EUROfusion

IR for protection of the JET ITER-Like Wall: overview & operational experiences

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JET

CCFE CULHAM CENTRE FOR FUSION ENERGY

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Contributors

The JET IR protection system has been in operation for over 10 years and many **JET Contributors*** have worked on the design, implementation and operation of the system during that time. I have tried to include suitable references where available.

Particular thanks to **Pedro Carvalho[1], Itziar Balboa[1], David Kinna[1], Valentina Huber[2] & Alexander Huber[3]** for material featured directly in this presentation and/or editorial contributions.

*See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)"

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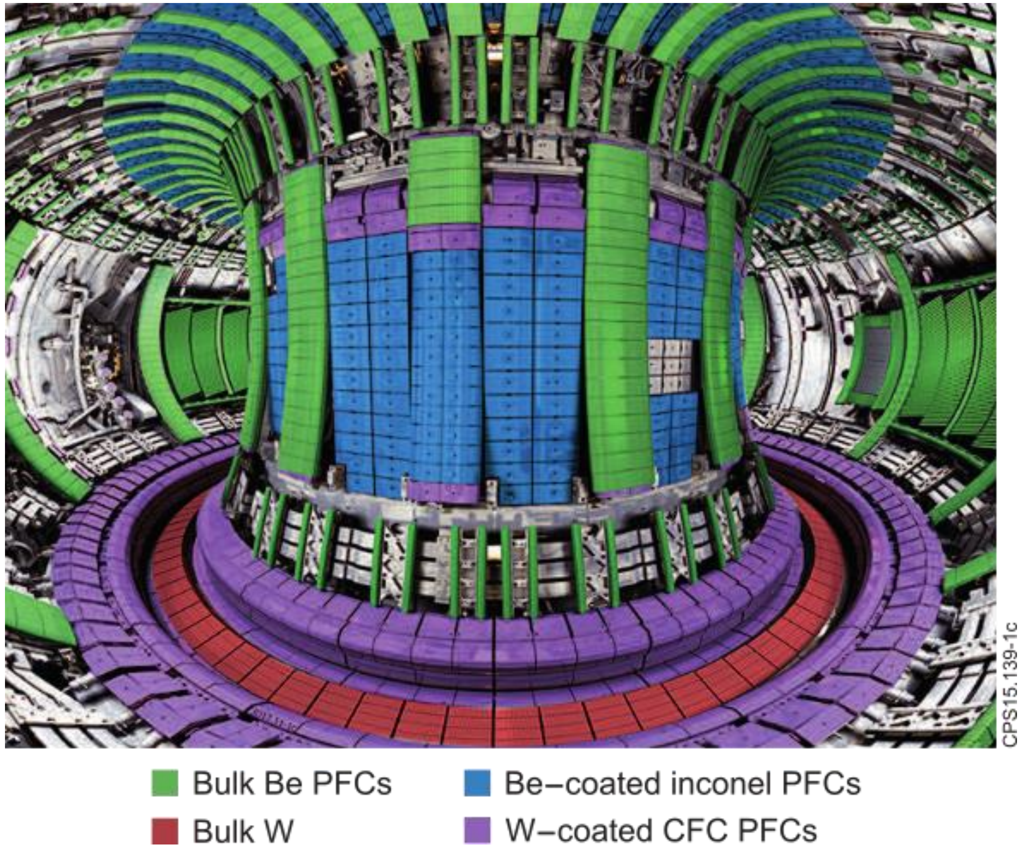
Contents

- ITER-Like Wall IR protection system objectives
- Overview of the IR protection system
- Operational experience

ITER-Like Wall Thermal Protection

The JET ITER-Like Wall (ILW) has inertially cooled metal surface PFCs with multiple materials and complex geometry



PFC operating temperature limits, enforced by real-time protection systems, must:

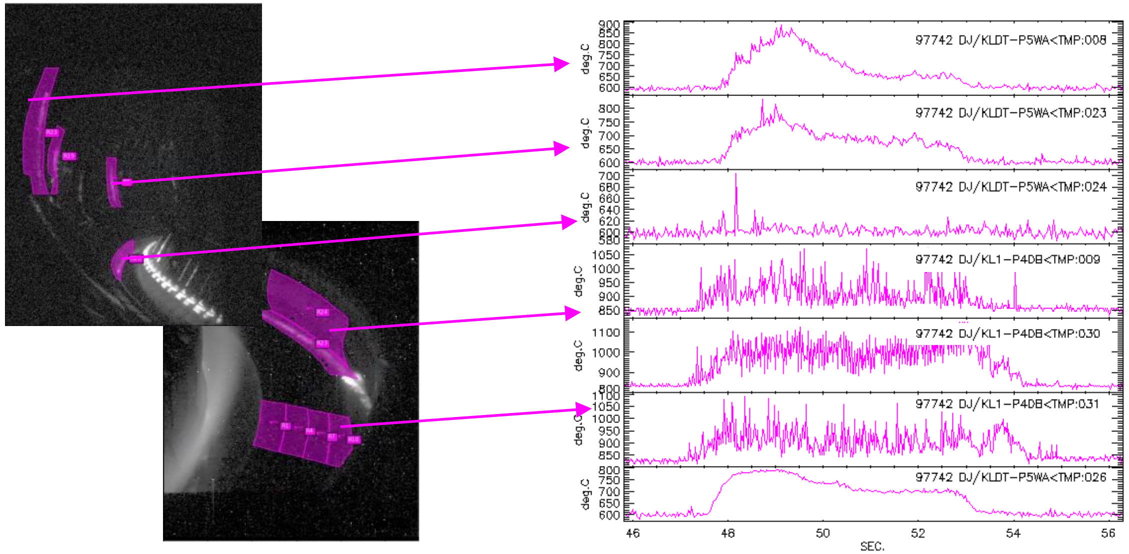
- Avoid melting of Beryllium components [1287 °C]
- Maximise lifetime of tungsten components by:
  - Limiting re-crystallisation in the bulk tungsten divertor target [~1200°C+]
  - Minimising degradation of tungsten coatings by brittle carbide formation [~1200°C+]

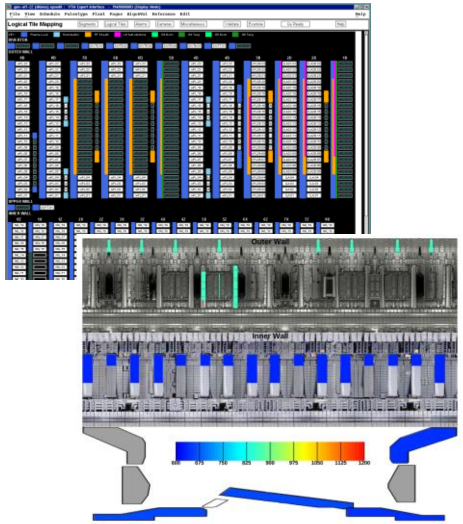
In practise, typical operating temperature limits used are set at:
Beryllium 925°C, Bulk tungsten 975°C, Tungsten coated CFC 1120 °C

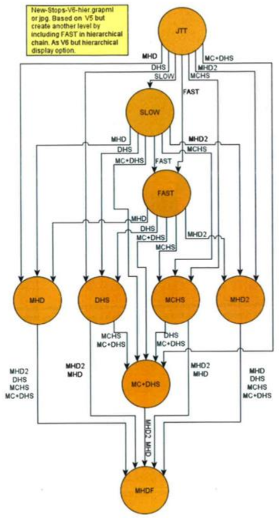
There are multiple systems on JET to provide this protection, but the IR camera system is the only one with access to real-time PFC temperature measurements.

IR protection architecture

The JET IR protection system architecture is modular and highly configurable.







Multiple IR camera diagnostics, each with many image Regions of Interest (ROIs)

Maximum surface temp measured within each ROI calculated from camera data in real-time

“Vessel Thermal Map” (VTM) system collects temperature signals & handles protection logic; raises alarms if configured temperature limits exceeded for configured assertion time (60 – 400ms depending on which PFCs).

Alarms from VTM sent to JET Real Time Protection Sequencer which coordinates actuator responses (e.g. heating systems; current & shape control)

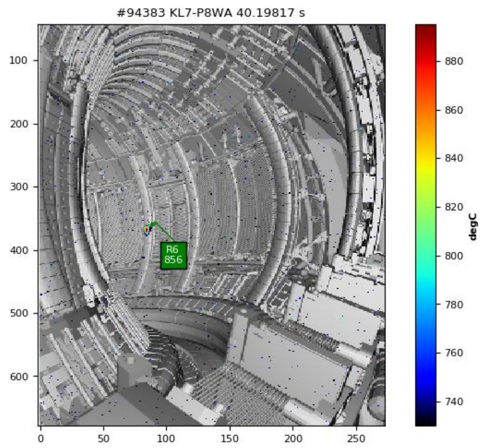
VTM: see Phys. Rev. ST Accel. Beams 15, 054701 (2012)

RTPS: A. V. Stephen et al., “*Centralised Coordinated Control to Protect the JET ITER-like Wall.*”, in Proc. 13th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS’11)

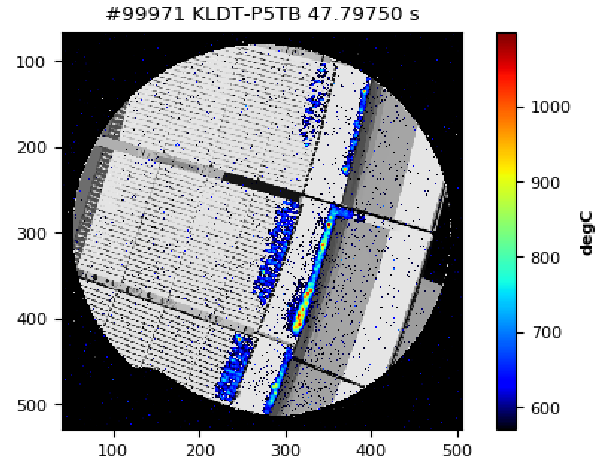
IR Protection Diagnostics

- All JET IR protection cameras operate in near-IR wavelengths (980 – 1200nm, depending on which system)
- 5 periscopes of varying designs, + 2 "direct" views through vertical ports. Total 4 tangential wide angle, 2 tangential divertor + 2 top-down divertor views.
- Detectors in machine hall: analogue output un-cooled CCDs (robust & reliable in JET environment), digitised @ 8-bit, 50Hz & transmitted over ethernet to processing PCs .

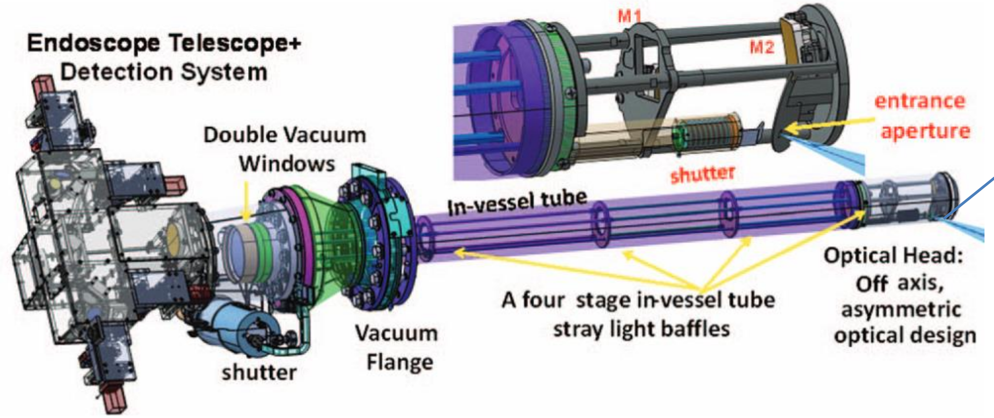
Wide Angle view example – KL7

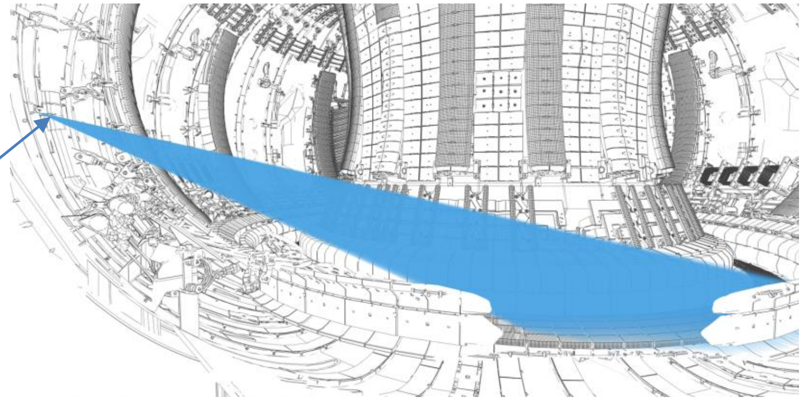


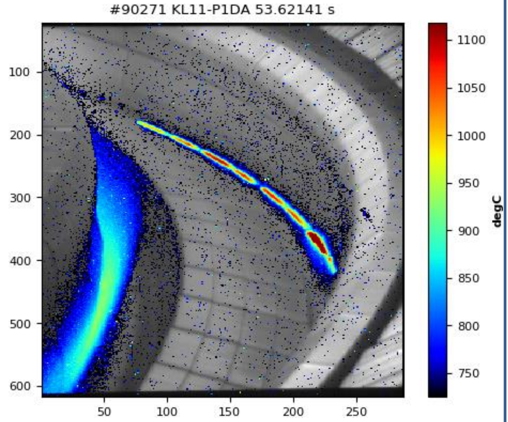
Top-down divertor view example: KL2D



Example of JET periscope – "KL11" developed at Forschungszentrum Jülich for divertor tangential view



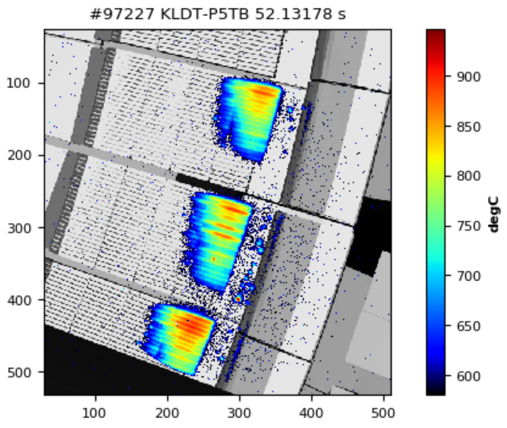


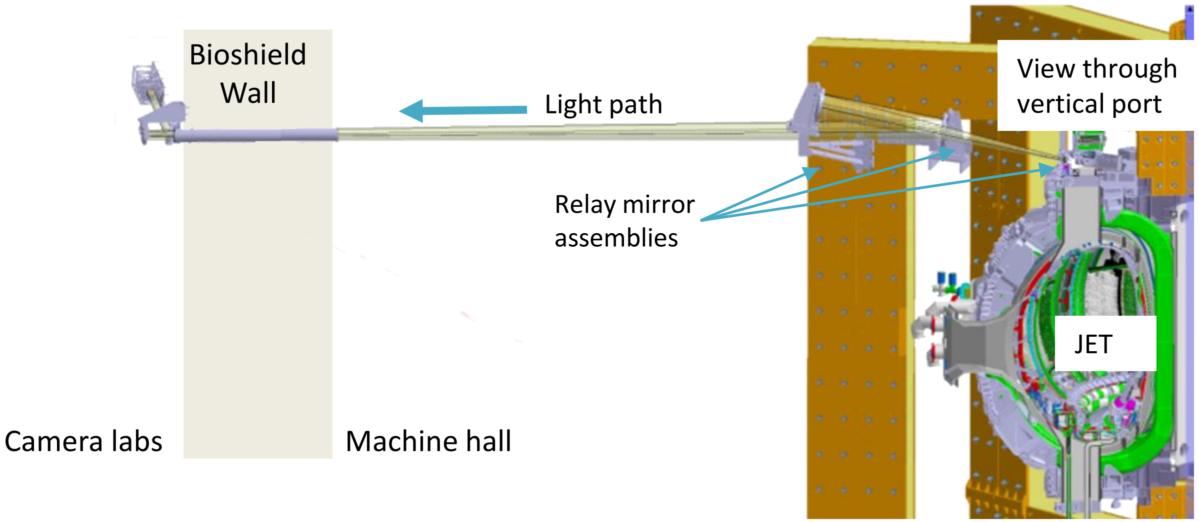


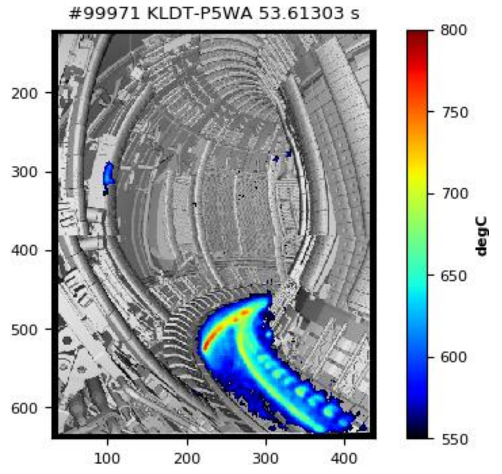
JET periscope designs, see: A. Huber et al Review of Scientific Instruments **83**, 10D511 (2012), E. Gauthier et al Fusion Engineering and Design 82, pp1335-1340 (2007), M. Clever et al Fusion Engineering and Design 88, pp 1342-1346 (2013)

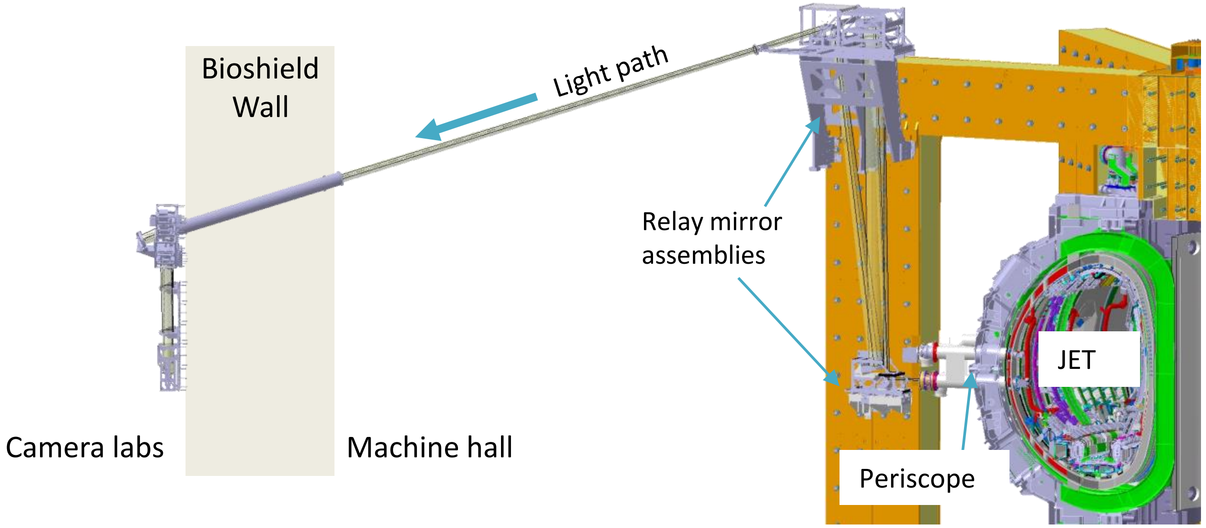
IR Diagnostics – D-T Operations

- Detectors + electronics in the machine hall would be quickly damaged beyond usability by ionising radiation during high power D-T experiments.
- Images from 1 existing wide angle periscope and 1 vertical port relayed outside the bioshield wall with mirror systems to maintain some protection camera capability during DTE2.
- Total linear distance from object plane to image plane ~40m!
- More sophisticated USB interface cooled InGaAs detectors used in “safe” environment of camera labs







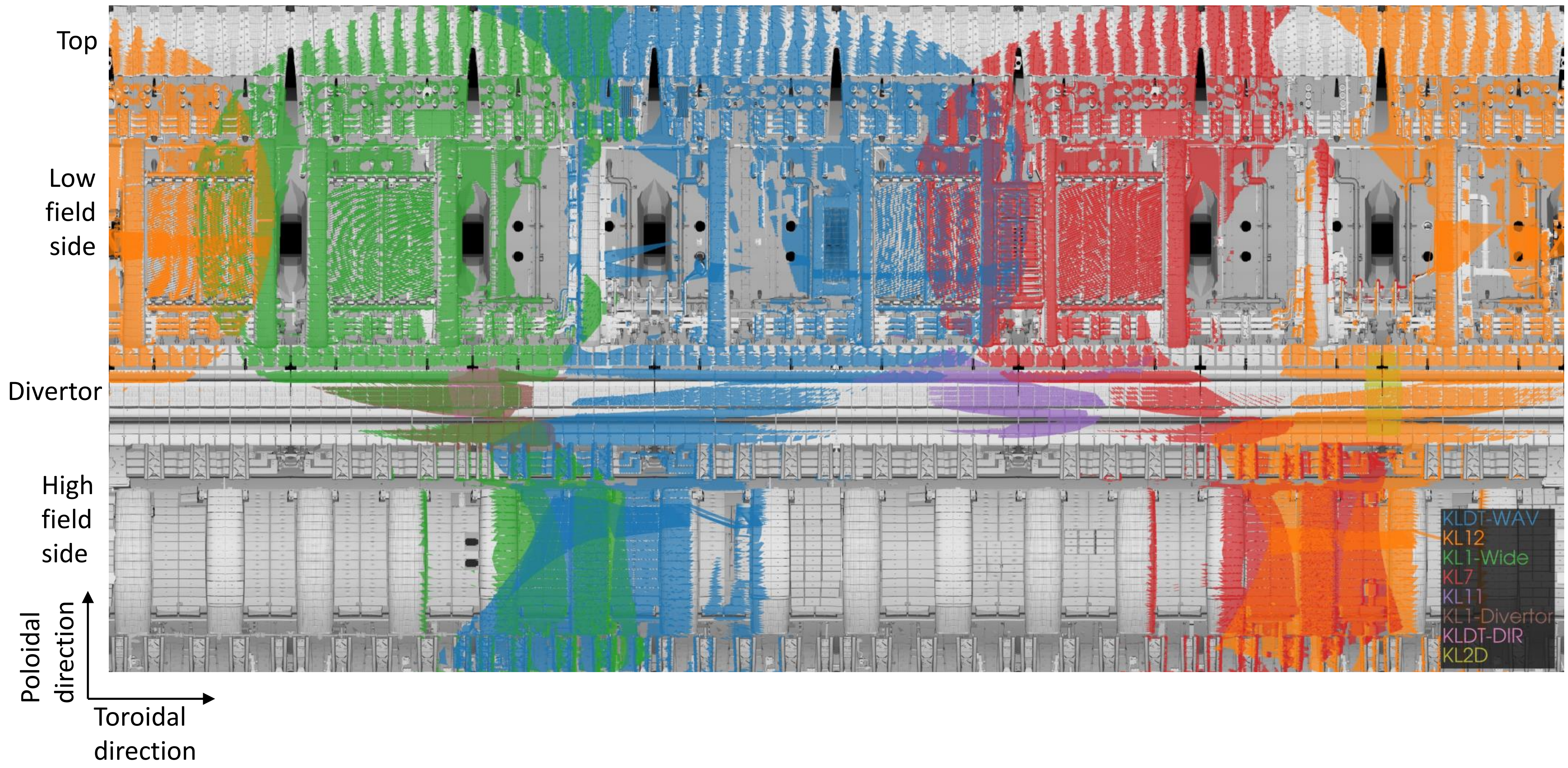


CAD figures: Effy Rose

Project report IDM ref: EFDA D 2NZBZ4
Journal publication in preparation by Itziar Balboa.

IR Diagnostics – Wall Coverage

Wall coverage including all used protection camera views (pre-DTE2):



~70% of Be at machine top visible

All antennas; almost all outer wall limiters

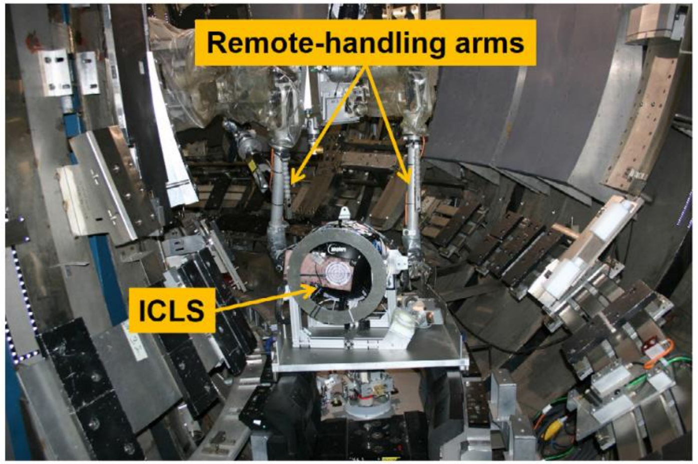
Total ~45% of divertor visible; 25% at high resolution

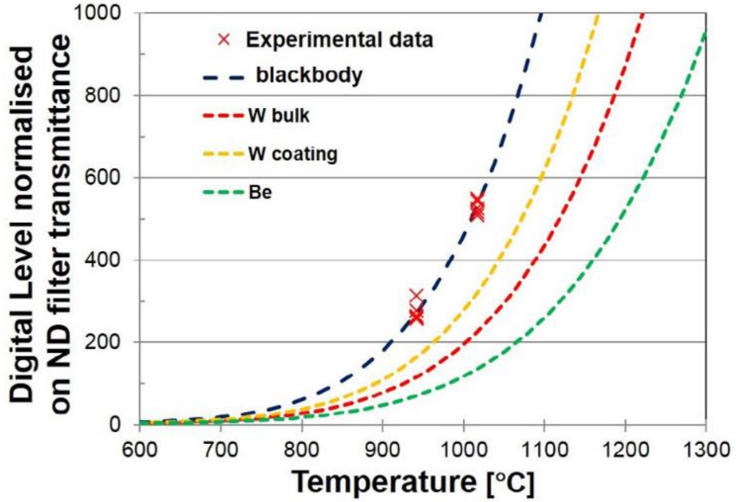
~6/16 inner wall limiters

IR Diagnostics - Calibration

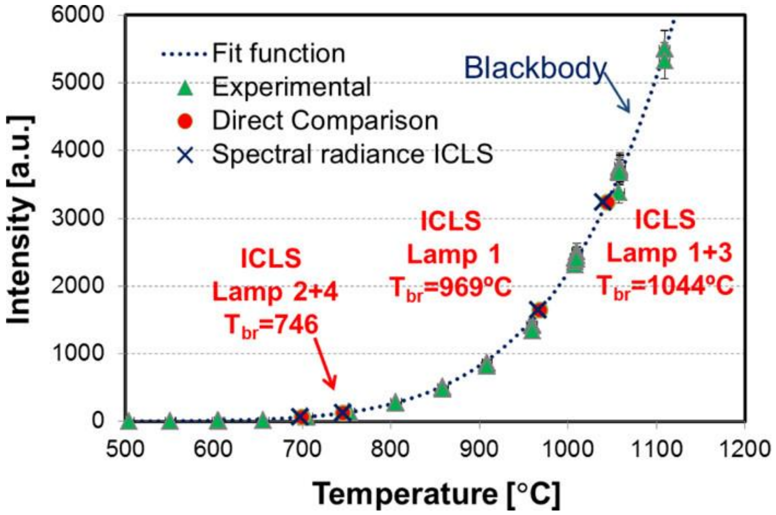
- Since 2015, the protection cameras have each been independently calibrated in-situ using the JET In-Vessel Calibration Light Source (ICLS) – integrating sphere illuminated by tungsten lamps positioned by remote handling

- For use in real-time, calibration curves stored as lookup tables (camera signal -> temperature) for the different PFC materials





V. Huber et al al Rev. Sci. Instrum. 87, 11D430 (2016)
N. J. Conway et al Rev. Sci. Instrum. 89, 10K107 (2018)
A. Huber *et al* 2018 *Nucl. Fusion* 58 106021



Real-time image processing

Camera Image

↓ Remove Dead pixels

↓ Pixel offset & gain correction

↓ Filtering (e.g. median)

↓ Maximum signal extraction

↓ Calibration

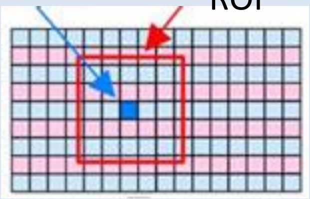
↓ **Temperatures**

- Real-time processing produces 1 temperature measurement per ROI per video frame
- FPGA solution developed at CEA with FPGA boards hosted in JET Windows PCs
- Equivalent algorithms now ported to run on Linux PCs with higher performance PC hardware (already in use for D-T compatible systems)

ROI treatment to further discount noise effects

Hottest pixel in camera ROI

N x N "Dynamic ROI"



To validate the pixel that will give the ROI temperature:

- Pixel with highest intensity in the ROI is considered with reference to its neighbours.
- If N neighbouring pixels also have >T% intensity compared to the centre one, the centre pixel is considered to be valid

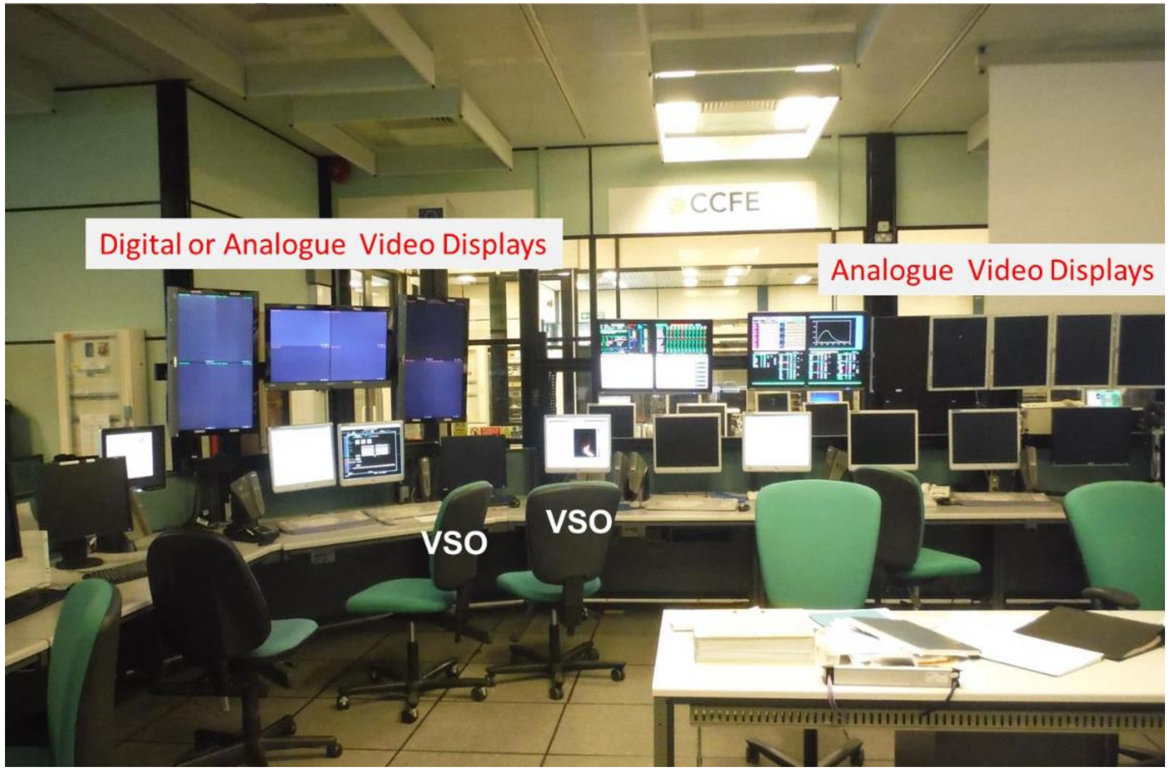
Calibration uses a look-up table for the material that the ROI is known to be observing

Adapted from slide by David Kinna

System operation: the VSO

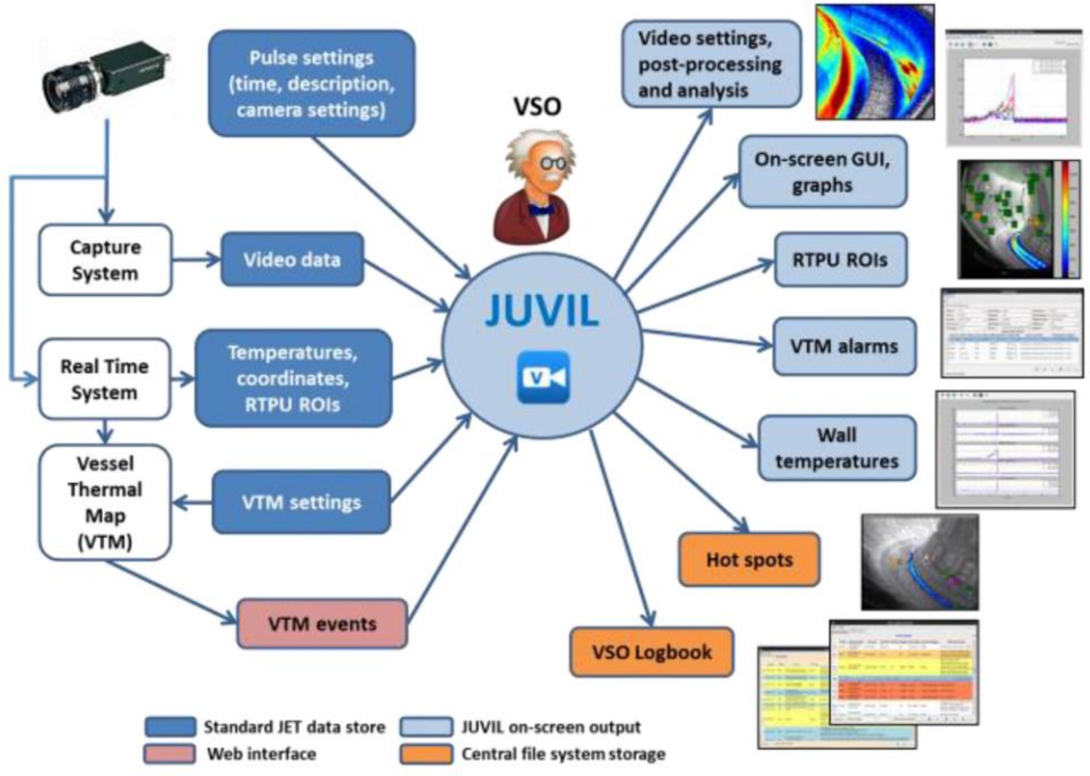
JET control room role of “Viewing Systems Operator” (VSO) specifically to provide support for the IR protection system during operations:

- Helping the session leader & engineer in charge interpret cause of alarms from the Vessel Thermal Map
- Monitoring & troubleshooting technical status of the system
- Monitoring for any unusual events seen by the cameras

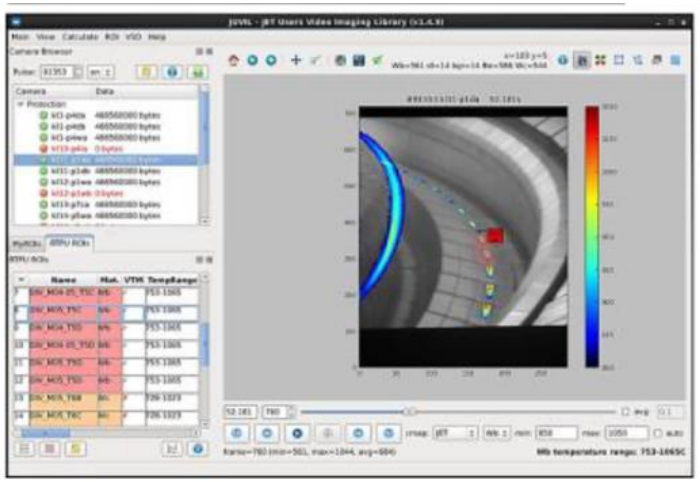


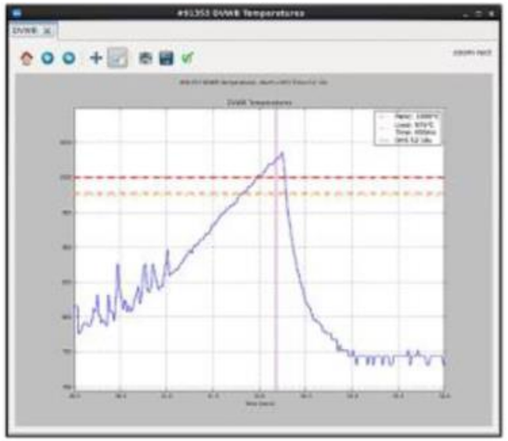
Offline analysis software (I)

JUVIL – extensive software framework in Python including GUI application + API for video access, offline data analysis, event logging, calibration - developed by Valentina Huber working closely with users and embedded in the operations team.



V. Huber et al Fusion Engineering & Design 123, pp979-985 (2017)

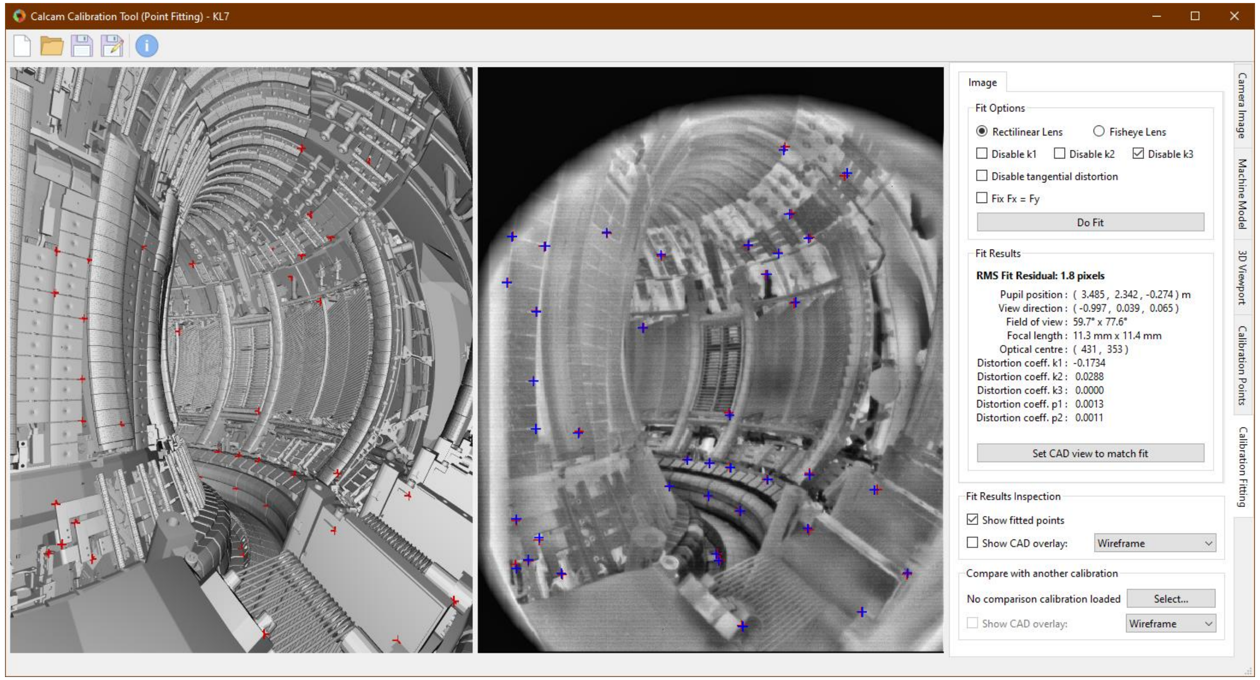




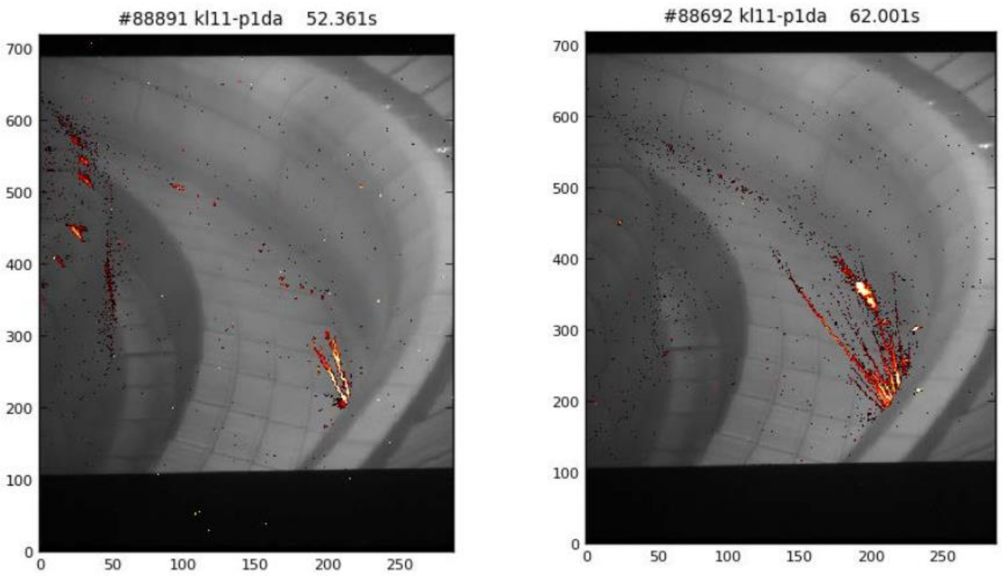
Offline analysis software (II)

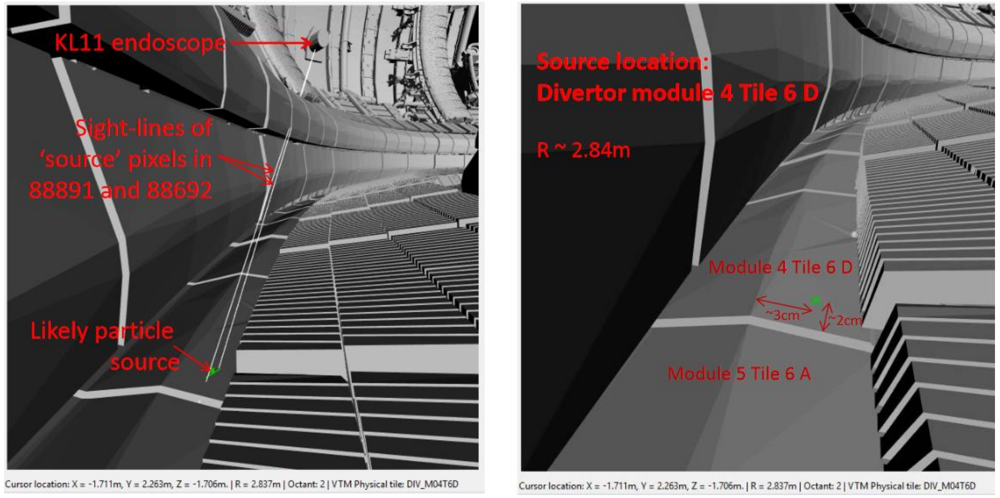
Calcam – open source machine independent Python package developed at JET for calibration of camera viewing geometry

- Identification of event locations for operational insight / targeting inspections & tile replacements
- Creation of CAD background images and geometry information used by JUVIL



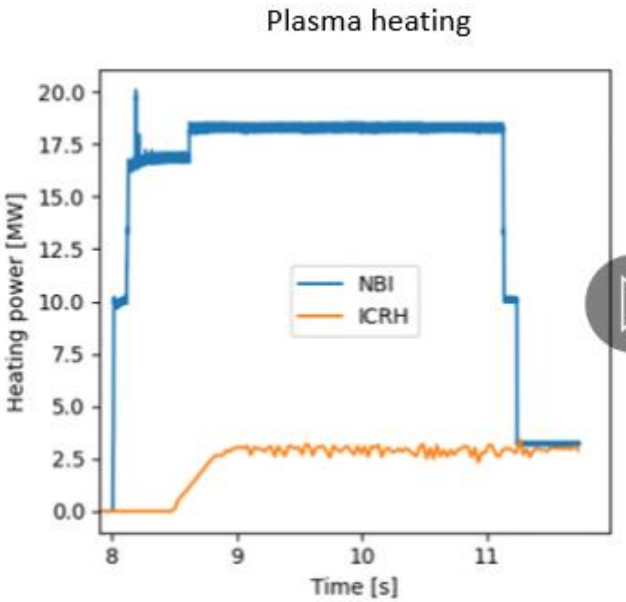
https://euratom-software.github.io/calcam/

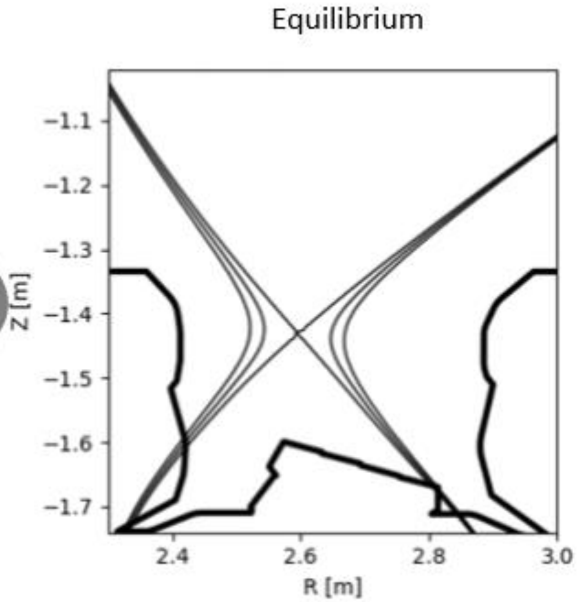


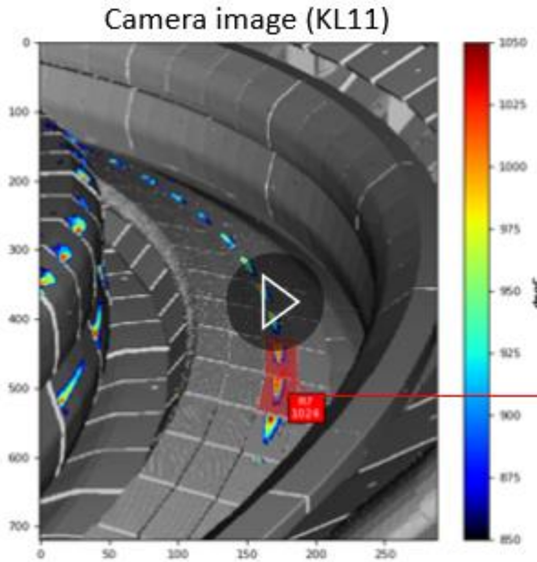


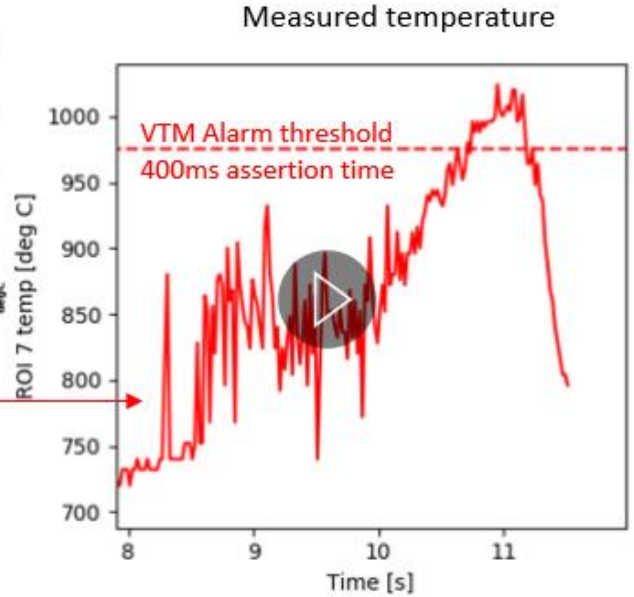
Operational Experience

Example of a successful protection event for overheating of bulk tungsten divertor tile (JPN 97418; H-Mode pulse for study of divertor tungsten source)





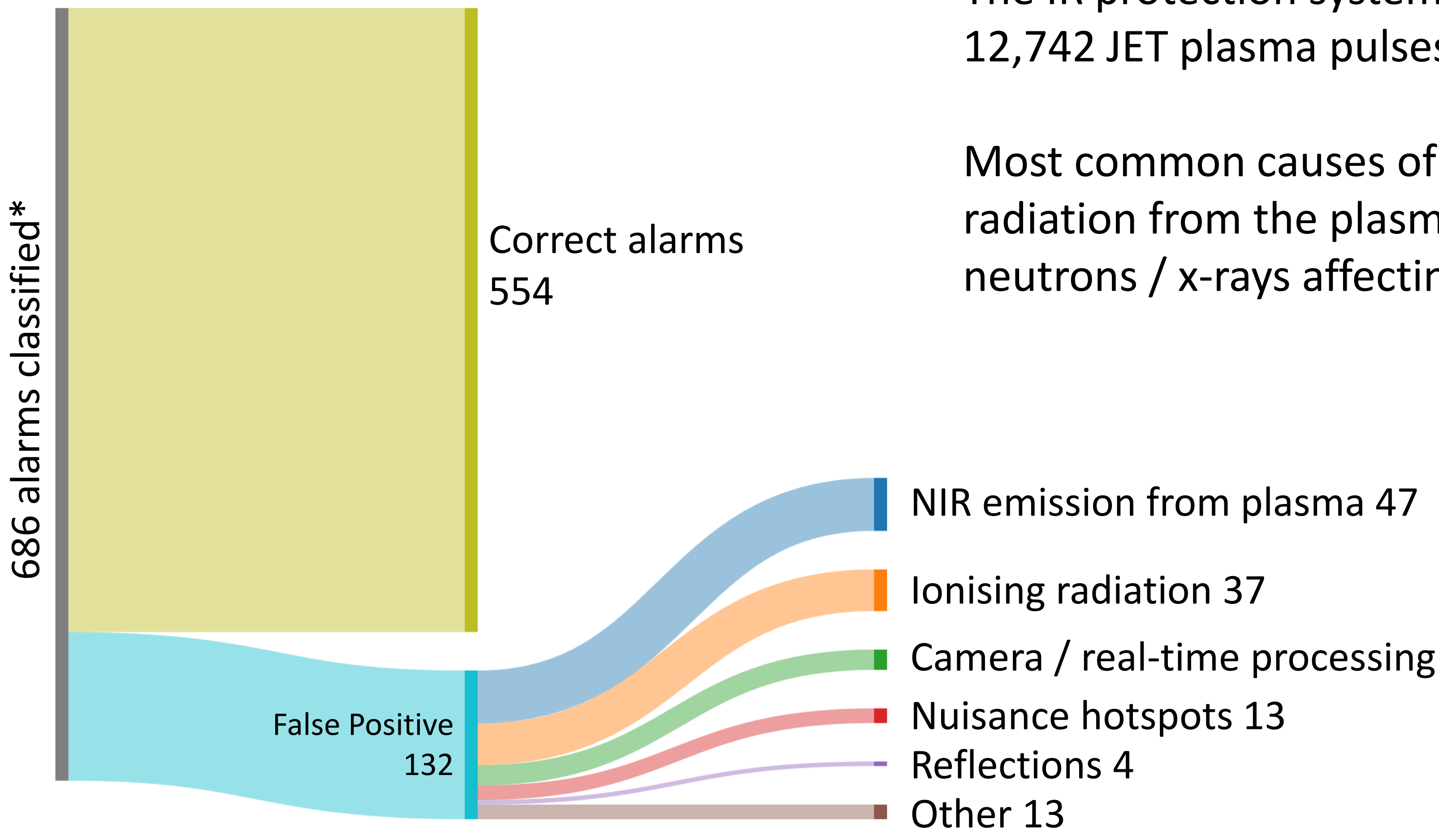




Heating & plasma equilibrium skip to pulse termination when temperature limit exceeded – heating power lowered & strike line moved away

Similar example is available in figure 5 of A Huber *et al* 2017 *Phys. Scr.* **2017** 014027

Temperature Alarm Statistics



*not included: any alarms raised *after* disruptions

The IR protection system raised alarms in ~5% of the 12,742 JET plasma pulses since mid-2013.

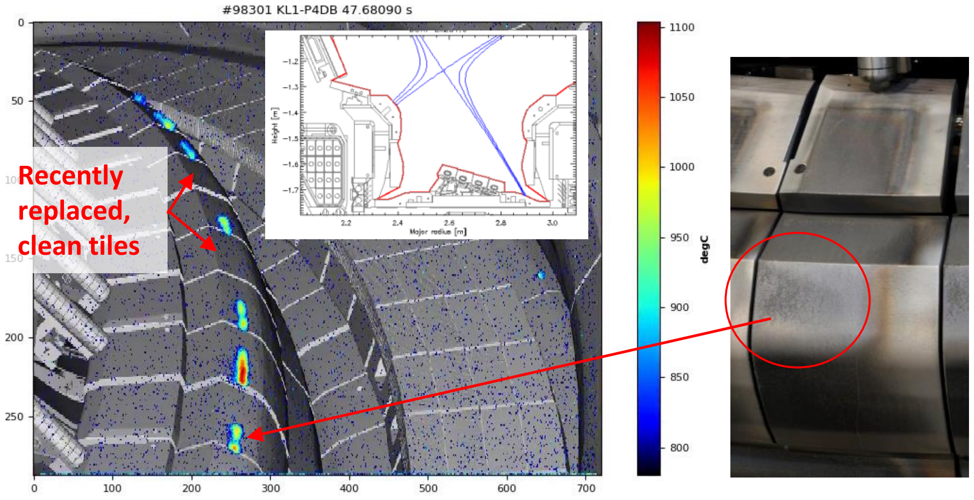
Most common causes of false alarms are pick-up of NIR radiation from the plasma and image noise caused by neutrons / x-rays affecting the cameras

Surface deposits, dust & droplets (I)

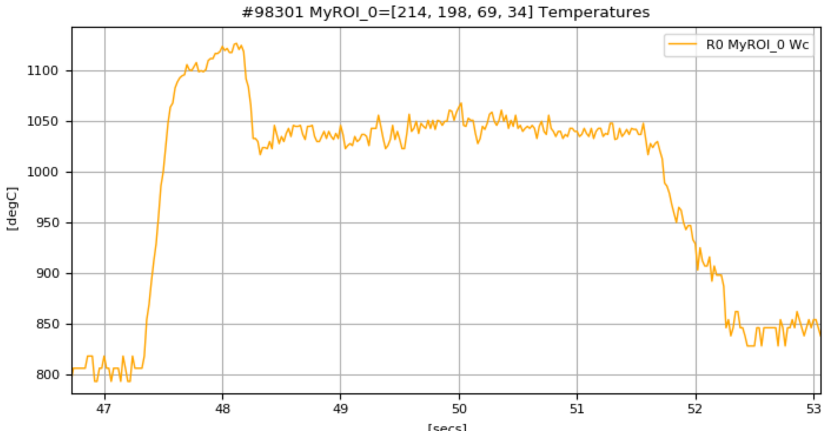
Reliable measurements and therefore protection cannot be obtained in some areas which have surface deposits in poor thermal contact with the bulk tile

- The surface deposits heat up to very high temperatures immediately on application of even low heat flux
- Some have to be manually excluded from the protection ROIs to avoid causing false alarms

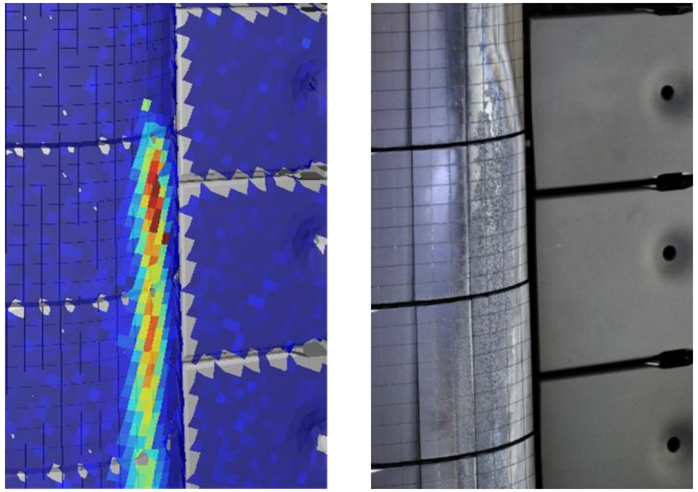
Thick deposits at upper inner divertor



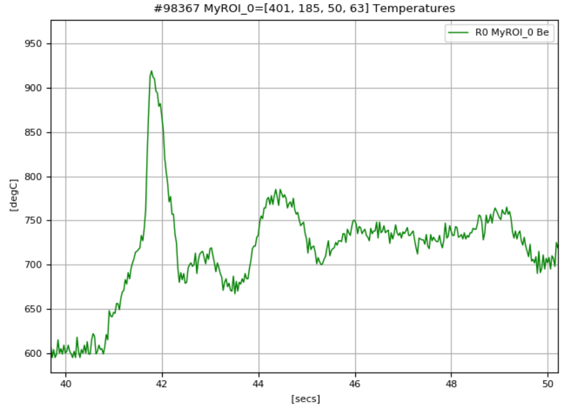
NIR protection camera image with inner strike point directly on region with thick deposits. Note difference on recently replaced clean tiles.



Flaky deposits on limiter wing



Protection camera image from JPN 98367 shown projected on to CAD model, compared with surface condition from high-resolution in-vessel photography.

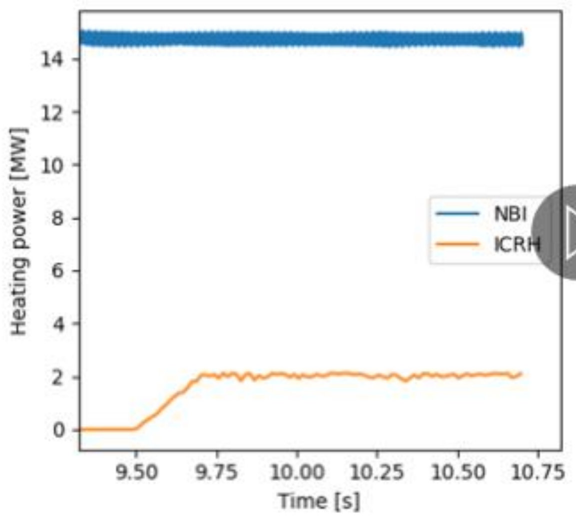


Surface deposits, dust & droplets (II)

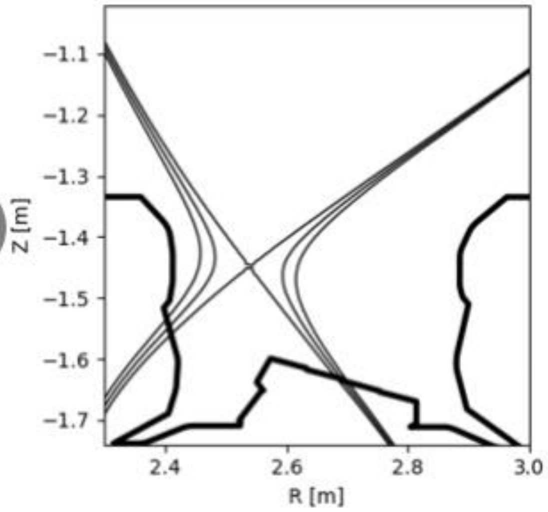
4Hz divertor strike point sweeping allows heating of droplets, dust & delaminations on divertor surfaces to be distinguished from heating of the underlying tiles:

Example H-mode pulse during campaign (89804)

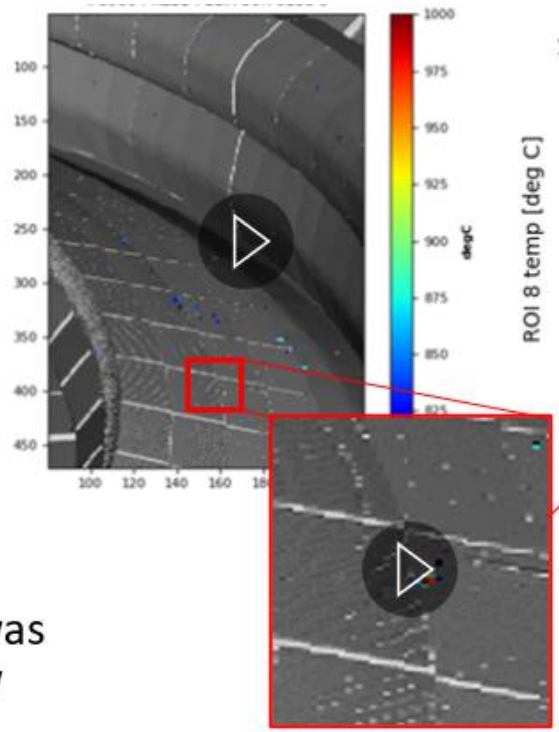
Plasma heating



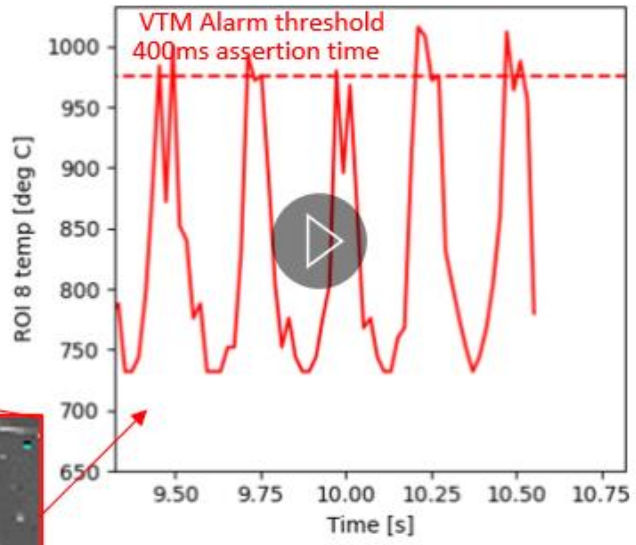
Equilibrium



Camera image



Real-time W tile temperature



System correctly did not raise alarm; the high temperature was a small piece of debris on the tile surface and not the bulk W we are trying to protect

Isolated hot-spot goes above temperature limit but not for long enough to trip the alarm

Summary

- Since 2011 JET has used near-IR cameras to protect against Be melting and maximise the lifetime of W and W coated PFCs
- The system uses up to 11 cameras across 8 views for good coverage of the wall
- During DTE2, long path mirror-linked optical systems were successfully used to provide IR imaging capabilities
- JET has a dedicated control room operator for the protection system and mature software tools for offline analysis of the camera images.
- The system has acted in ~5% of JET pulses over the last 9 years, with ~20% false positive rate mainly due to ionising radiation and NIR plasma emission
- Deposition on PFC surfaces in some areas causes significant difficulties for the IR measurements and these areas are excluded from protection coverage

Additional Slides

How the IR system fits in

- IR Cameras + Vessel Thermal Map
  - PFC surface temperature limits enforced based on real-time IR camera measurements
  - **Only system which uses real-time temperature measurements rather than models**

- WALLS
  - Plasma shape limits (gaps to the wall, strike point positions & field line angles) enforced based on real-time plasma equilibrium
  - PFC surface temperature limits enforced based on real-time surface temperature model (using equilibrium and power diagnostics as input)

- PEWS2
  - Protection from NBI shine-through heat loads
  - Limits enforced based on real-time model of PFC temperatures in the relevant areas

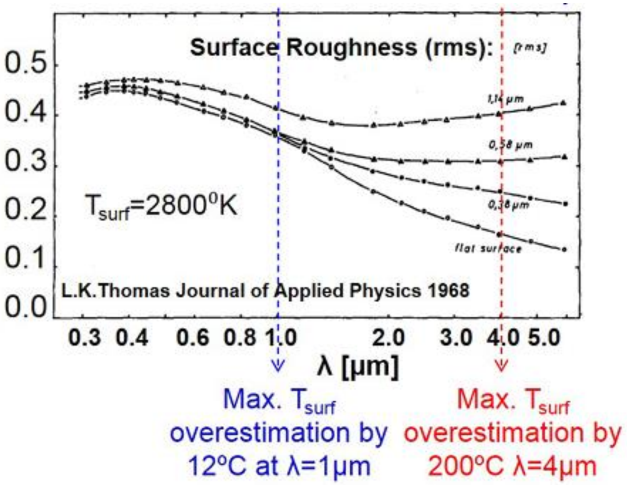
Wavelength Range

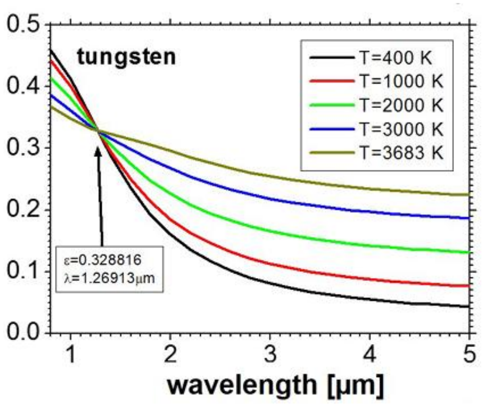
JET protection camera systems operate in Near IR
(980nm – 1200nm, depending on which diagnostic)

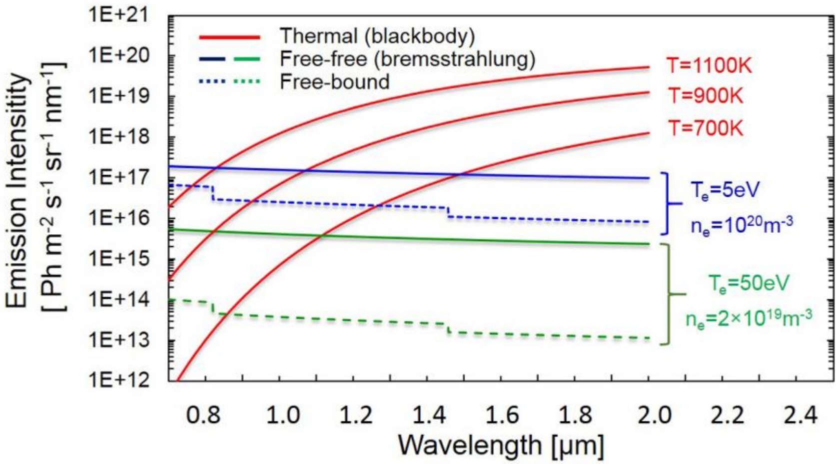
- Tungsten emissivity is higher & less sensitive to surface finish & temperature than longer wavelengths
  - Less uncertainty in emissivity for calibration
  - Smaller relative contribution from reflections

- At relevant temperatures for protection (1100K+), emission from tiles usually* dominates over emission from the plasma

- Allows use of common optical glasses, off-the-shelf camera lenses, low cost robust detectors



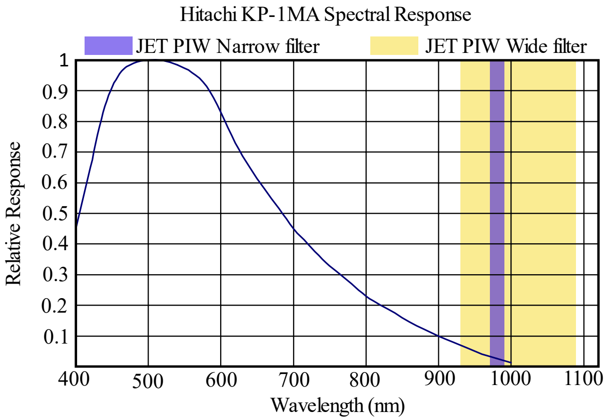




Figures: A. Huber *et al* 2018 *Nucl. Fusion* **58** 106021

Detectors

9 detectors in machine hall

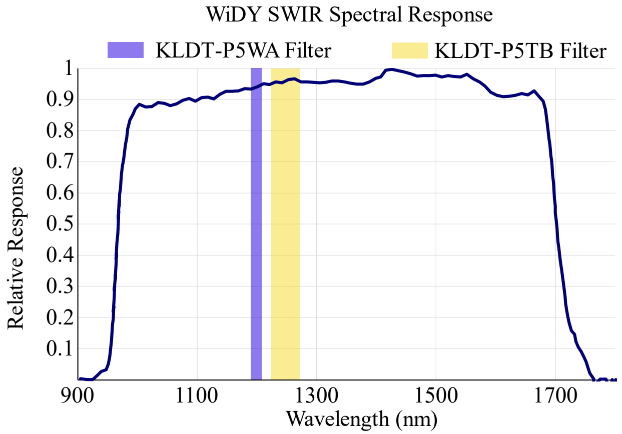


- 752 x 576 pixel inter-line transfer CCD (8.72 x 6.52mm)
- Factory hot mirror removed
- Analogue output, digitized & transmitted over fibre ethernet
  - 8 bits per pixel (256 digital levels)
  - 50 fields (752x288 px) per second

- Poor sensitivity at NIR wavelengths of interest
- Narrow temperature dynamic range (typ. ~400 – 600C)

- **BUT proven robust & reliable in the JET (D-D) magnetic field & radiation environment**

2 detectors outside bioshield



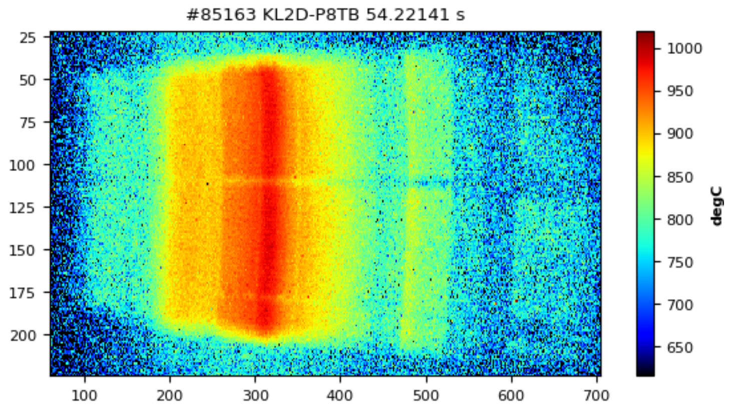
- Cooled 640x512 InGaAs array
- Logarithmic amplifier + 14 bit digitisation
- USB interface, connected to PC over optical fibre link
- 33 frames per second

- Optimised for NIR sensitivity
- Much wider dynamic range (~900 - 1000C)

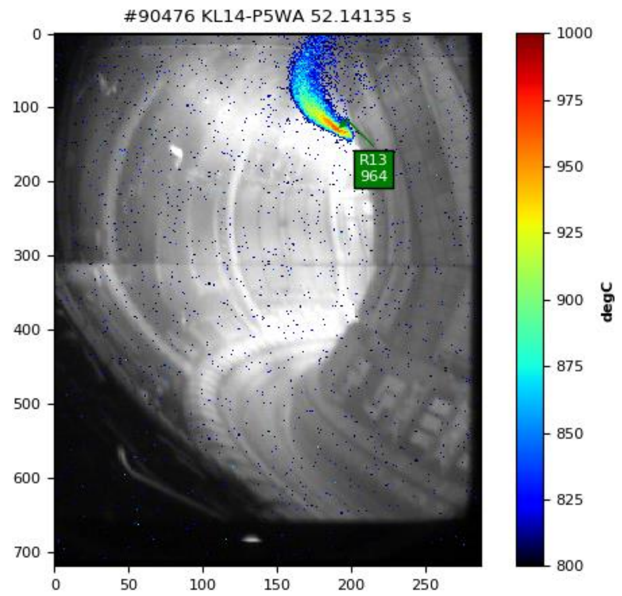
- Used with KLDT relay systems where not exposed to large magnetic fields or radiation dose

NIR Plasma Emission

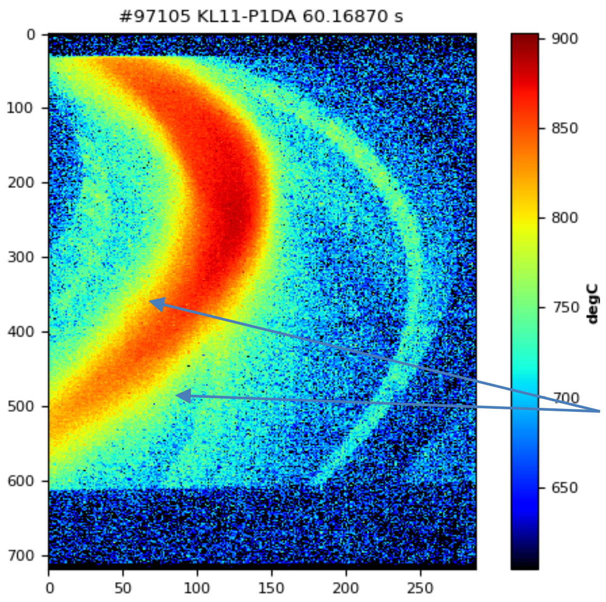
NIR emission from low temperature, high density edge plasma, e.g. in the divertor in detached conditions or in MARFEs is one of the most significant causes of false alarms, and makes protection of some components (e.g. the inner divertor tiles) impractical due to risk of false alarms



Bremsstrahlung from divertor during detachment experiment interpreted as high tile temperature



MARFE at top of plasma interpreted as heating of upper Be plates

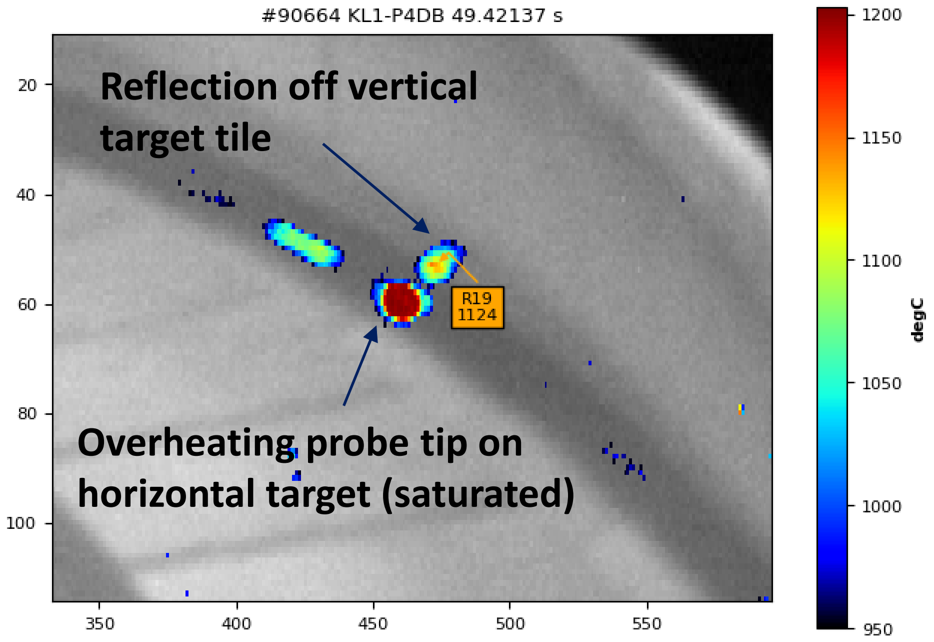


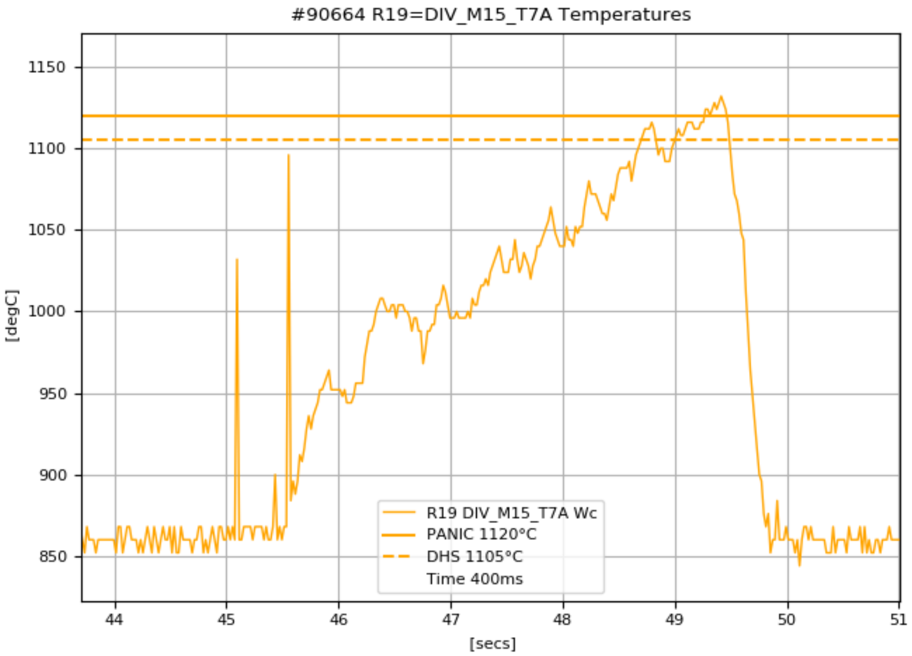
ROIs for inner divertor would need to be here!

Tangential view of X-Point MARFE during detachment experiment

Reflections

- Reflections from the metal surfaces have not been a significant problem for the JET NIR protection
- Only instances of false protection alarms due to reflections were reflections of overheating divertor Langmuir probe tips:





Apparent temperature of reflection on vertical target tile high enough to cause temperature alarm

Video Data Distribution

Composite video signal

Frame Grabber

Digital video signal

Dedicated Video Network

Live Display PC

Capture PC

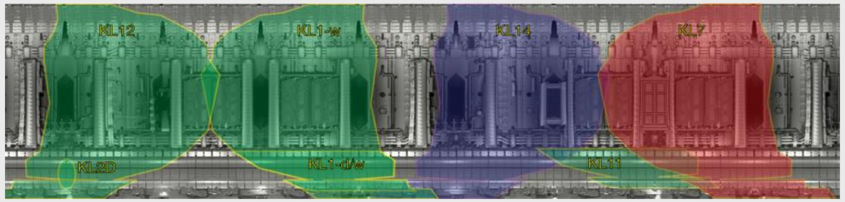
Real time host PC

CEA FPGA

Bulk video data Post-pulse

Vessel Temperatures In real time

Mass data store



Vessel Thermal Map

- **Pleora iPORT PT1000 ANL** Frame Grabber
- Using GigE video distribution enables us to use **standard network interface cards** and multiple client PCs

Video distribution – detail with backup link