Executive Summary

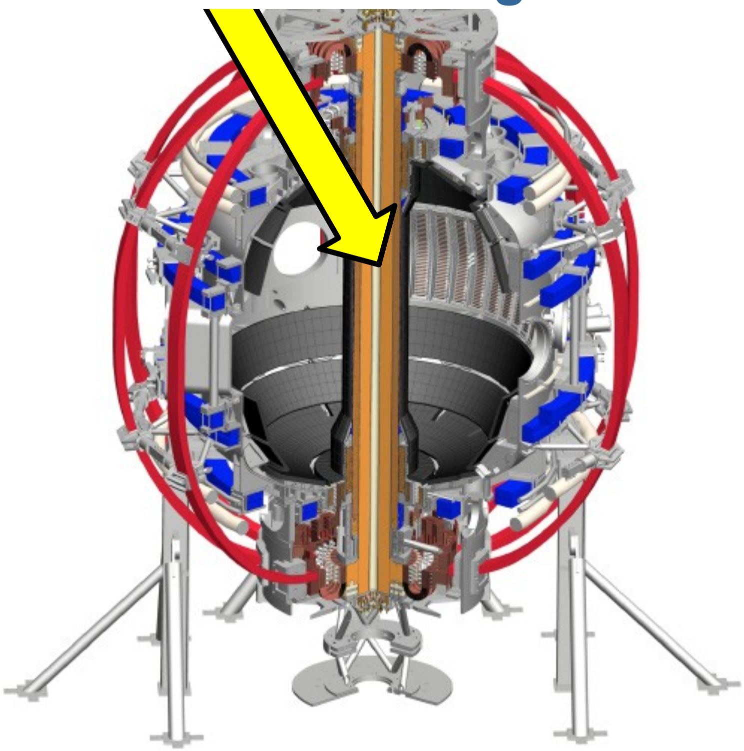
- Lower divertor infrared cameras installed and commissioned
- Initial data collected on NSTX-U during the FY16 run campaign
- Upper divertor, fast, IR camera is being installed during the outage
- Additionally adding IR coverage of the inner strike points
- Ongoing research into advanced, multi-spectral and hyperspectral infrared imaging of PFC surfaces

Motivation

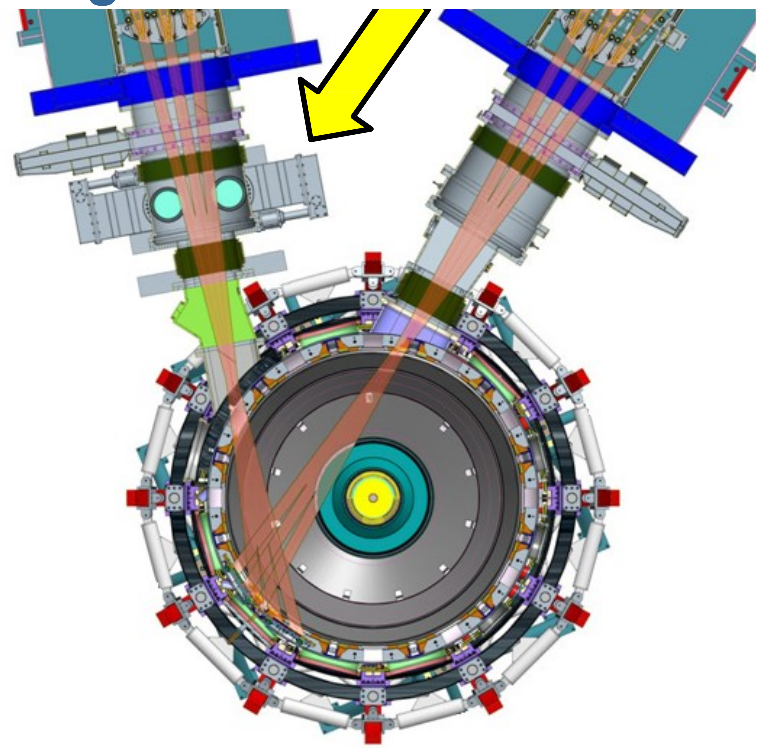
- Mitigating divertor heat flux to acceptable material limits is one of the biggest challenges facing fusion
- Projected NSTX-U characteristics:
  - $I_p \leq 2$ MA, $P_{NBI} \leq 12$ MW, 5 second pulse
  - $q_{pk,\ Inter\text{-}ELM} > 20\ MW/m^2$
- Accurately measuring divertor surface temperature is challenging in the divertor environment
  - Need to measure a wide range of surface temperatures at high speed (<1 ms)
    - Inter-ELM vs. intra-ELM
  - Eroding and redeposition of PFC material
  - Mixed material environment
    - Be + W for JET and ITER
    - Li/B + C/Mo for NSTX-U

NSTX-U will access new physics with 2 major new tools:

1. New Central Magnet



2. Tangential 2nd Neutral Beam



Higher T, low ν^* from low to high β

→ Unique regime, study new transport and stability physics

Full non-inductive current drive

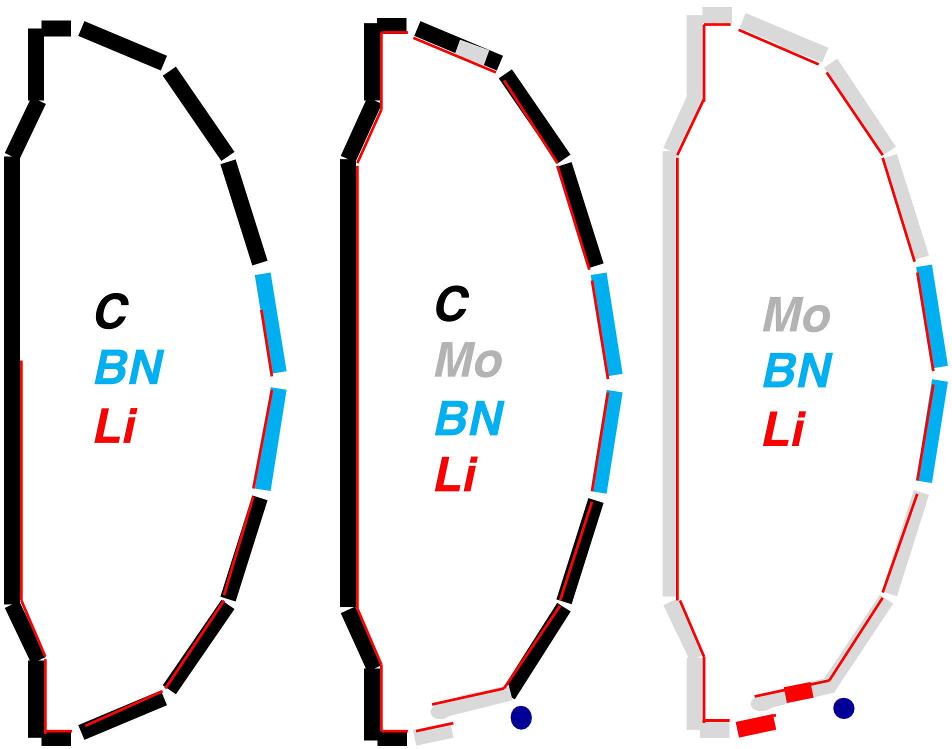
→ Not demonstrated in ST at high-β_T

Essential for any future steady-state ST

Challenges of Thermography in a Fusion Environment

NSTX-U is a Mixed Material Environment

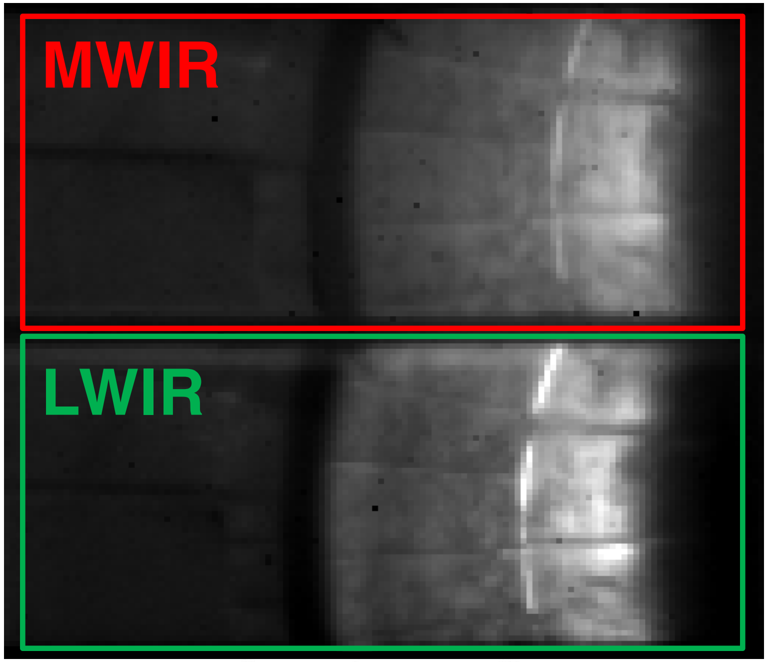
Incremental change-over to TZM Mo

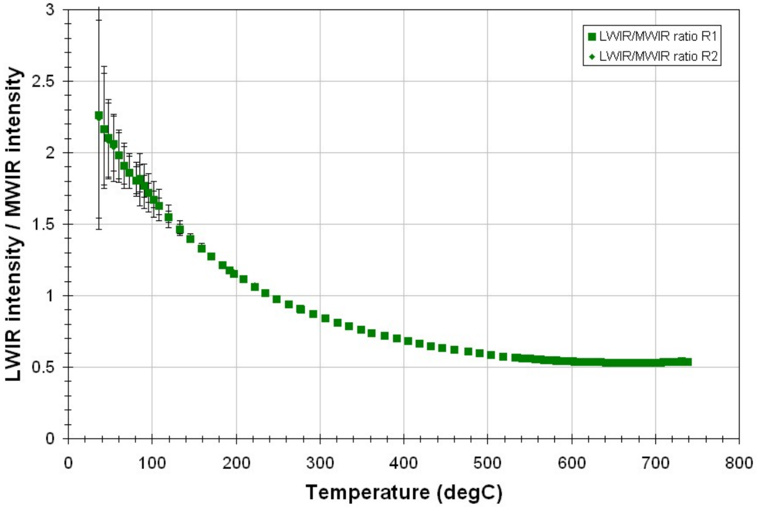


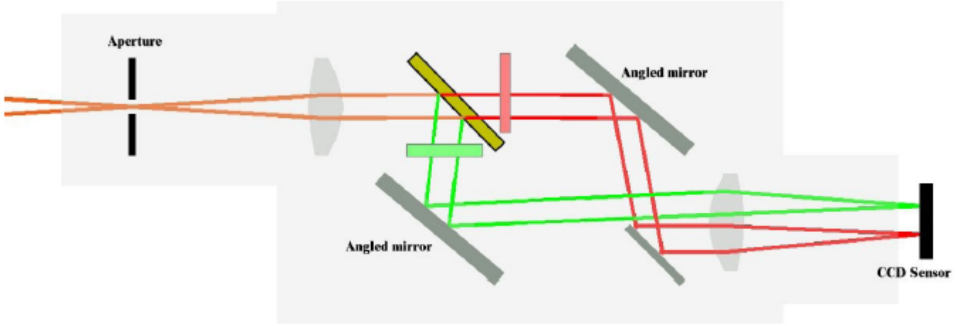
- Primarily ATJ Graphite plasma facing components (PFCs)
- Use of various wall conditioning techniques
  - Periodic Boronization via DC Glow discharge of Trimethylborane (Chemical symbol for this here)
  - Between discharge lithium evaporation
    - 10 – 300 mg per evaporation
- Planned incremental transition to metal walls – TZM Molybdenum
  - Row of tiles considered for next run campaign

Dual-band IR Thermography has been Employed to Account for Changing Emissivity with the Introduction of Lithium

- Use of an image splitter to simultaneously image both IR bands
  - Long-wave (LWIR): 6.5-10 μm transmit with T_{avg}~92%
  - Medium-wave (MWIR): 4-6.5 μm reflect with T_{avg}~99%
- Assumes constant emissivity across both bands
  - $\varepsilon_{MWIR} == \varepsilon_{LWIR}$
  - Grey-body emission



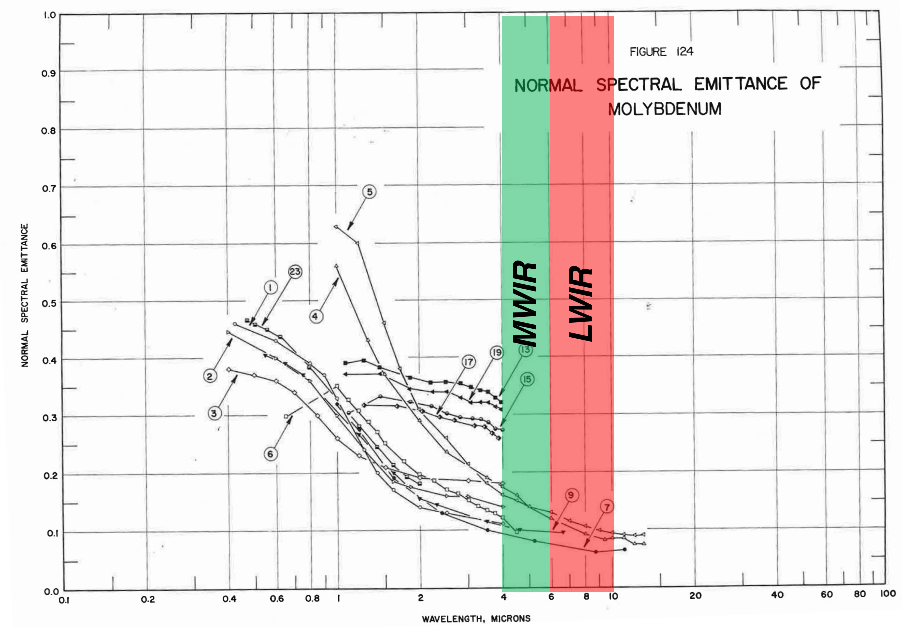


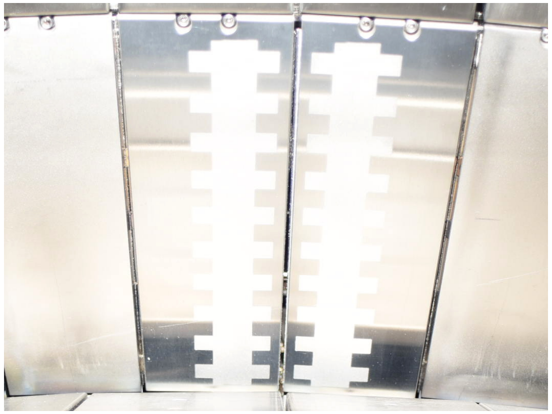


High-Z tiles and effects of Erosion

- NSTX-U plans to incrementally transition away from C PFCs to Mo
- Mo is highly reflective in the IR
- Emissivity of Mo, ε_{Mo} varies as a function of wavelength
  - Up to 50% in the MWIR and LWIR bands
  - Violates fundamental assumptions of dual-band technique
- ε_{Mo} also varies with surface roughness, which will change in an eroding environment

Emissivity of Mo vs wavelength for various surface finishes



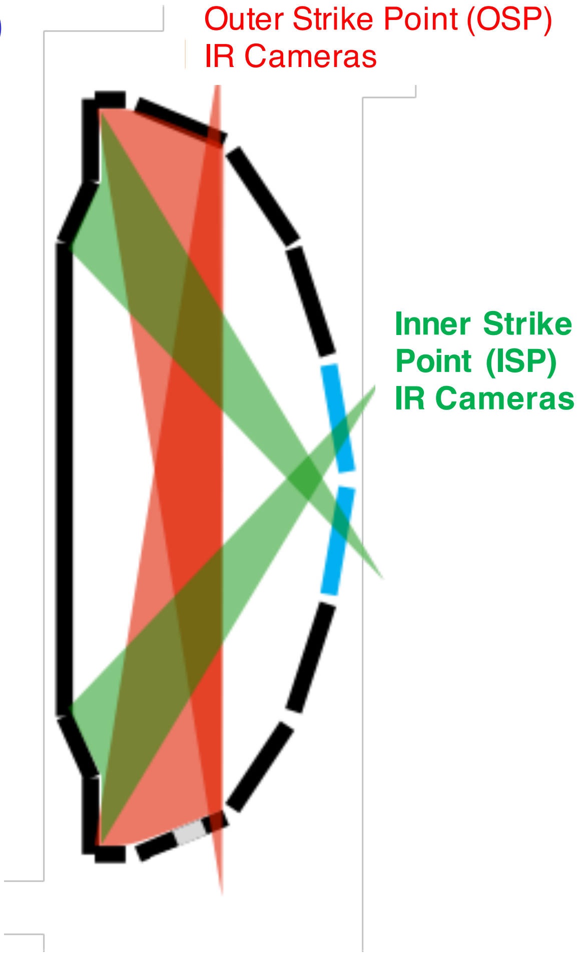


Sand blasted W tiles in ASDEX-U to increase emissivity – Image courtesy of B. Sieglin, IPP-Garching

Current and Planned Infrared Measurements on NSTX-U

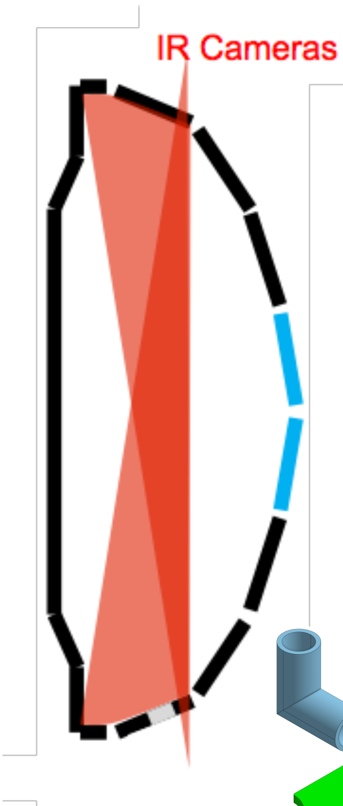
- Installed for FY16
  - Lower Divertor Outer Strike Point (Commissioning)
    - 1.6 kHz (128x128)
    - 15° field of view
    - Dual or single band IR Optics
      - 4 – 6.5μm and 6.5 – 10 μm
  - Lower Divertor Wide-angle View
    - 30 Hz (640x480)
    - Single band 7.5 – 13 μm
    - 120° field of view
- Planned for FY18
  - Upper Divertor Outer Strike Point
    - 1.6 kHz (128x128)
    - 15° field of view
    - Dual or single band IR Optics
      - 4 – 6.5μm and 6.5 – 10 μm
  - Lower Divertor Inner Strike Point
    - To be Determined
- Eventual goal is complete coverage of all strike points in NSTX-U for power balance studies

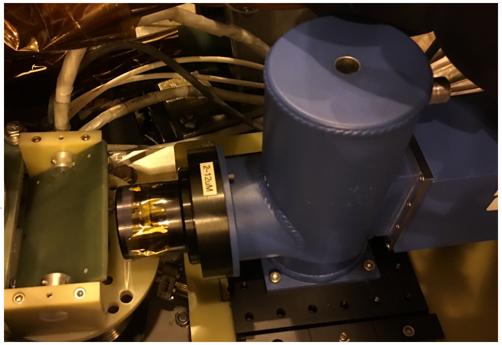
NSTX-U Cross-Section

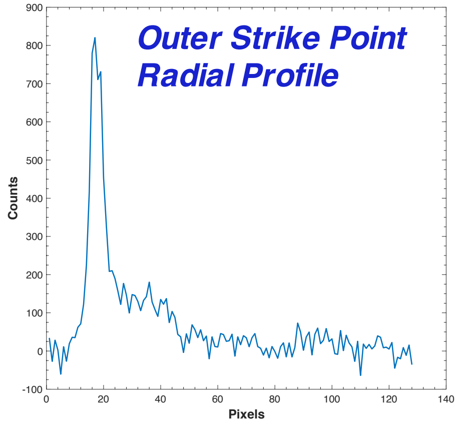


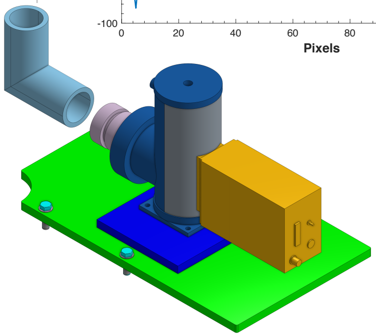
Fast IR Cameras Observe both the Upper and Lower Outer Strike Points

Lower Divertor Fast IR Camera Installation







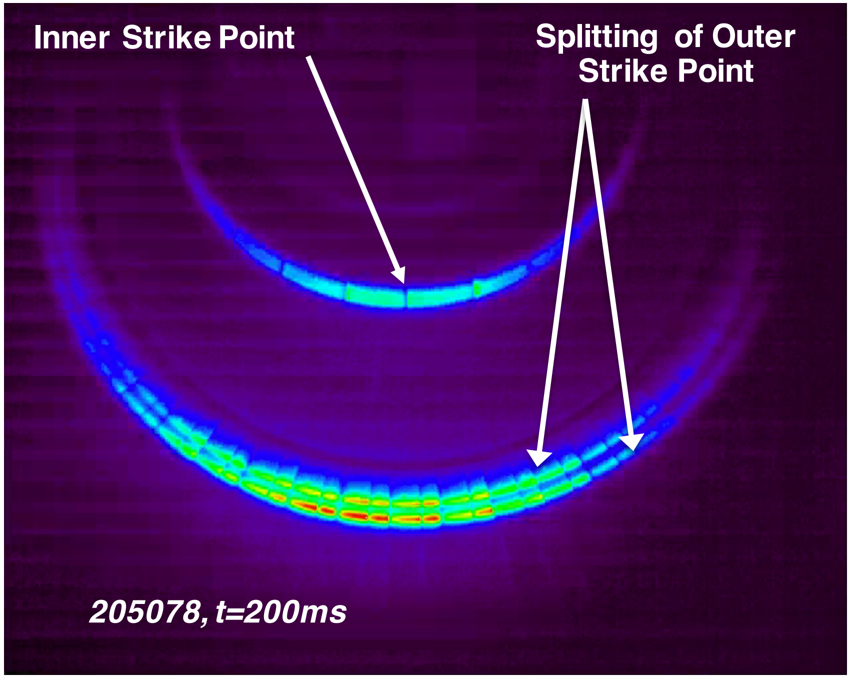


Upper Divertor Fast IR Camera + periscope

- Outer strike point cameras are:
  - Fast: 1.6 kHz frame rate (full frame)
  - Single or dual band optics
- Lower divertor fast IR camera installed for FY16 run campaign
  - Commissioning diagnostic when outage occurred
  - Limited single-band data acquired
- Upper divertor, fast IR installation is in progress
  - Expected completion before start of the next run campaign

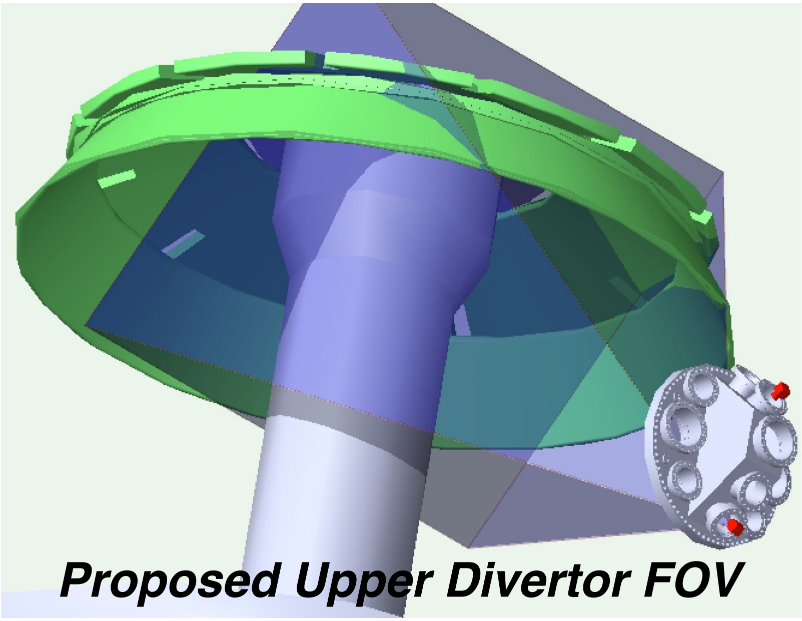
Study of 3D Divertor physics with Installation of Wide Angle IR Camera

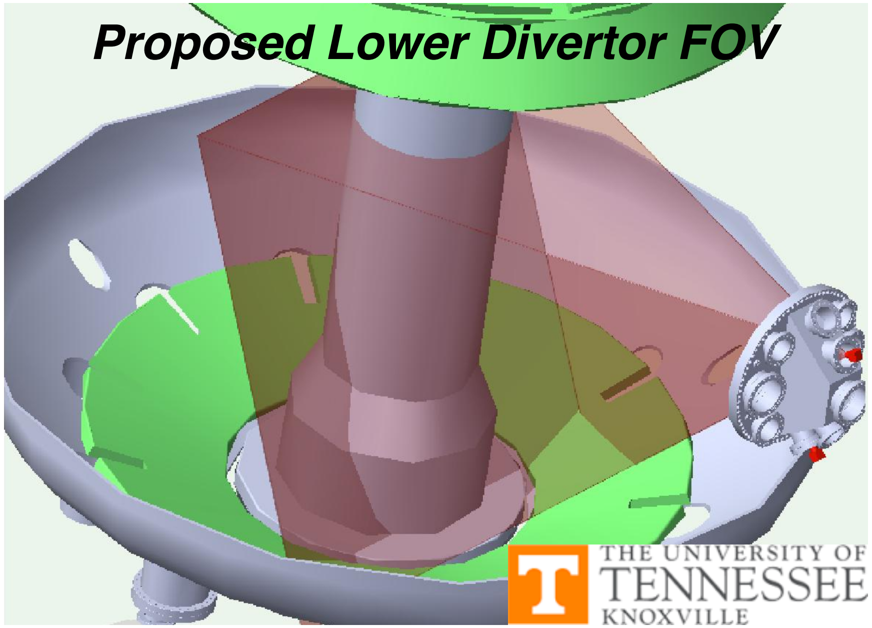
- Wide angle IR camera taking data during plasma operation
  - Nearly half of the lower divertor area is covered
  - 30 Hz, LWIR (8 – 14 μm)
- Important for 3-D physics study
  - Effect of error fields, internal MHD mode, and applied 3-D fields on divertor footprints
  - 3-D heat and particle flux, surface erosion studies, etc



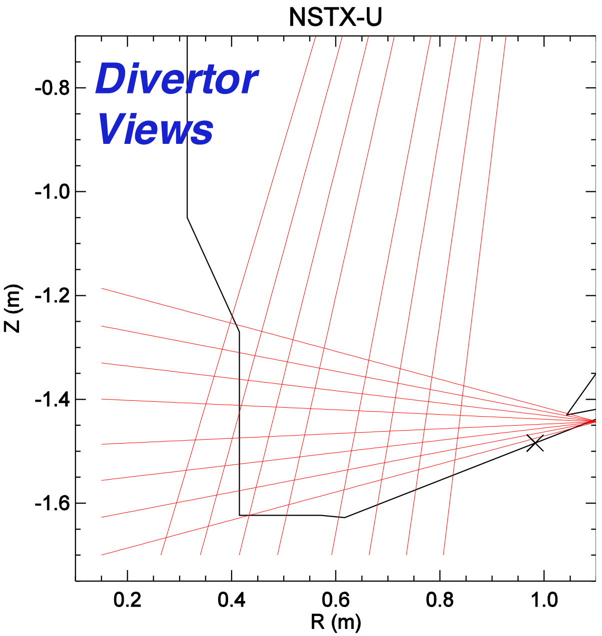
Inner Strike Point Cameras will Complete IR Coverage of Divertors

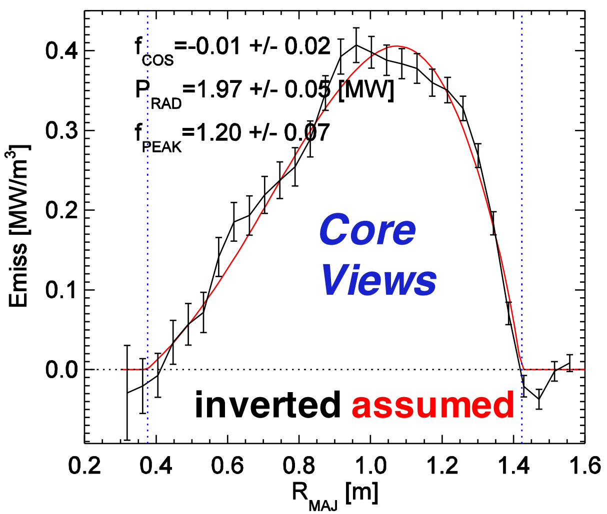
- Inner strike point (ISP) is often obscured from other divertor views
  - ISP is along the vertical section of the center stack
  - Infrared emission decreases drastically at shallow angles
- 2 new cameras proposed to cover the upper and lower inner strike points in collaboration with University of Tennessee - Knoxville





Radiated Power Measurements Coupled with IR Thermography Enable Power Balance Studies



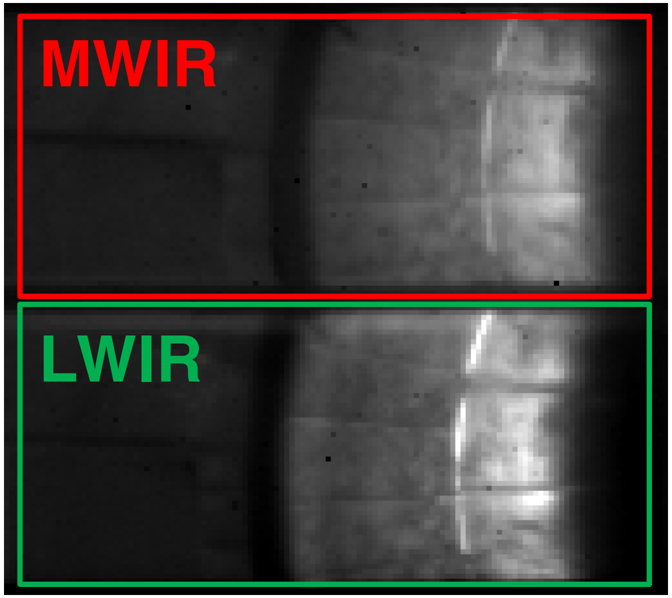


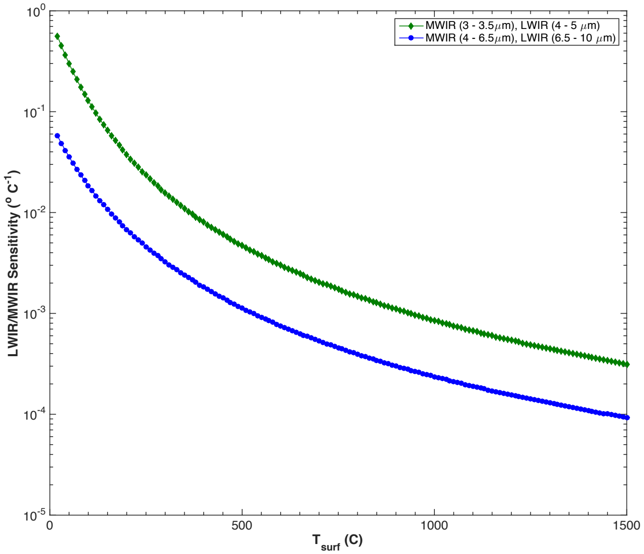
- Installing upgraded versions of the lower divertor resistive bolometers
  - Bay J-Upper, Bay I-Lower (16 ch)
  - NSTX-U views with new thermal management
- New tangentially-viewing midplane resistive bolometer array
  - Bay G-Midplane (24 ch), full midplane array
- Utilize new D-tAcq elec. (P_{RAD} < 100 Hz)
  - real-time output possible, but not available initially
- Will need to expand coverage in FY18+ to ensure full plasma coverage
- See Poster NP10.00047, “Development of Radiated Power Diagnostics for NSTX-U” for more details

Ongoing Thermography Research

Dual-band Thermography routinely used on NSTX but has Limitations

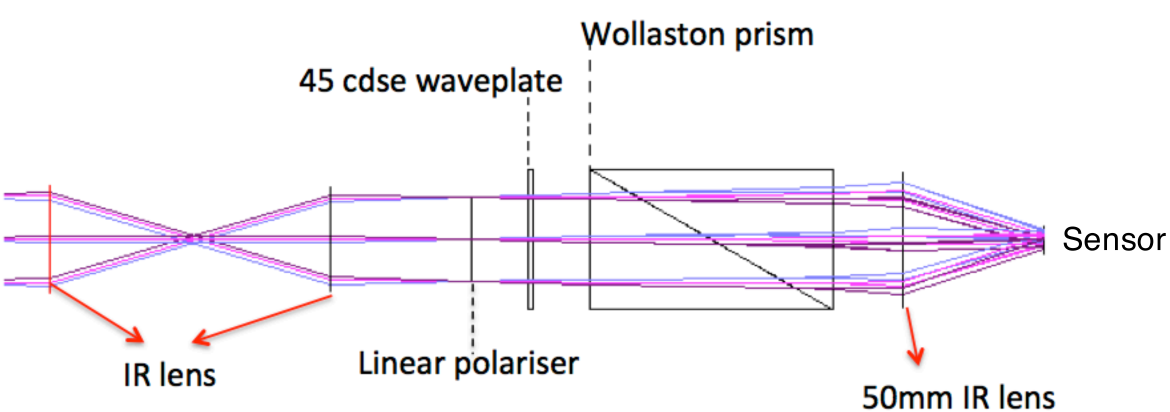
- Image registration errors between the 2 bands
- Lithium coatings on viewports affect IR absorption
  - Differential absorption in MWIR band vs LWIR
- Assumes constant emissivity across both bands
  - $\varepsilon_{MWIR} == \varepsilon_{LWIR}$
- Low of sensitivity at high temperatures
  - Theoretical 2x improvement in sensitivity at high temperature by moving to shorter wavelengths (3 – 5 μm)
  - Shorter wavelengths required for better sensitivity

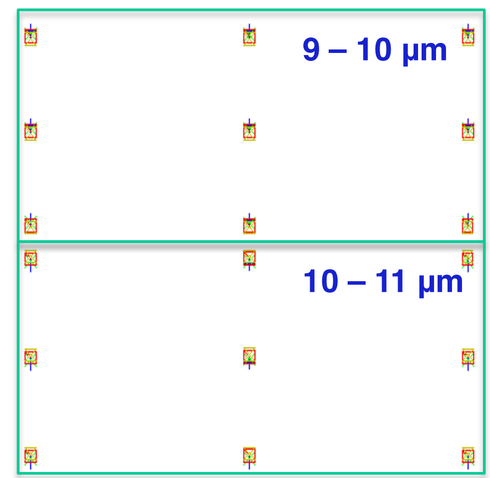




Preliminary Design for Dual-Band Optics Utilizing Wollaston Prisms

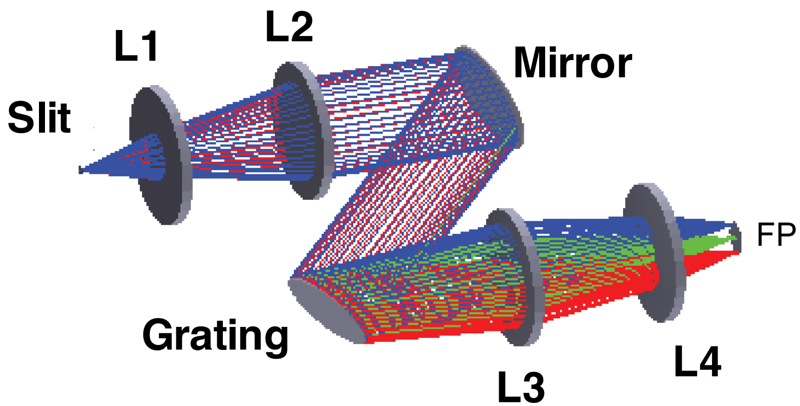
- Utilize the birefringent properties of CdSe to split incoming photons
  - Introduces chromatic aberrations that need to be corrected
- Single optical path is more resilient to vibrations
- Similar field of view as the reflecting, dual-band optical design
  - ~ 8° in each band
- Design then build and test a prototype

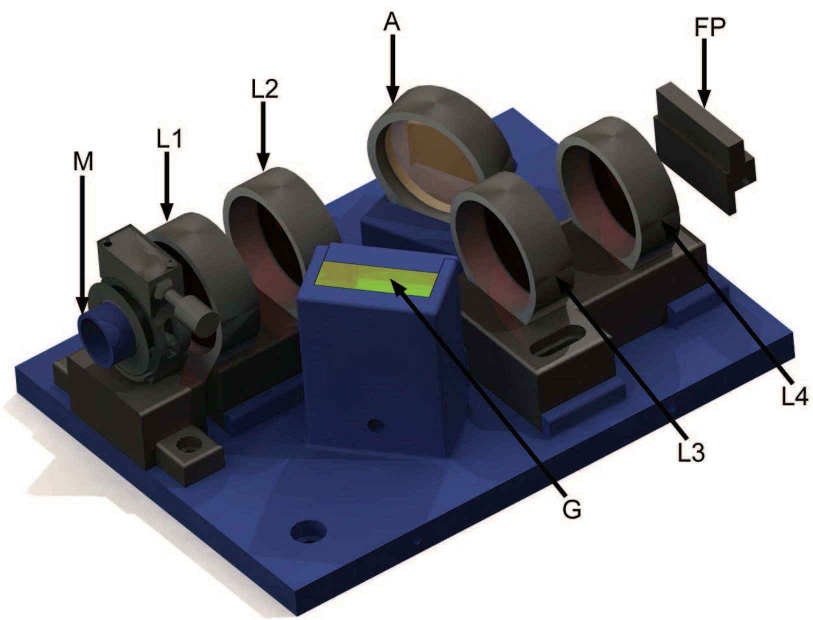




"Pushbroom" Multi-spectral Infrared Imaging

- Based off of similar techniques used in the visible and near IR
- Sacrifices 2D spatial measurement for 1D spatial (radial) and 1D spectral
  - Maintains fast frame rates using full frame
  - Adaptable to subwindowing of the sensor for faster frame rates
- Design is adaptable to true hyperspectral imaging using a coded aperture
  - Swap out slit for coded aperture
  - Yields 3D data cube (2D spatial, 1D spectral)





Conclusions

- Lower divertor infrared cameras installed and commissioned
  - Wide-angle fully commissioned and operational
  - Fast IR camera was partially commissioned
- Initial data collected on NSTX-U during the FY16 run campaign
- Upper divertor, fast, IR camera is being installed during the outage
- Additionally adding IR coverage of the inner strike points
- Ongoing research into advanced, multi-spectral and hyperspectral infrared imaging of PFC surfaces

Acknowledgements

The submitted manuscript has been authored by a contractor of the U.S. Government under contract DE-AC05-00OR22725. Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

Request for Reprints?