Research and Development of Imaging Bolometers

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Advanced Diagnostics for Burning Plasmas

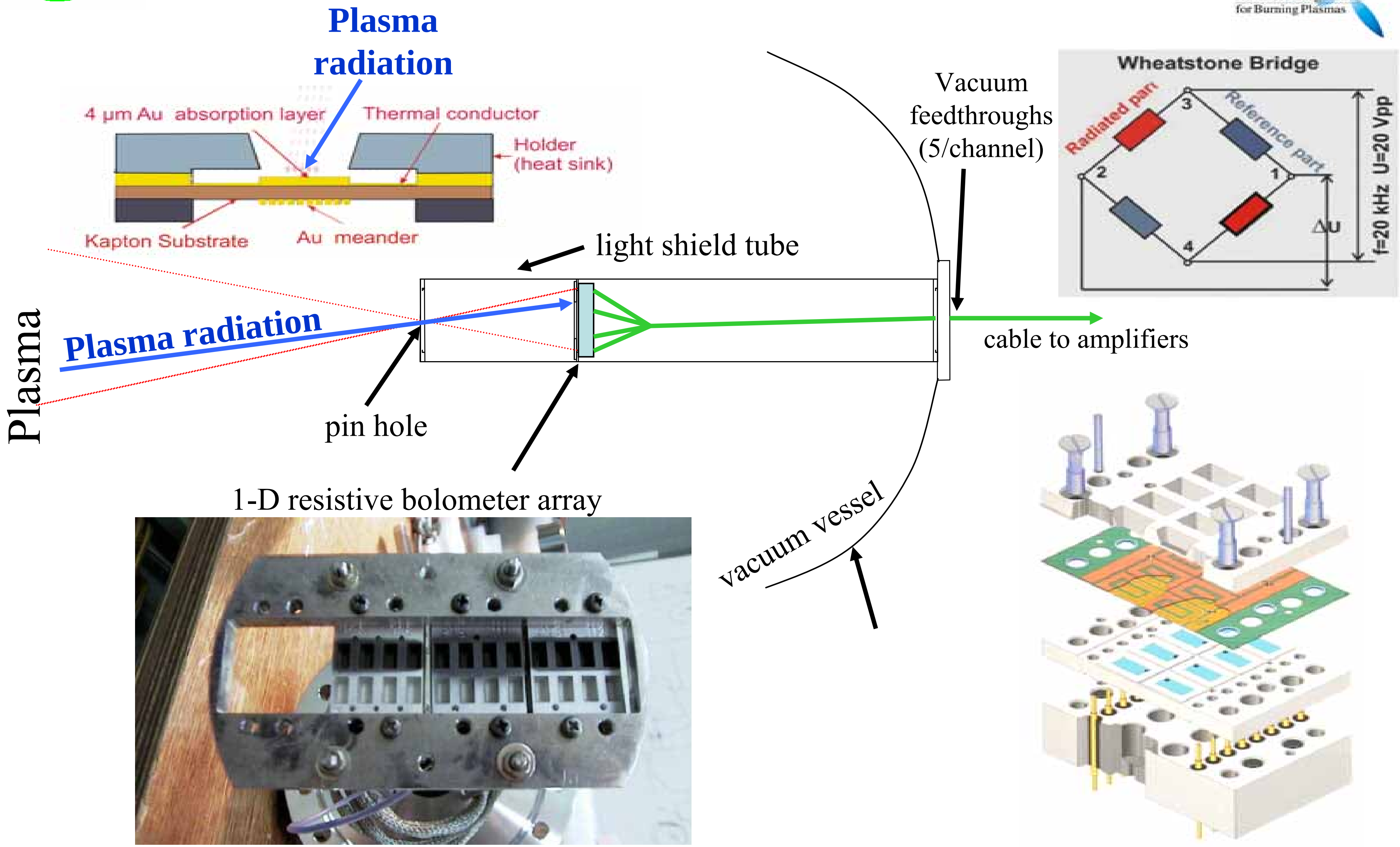
Topics

- Definition and Motivation
- Conventional resistive bolometers
- IRVB concept & data analysis
- Sensitivity, foil material & IR cameras
- JT-60U IRVB
- JT-60U IRVB sample data
- JT-60U IRVB bolometer video
- 2-D profiles with tomography of IRVB
- Plans for JT-60U IRVB Upgrade
- Imaging Bolometer for ITER
- New detector foil R&D
- Summary & Conclusions

What is a Bolometer?

- Original definition – device whose electrical properties change in response to radiation
- Resistive bolometer first conceived in 1878 by S. P. Langley to measure solar radiation
- Used in fusion plasma physics to measure total, broadband (IR – X-ray) radiated power
- For power balance and impurity radiation studies

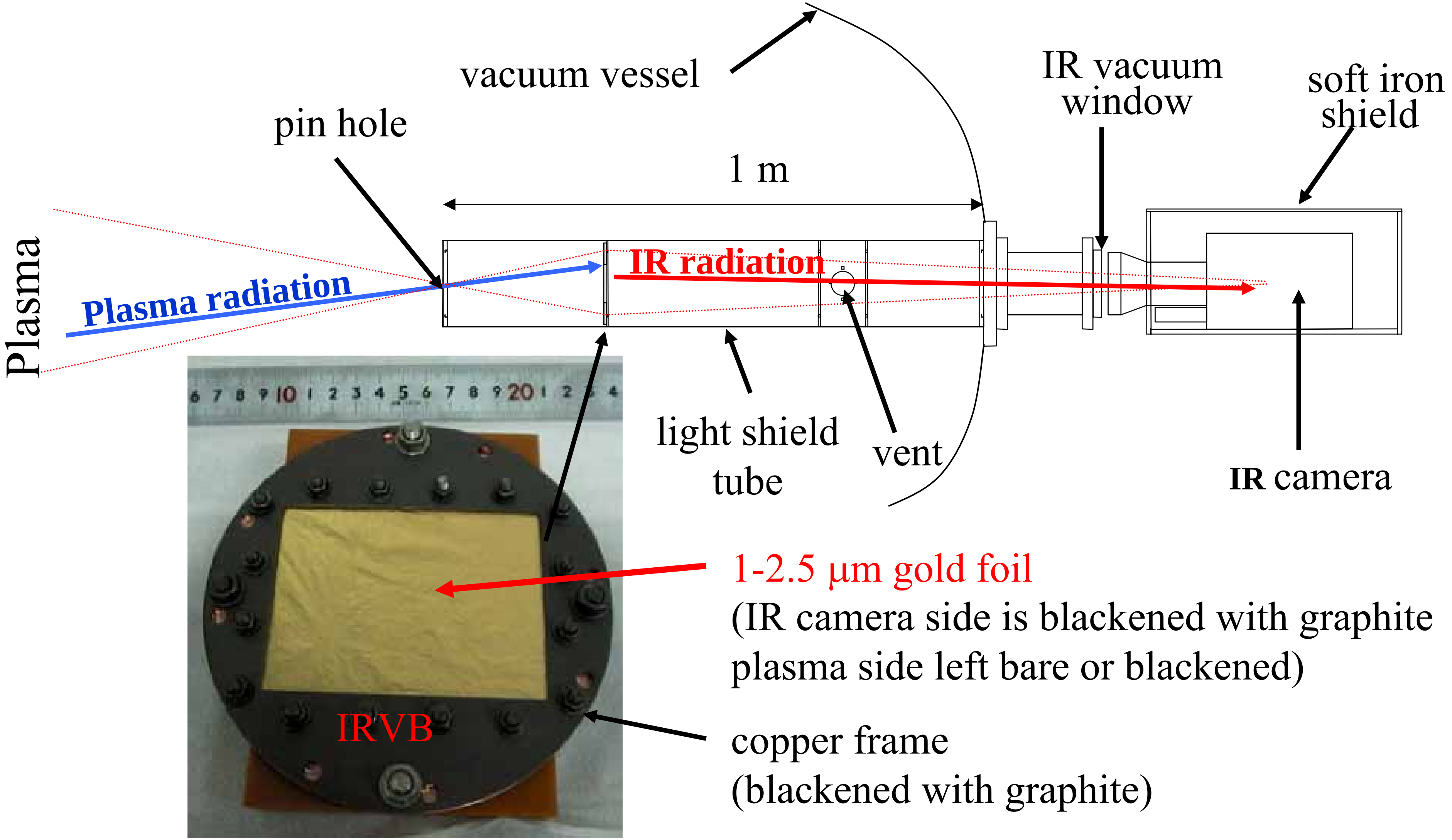
Resistive Bolometer – Concept



Motivation for IR Imaging Bolometer

- Real-time **measurements of** local **radiation** power loss **necessary for fusion reactor**
- Fusion **reactor conditions pose challenges** (RIEMF, fragile contacts, etc.) **to** conventional existing **wire-based** radiation sensing **devices** (resistive bolometers)
- **Lack of** a simple, reliable and cost effective **technique for** the **measurement of radiation** inside the vacuum vessel of a fusion reactor
- Continuing **advances in infrared detector** technology **provide** an **opportunity** to measure radiation fluxes in a reactor environment using thin absorber foils

IR imaging Video Bolometer (IRVB) – Concept



[1] B.J. Peterson, *Rev. Sci. Instrum.* **70** (2000) 3696. [2] B.J. Peterson *et al.*, *Rev. Sci. Instrum.* **72** (2001) 923.

IRVB - Concept

Heat diffusion equation for foil:

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

2-D Laplacian

foil thermal diffusivity

$$\Omega_{bb} = \frac{\varepsilon \sigma_{S-B}(T^4 - T_0^4)}{k t_f} \qquad \varepsilon \cong 1$$

black body cooling term

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

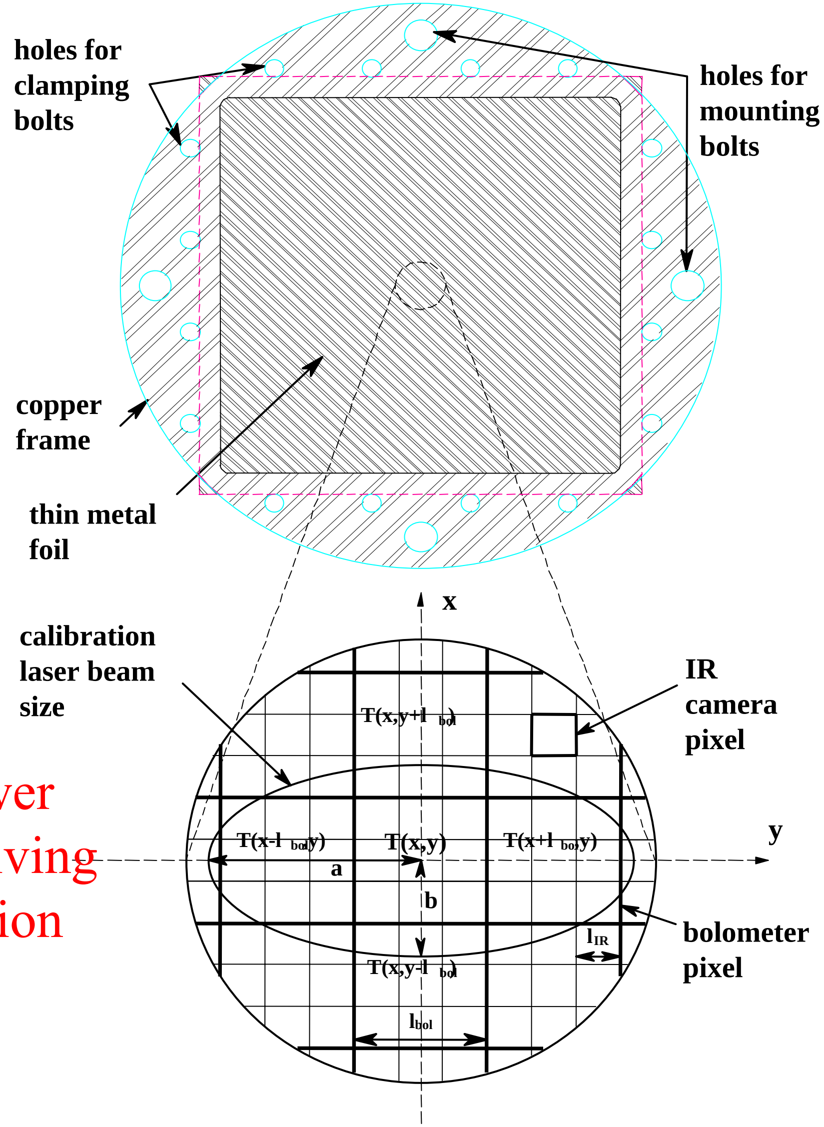
plasma radiated power is determined by solving heat diffusion equation

foil thermal conductivity

foil thickness

bolometer pixel area

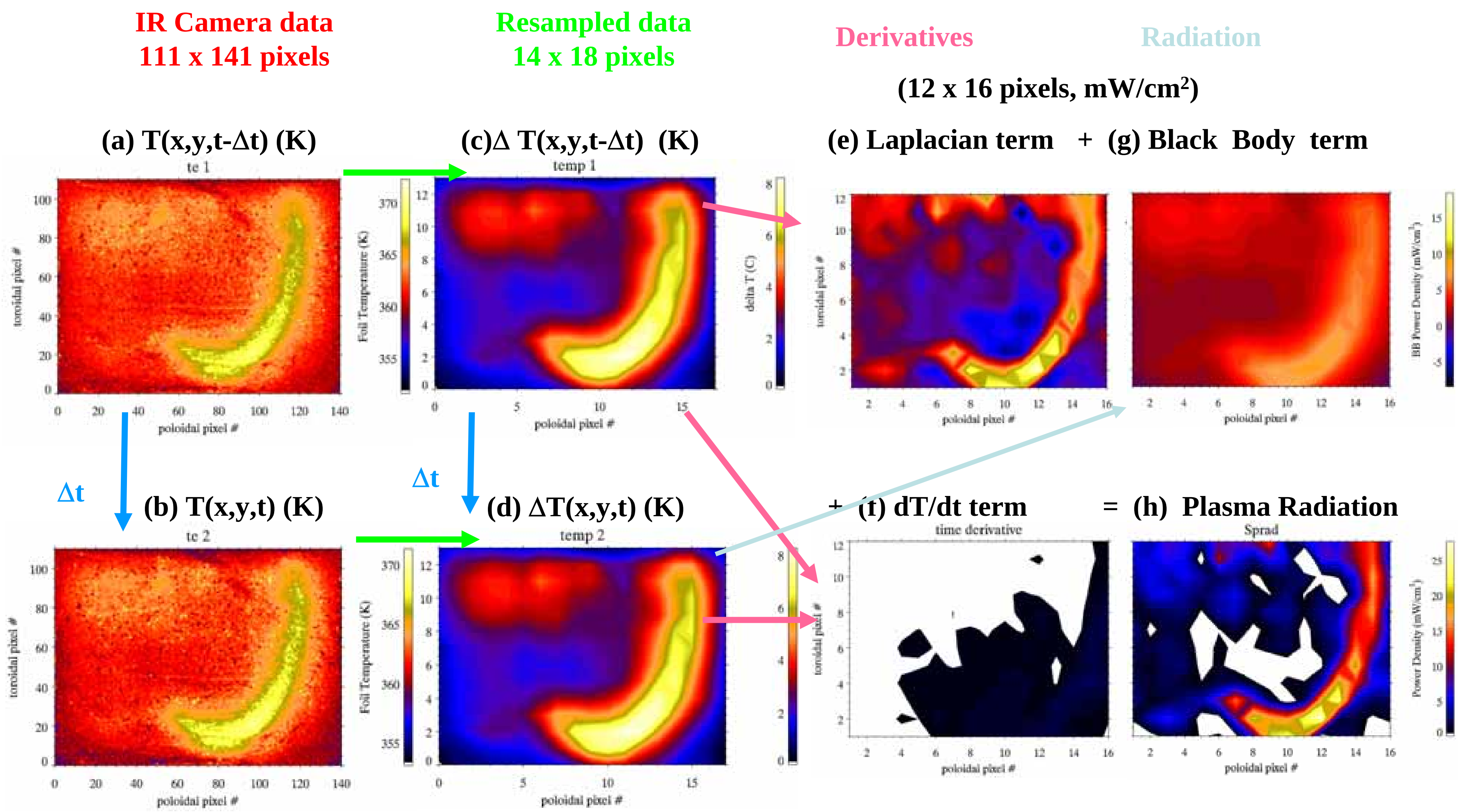
IRVB Foil and Frame



B.J. Peterson *et al., Rev. Sci. Instrum.* **74** (2003) 2040.

JT-60U IRVB Data Analysis

B.J. Peterson et al., IEEE Trans. Plasma Sci. **30** (2002) 52-53.



IRVB Sensitivity and Foil Material Selection

Advanced Diagnostics for Burning Plasmas

Noise equivalent power [1]: small small

$$\eta_{IB} = \frac{\sqrt{10}\,k t_f \sigma_{IR}}{\sqrt{mN}} \sqrt{1 + \frac{l^4}{5\kappa^2 m^2 \Delta t_{IR}^2} + \frac{4 l^4 \varepsilon^2 \sigma_{S-B}^2 T^6}{5 k^2 t_f^2}}$$

IR camera frame interval

# of frames averaged

IR camera sensitivity

# of IR pixels / bolometer pixel

Simplifying:

$$\eta_{IB} \cong \frac{\sqrt{2}\,k t_f \sigma_{IR} l^2}{\Delta t_{IR} \kappa \sqrt{m^3 N}} \propto k t_f / \kappa \propto 1/$$ **bolometer sensitivity**

bolometer pixel area

foil thermal conductivity, thickness, thermal diffusivity

Considerations in foil material selection:

- **sensitivity** $\propto \kappa / k$
- **max. photon energy (for 10 μm foil < 8 keV, 8-13 keV, <17 keV) [2]**
- **melting temperature**
- **commercial availability (min thickness of 10cm x 10 cm foil) [3]**
- **neutron - proof ? (transmutation of Au to Hg)**
- **outgassing? , cost? , others?**

[1] B.J. Peterson *et al.*, *Rev. Sci. Instrum.* **74** (2003) 2040.

[2] www-cxro.lbl.gov/optical_constants/atten2.html

[3] www.goodfellow.com; www.nilaco.jp

(a) metal	(b) κ/k (cm3C/J)	(c)Eph (keV)	(d)Tm (C)	(e)tmin (μm)
Sn	0.65	10.0	232	6
Pb	0.56	19.6	327	4
Mg	0.56	1.2	649	10
Zr	0.55	7.6	1852	3
Hf	0.52	18.4	2227	9
Cd	0.50	10.2	321	5
Mo	0.45	9.4	2617	4
Ta	0.43	20.1	2996	2
Nb	0.43	8.6	2468	2.5
Al	0.41	3.9	660	0.8
Au	0.40	23.2	1064	1
W	0.40	21.4	3410	10
Ag	0.40	10.7	962	2
Ti	0.36	7.8	1660	4
Zn	0.36	12.3	419	2.5
Pt	0.35	23.9	1772	2
Pd	0.34	11.0	1554	4
V	0.34	9.1	1890	5
Cu	0.29	6.0	1083	2
SS304	0.27	4.4	1400	8
Ni	0.25	12.6	1453	2
Co	0.25	12.0	1495	3

Ta and W are stronger and have smaller neutron x-section than Au or Pt

- Strength and thickness reduces motion of the foil
- Low $\sigma_{neutron}$ reduces nuclear heating

Foil Material Properties

	Tensile strength (MPa)	$\sigma_{neutron}$ (Barns)	k (W/m K) @0-100C	κ/k (cm^3 K/J)	T_m (C)	E_{ph} (keV) @10μm	t_{min} (μm)
Hf	745	103	23.0	0.52	2227	18.4	9
Ta	760	22	57.5	0.43	2996	20.1	2
Au	220	98.8	318	0.40	1064	23.2	2.5
W	1920	18.5	173	0.39	3410	21.4	10
Pt	200-300	9.0	71.6	0.35	1772	23.9	2

E_{ph} courtesy Lawrence Berkeley Laboratory: http://www-cxro.lbl.gov/optical_constants/atten2.html

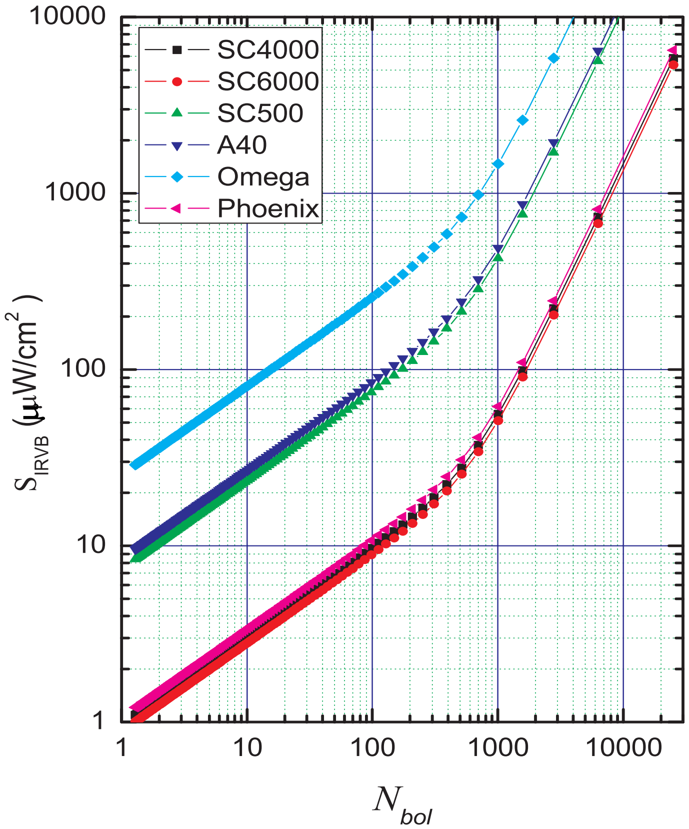
material properties from www.goodfellow.com

IRVB sensitivity improves with IR camera performance

$$S_{IRVB} = \frac{\eta_{IRVB} N_{bol}}{A_f} = \frac{\sqrt{10} k t_f \sigma_{IR}}{\sqrt{f_{IR} N_{IR}}} \sqrt{\frac{N_{bol}^3 f_{bol}}{A_f^2} + \frac{N_{bol} f_{bol}^3}{5\kappa^2}}$$

Maker/ IR Camera	FLIR/ Omega (2)	FLIR/ SC500 (2)	FLIR/ A40-M	FLIR/ Phoenix (2)	FLIR/ SC4000	FLIR/ SC6000
λ (μm)	7.5-13.5	7.5-13	7.5-13	3-5	3-5	3-5
σ_{IR} (°C@ 30°C)	0.1	0.1	0.08	0.025	0.025	0.025
type	μ bolo	μ bolo	μ bolo	InSb	InSb	InSb
cooling style	none	none	none	Stirling	Stirling	Stirling
N_{IR}	160x 120	320x 240	320x 240	320x 256	320x 256	640x 512
f_{IR} (Hz)	30	60	60	345	420	125
*S_{IRVB} (μW/cm²)	441	156	125	16	14	13

* for IRVB with 16 x 12 ch, 30 Hz, l = .5625 cm, Au, t_f = 4 microns



for Au IRVB foil with A_f=60.75 cm², t_f=4μm, f_{bol}=30/s

Imaging Bolometer for JT-60U

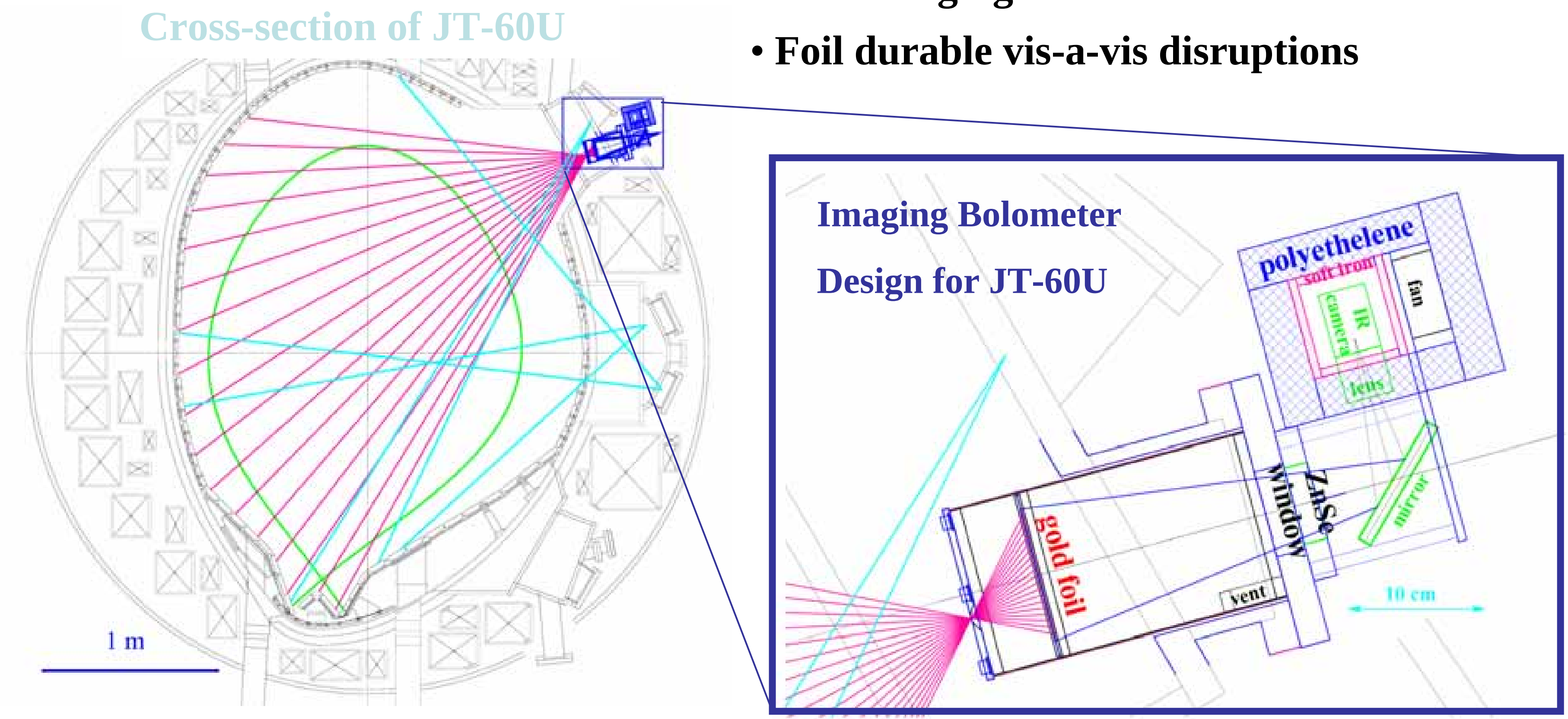
Design:

- IR camera: Indigo/Omega 67 mK, 30 Hz, 160 x 128 pixels, 14 bit
- Foil: Au, 0.0025 x 70 x 90 mm, $E_{ph} < 8$ keV
- Bolometer: 33 ms, 12(tor) x 16 (pol) = 192 ch

  NEPD > 350 μW/cm², S/N <100, Δx = 15 cm

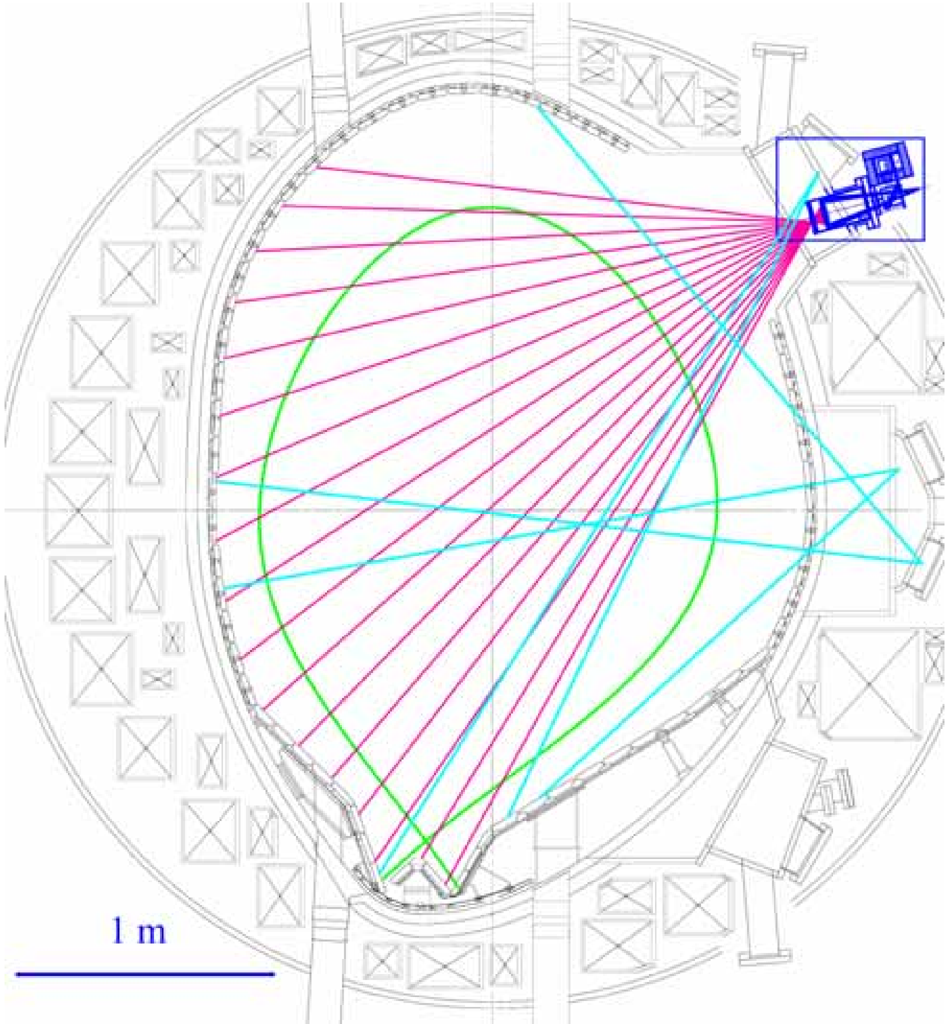
History:

- Foil installation 8/2003, operational 9/2004
- Shielding and data acq. upgrade 9/2005
- Analysis for brightness image 2/2006
- CT reconstruction of 2D profile 11/2006
- First imaging bolometer test in tokamak
- Foil durable vis-a-vis disruptions

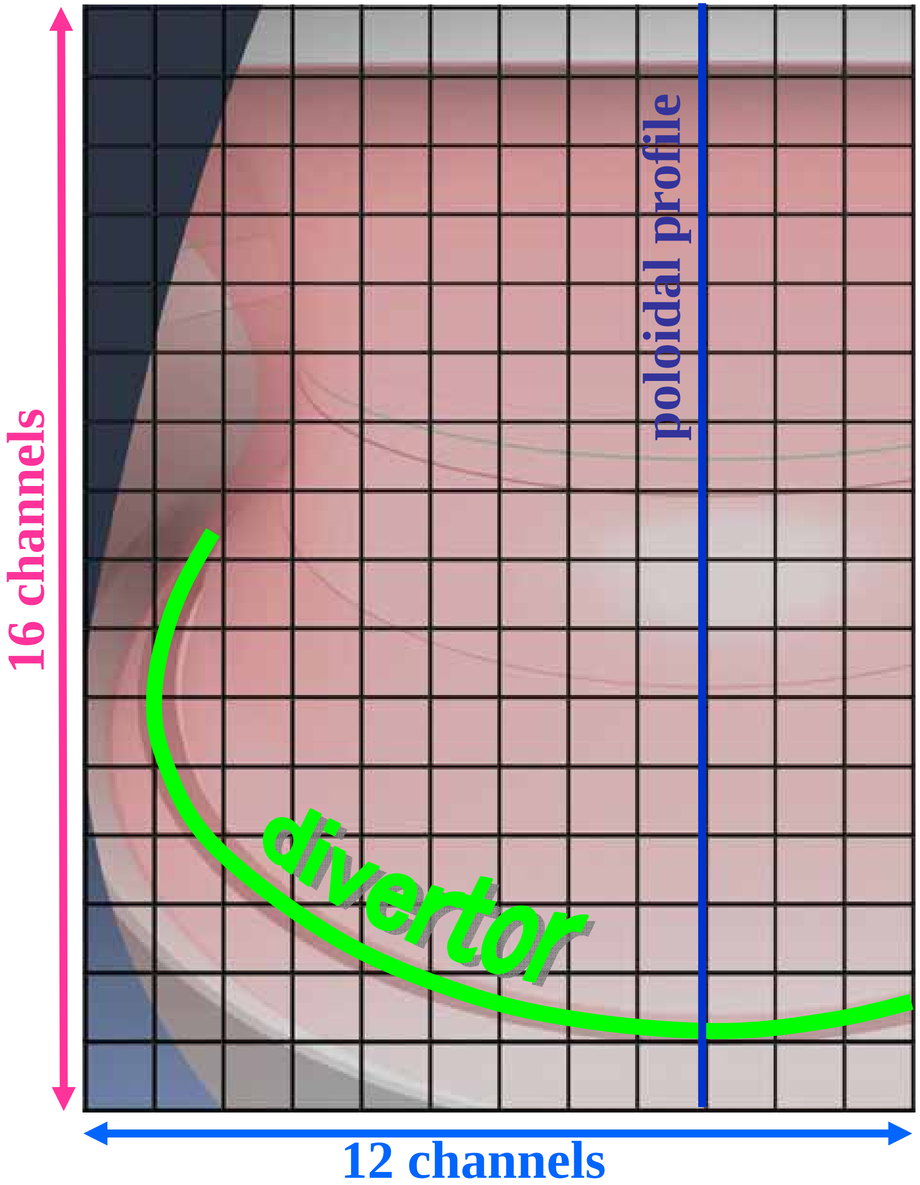


JT-60U Imaging Bolometer FOV

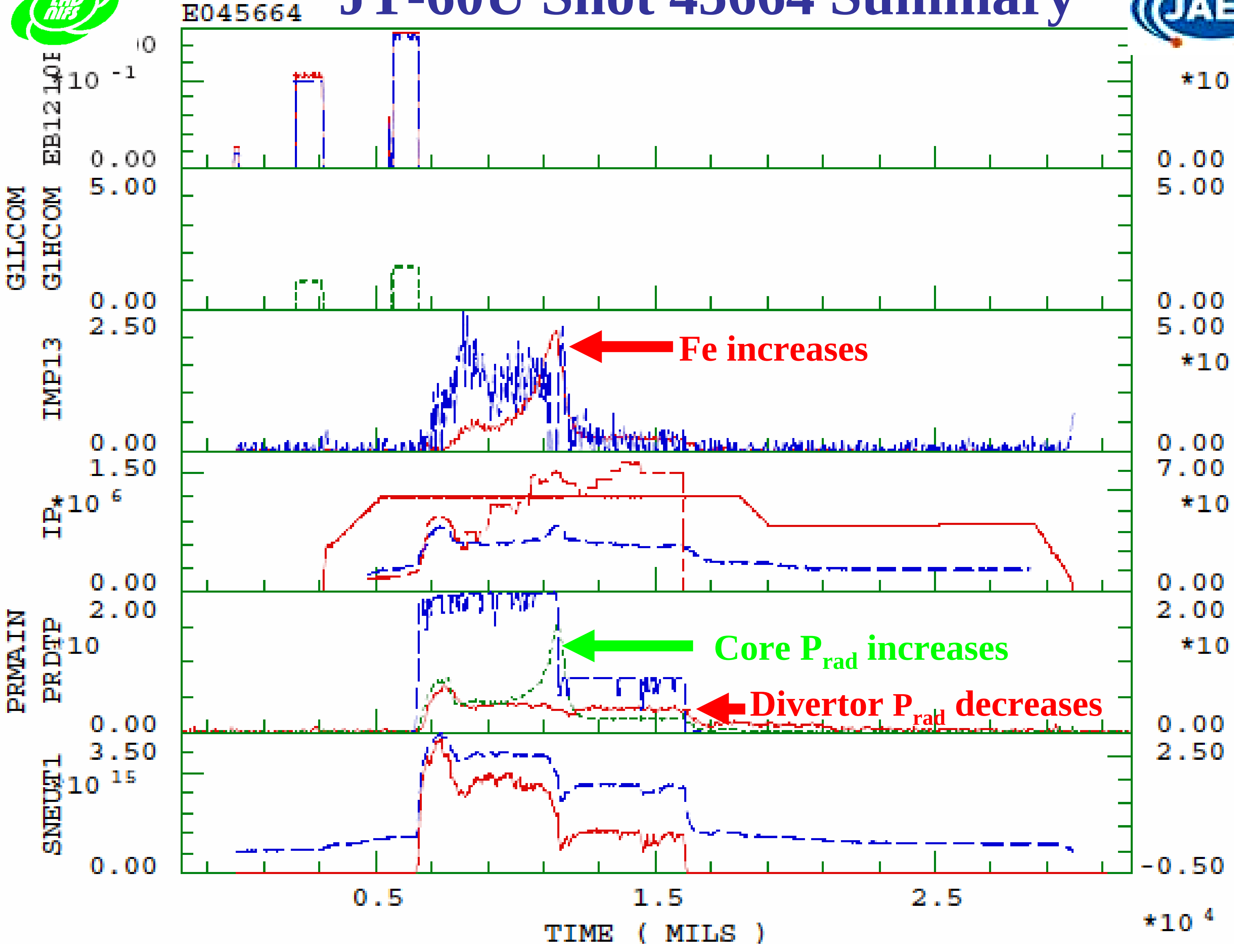
CAD of poloidal profile



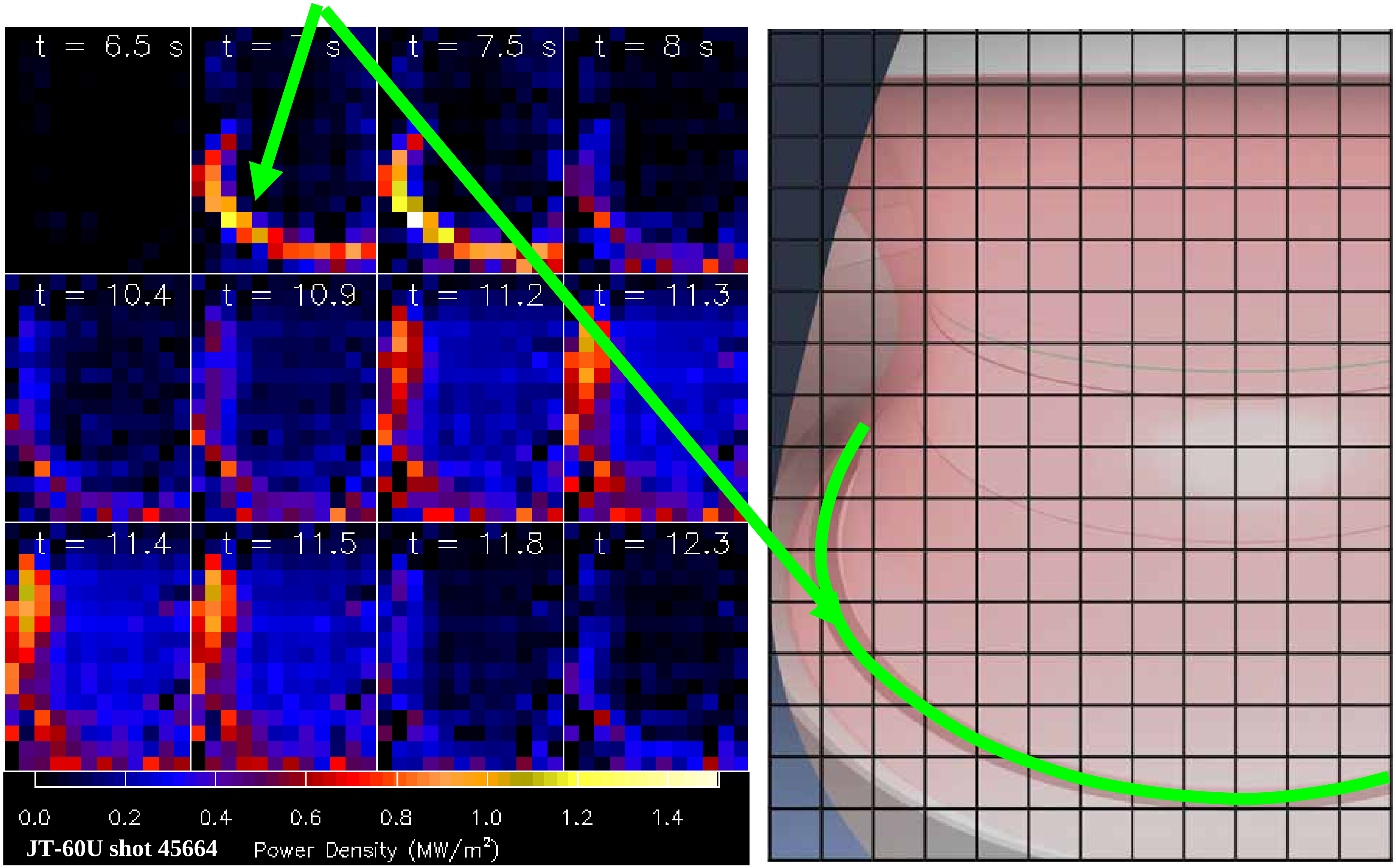
CAD of IRVB FOV



JT-60U Shot 45664 Summary



Radiation profile shifts from divertor to core with Fe influx



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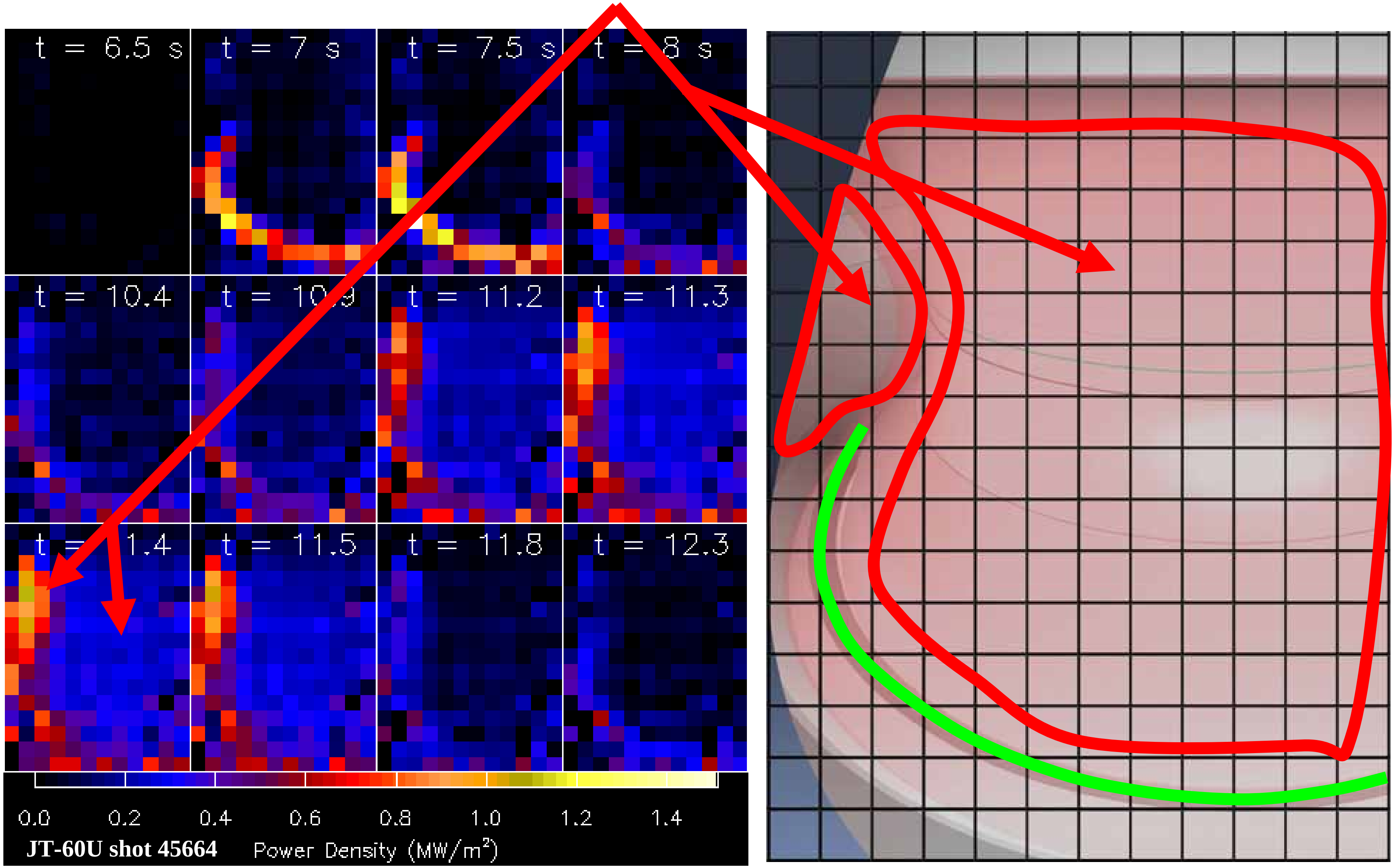
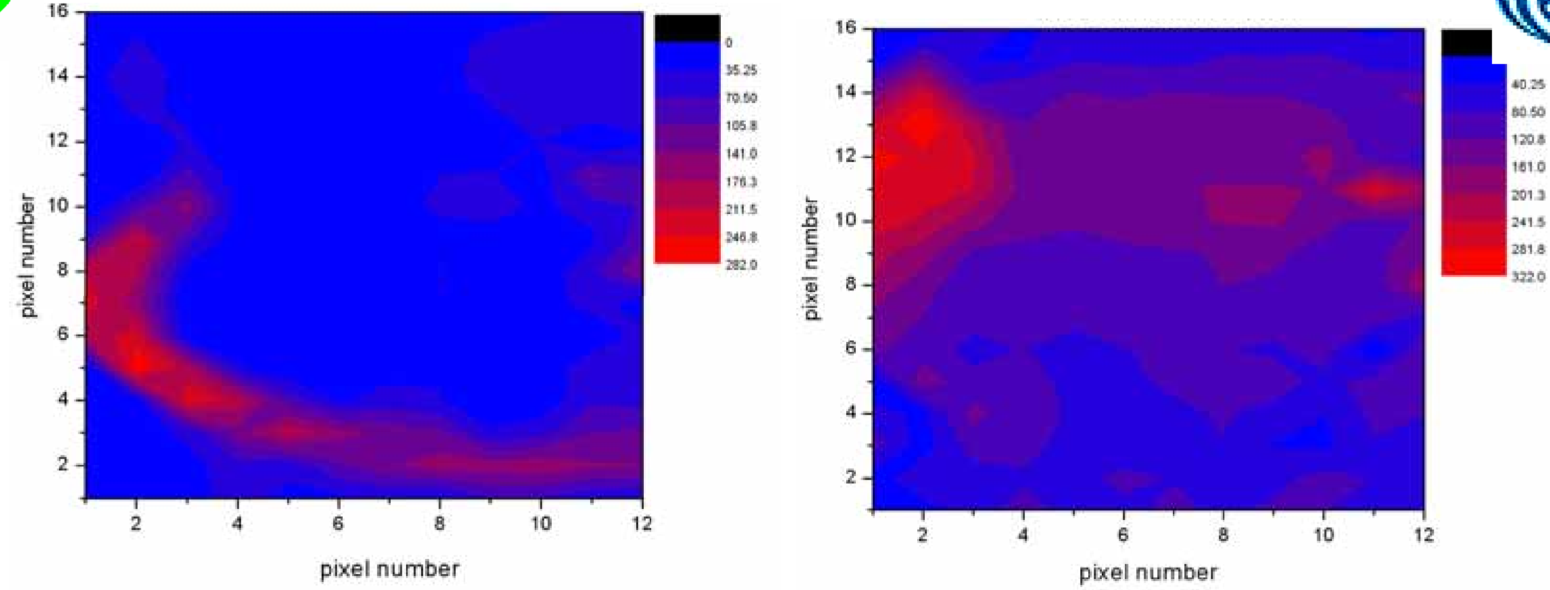
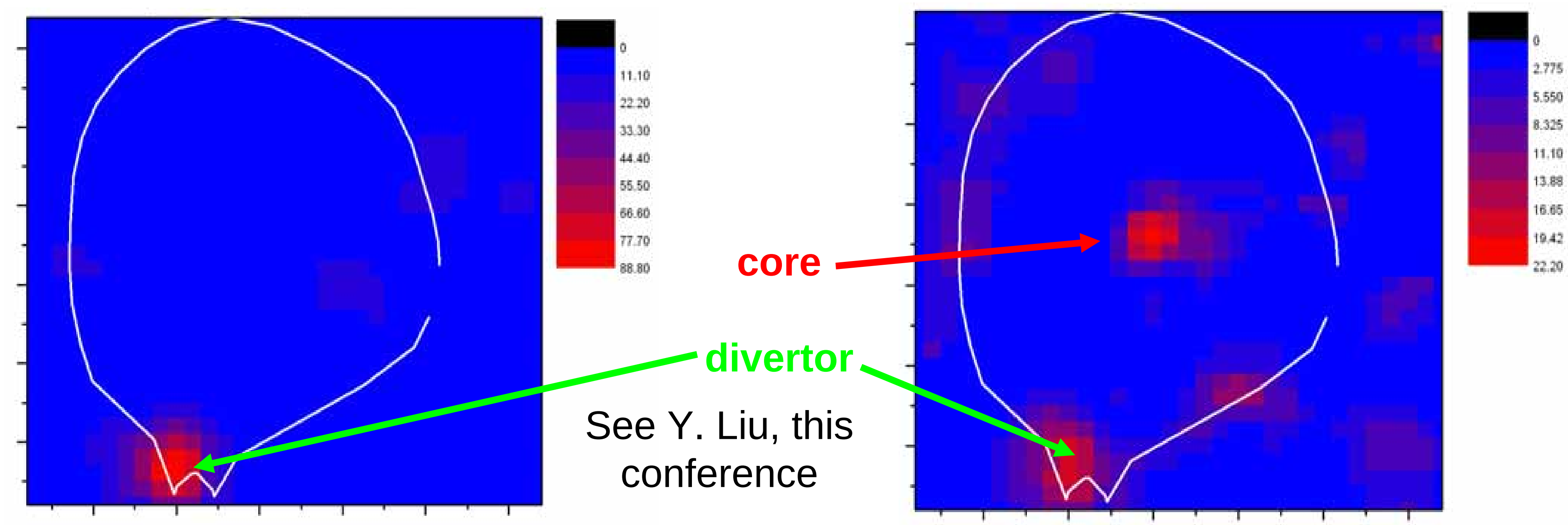


IRVB Tomography shows radiating divertor and impurity accumulation in core

7.5 s IRVB brightness data 11.3 s



2D tomographic inversion by minimizing chi-squared with Tikhonov-Phillips regularization

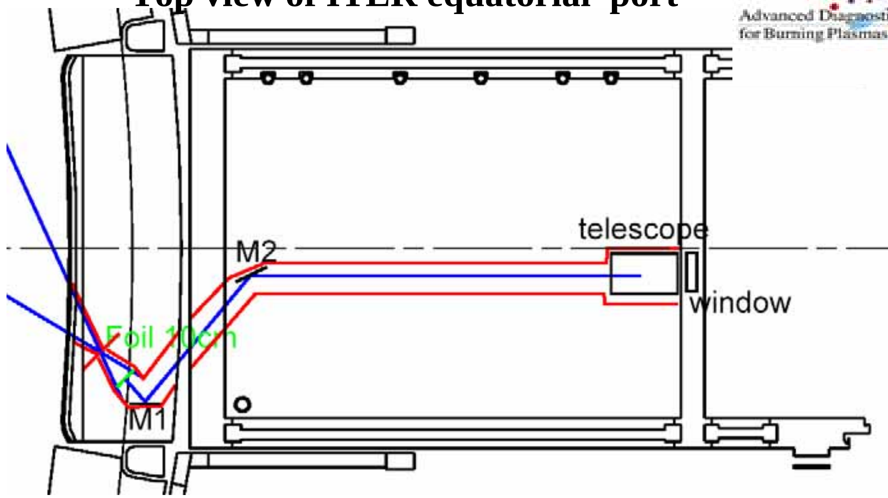


See Y. Liu, this conference

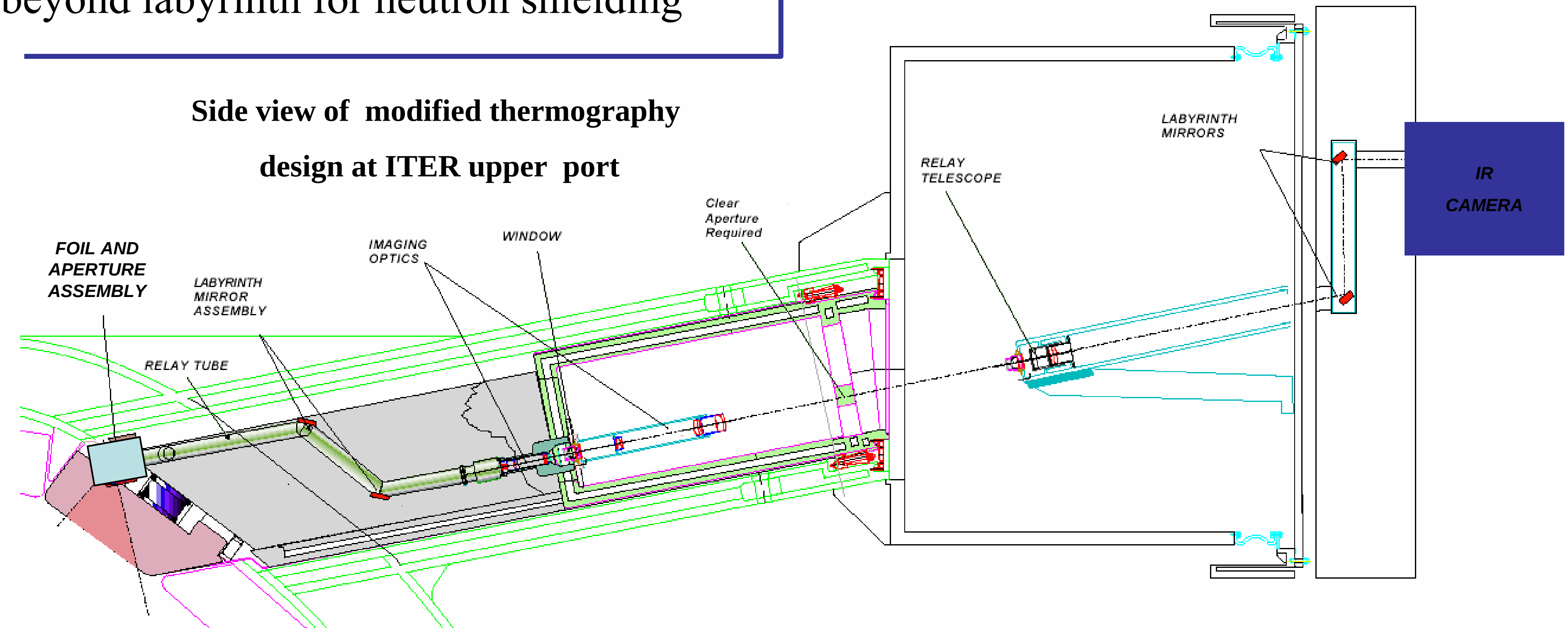
Imaging Bolometer for ITER: Installation

- Use endoscope/labyrinth similar to current IR thermography design by replacing final mirror with foil and aperture assembly
- Reflective optics near plasma, minimum 2 mirrors
- Refractive optics and IR camera beyond labyrinth for neutron shielding

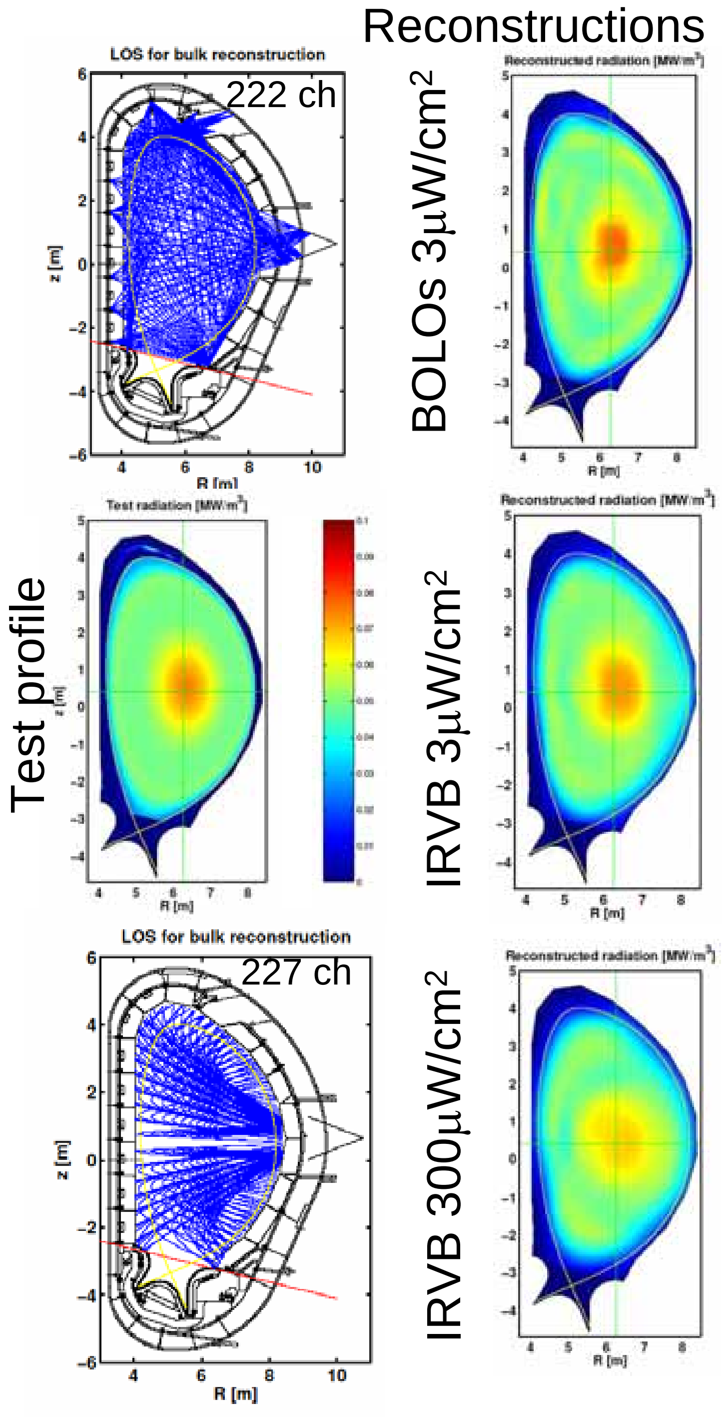
Top view of ITER equatorial port

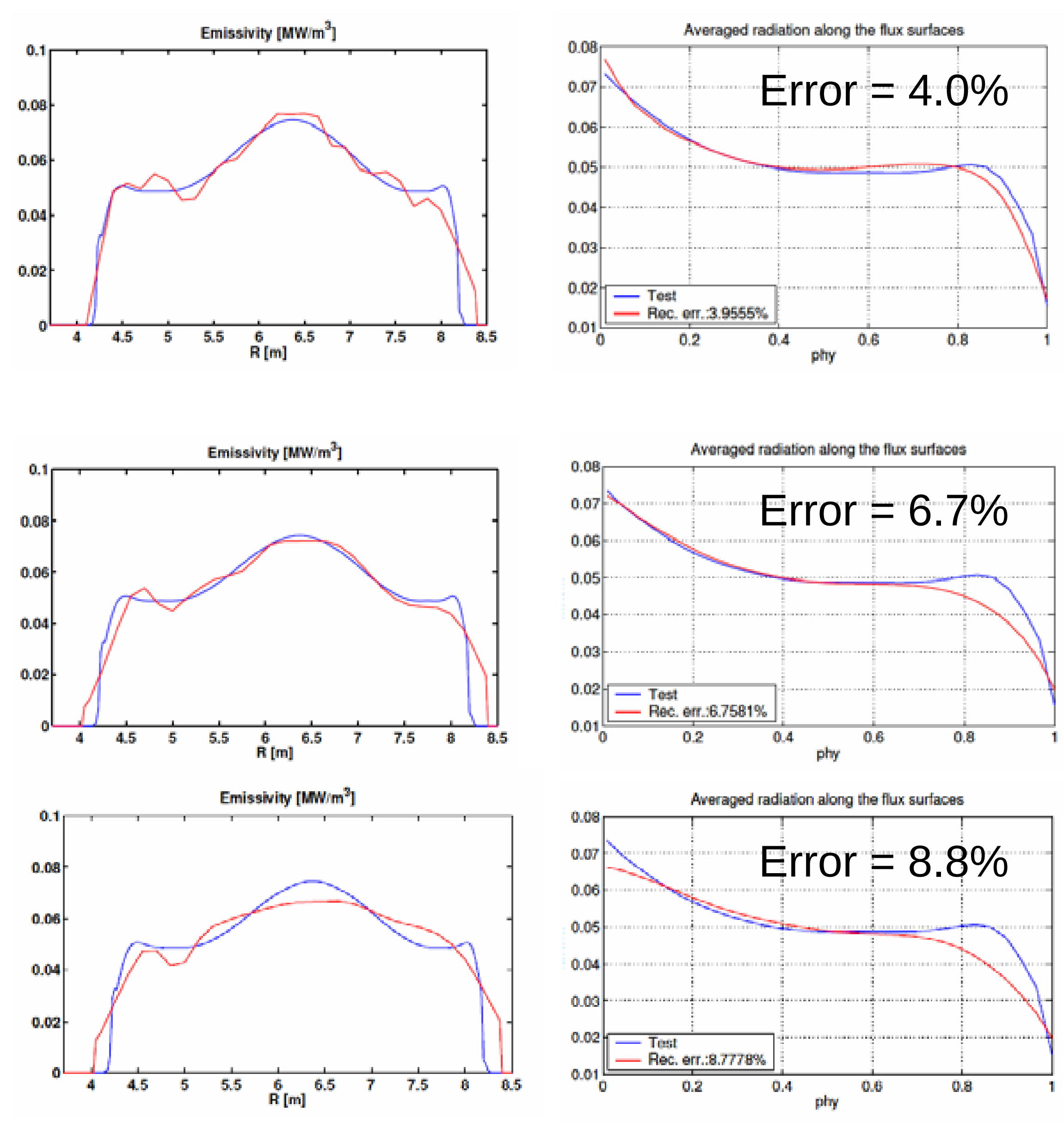


Side view of modified thermography design at ITER upper port



Reconstruction modeling from bolometer arrays





Radiation Tomography Modeling by S. Kalvin

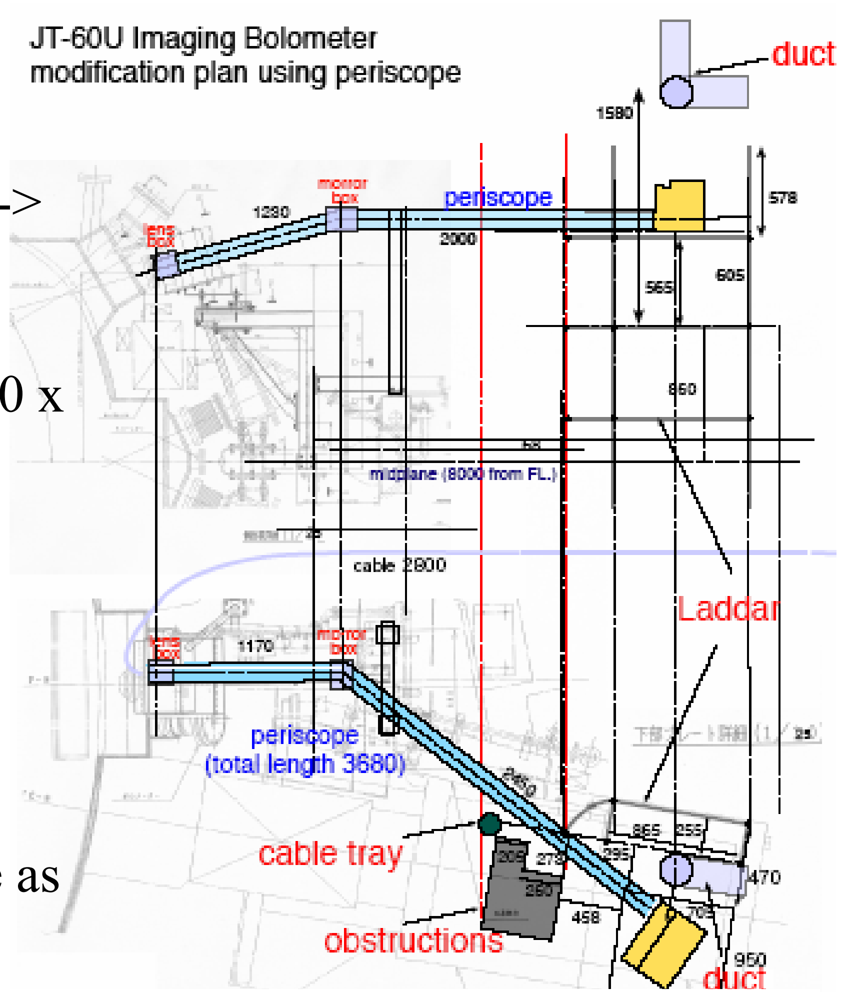
JT-60U IRVB telescope Upgrade: Improving diagnostic capability

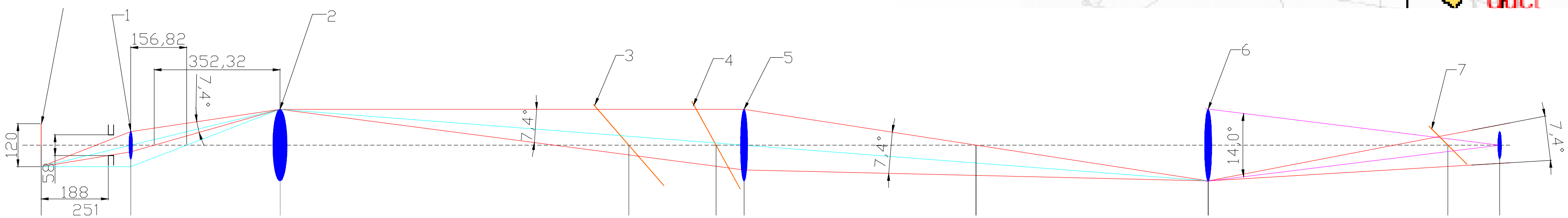
Improvement in bolometer sensitivity:

- IR camera upgrade (25 x sensitivity)
- 3.6 m telescope 42 times optical throughput ->
    - 2.5 x temperature sensitivity
- Improved shielding may decrease noise by 10 x
    - 1.8 x temperature sensitivity
- Total sensitivity increase up to 110 x

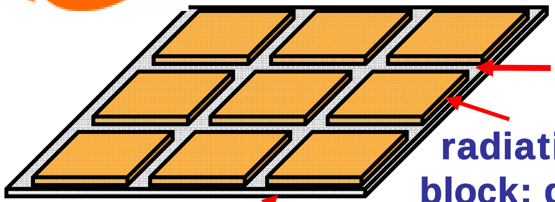
Improvement in diagnostic capability:

- 12 x 16 pixels -> 24 x 80 pixels
    - divertor resolution 15 cm -> 3 cm (same as resistive bolometers)

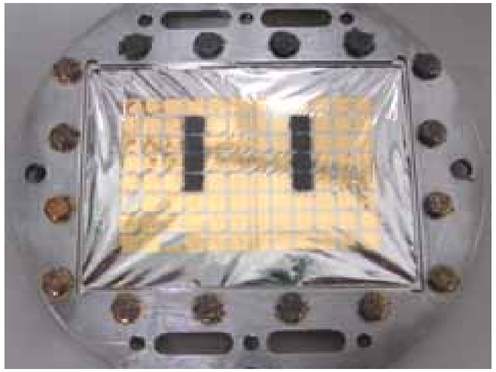




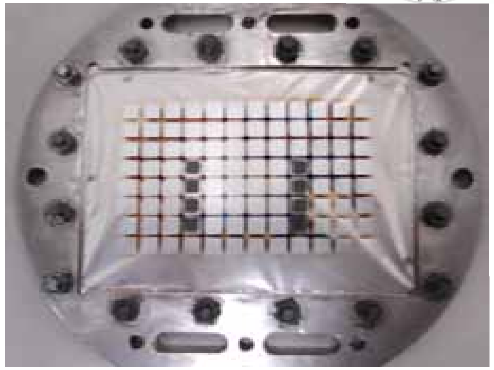
R&D of sensitive double layer foil



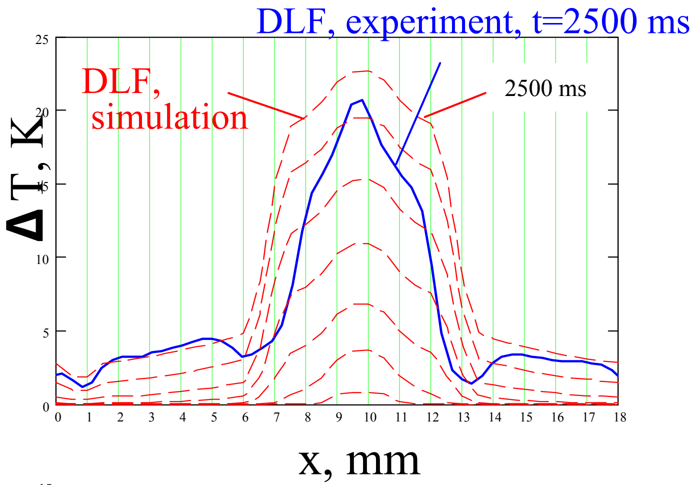
Double Layer Foil (DLF) prototype

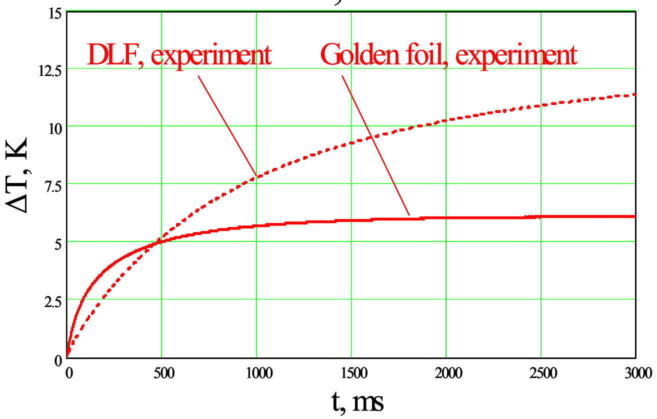


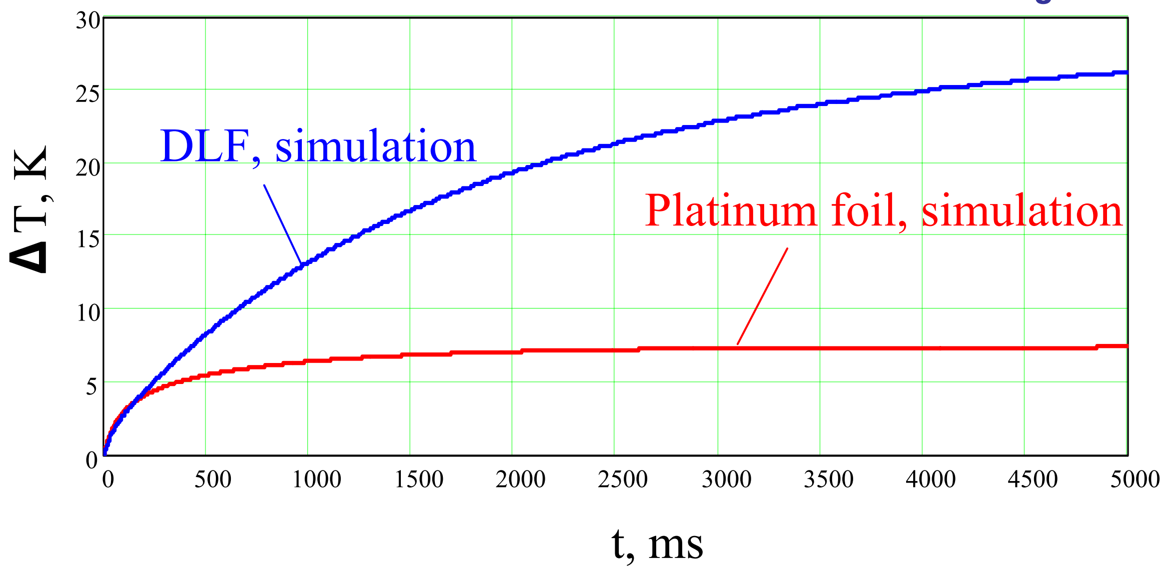
Front
(radiation absorbing) side
Gold: 2.1 / 0.85 ± 0.1 µm
Manufacturing process:
vacuum vapor deposition



Back
(IR camera viewed) side
Stainless steel 2.5 ± 0.1 µm
Manufacturing processes:
electrochemical etching,
ion beam etching







see I. Miroshnikov, Poster P6-11, this conference

Conclusions

• IRVB can operate in a fusion reactor environment

• A single imaging bolometer with a semi-tangential view can provide poloidal radiation profile through computed tomography

• Design similar to that for first wall thermography can be used for IRVB installation

• Single IRVB with tangential view can provide nearly the same poloidal profile information as equivalent number of resistive bolometer channels

• New double layer foil promises 3 – 10 times increase in sensitivity

Future Work

• 2-D tomography of JT-60U radiation with and without resistive bolometers

• Replace JT-60U 2.5 μm Au foil with 5 μm Ta (stronger and lower neutron x-section)

• Upgrade JT-60U IR camera (IRVB 10x faster or 25 x sensitivity or 10 x # of pixels)

• Upgrade JT-60U IR optics (ITER relevant, up to 4.5 x sensitivity)

• Improve 4 IRVBs on LHD with IR optics and camera upgrades

• 3-D tomography on LHD

• Design IRVBs for KSTAR, JT-60SA and ITER