Development of a prototype infrared imaging bolometer for NSTX-U

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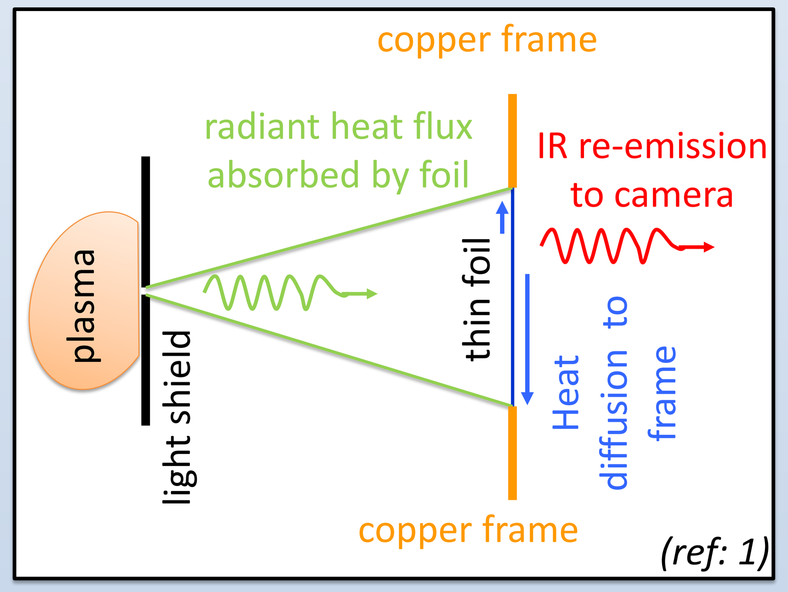
ABSTRACT - Measurements of the radiated power in fusion reactors are of high importance for studying detachment and the overall power balance. A prototype Infrared Video Bolometer (IRVB) system for NSTX-U is being developed for this purpose in addition to the planned resistive bolometer and AXUV diodes on the machine. The IRVB has proven to be a powerful diagnostic on the LHD and JT-60U devices for its 2D imaging quality and reactor environment compatibility. A poloidal view of the lower center stack and inboard divertor are envisaged for the 2015 NSTX-U run campaign. The IRVB measures radiation from the plasma by monitoring the temperature evolution of a 2.5 μm thick 9 x 7 cm² calibrated Pt foil using an IR camera (SB focal plane, 2-12 μm, 128x128 pixels, 1.6 kHz). The power incident on the foil is calculated by solving the 2D heat diffusion. Optimizing the camera settings resulted in a sensitivity of 17 mK and a noise equivalent power density of 60.8 μW cm⁻² for 4x20 bolometer pixels and 50 Hz time response. Based on a first estimation of the expected radiated power on the foil, a signal-to-noise ratio of 135 is hence obtained.

OBJECTIVES

- Testing feasibility of measuring 2D radiation structures in the NSTX-U divertor using the Infrared Video Bolometer (IRVB) technique (1D detector for prototype)
- Optimizing IRVB time response and sensitivity in comparison to conventional resistive bolometer and AXUV diode systems

IRVB CONCEPT AND METHOD



Advantages:

- 2D radiation measurement
- Condensing an increased number of bolometer channels on a single detector
- Absence of vacuum feedthroughs
- Absence of electrical pickup

Disadvantages:

- Previous implementations had limited time response
- Need for optical path from backside of detector

Raw IR signal → 2D temp. distribution → Radiated power

- Raw IR signal: optimized at low T signals; Full-array calibration; Flat-Field-correction
- 2D temp. distribution: calibrated foil parameters
- Radiated power: Crank-Nicolson scheme to solve 2D heat equation

$$-\Omega_{rad} + \Omega_{bb} + \frac{1}{\kappa}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}$$

$$\Omega_{rad} = \frac{P_{rad}}{k t_f l^2}$$

from calibration

$$\Omega_{bb} = \frac{\varepsilon \sigma_{S-B}(T^4 - T_0^4)}{k t_f}$$

from calibration

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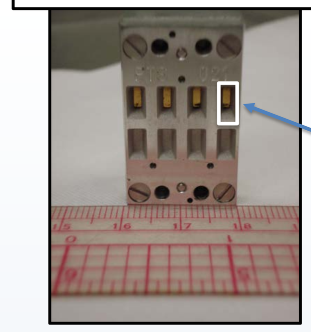
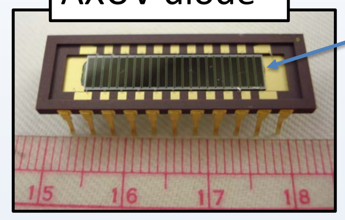
BOLOMETRIC DIAGNOSTIC METHODS

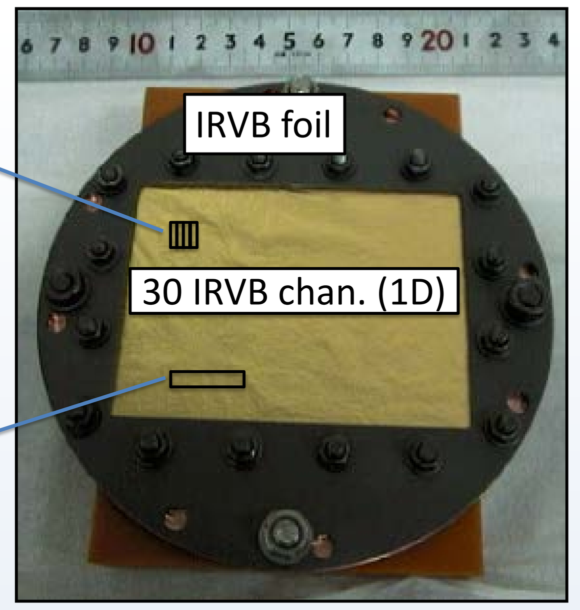
IRVB offers tremendous increase in channels/cm² compared to resistive bolometer and AXUV systems

Res. Bolo. sensor



AXUV diode

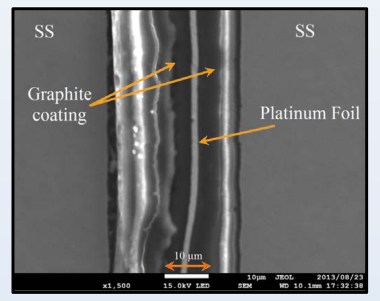




Foil calibration[2]:

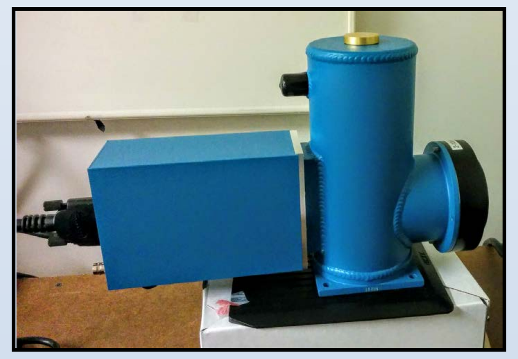
- Thickness (spatially resolved) determined from comparison FEM and laser heating
- Thermal diffusivity (spatially resolved) from thermographic method (expansion rate of heated area by laser pulse yields κ)

SEM picture Pt foil +graphite coating[2]



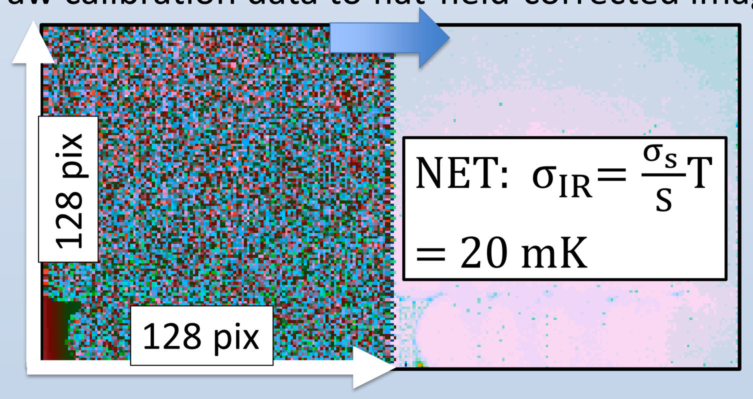
CAMERA CHARACTERISTICS

Camera performance is critical system component: Sensitivity maximized by minimizing "noise-equivalent-temperature" σ_{IR} → SNR ∝ $1/\sigma_{IR}$



- IR Cam: Santa Barbara Focal Plane
- 128x128 pixels
- 1610.31 fps
- Low temperature calibration of full IR detector using BB source
- Near-RT performance optimization: Δt=100.875 μs, gain=3, bias=0

raw calibration data to flat-field-corrected image

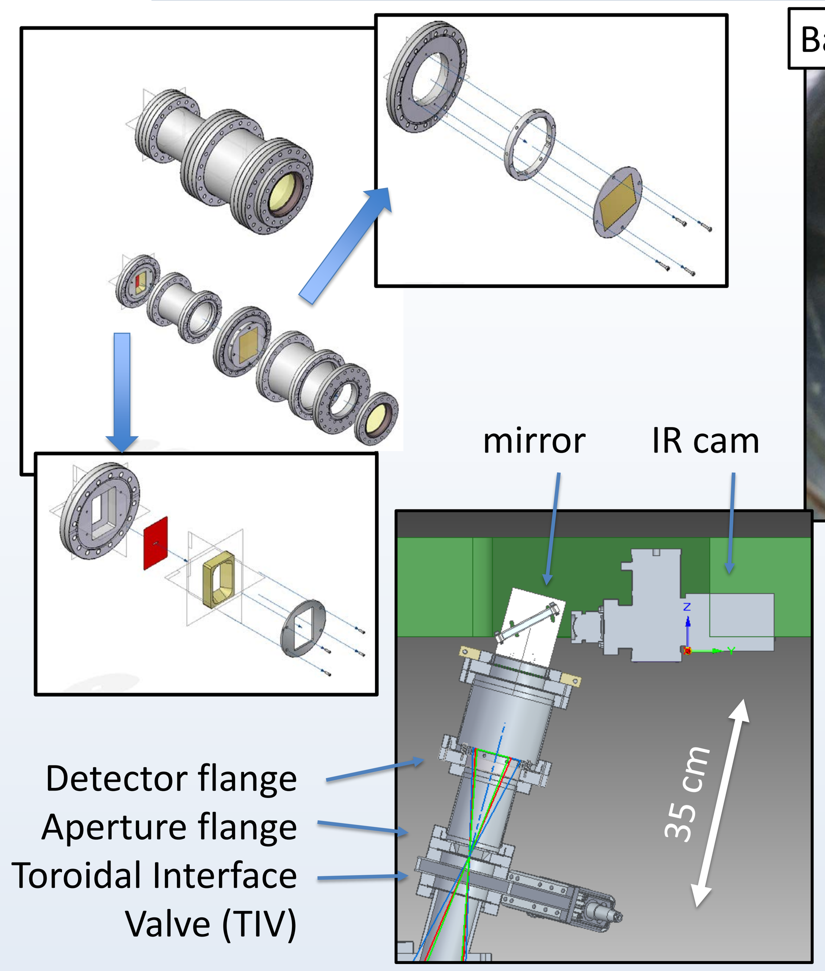


$$SNR = \frac{S_{signal}}{S_{noise}} = \frac{\kappa \cos^4 \vartheta P_{rad} l_{plasma}}{4\pi k t_f \sigma_{IR} l_{ap-f}^2 V_{plasma}} \sqrt{\frac{f_{IR} N_{IR} A_{bol}^3}{2 A_f f_{bol}^3}} = \frac{\kappa \cos^4 \vartheta P_{rad} l_{plasma} A_{ap}}{4\pi k t_f \sigma_{IR} l_{ap-f}^2 V_{plasma}} \sqrt{\frac{f_{IR} N_{IR}}{2 N_{bol} f_{bol}^3}}$$

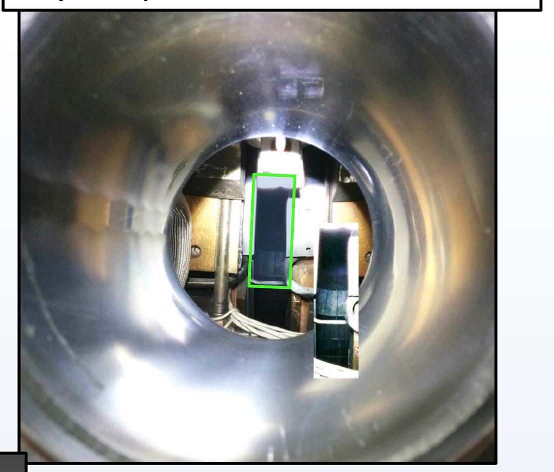
*ref 3

- k – foil thermal conductivity
- κ – foil thermal diffusivity
- t_f = 1.5 - 4 mm – foil thickness
- A_f – utilized area of the foil
- f_{IR} – frame rate of IR camera
- N_{IR} – number of IR pixels
- A_{bol} – area of the bolometer pixel
- f_{bol} – frame rate of IRVB (t.b.d.)
- N_{bol} – number of bolometer pixels (9x7)
- A_{ap} – area of aperture (t.b.d.)
- l_{ap-f} – distance from foil to aperture (16.2 cm)
- V_{plasma} = plasma volume (11 m³)
- θ – angle between sight line and aperture normal
- l_{plasma} – length of sight line through plasma (2.5 m)
- P_{rad} – total power radiated by plasma (~2 MW)

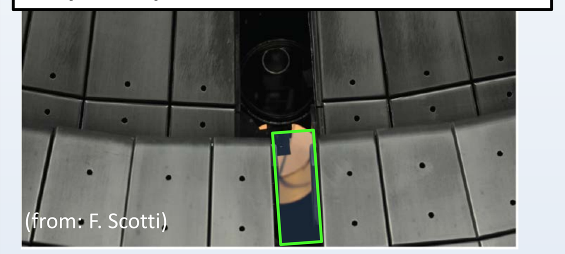
MECHANICAL DESIGN



Bay-J top view outside→inside



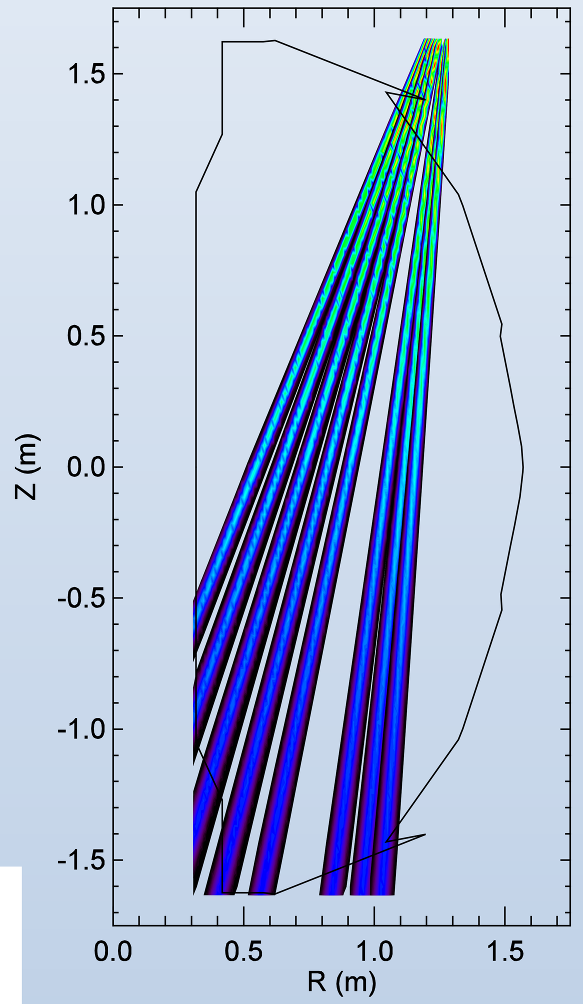
Bay-J top view inside→outside



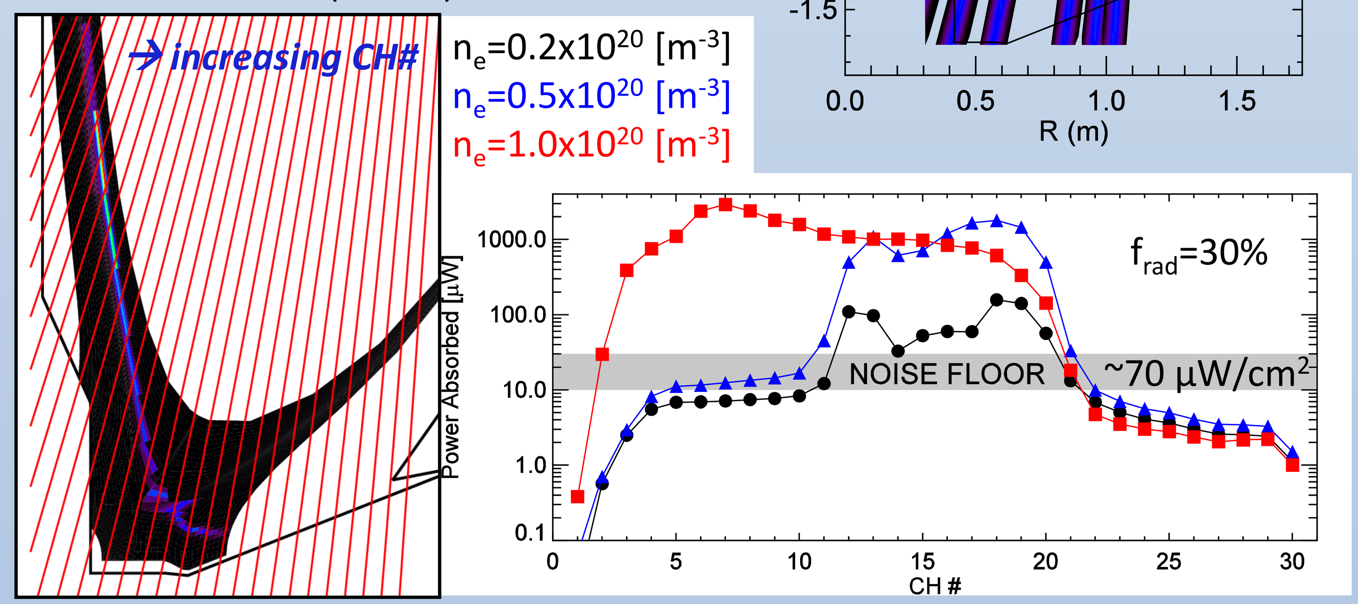
EXPECTED RADIATION LEVELS

Success of spatially resolving divertor regimes depends on sensitivity and number of channels

- For prototype design: 1D array of bolometer pixels: 30 channels of 7.5x2.11 mm
- Integration along LOS shows overlap of channels
- Spatial resolution versus signal can be changed later in design and analysis; 4, 3, 2 channels combined shown in plot →
- Bolo pixel area: 0.15 cm²

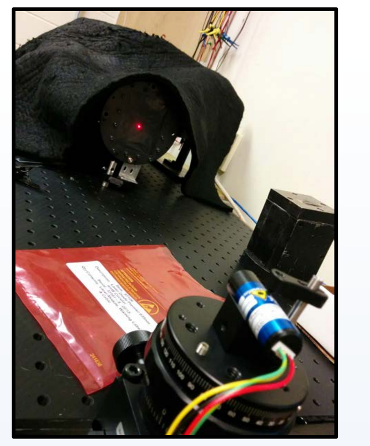


Expected radiation levels from SOLPS simulations (J. Lore):



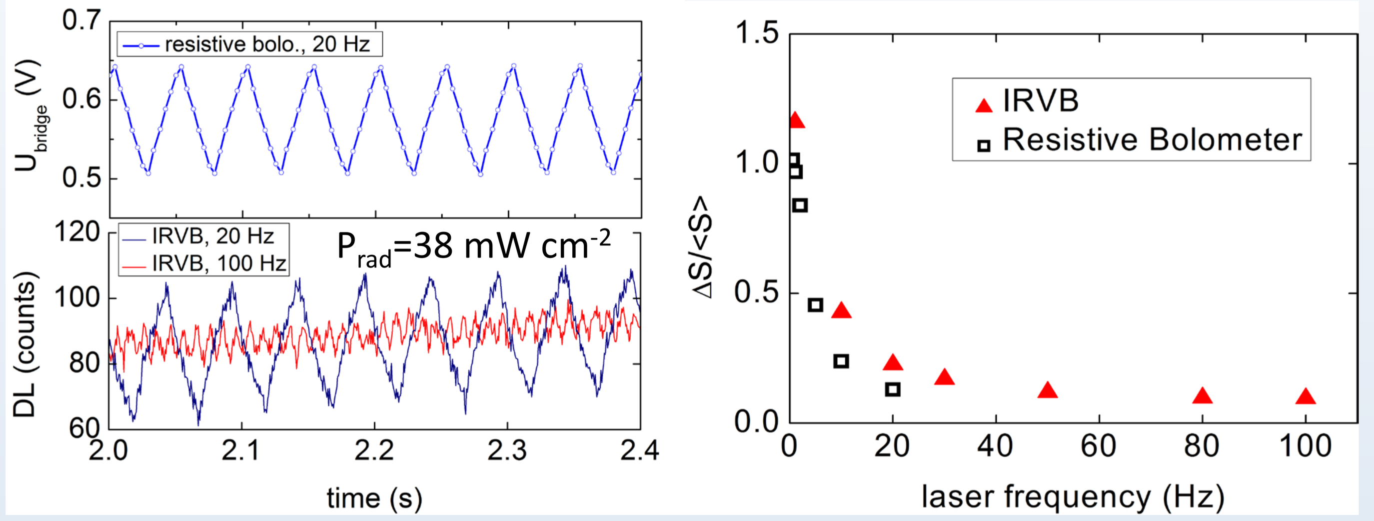
TIME RESPONSE TESTING ON BENCHTOP

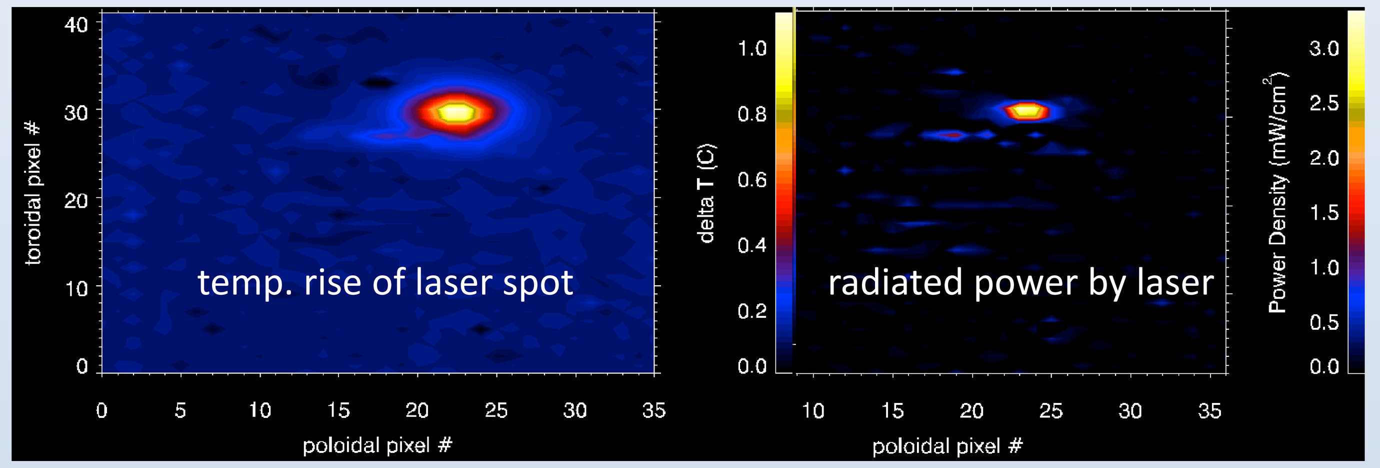
Motivated by assessing time response limit using a (faster) IR cam and allowing for one-to-one comparison to a resistive bolometer



Foil irradiated by 4mW HeNe laser (λ=635 nm) and arbitrary pulse shape generator

- 2.5 μm Pt foil, irradiated in air (vacuum to be done)
- Power scan: 0.1-4 mW
- Frequency scan: 0.1-150 Hz





SUMMARY AND FUTURE WORK

- IRVB prototype system for NSTX-U tokamak currently in development
- Prototype Designed to provide 1D view of NSTX-U divertor radiation
- IRVB allows for many more detector channels per unit area than resistive bolometer or AXUV systems
- Installation planned early 2016. Acquiring data for upcoming FY16 campaign.

future work:

- Optimization of IRVB time response (laser in vacuum)
- Studies of IRVB time response and sensitivity in comparison to conventional resistive bolometer systems (ongoing)
- Finalizing design for multiple IRVB application for tomographic reconstruction purposes (FY16 NSTX-U run campaign)

[1]G.A. Wurden et. al., Rev. Sci. Instr. 68 (1997)
[2]S.N. Pandya et. al., Rev. Sci. Instr. 85 (2014)
[3]B.J. Peterson, Rev. Sci. Instr. 71 (2000)