NSTX

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Divertor surface temperature measurements with a high-speed camera and NIR filters

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and the NSTX Research Team

52nd Annual Meeting of the APS Division of Plasma Physics
Chicago, IL
November 8, 2010

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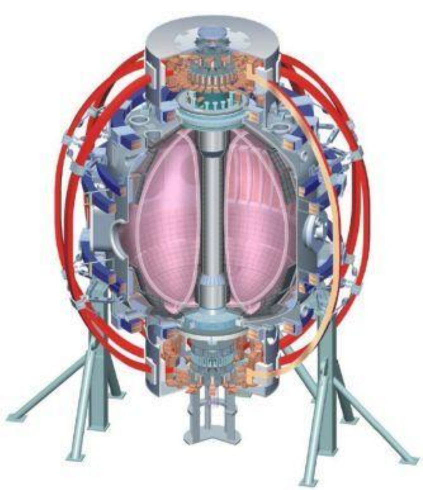


Abstract

IR band-pass filters (>720 nm or >900 nm) were used with a Phantom v7.3 high-speed camera to try to measure the surface temperature of plasma facing components and the Liquid Lithium Divertor (LLD) in NSTX. The present camera looks through an upper port with a view of more than half of the lower divertor. With several megawatts of RF heating power, the observed surface temperature increased by ~700 ^{o}C in a localized region magnetically connected to the RF antenna. Such a wide-angle, high-speed (up to 10^4 fps) IR system could also evaluate the thermal response to transient events such as ELMs and disruptions, which can cause large, uneven heat loads over a wide area of the divertor. The rise/fall time during power transients and emission spectroscopy diagnostics were used to help distinguish plasma IR line emission from surface blackbody emission. The entire system has been calibrated with a blackbody source from 350 to 700 ^{o}C.

This work is supported by DOE contract # DE-AC02-09CH11466.

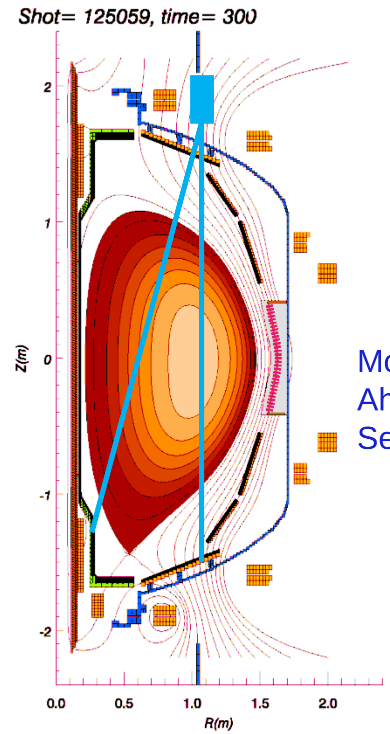
Motivation for NIR high-speed camera on NSTX

- Want to measure temperature of divertor over wide area
  - Will hot spots reach melting point on liquid lithium divertor (LLD)?
  - Full coverage needed for next-generation devices with high-Z divertors in which any melting can contaminate plasmas
- Can we measure surface temperature with a visible camera and near-infrared (NIR) filter?
- Several potential advantages
  - LLD cameras have FOV of >50% of lower divertor
    - Much wider view than current NSTX IR cameras
    - Observe full toroidal impact of non-axisymmetric loads
  - Framing rate of ~50 kHz with full FOV
    - Up to 500 kHz with smaller FOV
    - Could image some transient events as they occur
- NIR background light could cause difficulties†

† Soukhanovskii, V.A. 2008. "Near-infrared spectroscopy for burning plasma diagnostic applications." *Rev. Sci. Instrum.* 79, 10F539.

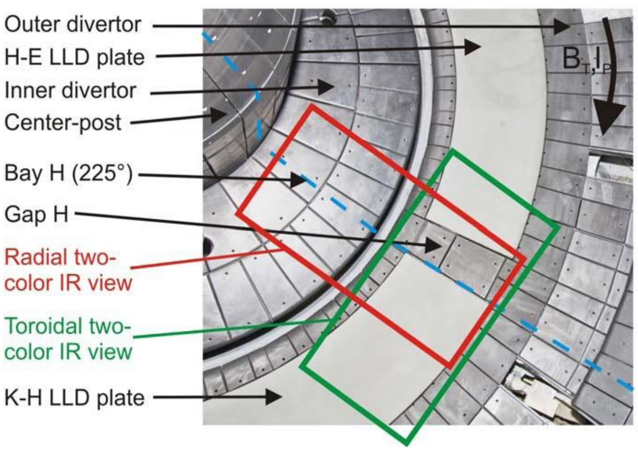
Existing ORNL infrared cameras on NSTX

- Two slow IR cameras
  - 30 Hz
  - 0.2 m – 1.2 m radial view
  - ~15^o toroidal view
  - View upper (Bay G) and lower divertor (Bay I)



Modified from J-W. Ahn. 09/03/2008. Seminar at ORNL.

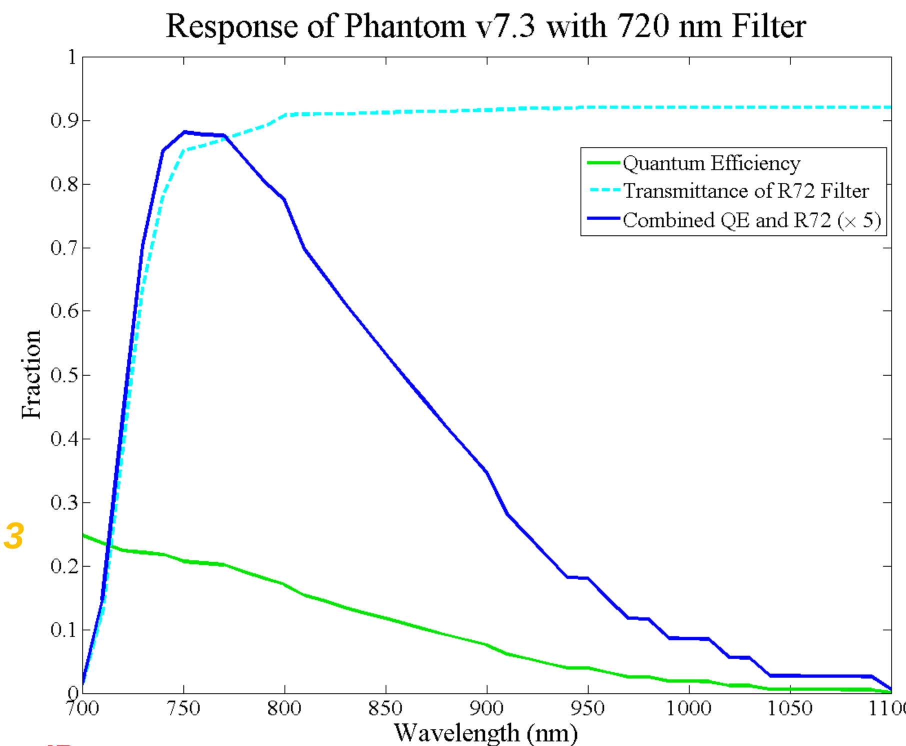
- A fast dual-band IR camera
  - 4-6 µm and 7-10 µm bands
  - ~1-6 kHz
  - ~0.2 m – 0.85 m radial view
  - ~15^o toroidal view

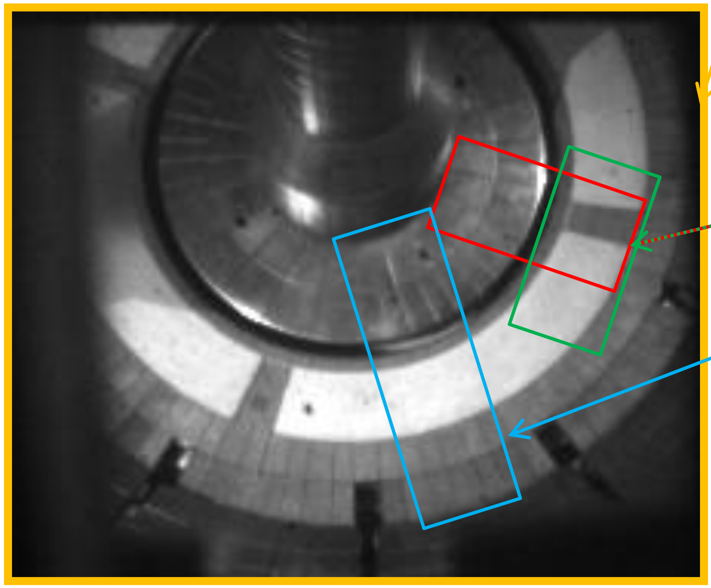


A. McLean. 5/10/2010. PPPL Physics Meeting.

High-speed camera with NIR filter

- Phantom v7.3
  - Capable of 1 μs exposures
  - FOV: majority of the lower divertor
  - Low spectral responsivity beyond 1100 nm





Phantom 7.3
Bay J

Dual-Band Fast IR
Bay H

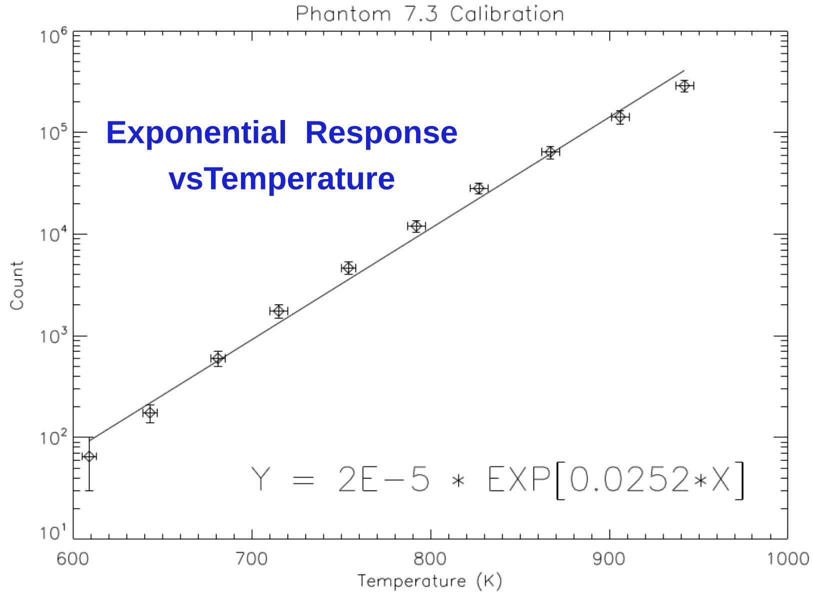
Slow IR
Bay I

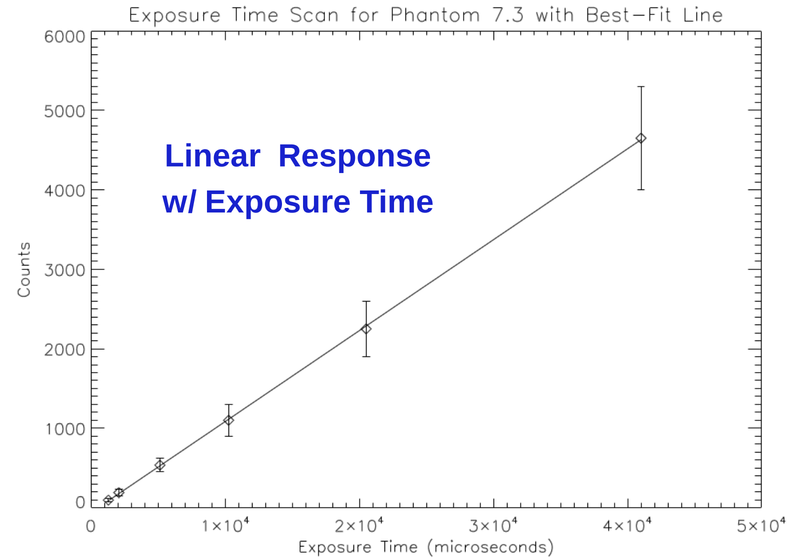
Modified from F. Scotti.

- Filters
  - Hoya R72 (>720 nm)
  - Hoya RM90 (>900 nm)

Benchtop calibration of system

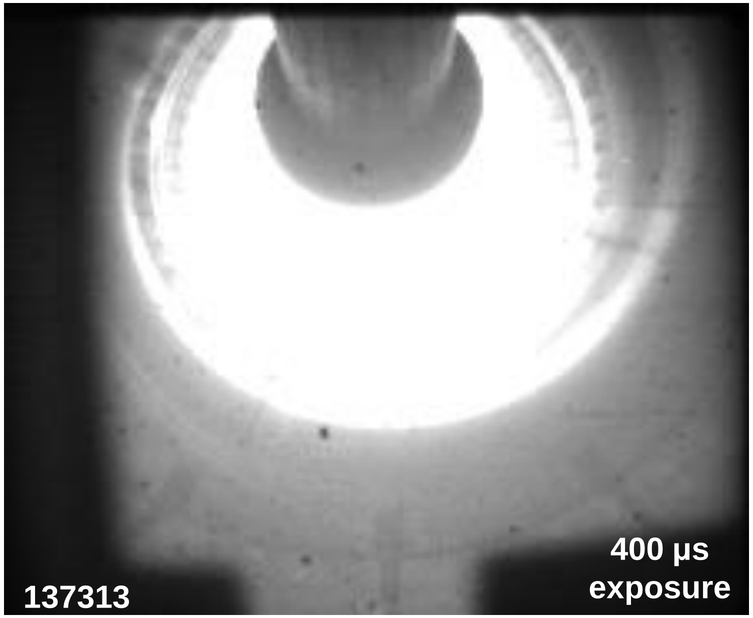
- Calibration
  - 720 nm filter
  - all available optics (filter, lenses, and fiber)
  - 41 ms exposure time
  - 335 °C to 670 °C
- Linear variation w/ exp. time
- Corrections for emissivity or other *in situ* effects difficult to account for
  - Conditions change over time
  - Can't periodically calibrate *in situ* as vessel under vacuum throughout run

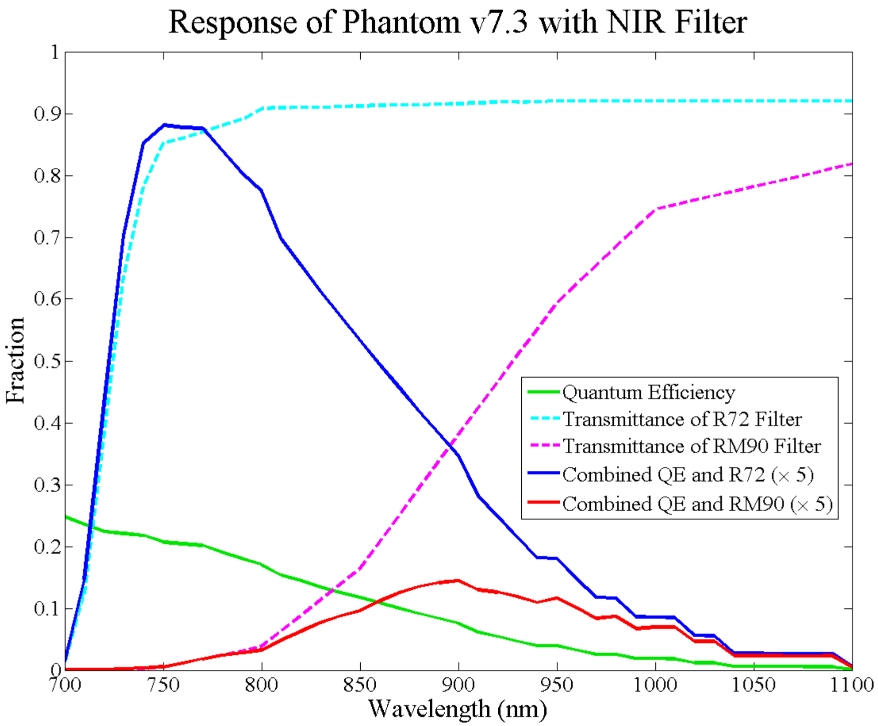




Change to a higher cutoff filter

720 nm

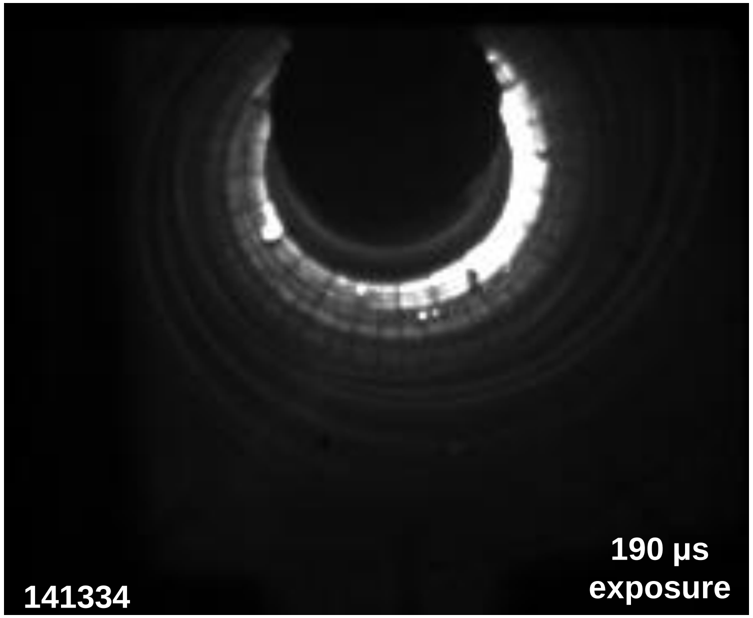




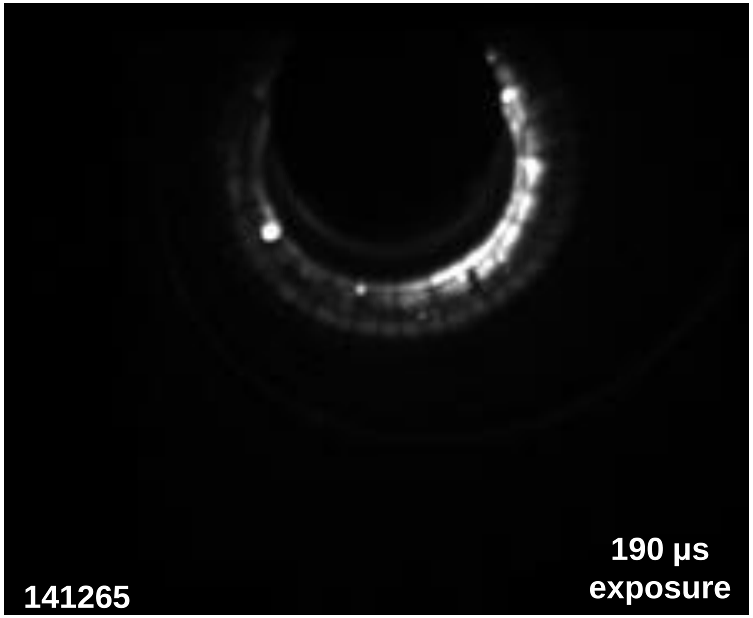
- **Potential reduction in background with 900 nm filter w/o losing much thermal light**
- **Calibration curve modification necessary**
  - Currently corrected using blackbody theory
  - Second benchtop calibration may be performed in the future

Comparison of filters' signal/noise ratios

720 nm



900 nm

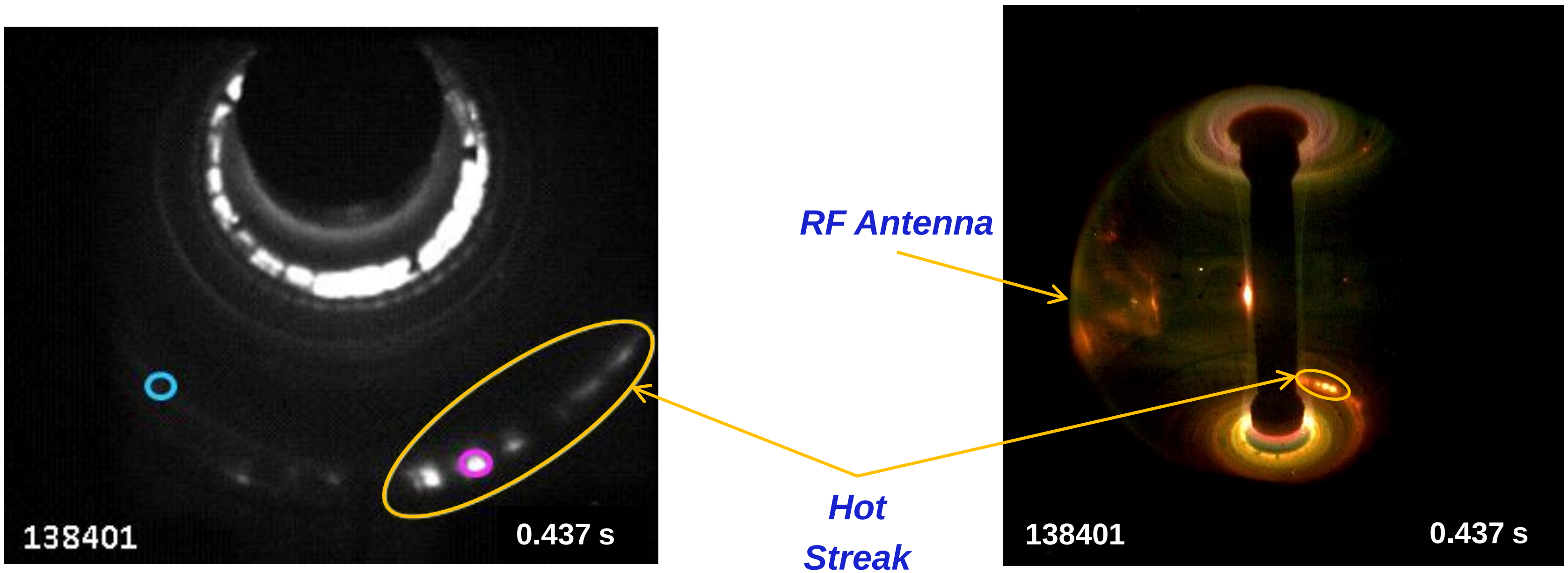


- **Clear reduction in amount of light observed for nearly identical shots**
- **Blackbody curves tell you expected decrease, but this changes with temperature (and thus location)**
- **Requires data w/ both filters with same shot for best results**
  - Second camera w/ both filters and overlapping view available
  - Analysis of data from both cameras with both filters currently underway

Heating of the divertor by HHFW (1)

- RF power coupled to SOL plasma
- Hot streak magnetically connected to antennae
- Hot spots on the order of 10 cm^2
- Previous data showed heat flux ~3 MW/m^2 †
- Data recorded for 17 shots with 2-3 MW RF power and 2 MW NBI heating on 6/9/10 using 900 nm filter

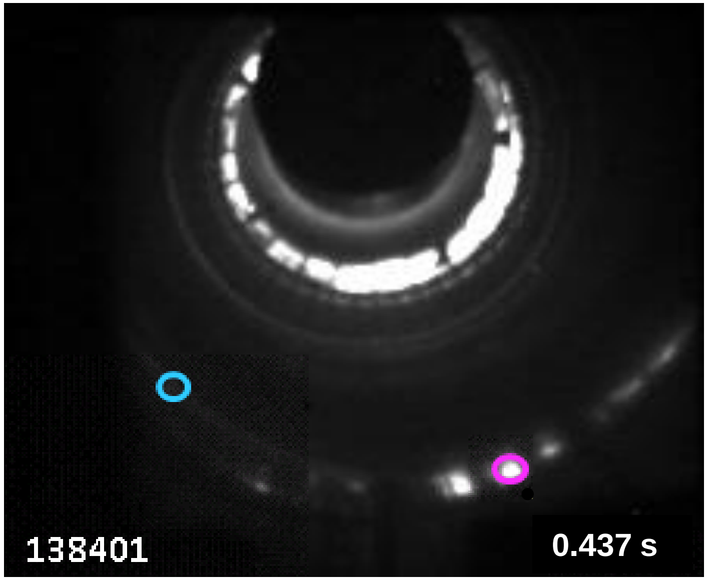
† Taylor, G. et al. Nov. 5, 2009. "Advances in High Harmonic Fast Wave Physics in NSTX." *51st APS DPP Meeting.* Atlanta, GA.

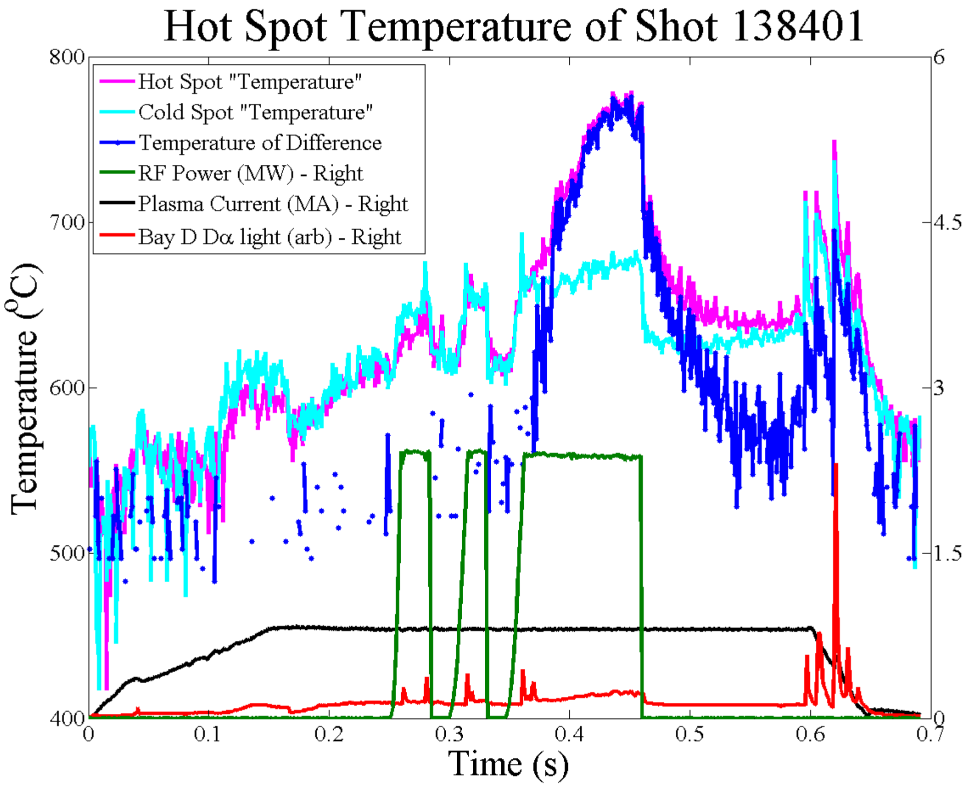


Bay B Miro

Heating of the divertor by HHFW (2)

- Hot spot temperature determined from average counts inside pink circle
- Cold spot “temperature” and counts determined inside blue circle
  - Lies on the same plasma filament as pink circle
- Dark blue temperature determined from difference in counts
- Initial high “background equivalent temperature” before RF





1D Heat Diffusion Simulations

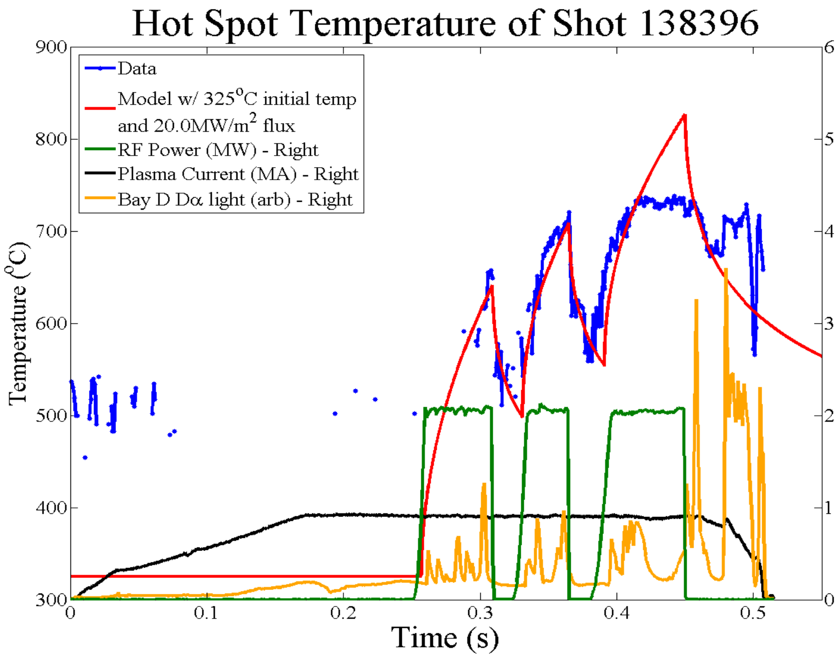
- Model
  - Heat diffusion equation: $$\frac{\partial T}{\partial t} = D\frac{\partial^2 T}{\partial x^2}$$
  - 1in. thick ATJ graphite tile
  - Constant diffusivity (D = 0.34 cm^2/s) & conductivity (κ = 0.94 W/cm*K)
  - Piecewise constant flux that increases during RF
  - Zero flux out of tile
- Code
  - Explicit Forward Time Centered Space (FTCS) finite difference

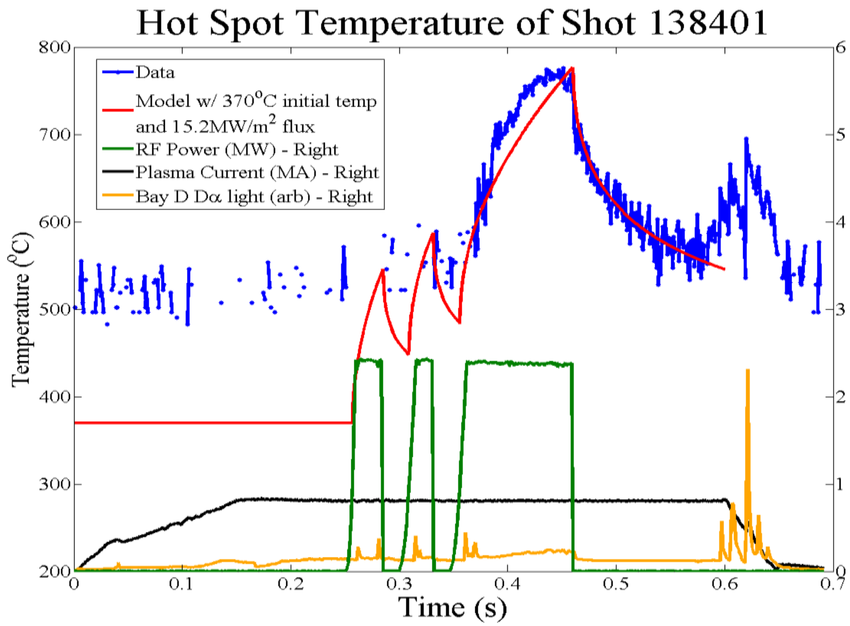
$$T_i^{n+1} = T_i^n + \frac{D\Delta t}{(\Delta x)^2}(T_{i+1}^n - 2T_i^n + T_{i-1}^n)$$

  - Neumann boundary conditions
    - Top of tile: $$T_0^n = T_1^n + \frac{F^n \Delta x}{\kappa}$$
    - Bottom of tile: $$T_N^n = T_{N\text{-}1}^n$$

Results with flux only during RF

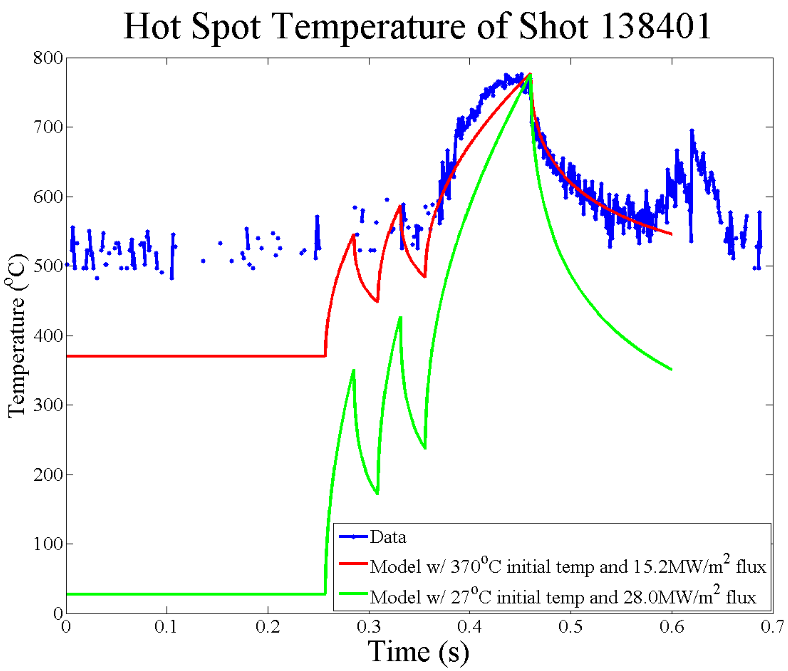
- Temperature profile fit well by thermal rise during RF
  - Time dependence of temperature rise and fall
  - Magnitude of relative peaks
- 15-20 MW/m^2 flux
  - Generally matches measurement from ORNL Slow IR camera
- ~320 ^{o}C initial temperature seems unrealistic

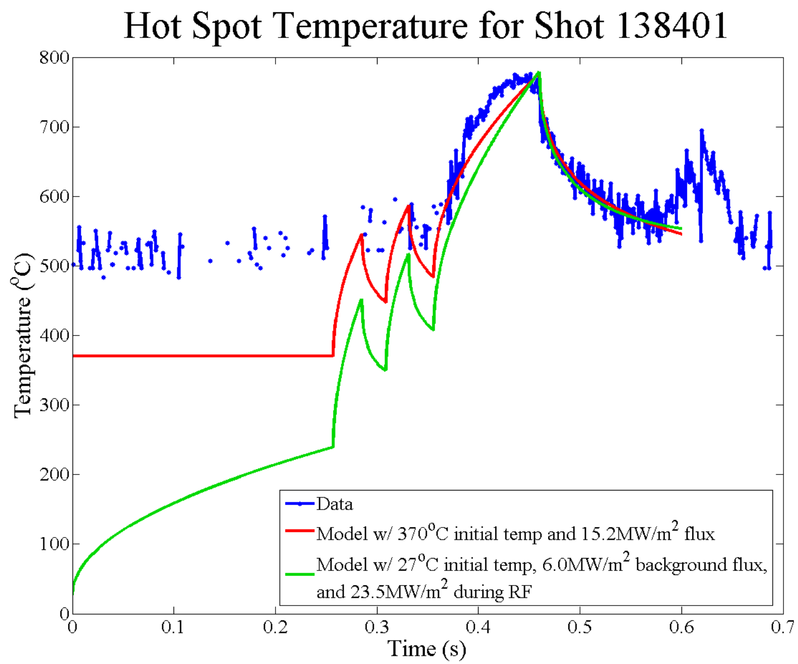




Results from low initial temperature simulations

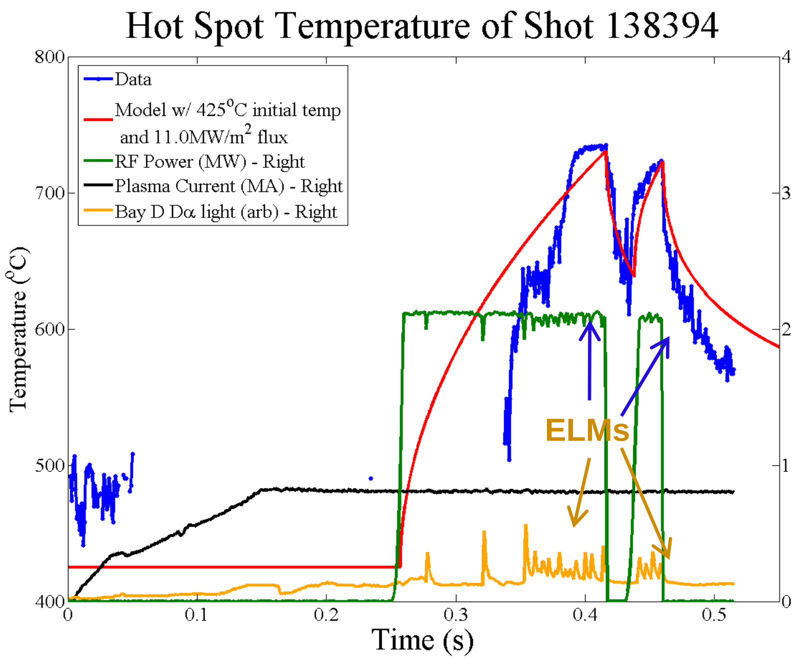
- Zero background flux
  - Large 28 MW/m² flux needed to reach peak temp
  - Model's rise/fall time too fast
- Constant background flux
  - 6.0 MW/m² background flux a little large
  - 23.5 MW/m² flux during RF also a little large



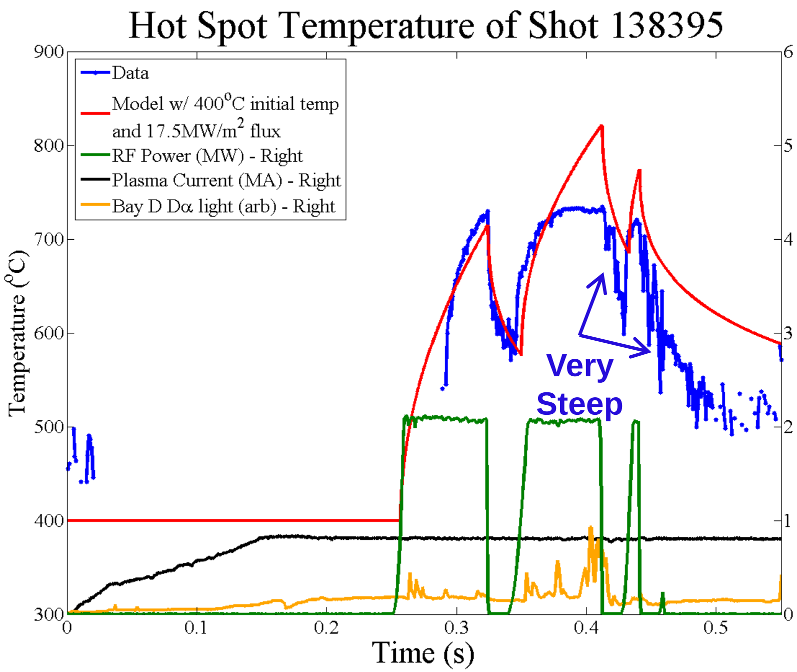


Some odd thermal signatures

Shot 138394: Rise delayed after RF



Shot 138395: Rise/fall too steep

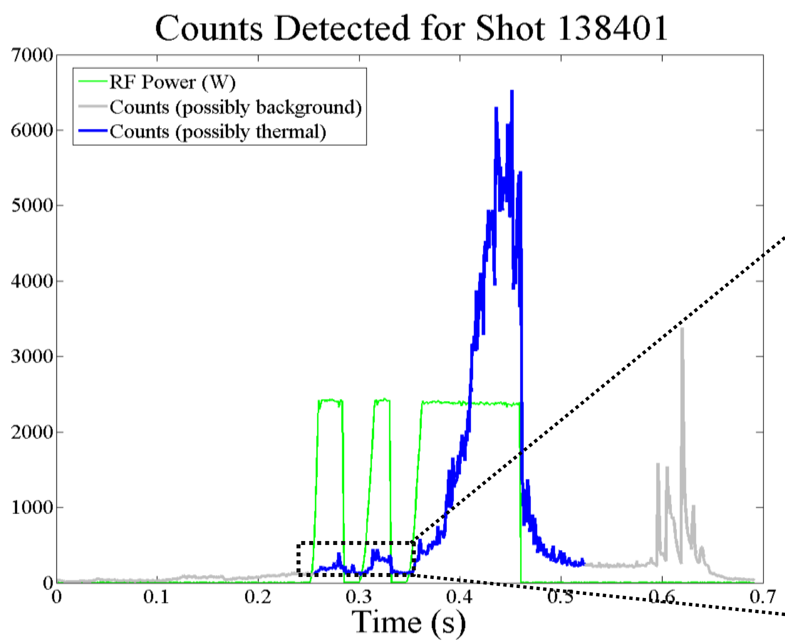


- Possible causes
  - Movement of “RF strike point” could cause delay?
  - ELMs?
  - Additional background light?

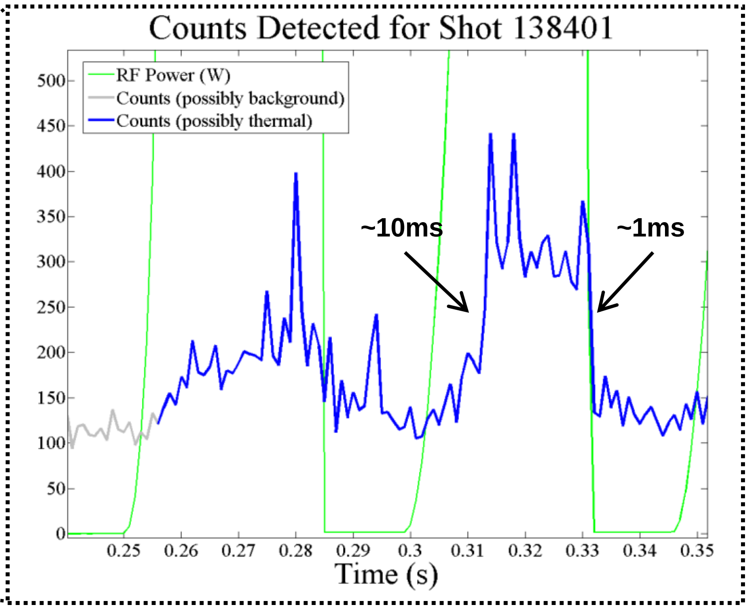
Sources & time dependence of background

- Several possible sources
  - Plasma line emission
  - Bremsstralung
  - Reflection from breakdown filament (measured to be small)

- Signal before RF is 1-10% of signal during RF

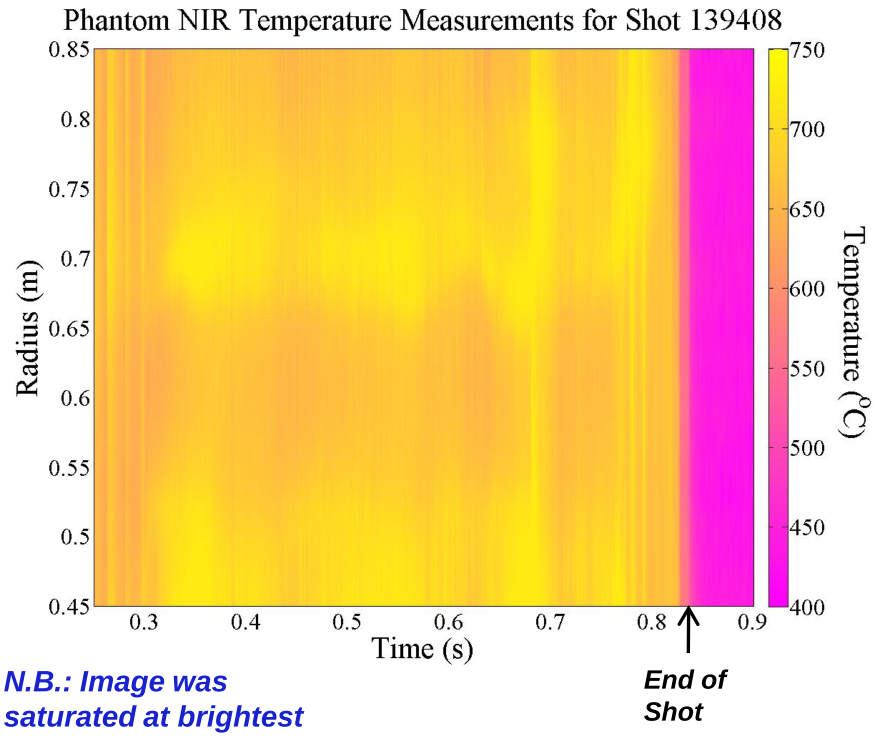


- Increases during RF?
- Rise/fall times seem too fast for heating



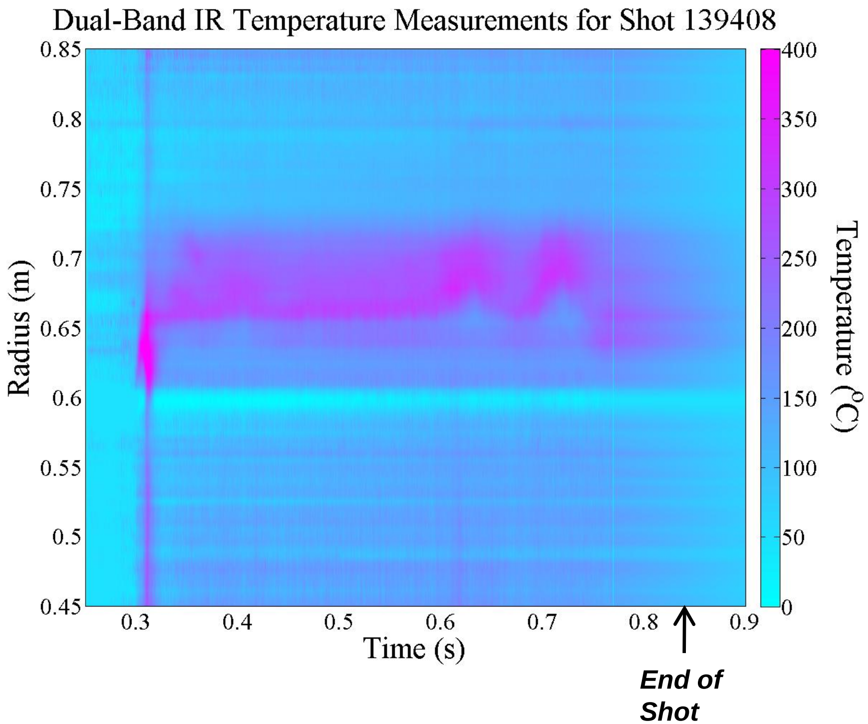
Comparison of Measurements to ORNL Dual-Band IR Camera (1)

Phantom v7.3 w/ 900 nm Filter and 990 μs exposure time



N.B.: Image was saturated at brightest locations.

ORNL dual-band camera [†]



- Same shot and approximate location
- No RF Heating
- Strike point on LLD (between 0.65 m to 0.85 m)
- CHI gap: ~0.6 m

[†] Unpublished data from A.G. McLean. Received 10/8/2010.

Comparison of Measurements to ORNL Dual-Band IR Camera (2)

- Phantom measurement compared to dual-band
  1. During shot, ~400 ^oC hotter
  2. Spatial variation much smaller (ΔT ~ 150 ^oC vs. ΔT ~ 300 ^oC)
  3. Steeper drop as shot ends (ΔT ~ 150 ^oC in 10 ms v. >100 ms)
  4. Strike point visible in both
  5. Dual-band temperatures below measurable range for Phantom system at this exposure time

- Plasma light likely responsible
  1. Additional counts raise measured temperature
  2. If plasma light dominates, spatial variation in temperature would only be a small correction: Temp ~ log(counts)
  3. Disappearance at end of shot would lead to steep drop
  4. Strike point should be bright in plasma light as well

Summary & Conclusions

- High-speed Phantom cameras with NIR filters are capable of measuring temperature as demonstrated during calibration.
- *In situ*, background light (likely due to plasma line emission) produces a background equivalent temperature between 500 ^{o}C and 700 ^{o}C.
- Temperature of RF heated hot spots in excess of 700 ^{o}C have been measured with this system.

Future Work

- Better determination and/or elimination of background
  - Use CI filter on Phantom 7.3 camera to determine level of line emission background
  - Use narrow band-pass filter in region where there are few emission lines
    - Reduction of counts by a factor of 10-100 *should* be okay, but will restrict measureable temperature range
    - Band TBD by V.A. Soukhanovskii's NIR spectrometery results
- Improved thermal model necessary?
  - Explain the temperature rise before RF needed for best fit
  - Include effects of impurity buildups on tiles (esp. lithium)
- More extensive comparison with slow & fast IR cameras observed heat flux
- Study transient heating due to ELMs/disruptions