NSTX

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PPPL
PRINCETON PLASMA PHYSICS LABORATORY

Design and Deployment of a Wide-Angle, Two-Color Infrared Camera with Optical Relay on NSTX

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53rd APS-DPP, Salt Lake City, UT, November 14-18, 2011

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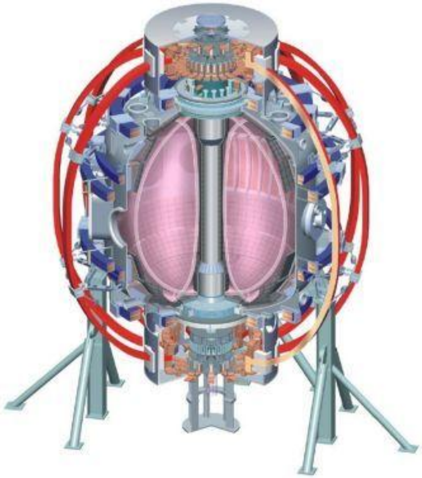

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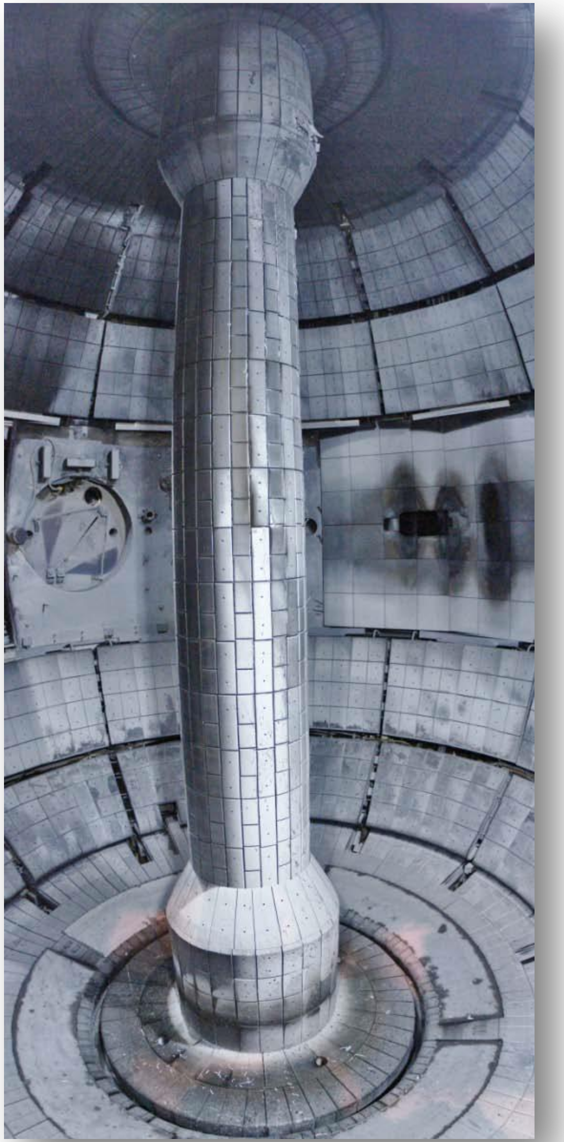
Abstract

A new 30 Hz infrared camera featuring a wide-angle view of the lower divertor is to be installed on the National Spherical Torus Experiment (NSTX). This camera utilizes a dichroic beamsplitter to project two IR channels (a 7-10 µm wavelength band and a 10-14 µm wavelength band) of the same image side by side on its uncooled microbolometer detector; taking the ratio allows the camera to make temperature measurements that are nearly independent of surface emissivity, an important quality because of the use of highly reflective lithium coatings on top of highly emissive graphite tiles. The camera looks through a reentrantly-mounted chemical vapor deposited (CVD) diamond window, chosen because of its high infrared transmission and ability to withstand a 350°C vessel bakeout. A cost-effective reflective relay has also been built to remove the camera from regions of strong magnetic field while avoiding chromatic aberrations.

Work supported by US DOE contracts DE-AC05-00OR22725 and DE-AC02-09CH11466 as well as the DOE Fusion Energy Sciences Fellowship Program.

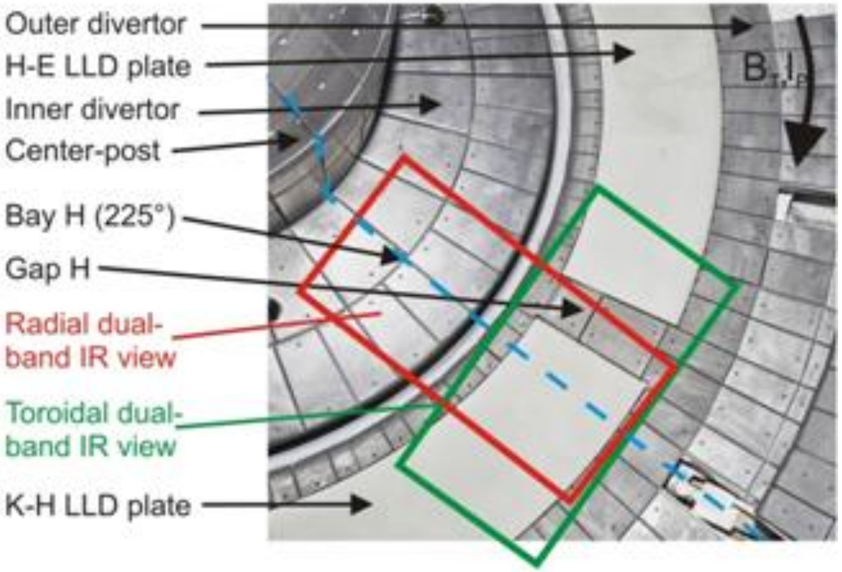
Motivation: NSTX needs accurate temperature measurements despite a complex and changing environment

- NSTX interior involves mixture of 3 PFC materials (C, Mo, Li)
  - Base: ATJ Graphite
  - Routinely operate with evaporated Li thin film coating (LITERs)
  - Liquid Lithium Divertor (liquid Li on top of heated Mo plates) installed at outer divertor for FY2010
  - Row of Molybdenum tiles installed at inner divertor for FY2011
- Assumption of high surface emissivity is no longer accurate
  - $\varepsilon > 0.85$ for graphite, $\varepsilon < 0.1$ for molten lithium
- Surface layer composition/emissivity is not well diagnosed, and changes during/between shots
  - Dual-band imaging measures temperature via the ratio of intensities from two IR bands, reducing the dependence on emissivity

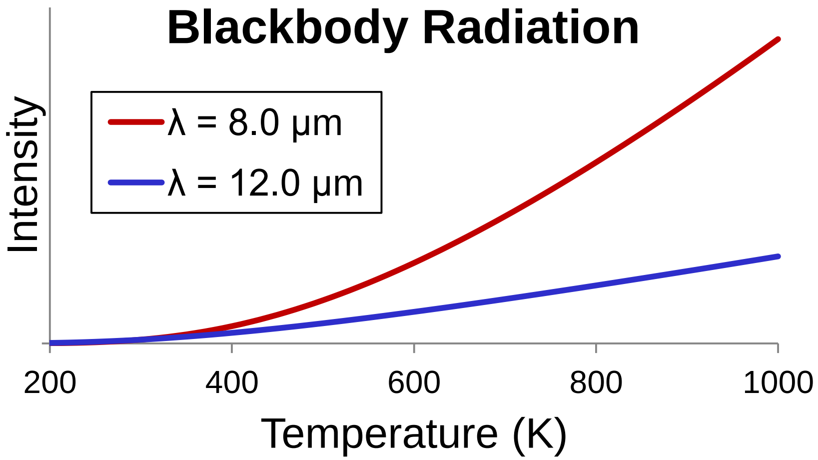


Existing IR camera coverage on NSTX

- 2 slow (30 Hz) single-band IR cameras
  - Indigo Omega, 160x128 pixels, 12 bit depth, uncooled microbolometer focal plane array, 7-13 µm spectral band
- 1 fast (1.6-6.3 kHz) dual-band IR camera
  - Santa Barbara Focal Plane (Lockheed Martin) ImagIR, 128x128 pixels, 14 bit depth, HgCdTe focal plane array (LN$_2$-cooled), 1.5-11 µm spectral band



Calibration of ratio of intensities to temperature reduces emissivity dependence



- Planck’s Law for spectral radiance (W/m²/μm):

$$I_{BB}(\lambda,T)=\frac{2\pi hc^2}{\lambda^5[\exp(hc/\lambda kT)-1]}$$

- Measured intensity is modified by transmission efficiency (η) and grey-body emissivity (ε)

$$I_{surf}(\lambda,T)=\eta(\lambda)\cdot\varepsilon(\lambda,T)\cdot I_{BB}(\lambda,T)$$

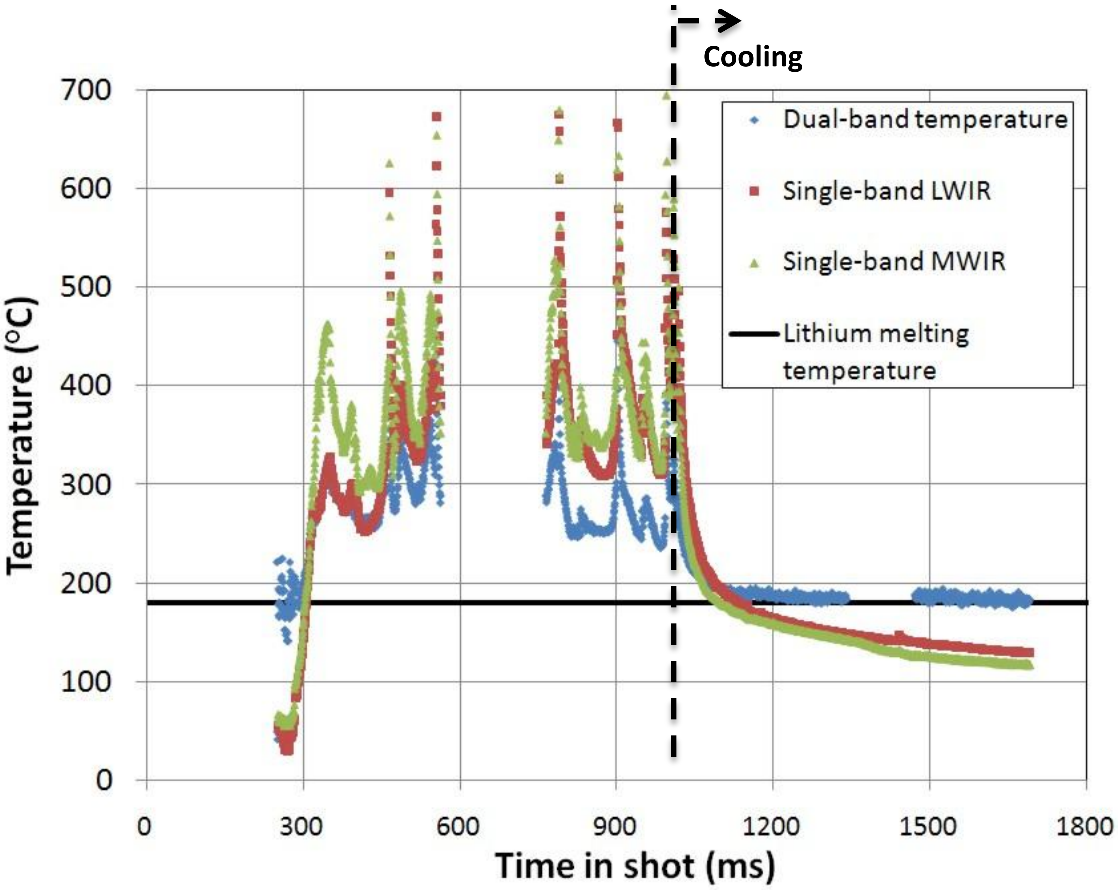
- Intensity ratio:

$$\frac{I_{surf,1}(\lambda_1,T)}{I_{surf,2}(\lambda_2,T)}=\underbrace{\frac{\eta_1(\lambda_1)}{\eta_2(\lambda_2)}}_{\text{Known from optics}}\cdot\frac{\varepsilon_1(\lambda_1,T)}{\varepsilon_2(\lambda_2,T)}\cdot\underbrace{\left(\frac{\lambda_2}{\lambda_1}\right)^5}_{\text{Known}}\cdot\underbrace{\frac{\exp(hc/\lambda_2 kT)-1}{\exp(hc/\lambda_1 kT)-1}}_{\text{Some f(T)}}$$

If ε(λ_1)=ε(λ_2), the emissivity dependence completely falls away!
The wavelength dependence of ε is usually very weak

Dual-band technique verified by fast IR camera during 2010 LLD experiments

- LLD was brought above the melting point of Li by plasma heating, then allowed to cool after the shot
  - Single-band results suggest that post-shot T_{LLD} decreased monotonically
  - Dual-band result suggests that post-shot T_{LLD} steadied at Li melting temperature (180°C), indicative of the latent heat of solidification
- Gaps in data are due to camera faults (since fixed)



[McLean RSI 2011]

Why install a new camera?

- Slow single-band cameras are outdated and not reliable in lithiated environments
- Fast dual-band camera has limited field of view, spatial resolution (5 mm)
- Wide-angle view would enable new measurements
  - Detection of hotspots on Mo tiles
  - Direct evidence of how non-axisymmetric phenomena affect heat flux footprint (e.g. strike point splitting, striations, etc.)
- Developing dual-band technique for LWIR (8-12 µm) has numerous advantages
  - No plasma emission in LWIR band (unlike NIR or SWIR)
  - LWIR cameras are smaller, cheaper, and more widely used
  - 8-12 µm broadband anti-reflection coatings are more common than 4-10 µm
  - Many LWIR cameras do not require cooling

Camera chosen: Tau 640 from FLIR Systems, Inc.

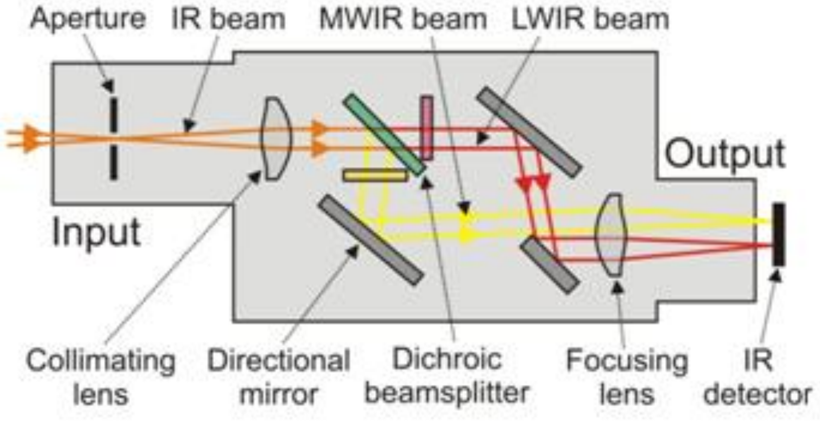
- Camera features
  - 30 Hz continuous operation
  - Uncooled vanadium oxide microbolometer focal plane array
  - 640x512 pixels, 17 µm pitch
  - 22 ms integration time
  - 7.5-13.5 µm spectral band
  - Powered/controlled via USB connection
  - Digital data out via Camera Link
  - It's tiny! 1.5"x1.5"x1.2" w/o lens
  - 14 bit depth (raw) or 8 bit depth (with gain control and noise reduction)
    - We use raw 14 bit signal because 256 gray levels (8-bit) gives insufficient precision
- We have 2 LWIR lenses which can be used with this camera + dual-band adapter
  - Ophir SupIR athermalized lens, 35 mm, f/1.4, T_{avg}~87%
  - Janos Varia lens, 25 mm, f/2.0, T_{avg}~95%

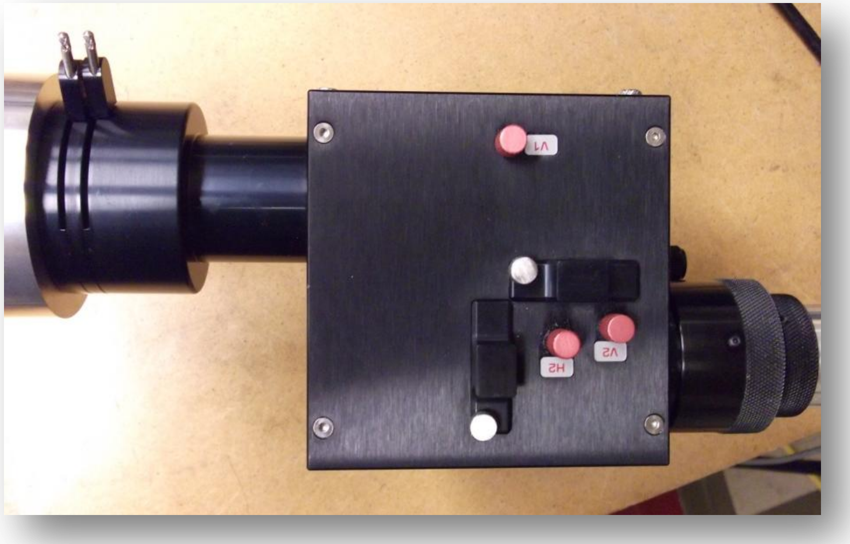
Data acquired via Camera Link framegrabber and stored on a local CPU

- Dedicated CPU (outside test cell): Dell Optiplex GX620, 3.4 GHz, Win7
- Framegrabber: EDT PCI DV C-Link, 220 MBps bandwidth, supports 1 Medium CL or 2 Base CL
  - Optical trigger to enable sync with NSTX trigger pulse
  - Versatile C library controls image capture
  - Integrated with libtiff to save 14 bit images in tiff format
- Fiber optic extenders provide electrical isolation and protect host CPU
  - Data: Thinklogical CFL-4000, Full/Med/Base CL, 350m range, 680 MBps
  - Control: Icron USB Ranger 2224, 4 USB 2.0 ports, 500m range, 60 MBps

Future work: Link data to MDSplus tree, and integrate with IDL software suite (FIRNACE) that handles dual-band analysis and calculates heat flux

Dual-band technology is contained in a modular package

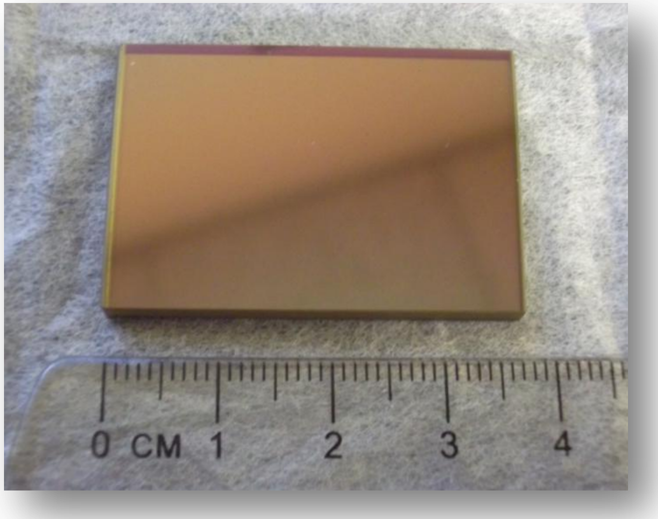


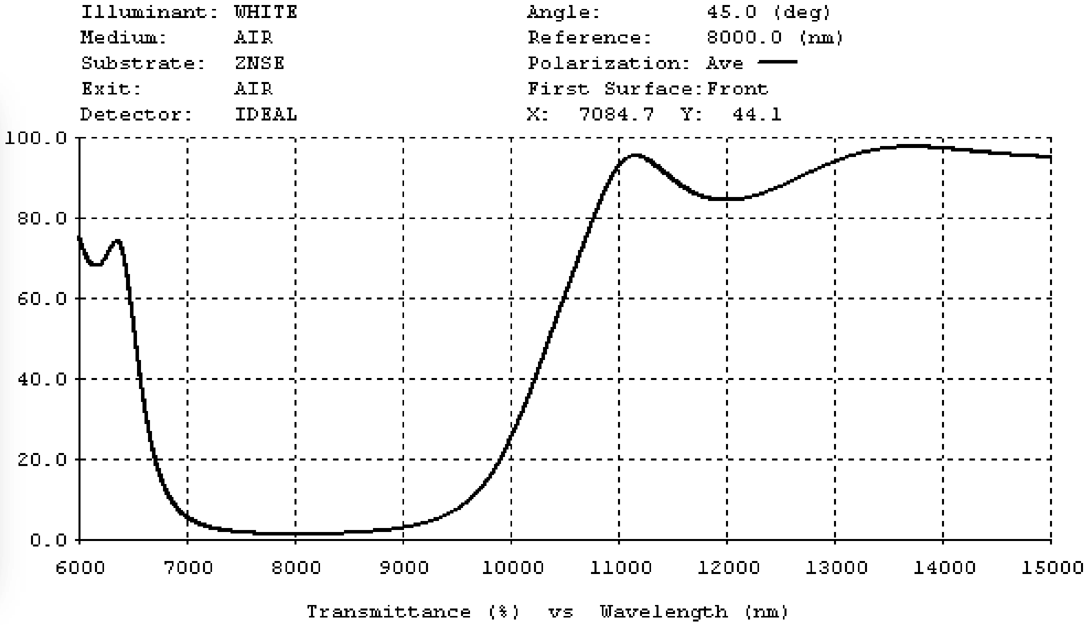


- Chassis: CAIRN Research OptoSplit II
  - Precision multi-axis optical alignment
  - C-Mount input/output threads
  - Adjustable razor baffles provide windowing
- Lenses: ZnSe singlet hybrid diffractive optical elements (DOE)
  - BBAR coated 4-10 µm, T_{avg}~97%, T(12 µm)~85%
  - Diffractive profile sharply reduces chromatic aberrations in 4-10 µm range, though some remain in the long wavelength band
  - Potential upgrade: Lenses optimized for 8-12 µm band
- Mirrors: Protected Aluminum coating, T>96%

New dichroic coating developed to split LWIR band

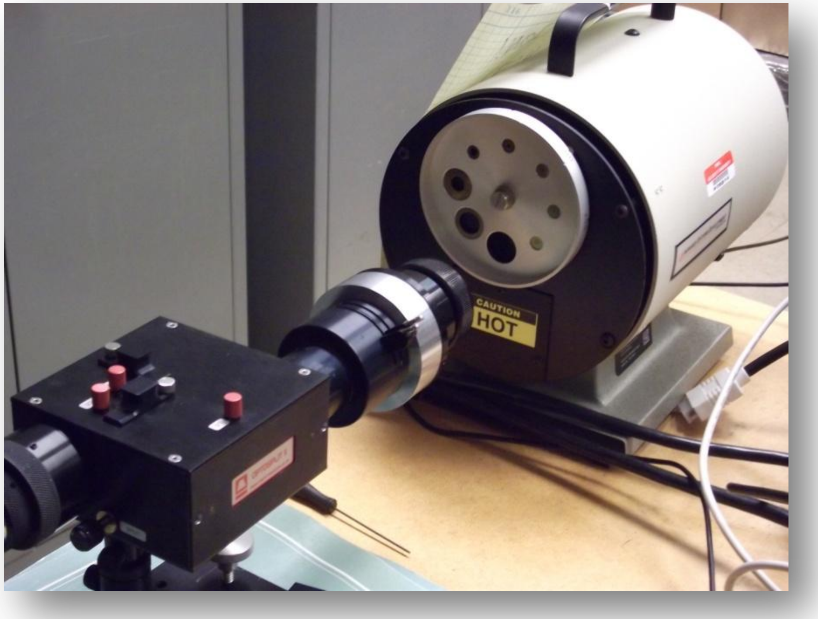
- Dichroic beamsplitter manufactured by Lambda Research Optics
  - Long-wave pass (T_{avg}~91% over 10.5-15 µm)
  - Short(er)-wave reflect (R_{avg}~95% over 7-10 µm)
  - Long/short-wave pass filters available to further reduce spectral contamination

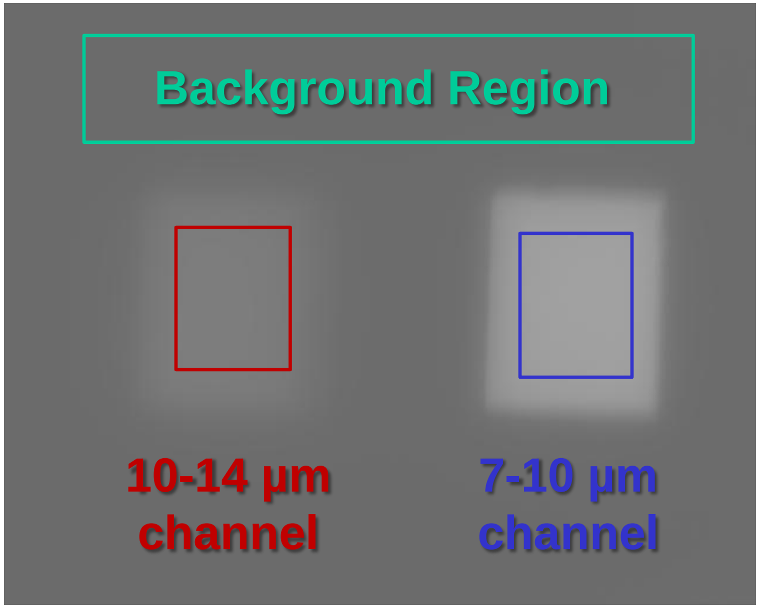




- Even with beamsplitter R&D, full cost of dual-band adapter was <$20K

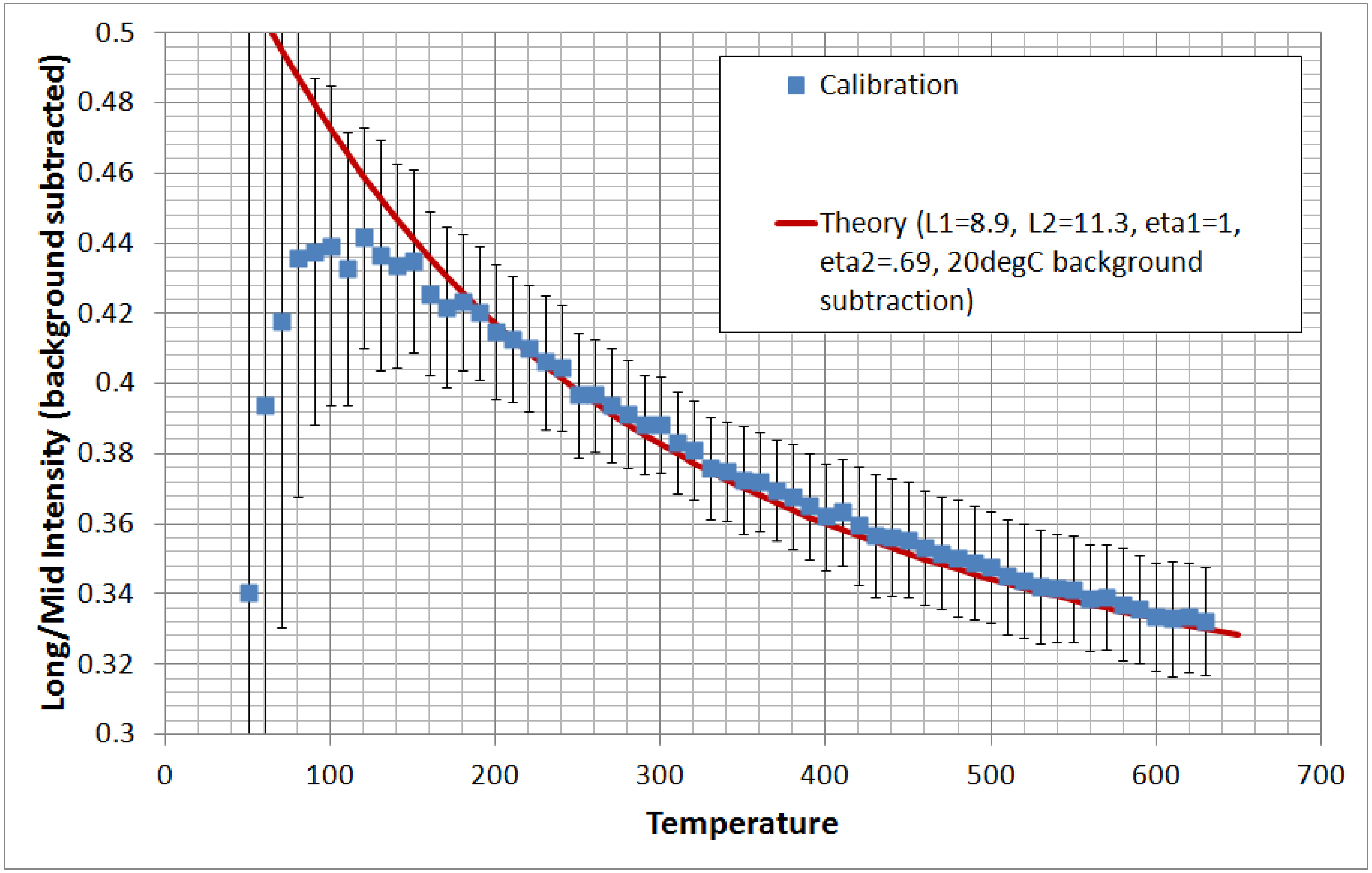
Ex-situ calibration performed with a tabletop blackbody source





- Blackbody source capable of 1200°C
  - Often trips circuit breakers in room well before that
- Calibration routine:
  - Each channel is windowed so that blackbody fills FOV
  - Average background is calculated and subtracted from each channel
  - Ratio of subtracted signals (long/mid) is taken
- Currently performed manually, but will be automated soon

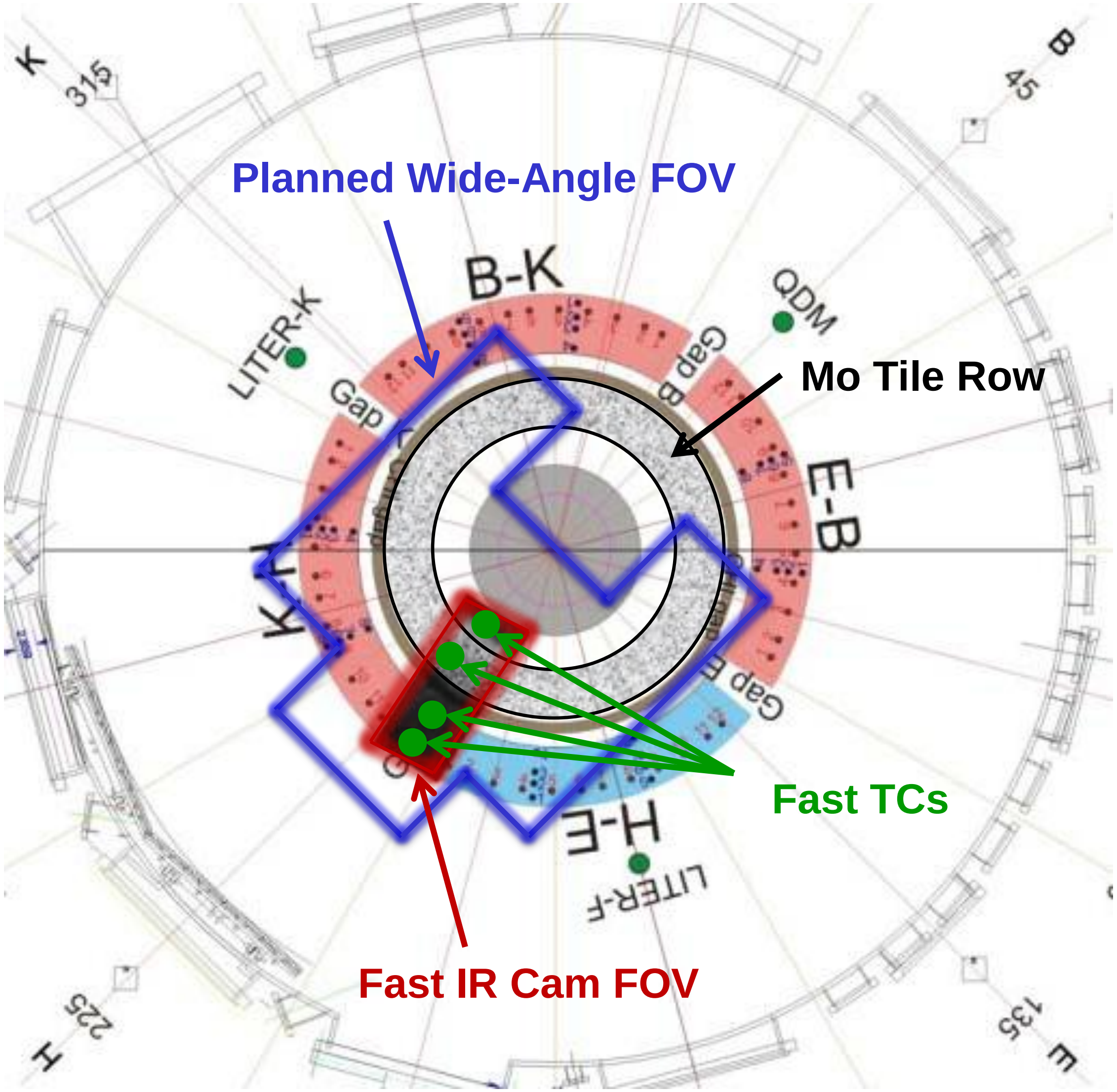
Ex-situ dual-band LWIR calibration fits theory, suggesting that the technique will be effective



- Not very useful for T<100°C
- Poor SNR leads to large uncertainties, so this will need to be improved before diagnostic can be put to effective use

Planned Field of View of 24° covers most of inner divertor, much of outer divertor

- 4 mm spatial resolution
- Maximum coverage of Mo tiles allowed by center stack + two LLD plates
- Overlaps with Fast IR FOV and current/ proposed fast thermocouples for validation & calibration
- Similar to views obtained for wide-angle visible divertor cameras
  - Both limited by width of gap between passive plates



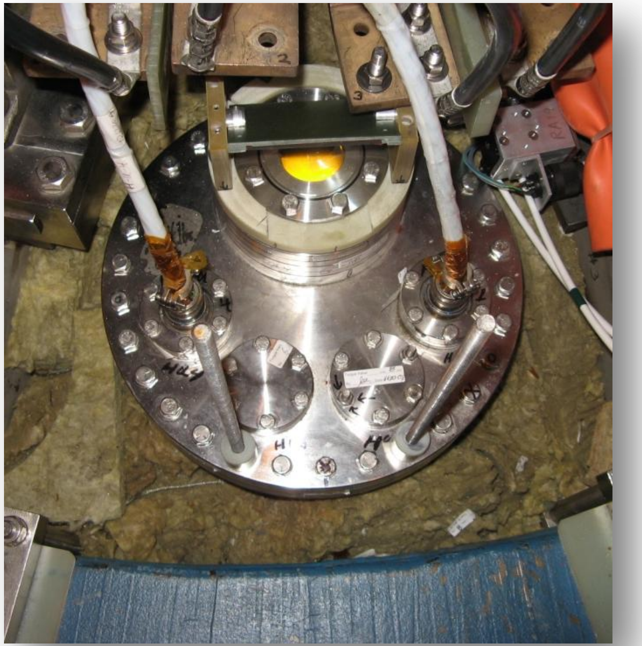
Planned Wide-Angle FOV

Mo Tile Row

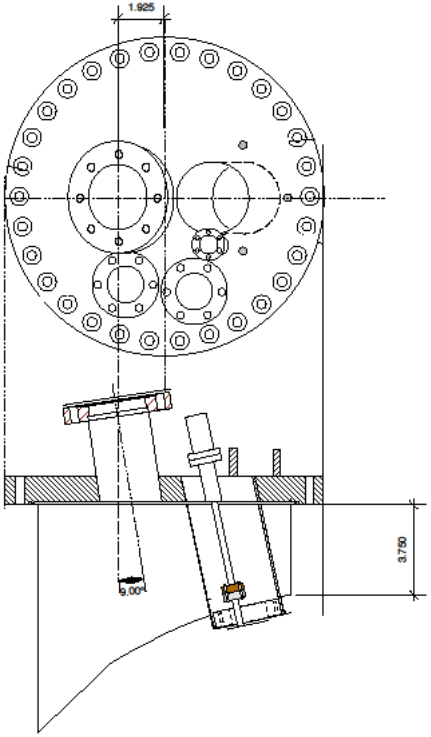
Fast TCs

Fast IR Cam FOV

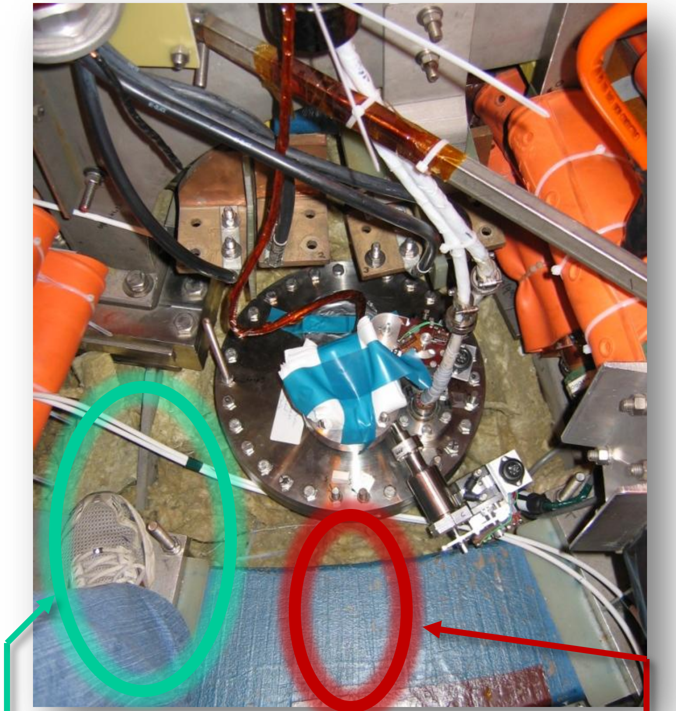
Bay H Top port cover has been remade to accommodate both Fast IR camera and Wide-angle IR camera + relay



Old design: only 1 window



- Re-entrant IR port (for Wide-angle IR) at 12° tilt
  - Pneumatic rotary shutter
  - Gets within ¼” of passive plate backing
- Raised IR port (for Fast IR) at 9° tilt
  - Pneumatic flap shutter
- 2 feedthroughs for existing magnetic diagnostics



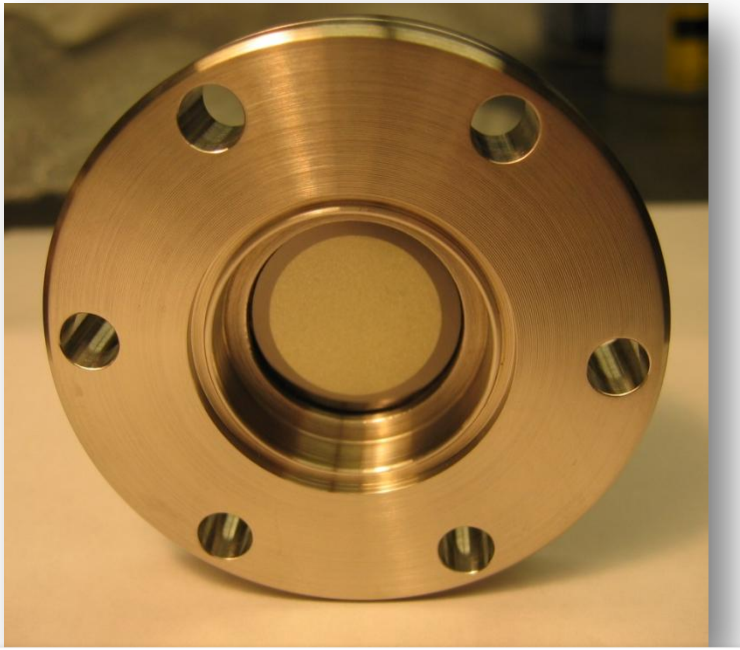
New design: 2 windows (1 re-entrant)

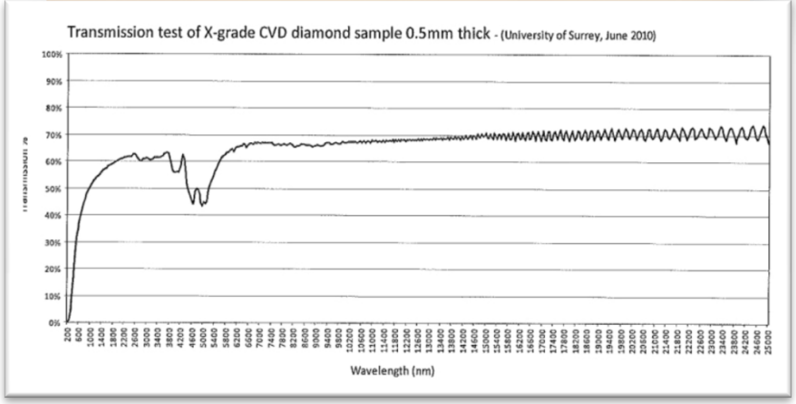
Relay mirrors go here

Fast IR camera goes here

Bakeout necessitated the first use of a CVD diamond vacuum window for imaging on a fusion device

- Window proximity to hot passive plates during 350°C bakeout ruled out common IR window materials
  - ZnSe & Ge rated to <200°C
- Chemical Vapor Deposited diamond window from Torr Scientific Ltd. (UK)
  - 20 mm clear aperture
  - Brazed to Kovar weld ring in 2.75" Conflat (316LN SS)
  - "X-ray grade": >60% LWIR transmission (can pay more for "optical grade")
  - Bakeable to 450°C
  - Fantastic thermal conductivity
  - Passed He leak check and 1.5 atm pressure test

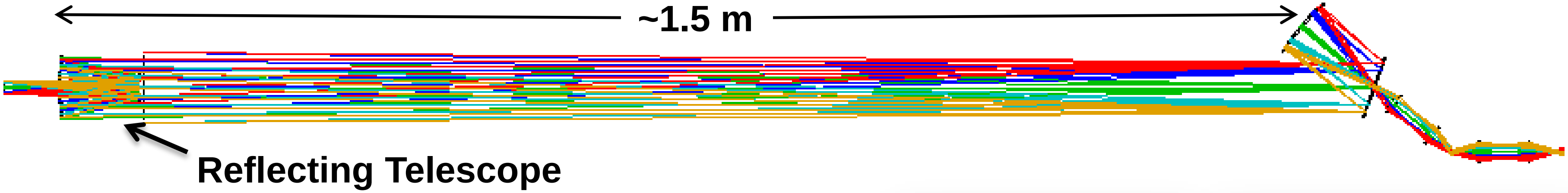


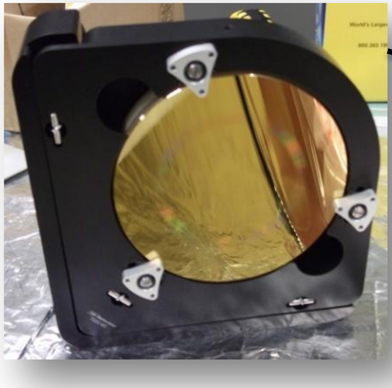


Transmission test of X-grade CVD diamond sample 0.5mm thick - (University of Surrey, June 2010)

Survived vessel bakeout without incident!

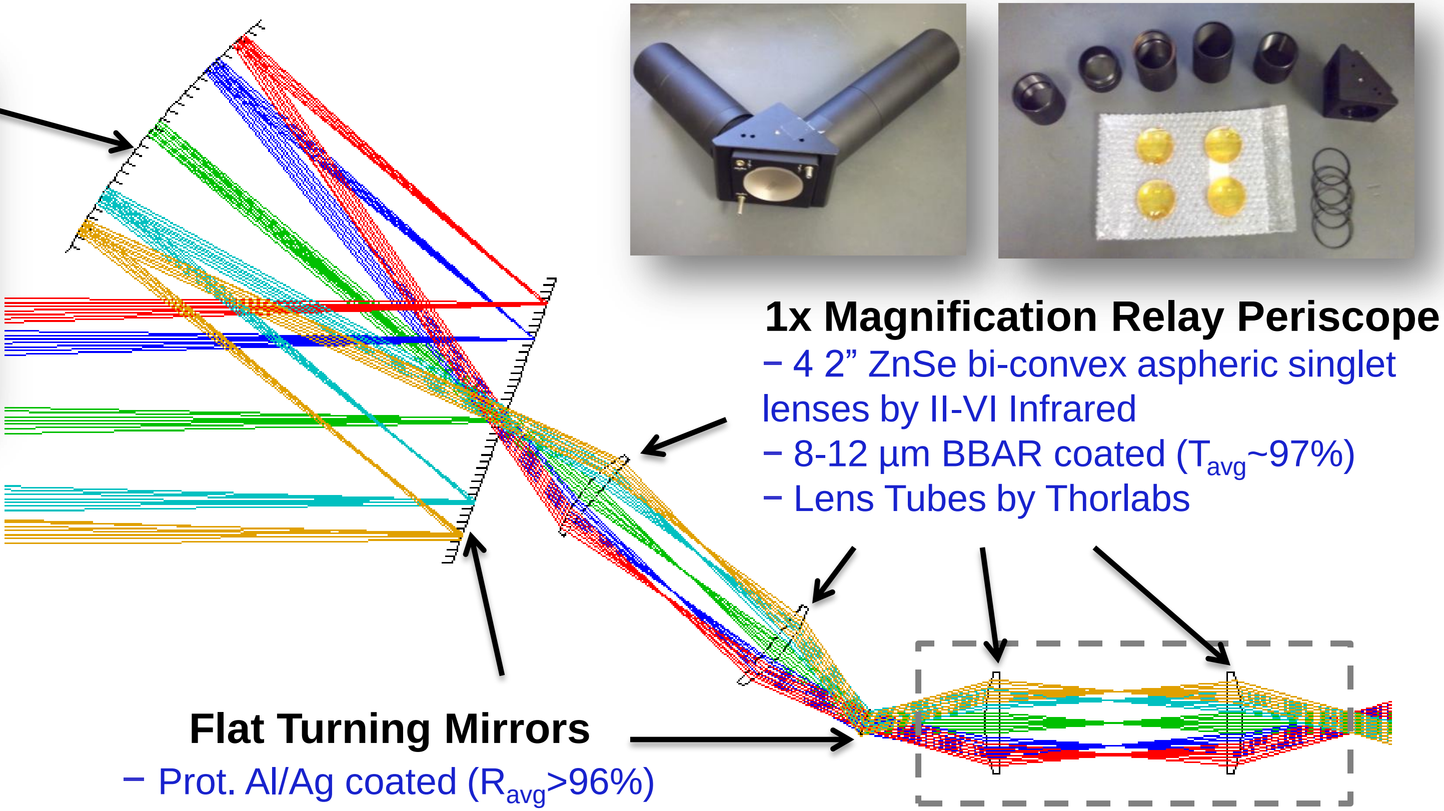
Optical relay design is based on JET/ITER IRTV designs (except much cheaper)





6" ZnS Ellipsoidal collection mirror

- Diamond turned by AMF Optics Inc.
- Prot. Au coated (R_{avg}~98%) by Majestic Optical Coatings Inc.
- Foci @ 30cm, 170cm
- Precision ultrastable kinematic mount



1x Magnification Relay Periscope

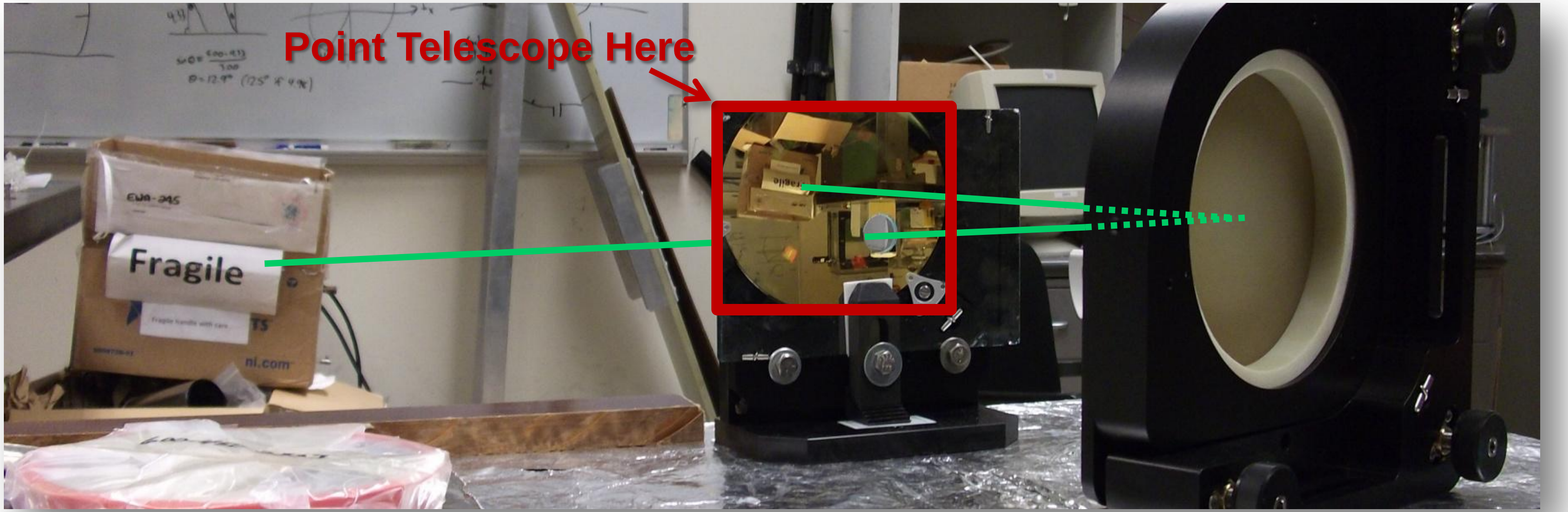
- 4 2" ZnSe bi-convex aspheric singlet lenses by II-VI Infrared
- 8-12 µm BBAR coated (T_{avg}~97%)
- Lens Tubes by Thorlabs

Flat Turning Mirrors

- Prot. Al/Ag coated (R_{avg}>96%)
- Kinematic mounts

Inside re-entrant port

Reflective relay allows high-fidelity imaging of a wide-angle FOV using a narrow FOV lens at a distance



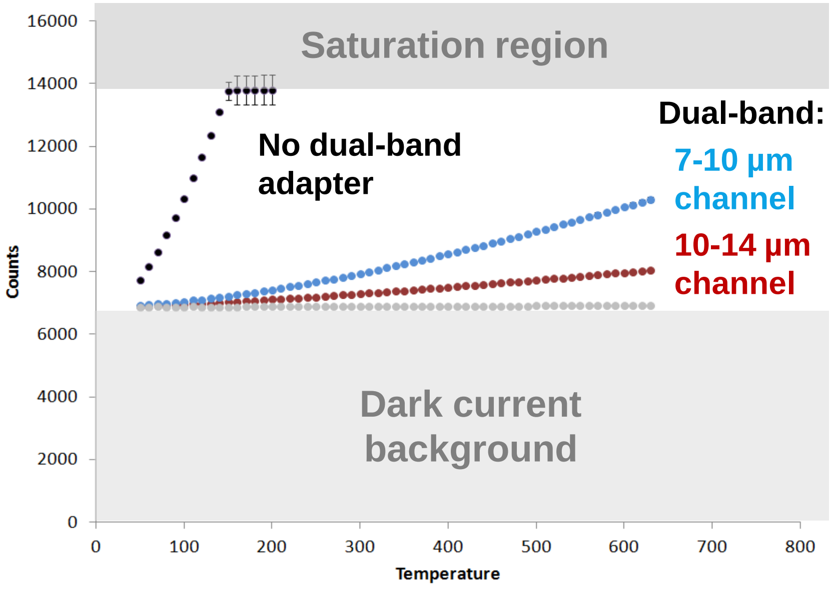
- Plan: Use a stock astronomical telescope (<$1K) as a zoom lens
  - Purely reflective, so no chromatic aberrations
  - Ritchey-Chretien design (hyperbolic primary & secondary) is coma/astigmatism-free
- Problem: Long focal length leads to excessive minimum focus distance
- Solution: Change mirror separation to shorten FL, or find a new lens

Orion 6” AT6RC
Ritchey-Chretien
f = 1370 mm

Theoretical system transmission efficiency is reasonable, but dual-band adapter currently suffers from anomalous losses

Component	7µm	8µm	9µm	11µm	12µm	13µm
X-ray grade CVD diamond window	68%	68%	68%	69%	68%	69%
ZnSe Relay lens (8-12µm BBAR) x4	67%	90%	90%	92%	91%	83%
Prot. Ag turning mirror	99%	98%	98%	98%	98%	97%
Prot. Au ellipsoidal mirror	98%	98%	98%	98%	98%	98%
Prot. Al turning mirror	98%	98%	98%	98%	98%	98%
Primary IR lens	95%	95%	95%	95%	95%	95%
ZnSe DOE lens (4-10µm BBAR) x2	94%	94%	94%	89%	81%	72%
Dichroic beamsplitter	94%	98%	96%	92%	85%	91%
Ge 7.3µm LWP filter	N/A	N/A	N/A	95%	95%	95%

Relay efficiency	64%	85%	85%	87%	86%	77%
Dual-band adapter efficiency	88%	92%	90%	78%	65%	62%
Total transmission efficiency	36%	50%	49%	44%	36%	32%



- Even without adapter, camera doesn't efficiently use full 14-bit depth
- Dual-band adapter is losing more photons than it should
  - Leads to poor SNR, excessive error bars
- Once problem is fixed, control dynamic range with neutral density filters

Future plans

- Was originally scheduled to be on NSTX for 2011 run, but has now been postponed until NSTX-Upgrade in 2014
  - Would be nice to find another experiment to test dual-band adapter on
- SNR losses will be addressed ASAP in collaboration with FLIR
- Software development is in progress and will continue
  - Reduce need for user input/attention
  - Integrate with dual-band heat flux code suite (FIRNACE)
  - Migrate away from local data storage
- Optical relay will need to be redesigned for NSTX-U
  - Shorten focal length of R-C telescope, or find another IR-capable lens or telescope with a more appropriate focal length
  - Should be able to reuse majority of components (CVD diamond window, port cover, periscope, collection mirror, turning mirror, optomechanics)

Conclusions

- Dual-band techniques are critical for making accurate thermographic measurements in low-emissivity and variable-emissivity environments
- A dual-band adapter for LWIR cameras shows great promise…
  - …but it's not quite ready for primetime yet
- PPPL now owns a CVD diamond vacuum window, enabling re-entrant infrared ports without risky cooling schemes
  - This re-entrant port will allow a wide-angle field of view that will allow diagnosis of the entire inner divertor in NSTX-U
- ORNL now owns most of the parts necessary to make an infrared relay once NSTX-U comes online

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