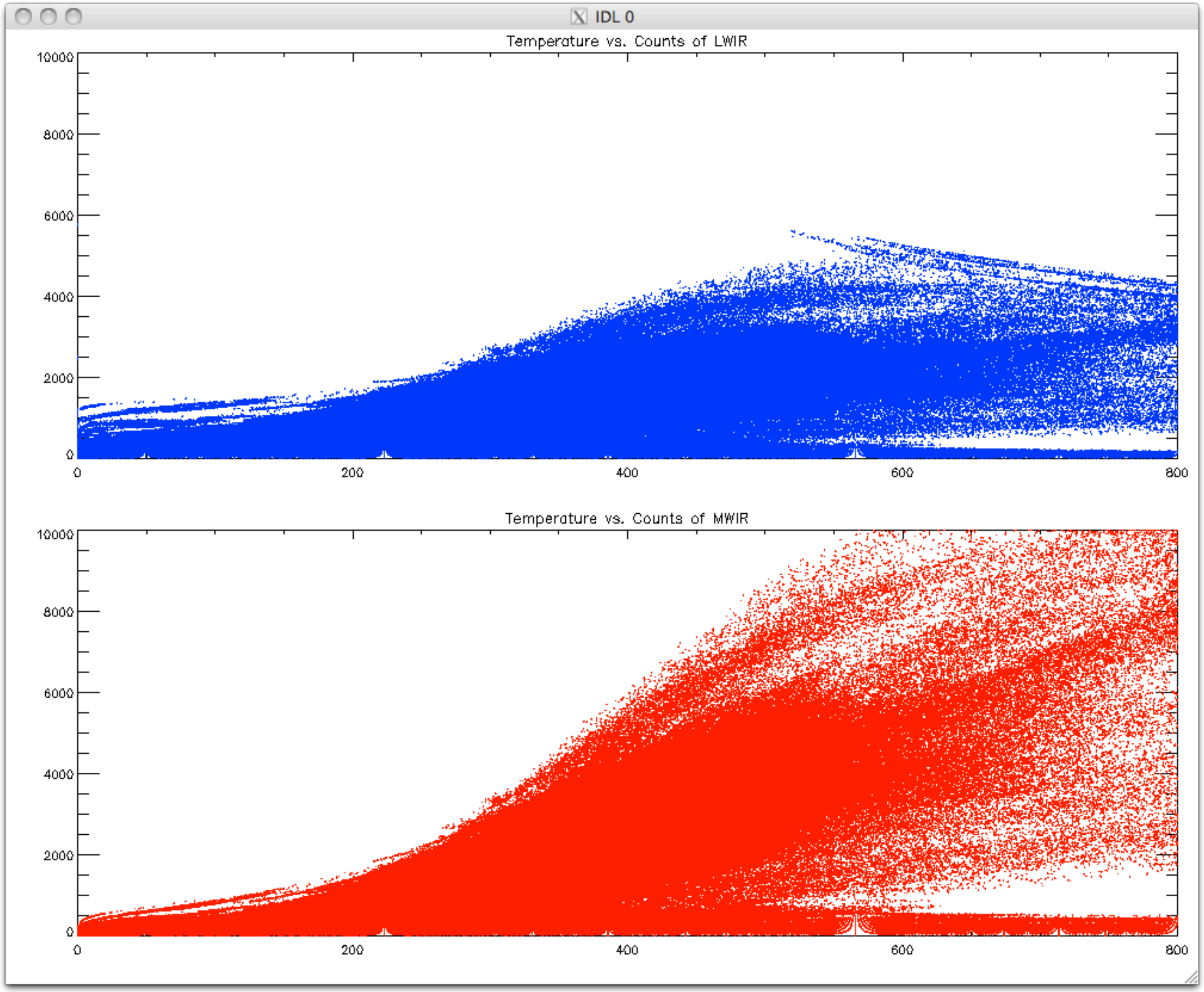



Shot 139685



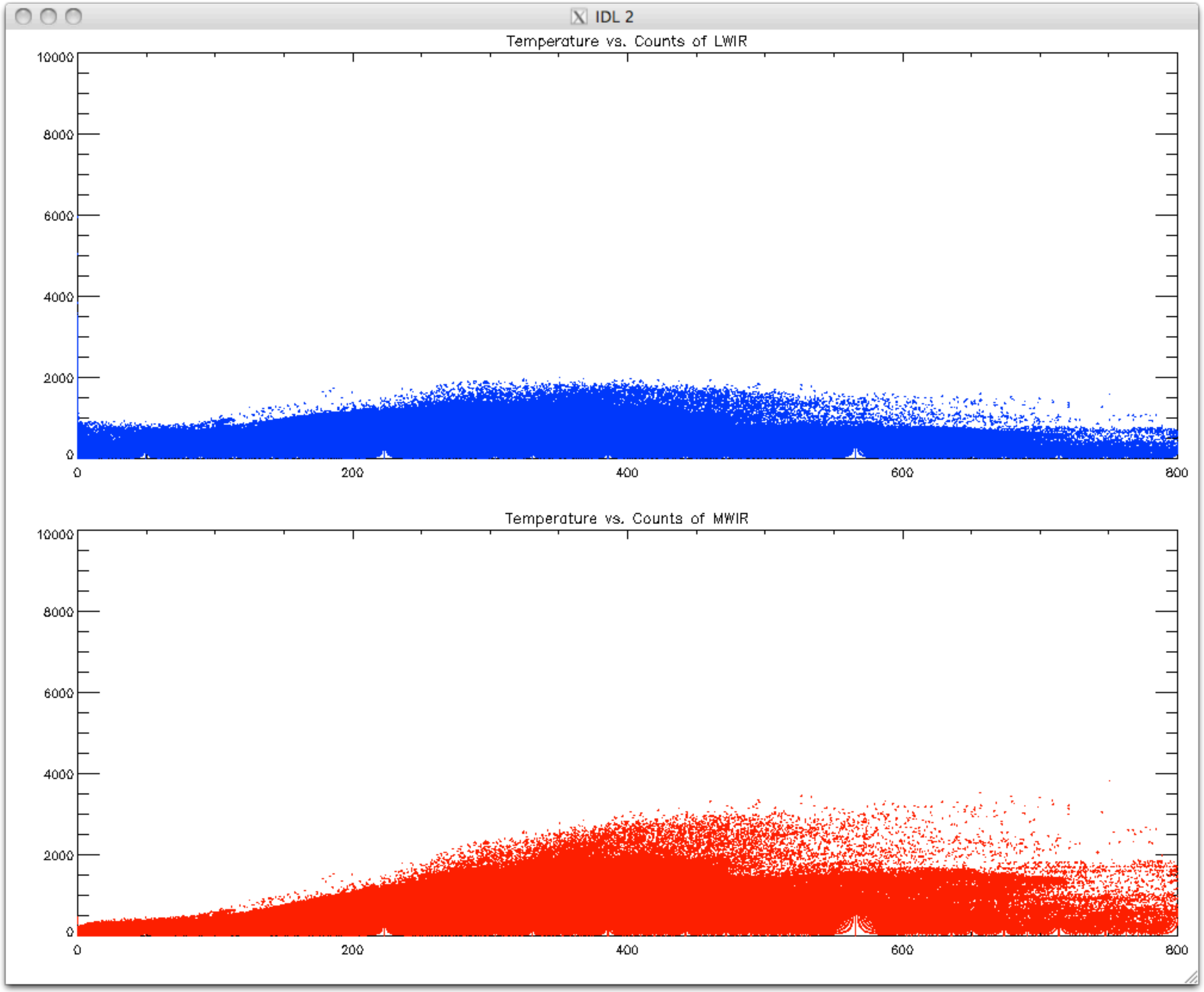
# Consequence of drop in window transmission
# A) When transmission was good…

- Shot 138242, 06/04/2010
- Plot shows dual-band calibrated surface temperature on X axis, LWIR (blue) and MWIR (red) raw counts on Y axis
- Noise level:
  - ~500 counts
- Peak SNR:
  - 12 LWIR
  - >20 MWIR
- **Spread demonstrates wide variation in surface emissivity**



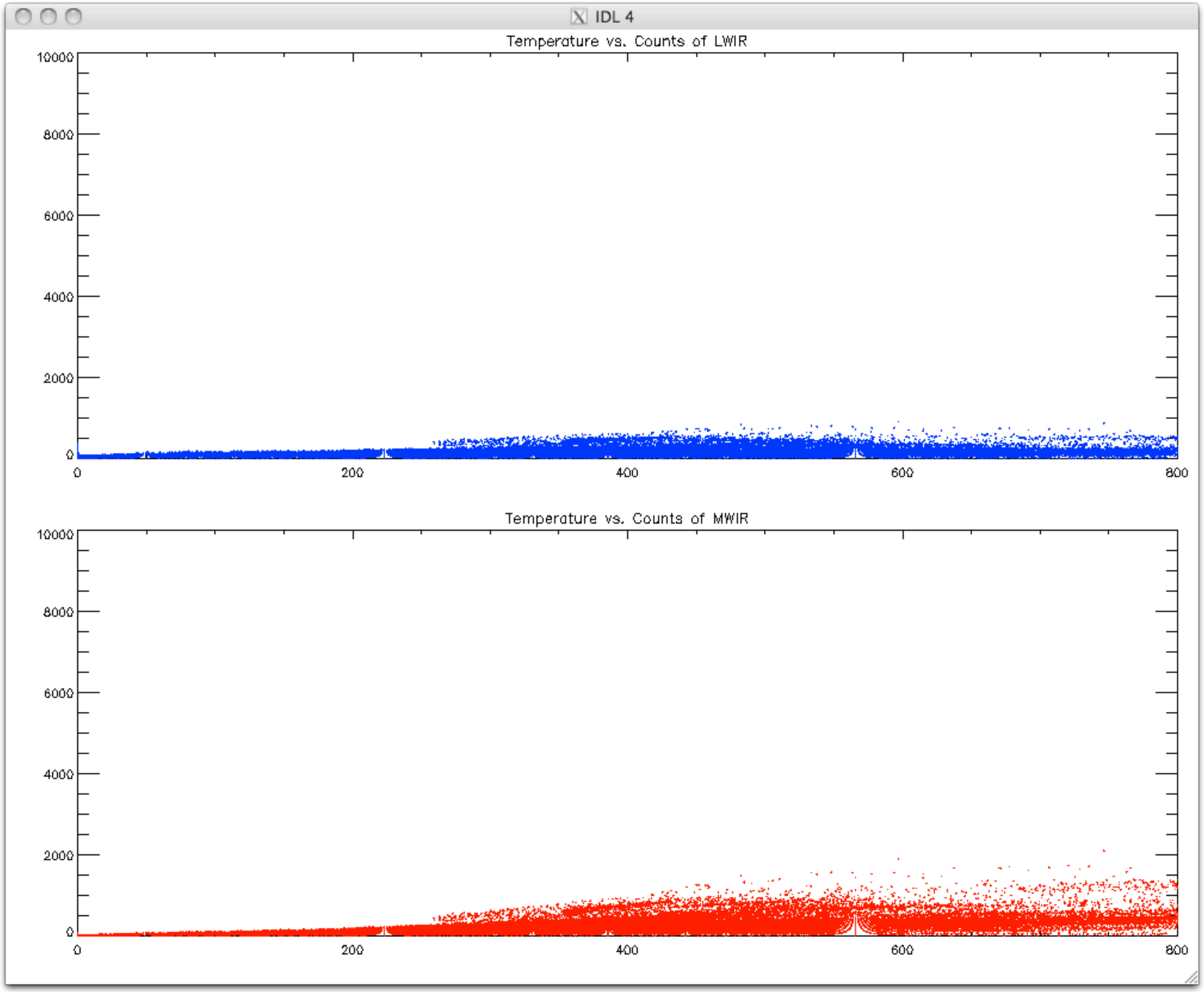
# Consequence of drop in window transmission
# B) Transmission plummeting…

- Shot 139952, 8/17/2010
- Plot shows dual-band temperature on X, LWIR (blue) and MWIR (red) raw counts on Y
- Noise level:
  - ~500 counts (unchanged)
- Peak SNR:
  - 4 LWIR
  - 6 MWIR
- Minimum reliable temperature is ~200 C
- Limits heat flux calculation spatially and temporally



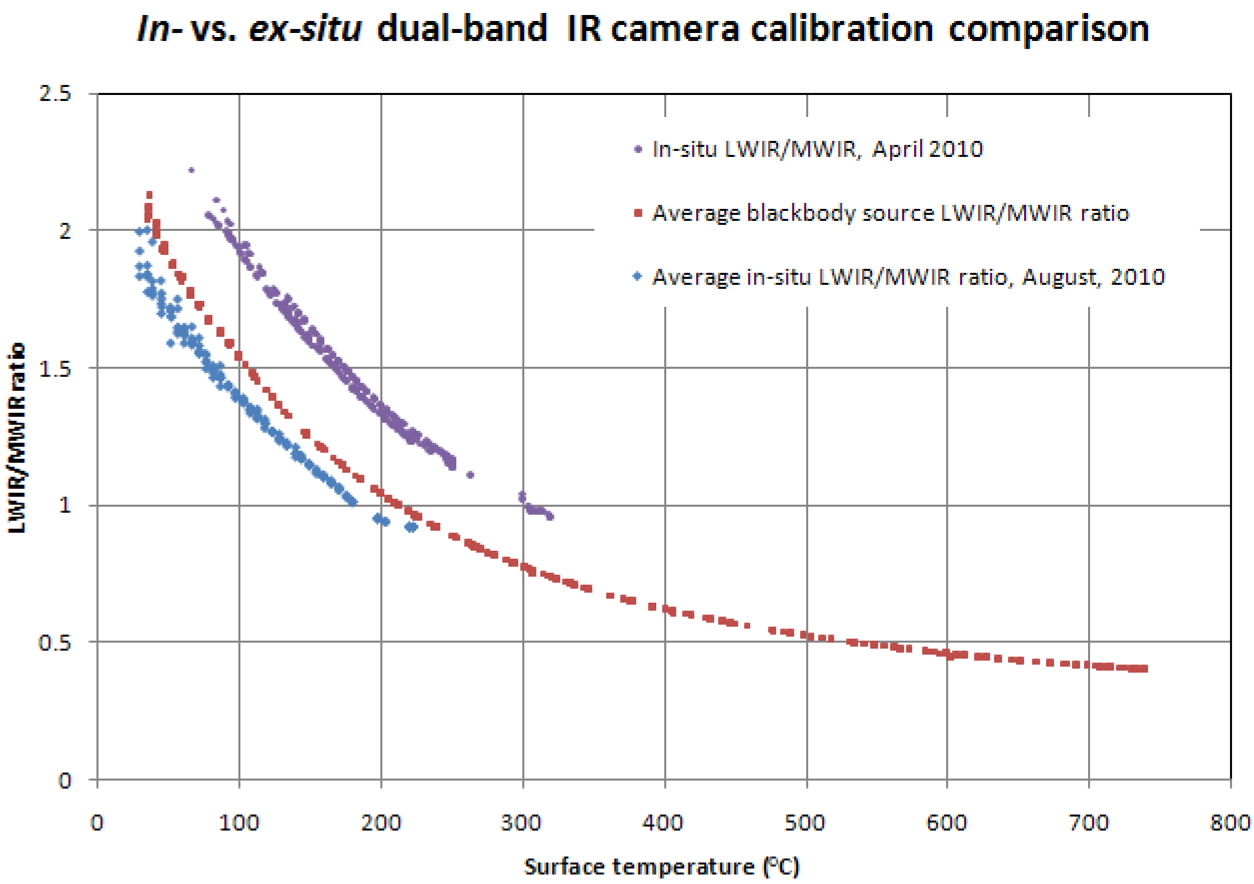
# Consequence of drop in window transmission B) Worse at low integration time…

- Shot 139818, 8/13/2010
- $T_{int}$=10.125 us as determined in April to maximize dynamic range
- Minimum reliable temperature measureable is ~400 C



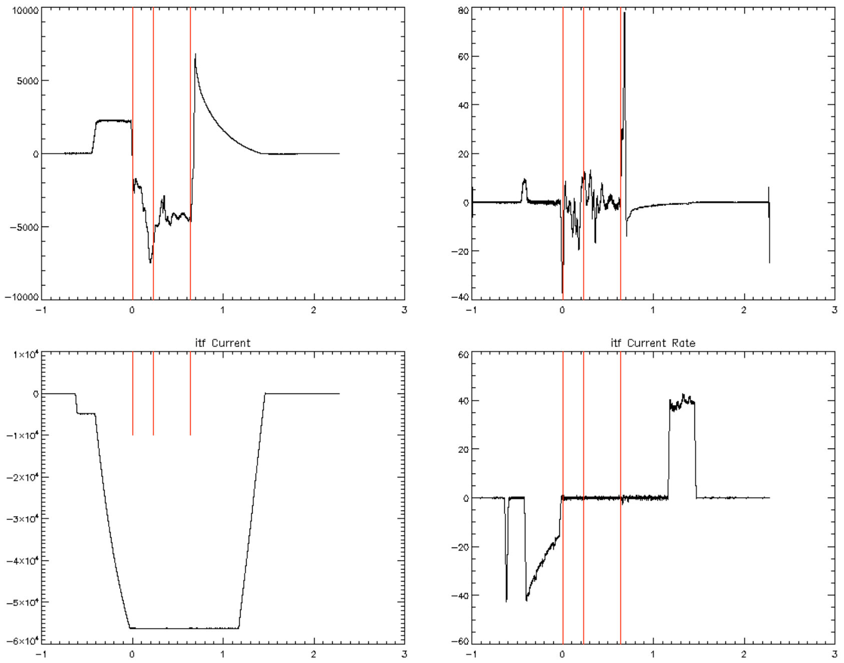
# Dual-band IR calibration has also changed…

- Original LWIR/MWIR ratio as expected with enhanced LWIR transmission through port window
- Decrease in LWIR transmission with coating higher than that of MWIR
- Limited to two in-situ calibrations
  - Challenge for interpretation of data between April and August



# Second challenge: Camera resets

- SBFP camera pauses for ~200-225 ms during periods of high dB/dt, caused by either the TF or PF coils nearby.
  - No video data written during this time
  - More recently, resets frequently occur back-to-back
  - Even a single reset creates a challenge for temporal heat flux calculation
- Resets only appear after extended exposure (i.e., first 6-8 weeks of use on the machine had no problems).
- Repair for resets was made in 2009, but extent of repair done at the time is uncertain.



# Second challenge: Camera resets

- Solution not yet isolated in 2010: Separate replacement of detector, primary FPGA, and digital electronics board has not led to improvement.
- Final replacement of analog control board this week hoped to fix problem (at least temporarily).
- **Shielding of camera at its location above PF3 coil is not possible**
- **Future implementation of optical relay by M. Benjamin (PU) is certain to alleviate problem.**

# Backup slides

# 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

# 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

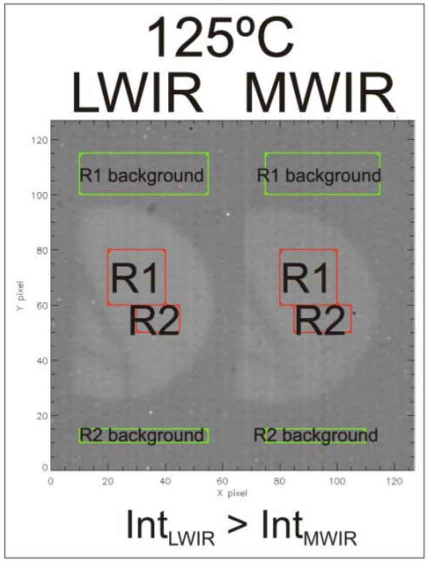
# Spectral throughput comparison for IR camera assembly

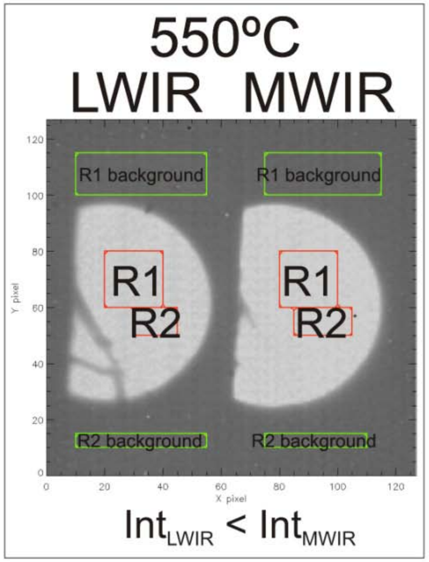
- Comparison of static throughput losses due to optical components in the dual-band adaptor
- Initial dual-band adaptor reduces throughput by ~4X compared to highest efficiency single-band mode
- Near-term improvements will reduce the difference to ~2X
- Significant margin is available in terms of integration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

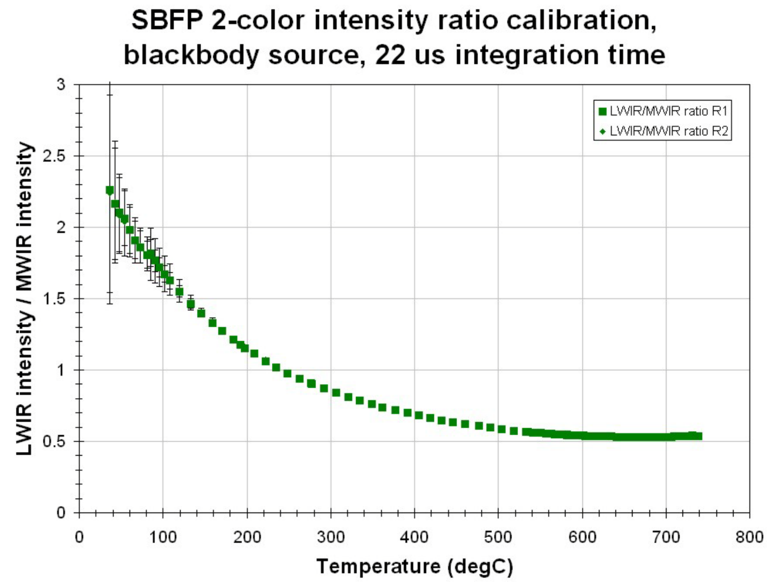
| Optical element | | Wideband operation | | Dual-band operation meniscus lenses | | Dual-band operation DOE lenses | |
|---|---|---|---|---|---|---|---|
| | | 8–12 μm operation | 3–12 μm operation | 4–6 μm band | 7–10 μm band | 4–6 μm band | 7–10 μm band |
| Observed bandwidth | | 4 μm | 9 μm | 2 μm | 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

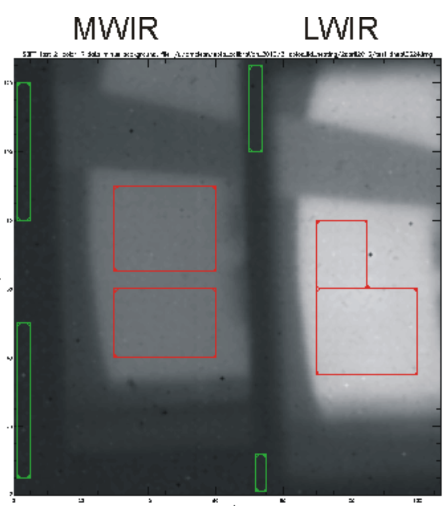


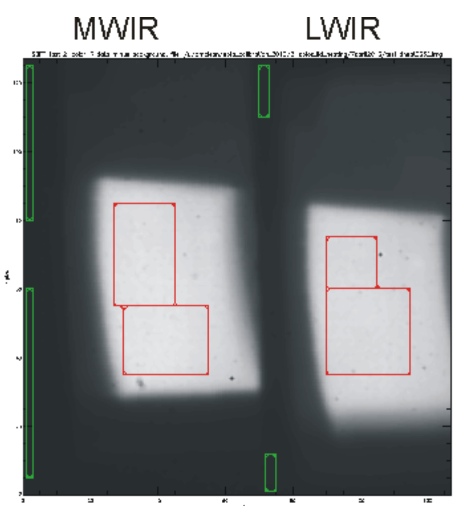



# *In-situ* calibration accomplished during heating of the LLD

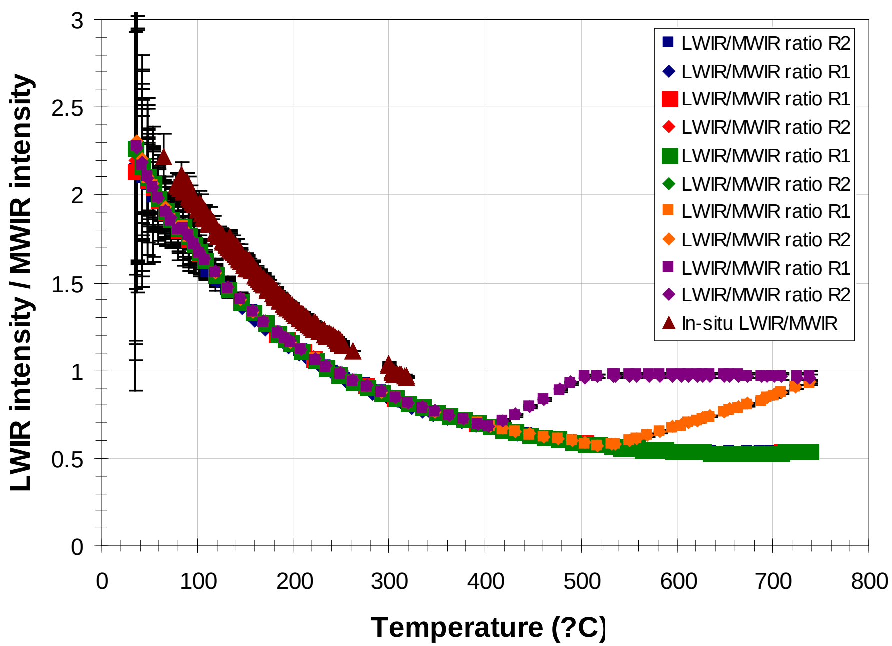
- Data captured with dual-band camera viewing LLD plates at 20-320˚C
  - Each LLD plate contains 20 thermocouples embedded in their copper substrate, 5 of which are in positions in the view of the fast IR camera
  - Nearly 500 frames of data taken with 10-75 μs integration time for complete comparison 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




April 2, 2010 12:46.06 PM
Both LLD plates at ~60°C, ratio=2.2

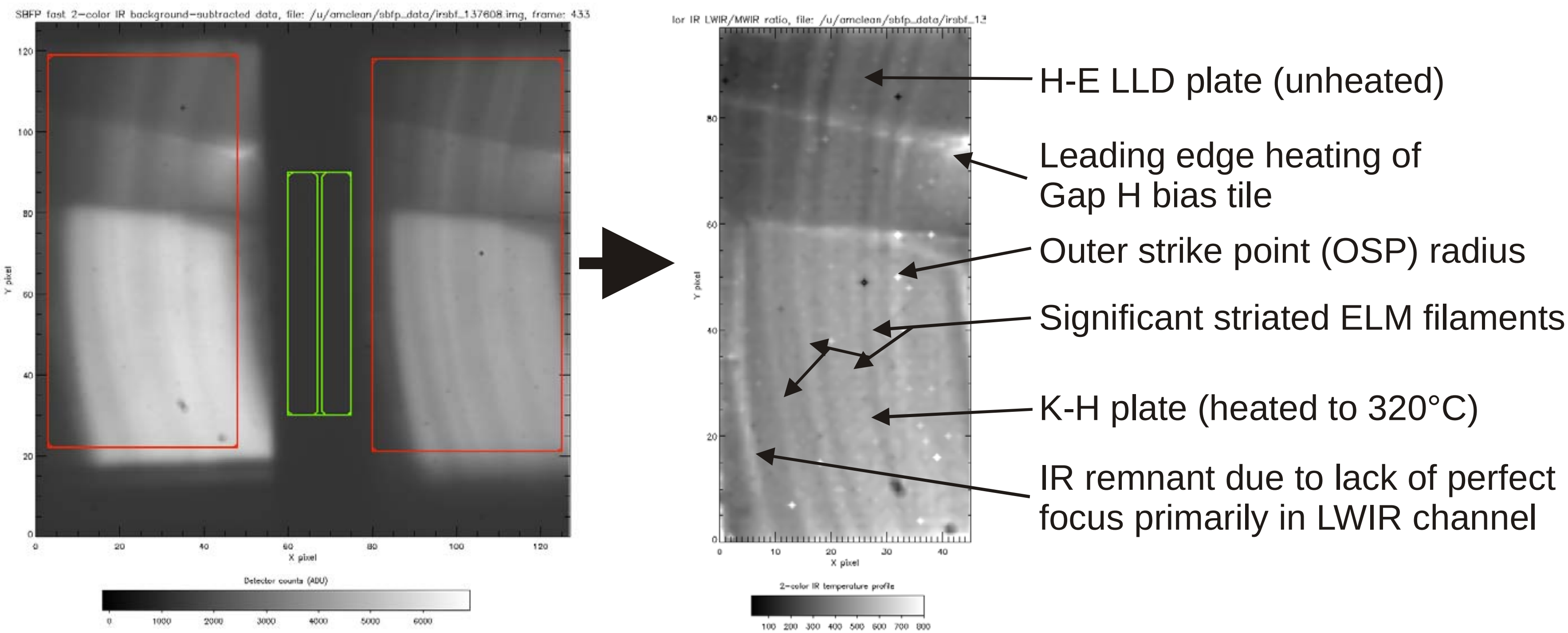



April 7, 2010 3:25.26 PM
K-H LLD plate at ~320°C, ratio=1.0



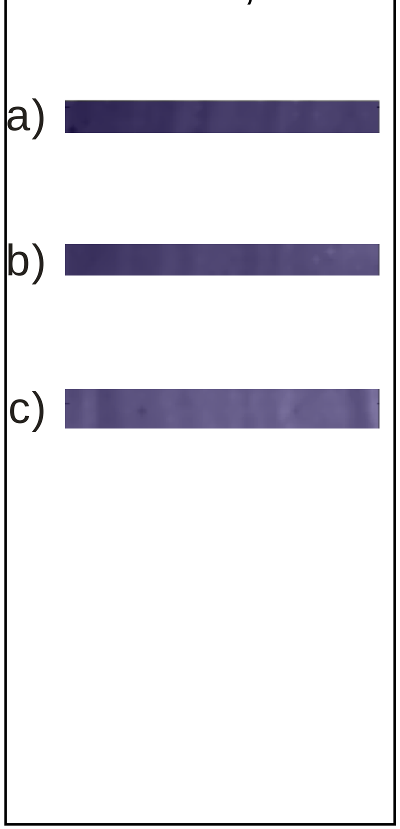
# Dual-band IR technique demonstrated on images taken during plasma operation in NSTX with heated LLD

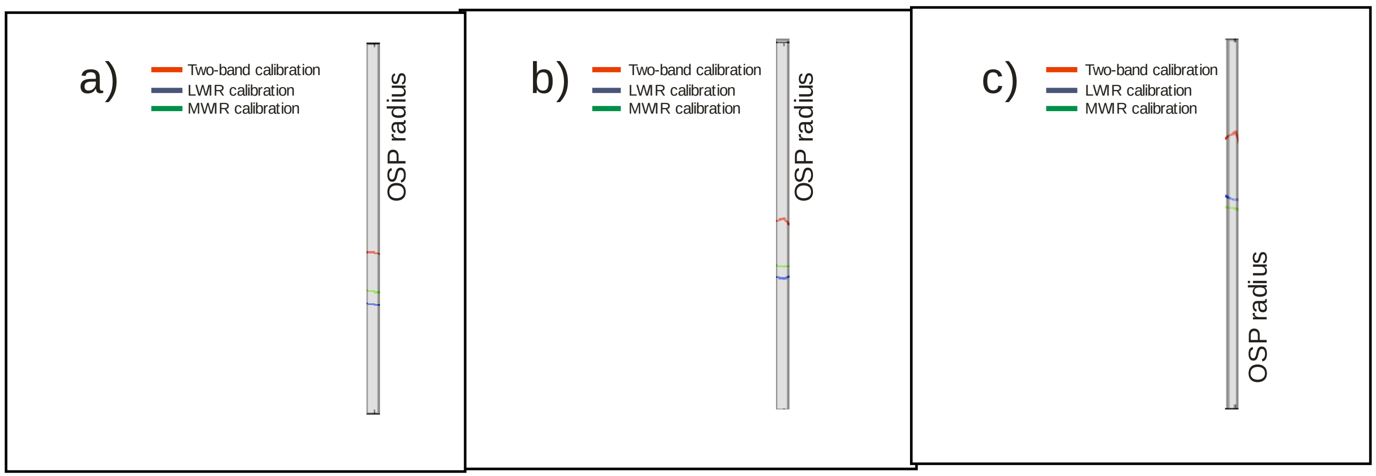
- *Ex-situ* calibration data of T vs. LWIR/MWIR ratio fitted to functional form, then shifted for best fit to available *in-situ* data
- Data captured in ~350 shots so far, stored to MDSplus
- Maximum 128x64 pixels on IR detector per channel (i.e., band), 1.6 kHz frame rate
- In practice, limited to ~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



# 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

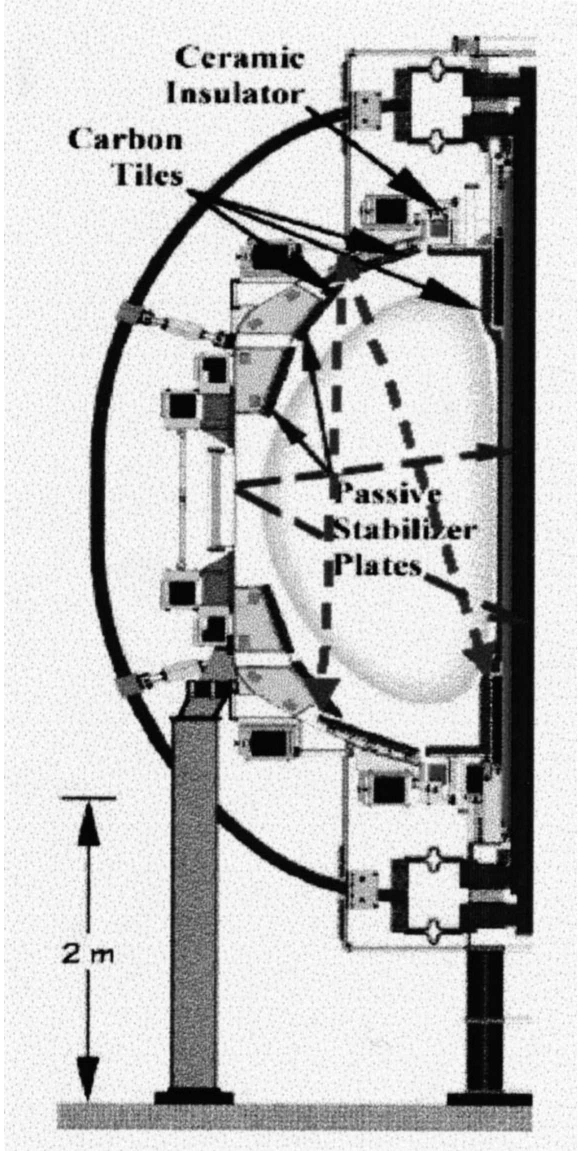



- Analysis of frame-to-frame temporal continuity with limited/damaged detector in progress
- Detailed analysis of temperature vs. time and heat flux to LLD (1-D and 2-D) can now proceed

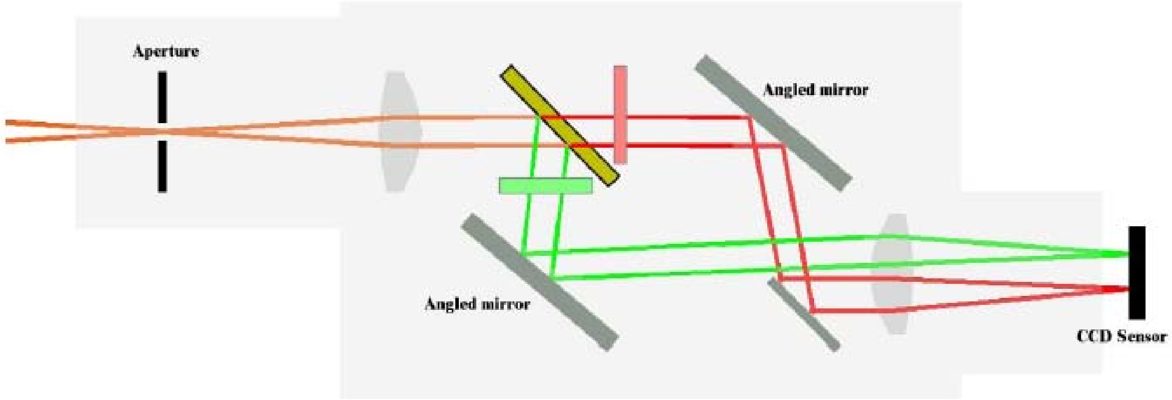
# ORNL IR system currently on NSTX

- 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

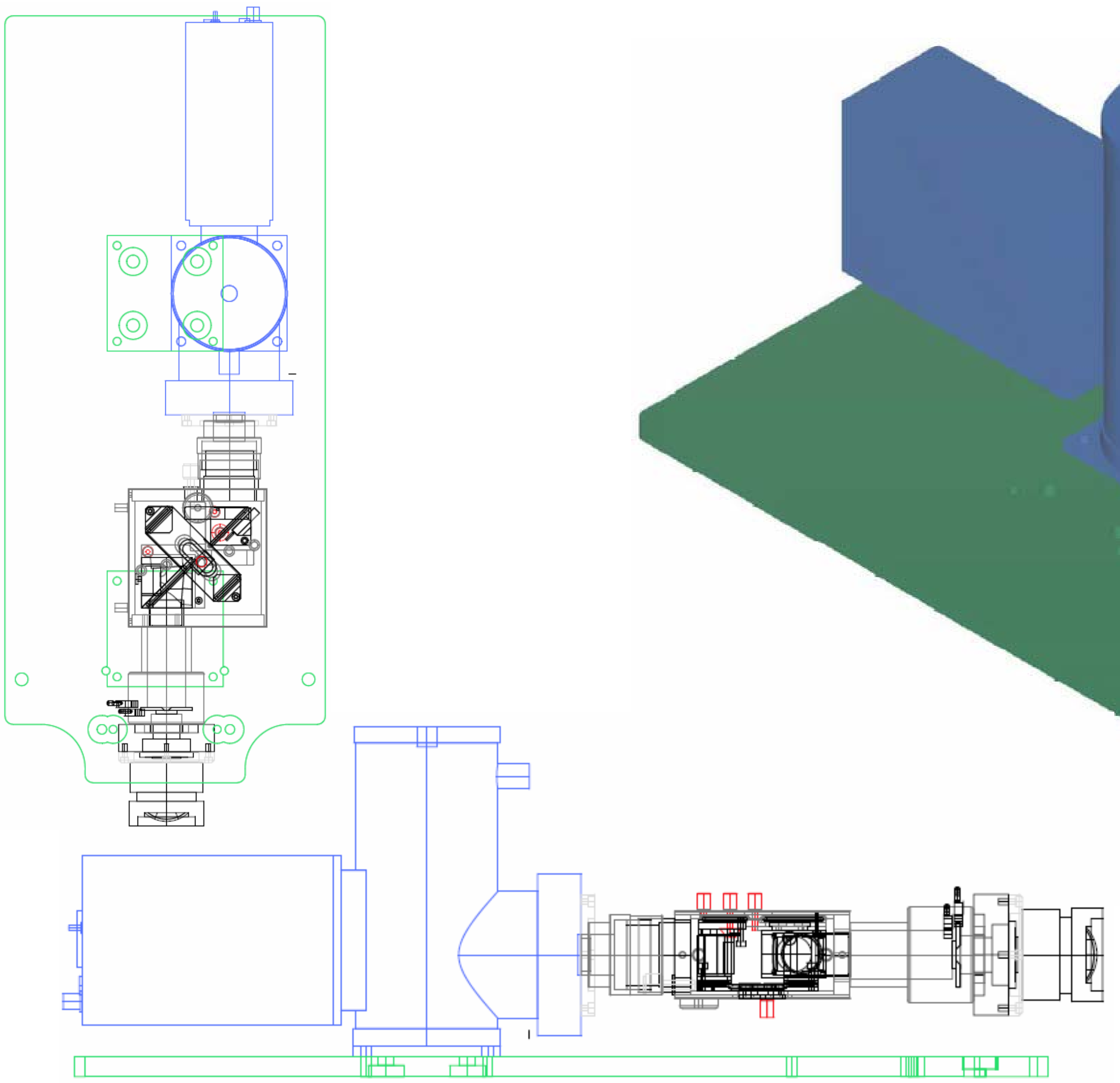


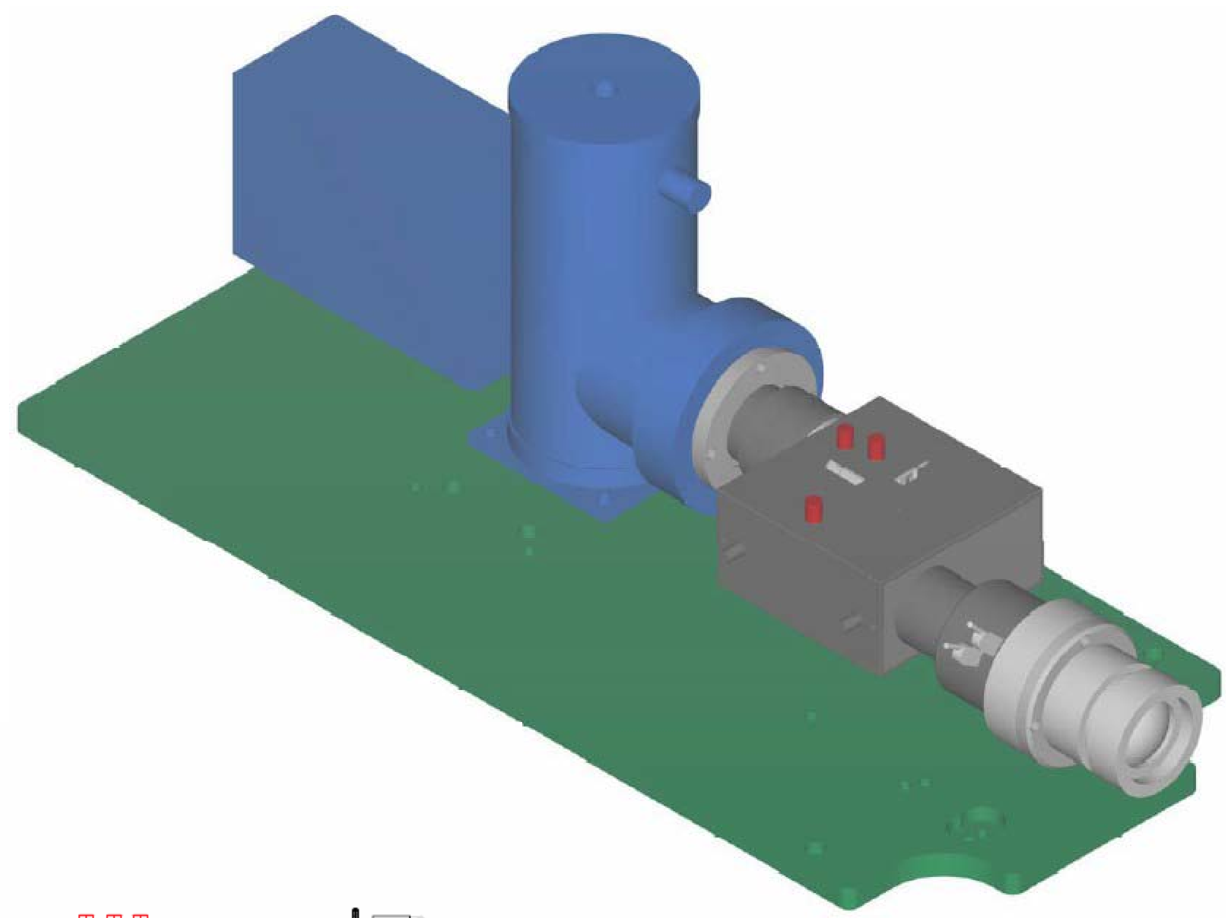
# Two-color infrared camera

- 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