cea irfm

34th SOFT 2026

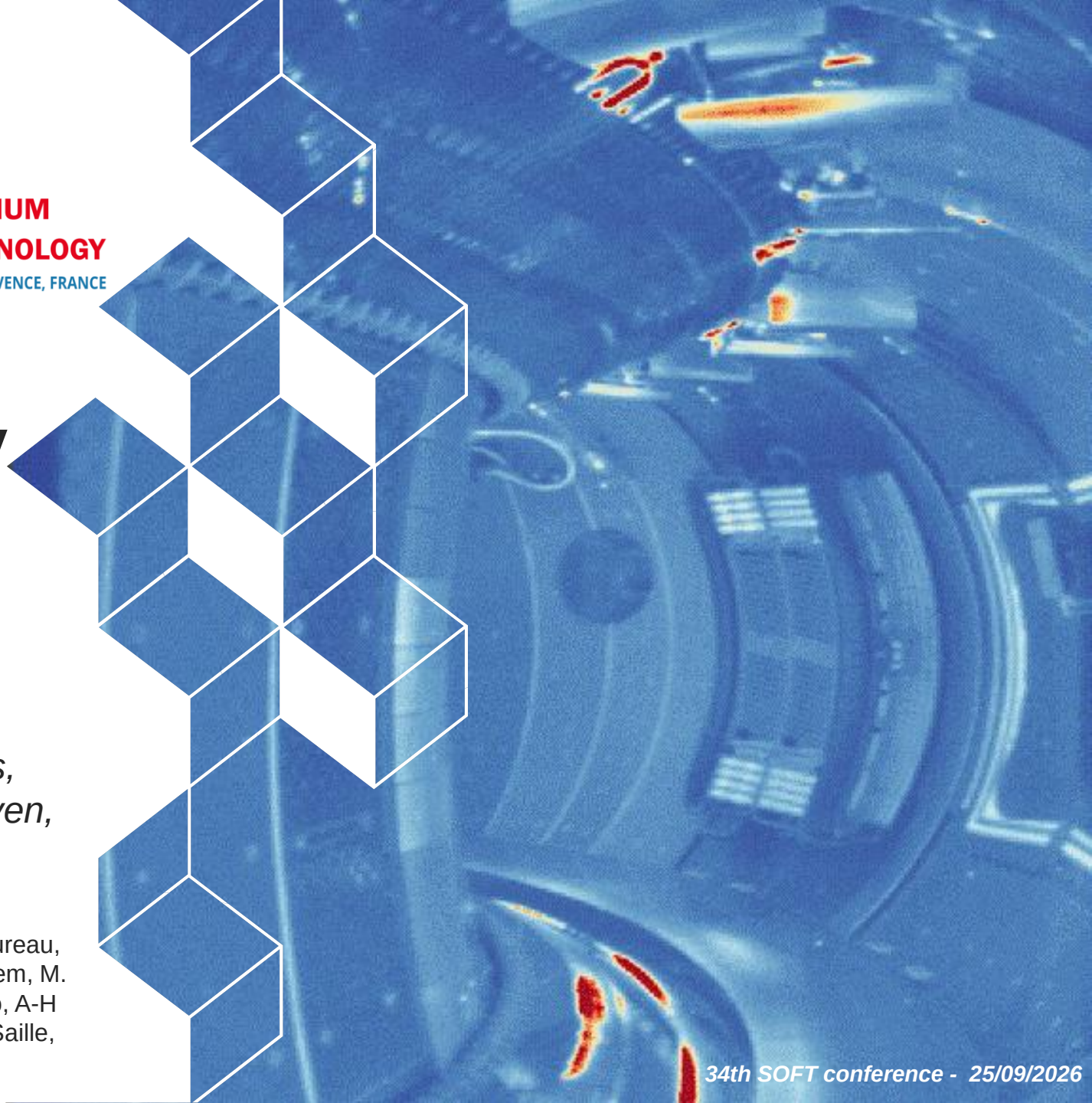
34th SYMPOSIUM ON FUSION TECHNOLOGY

SEPT. 21-25, 2026 AIX-EN-PROVENCE, FRANCE

Infrared Thermography System for First Wall Protection in WEST

S. Vives, M.-H. Aumeunier, X. Courtois, L. Dubus, E. Grelier, Y. Corre, E. Gauthier, J. Gerardin, A. Juven, P. Malard, R. Mitteau, V. Moncada, F. Ortega

C. Balorin, H. Bec, C. Belafdil, K. Blanckaert, J. Bonnail, R. Brunet, A. Bureau, C. Cisse, L. Devos, M. Ferlet, J. Gaspar, V. Gorse, A. Grosjean, D. Guilhem, M. Houry, M. Joanny, M. Jouve, M. Le Bohec, B. Leurquin, T. Loarer, T. Ngo, A-H Mboumba-Pouaty, Y. Mouden, C. Pocheau, F. Retailleau, H. Roche, A. Saille, C. Staron, Q. Tichit, JM Travere, ...

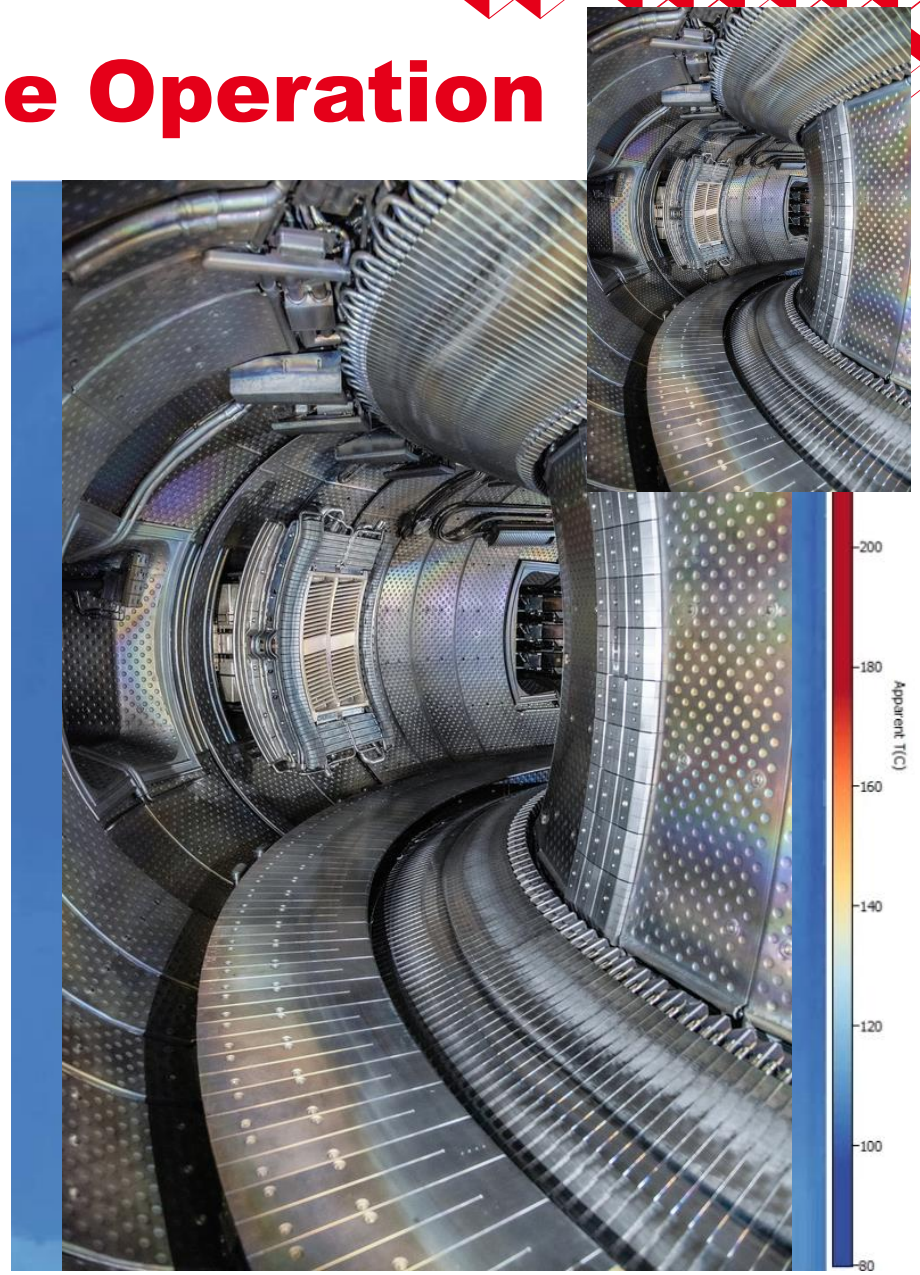


First Wall Protection for long pulse Operation

- First-wall protection becomes a system-level challenge
  - With increasing plasma duration and 10–20 MW/m² of steady-state heating
  - Safe operation requires continuous monitoring of the wall thermal state

- **Infrared thermography** is a key tool for monitoring plasma-facing components (PFC)
  - Remote, wide-field observation of multiple PFCs
  - High spatial and temporal resolution
  - Wide temperature range, from ~100 °C to several thousand °C
- However, IR thermography measures an apparent temperature
  - Quantitative temperature depends on surface emissivity and can be affected by reflections and other image artifacts

- **Reliable machine protection**
  - **requires dedicated instrumentation, calibration, models, algorithms and simulations**



WEST IR thermography

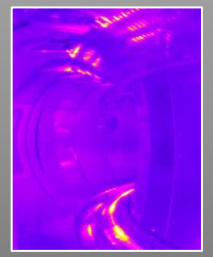
Level 1: IR data Acquisition

Level 2: Off-line Machine Protection (MP)

Level 3: Real-Time Machine Protection

Level 4: IR quantitative thermography

Thermal Scene



Digital Twin

Endoscope & Acquisition system

Image in Apparent Temperatures

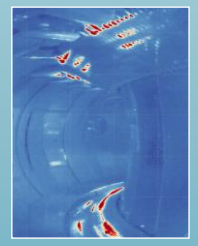
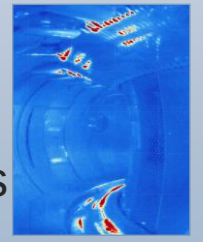


Image in Absolute Temperatures



Archiving/Storage

Visualization

Image in Digital Level (Luminance)



Post processing

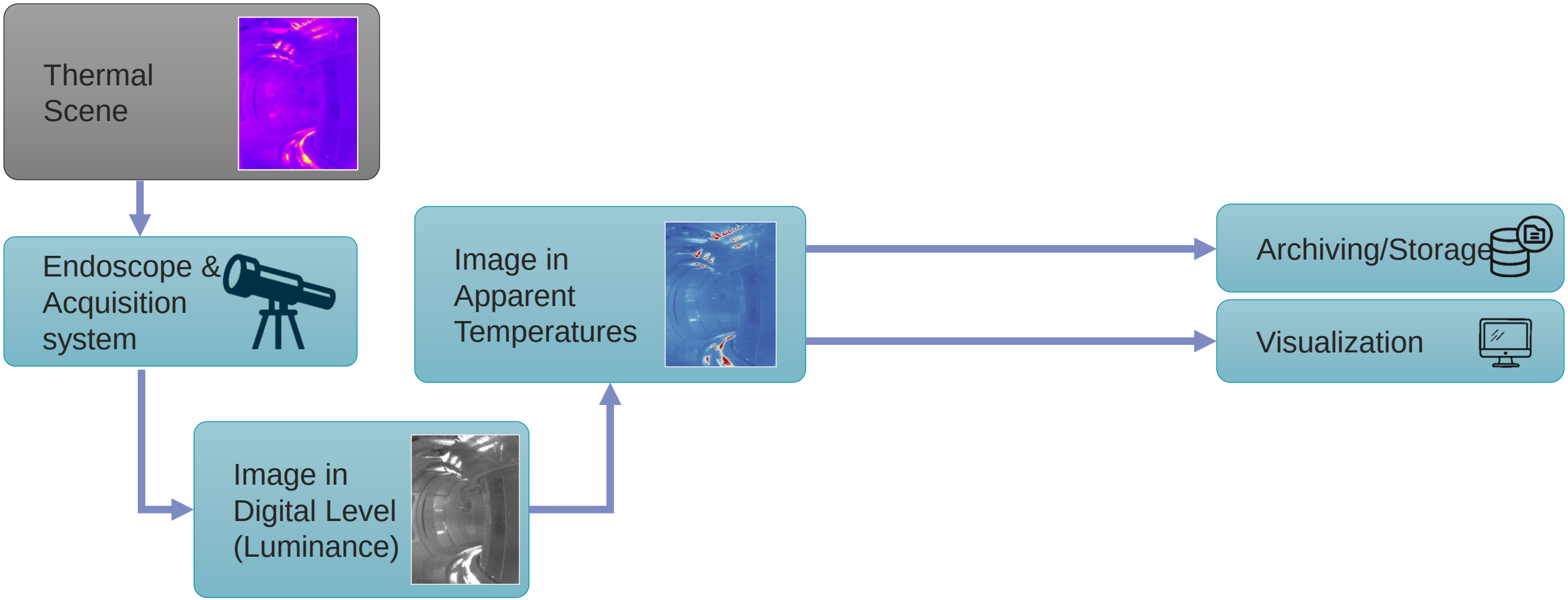
PCS

Real-Time Basic or advanced Post processing

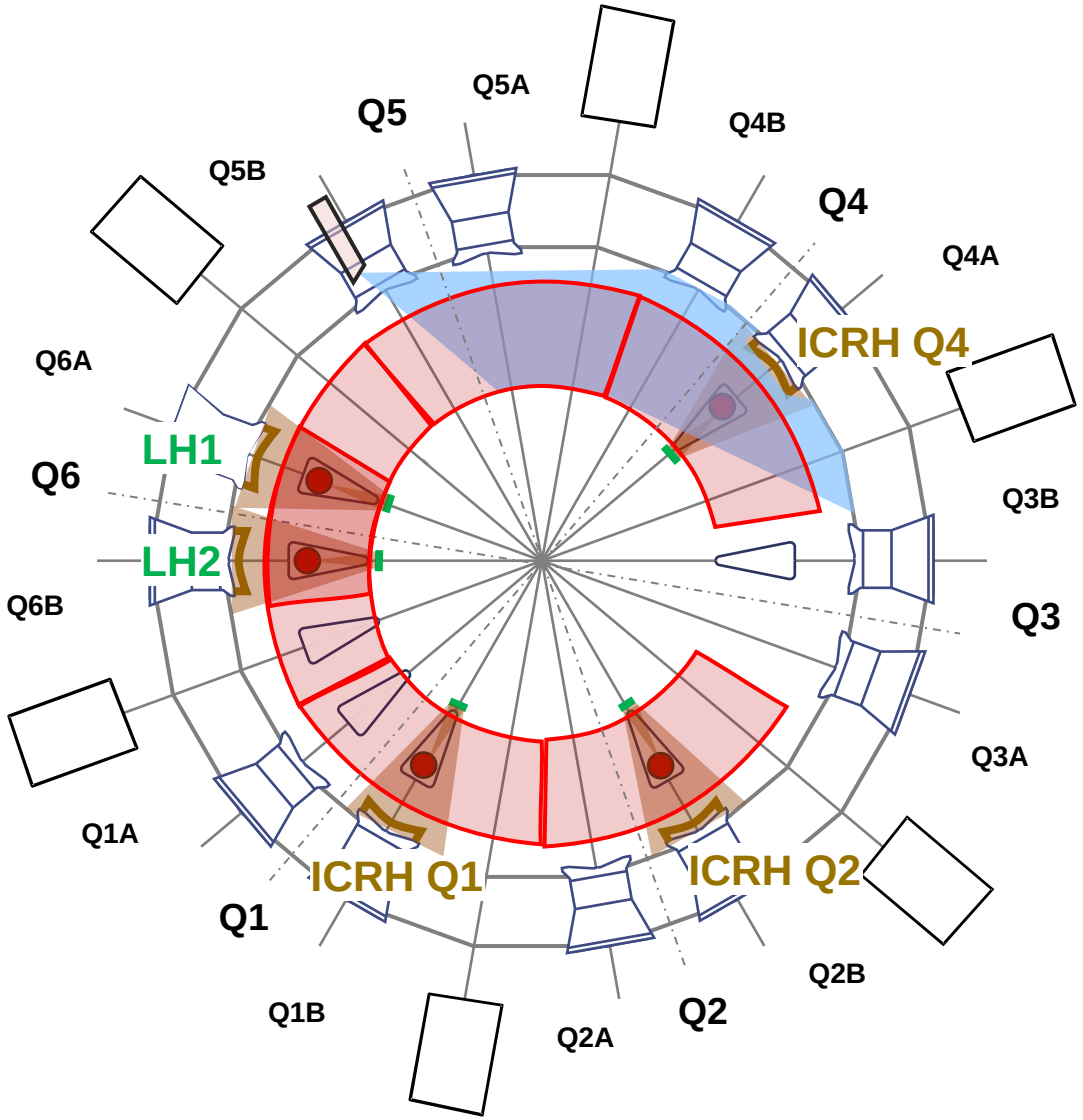
Human analysis In Control Room

WEST IR thermography

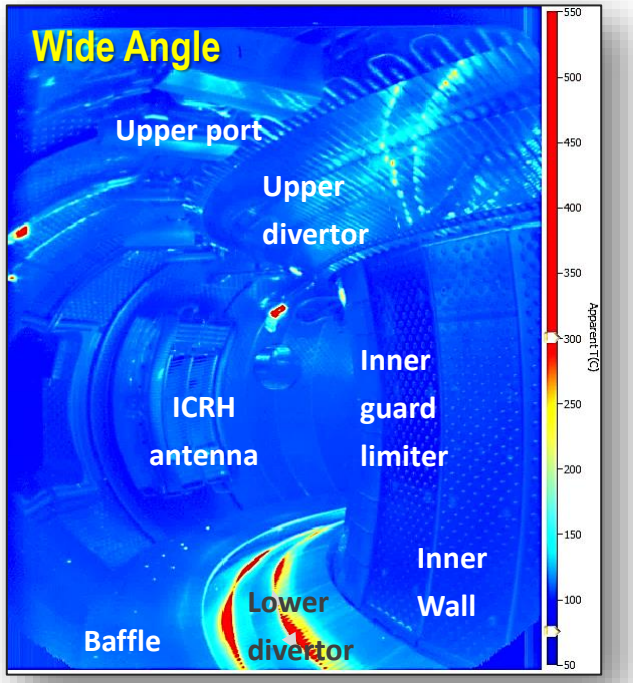
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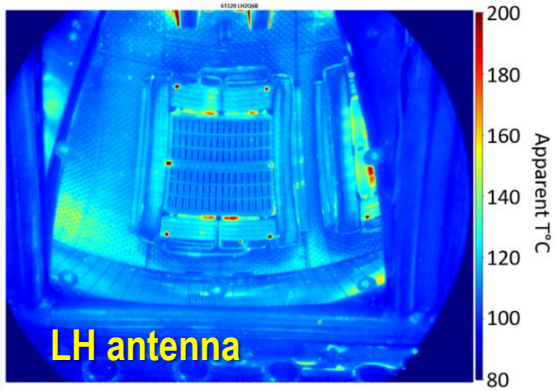


A distributed IR system covering the First Wall

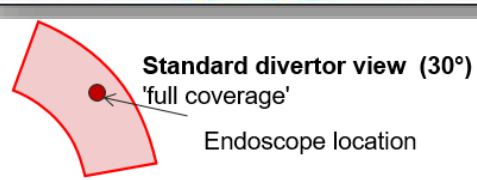


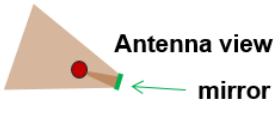
- One wide angle view
- Antennas fully covered (3 ICRH + 2 LHCD)
- 82% of the lower divertor
- **52% (45m2) of the inner wall**













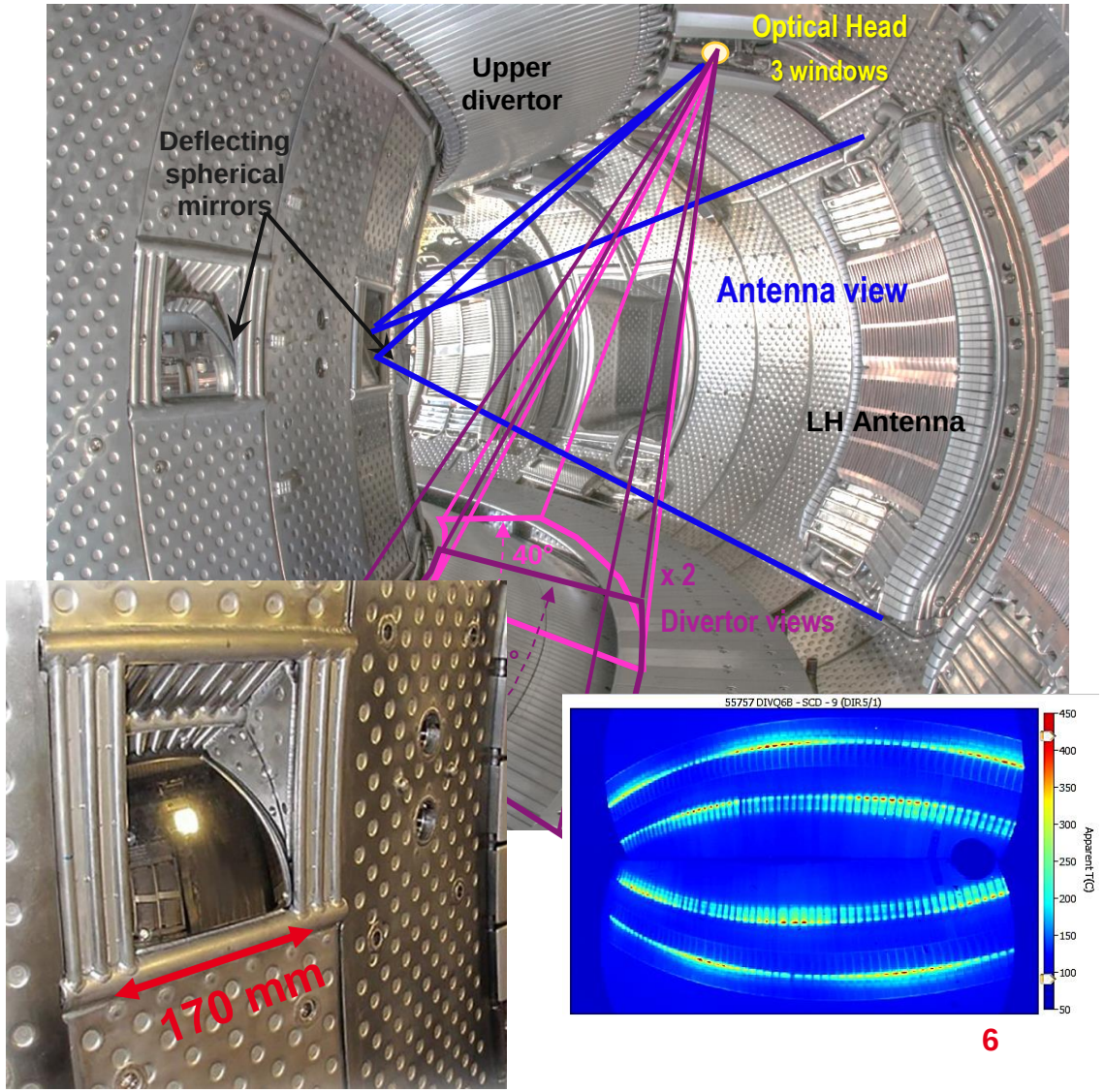
A distributed IR system covering the First Wall

- **6 water-cooled endoscopes**
  - **equipped with 11 purpose-built IR cameras**

- Two types of endoscope:
  - **Wide-Angle view**
    - FoV: 39.5 x 50°, compatible SWIR and MWIR
  - **Upper views**
    - Combine 2 divertor views and 1 antenna view
    - Two divertor views are optically recombined on the same detector
    - The antenna view uses a mirror located in the equatorial plane

- Mo Mirrors are directly exposed to plasma radiation and erosion
  - Between campaigns, in-situ cleaning can recover close to the initial reflectivity
  - Significant erosion after 3-4 campaigns eventually requiring mirror replacement

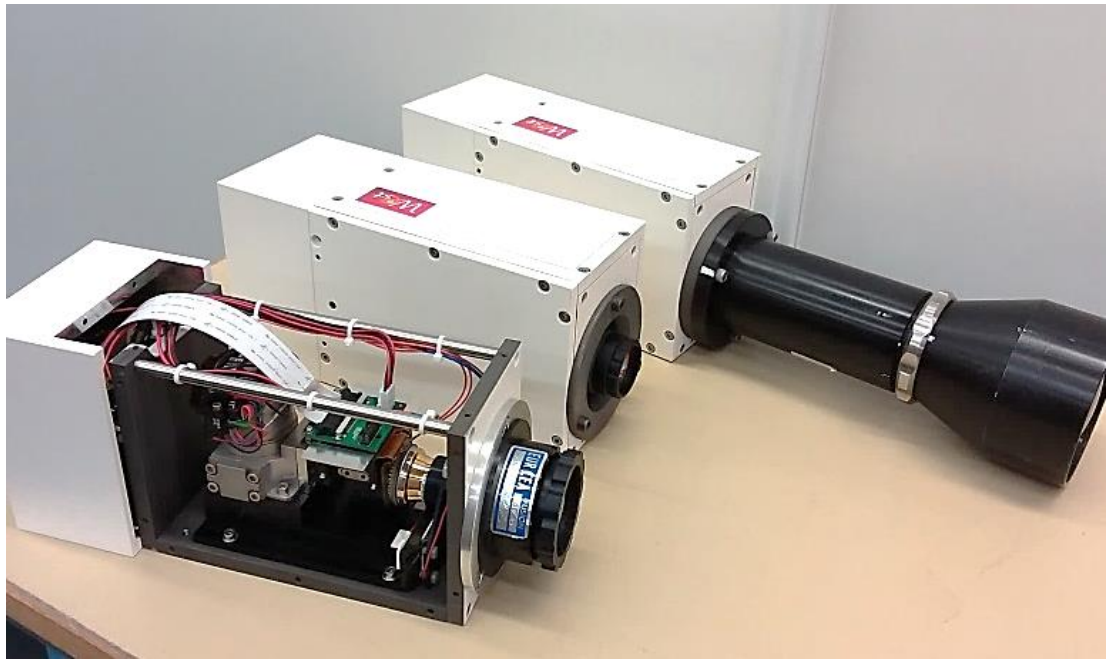
X. Courtois et.al. (2018)



Purpose-Built IR Cameras for Long-Term Operation

- All machine protection endoscopes use in-house IR cameras, based on:
  - **A commercial InSb detector**
    - 640 × 512 pixels, up to 200 Hz full-frame
  - **A dedicated FPGA control**
    - Real-time processing
    - 50–3500 °C measurement range at 50 Hz with 4 integration times

- Nearly 10 years of operational experience with 10 cameras demonstrates strong long-term reliability
  - ~6000 operating hours per camera
  - Stable sensitivity over several years
  - No routine recalibration or scheduled maintenance required
  - Only one abnormal failure, associated with a Stirling cryocooler



X Courtois et al. (2019)

From raw IR data to apparent temperature

Raw IR data → **Calibration** → Apparent temperatures

- A dedicated calibration strategy
  - Initial End-to-end laboratory calibration
  - Between campaigns
    - Regular Ex-Vessel calibration (in lab.)
      - No major sensitivity variation observed
    - In-situ verification of optical transmission using a blackbody source





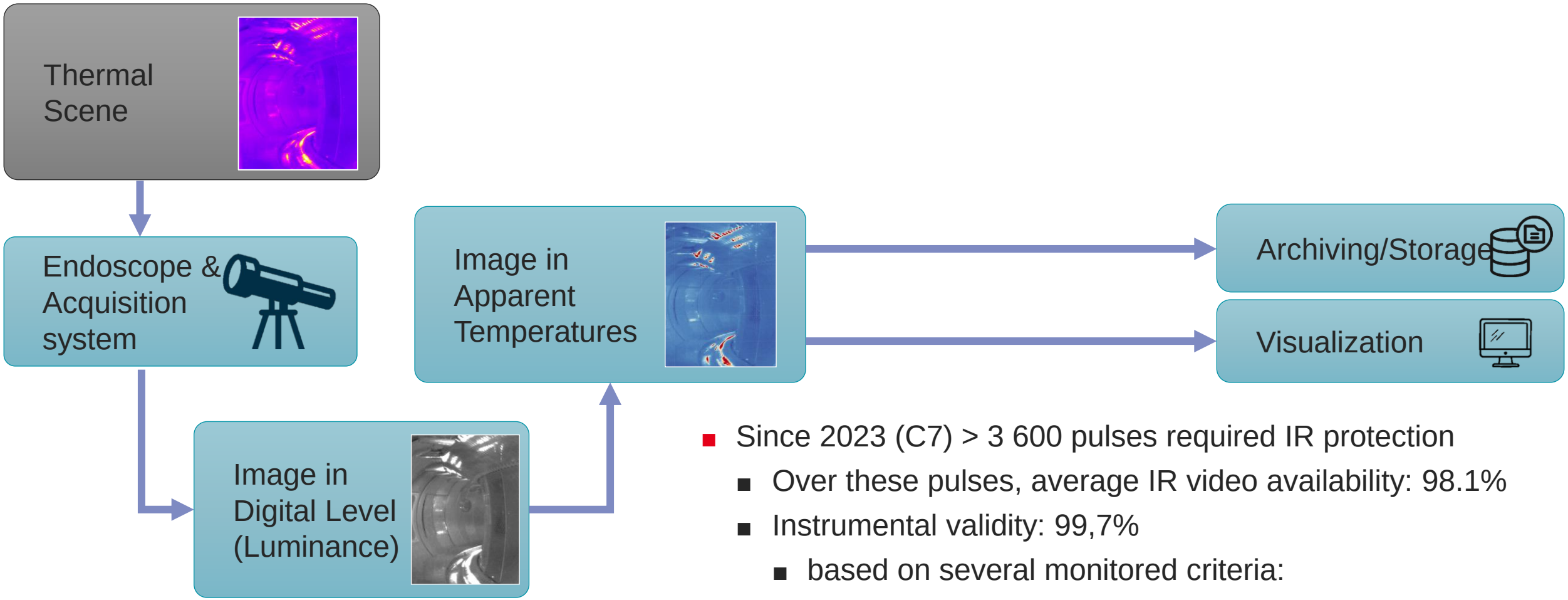
X. Courtois et.al. (2023)

- Efficient data compression is essential
  - The last campaign C13 (May-July 2026) produced ~20 TB of uncompressed IR video (~166 h)
- Because pixel values correspond to physical temperature information
  - Lossy compression must control the induced temperature error.
- Stenos a new compression algorithm provides dedicated IR compression
  - Higher compression ratios (e.g. for C13 ~1.2 TB compressed)
  - Enabling faster temperature-trace extraction and large-scale cross-campaign data mining

V. Moncada - This conf. S1-030

WEST IR thermography

Level 1: IR data Acquisition



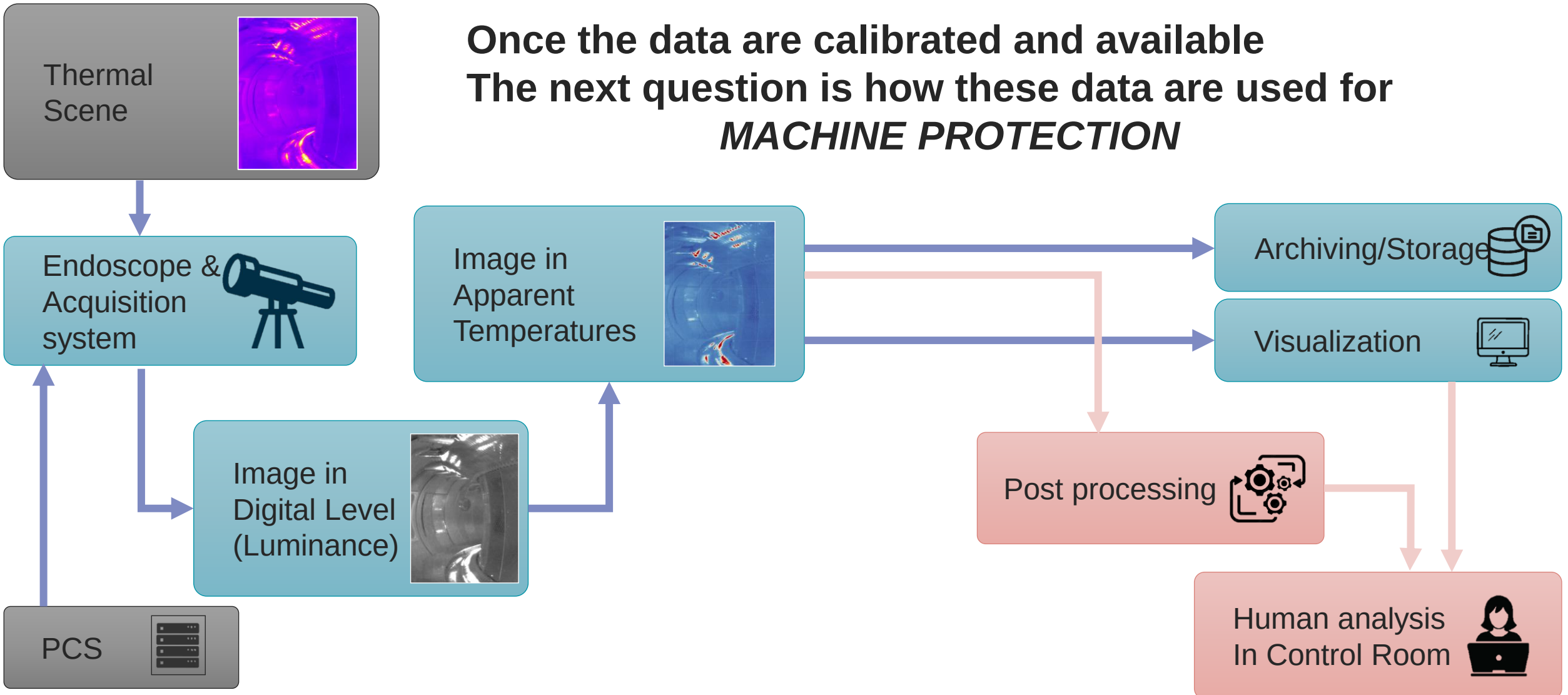
- Since 2023 (C7) > 3 600 pulses required IR protection
  - Over these pulses, average IR video availability: 98.1%
  - Instrumental validity: 99,7%
    - based on several monitored criteria:
      - sensor, filter, camera body temperatures

WEST IR thermography

Level 1: IR data Acquisition

Level 2: Off-line Machine Protection (MP)

Once the data are calibrated and available
The next question is how these data are used for
MACHINE PROTECTION

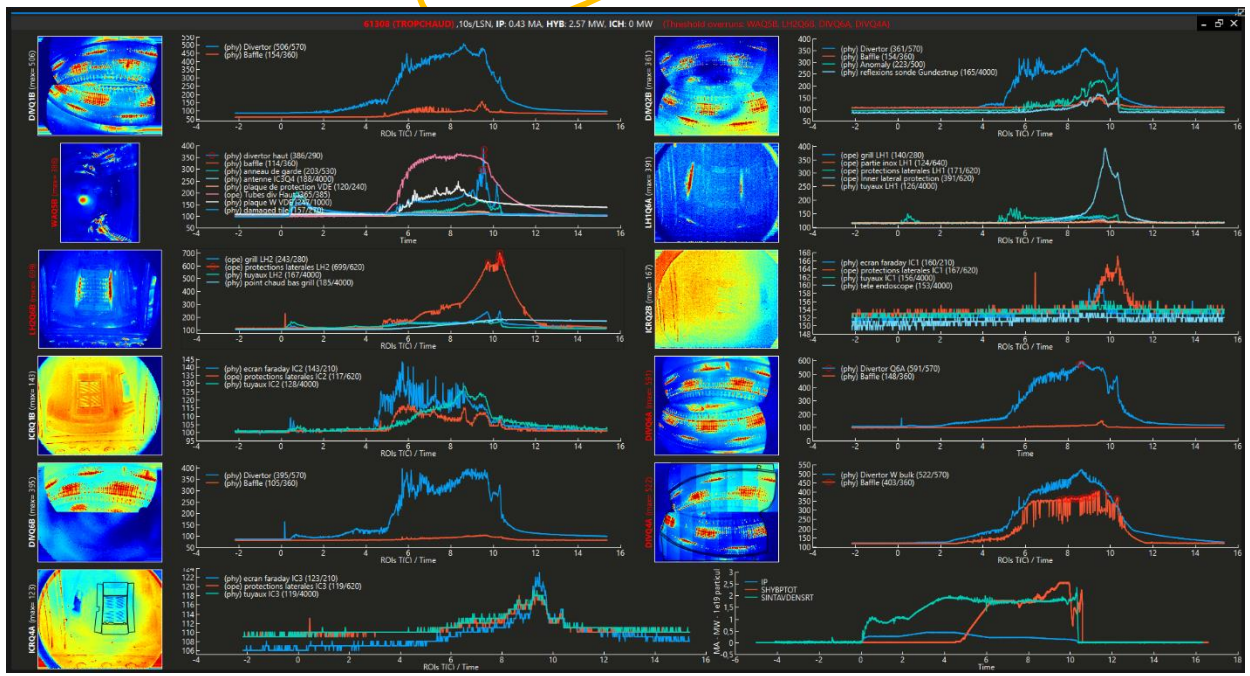


Between-Pulse Wall Protection: Supporting Human Decisions

- **Wall Protection Starts in the Control Room**
  - **Human expertise remains a central element of first-wall protection, particularly between consecutive pulses**
- Analysis performed by the PFC Protection Officer (PPO)
  - Needs for a framework to access the movies automatically, analyze them and save the results in a dedicated database
  - Needs for tools to condensate the large volume of IR information



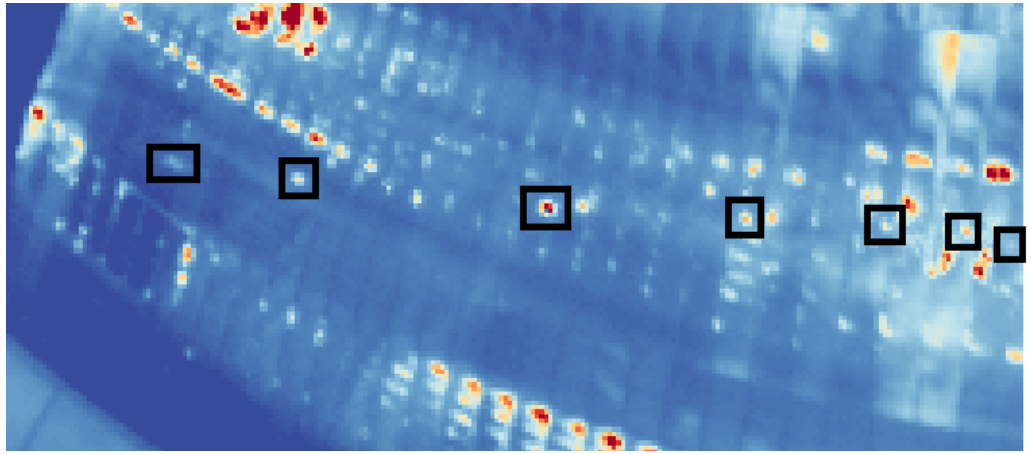
- The Shot-summary, a dedicated visualization tools for between pulses analyses
  - Available within seconds after the pulse
  - Summarizes the main pulse parameters (Power, Density, Magnetic configuration…)
  - Provides one synthetic image per camera summarizing the full video and highlighting the main thermal events
  - Highlights threshold overruns on security ROIs



V. Moncada et.al. (2023)

Advanced Post-Pulse Tools for IR interpretation

- UFO detection (named UFOund)
  - Run automatically after each pulse on all IR views
  - Spatio-temporal convolutional neural network (~1M parameters)
  - Detect and Track moving particles
  - Detected UFOs are stored in the WEST thermal-event database



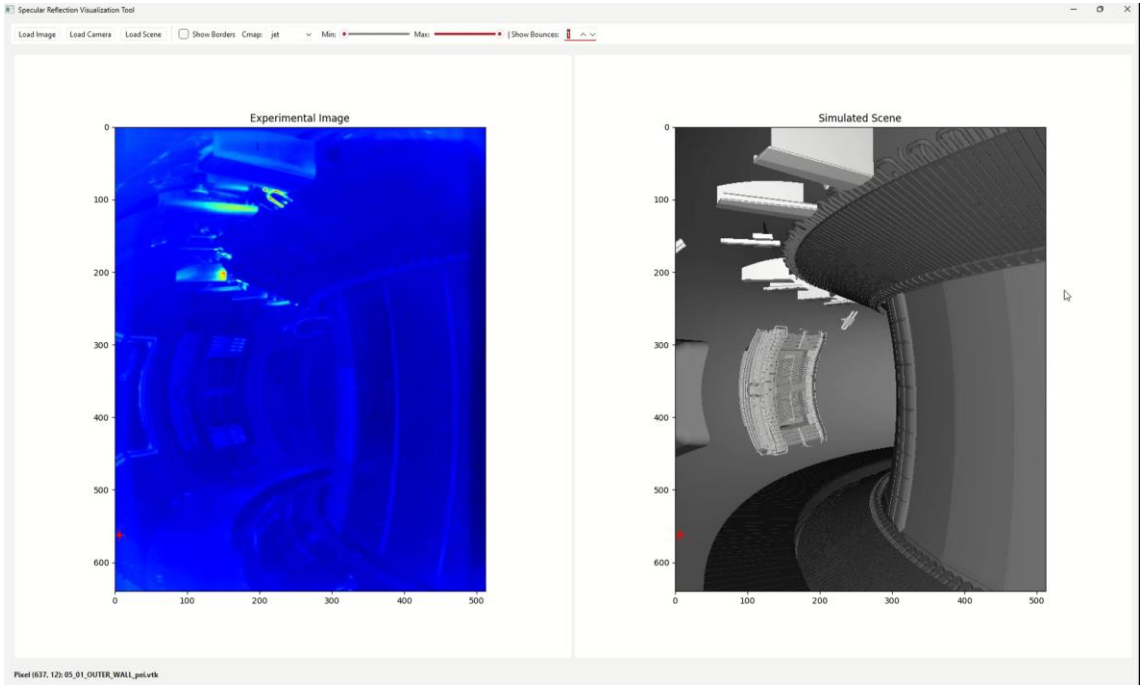
E. Grelier et.al. (2025)

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- SpecuViz
  - Helps identify possible origins of specular reflections in experimental IR images
  - Based on the deterministic raytracing code called Speculos

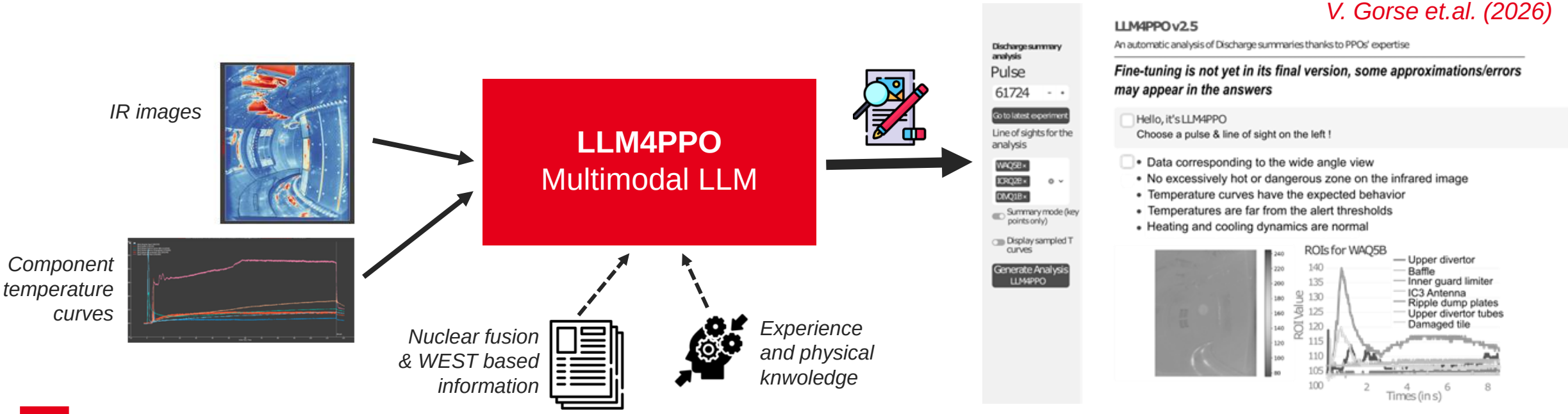
A. Juven et.al. (2022)



Multimodal LLM for decision support

- LLM4PPO is a multimodal Large language model (LLM) to support human (PPO) post-pulse analysis
  - Uses IR images and temperature time traces from the shot-summary
  - Produces a structured pulse summary informed by PPO expertise
- Its goal is to accelerate the identification of protection-relevant events while keeping the PPO in the decision loop
  - Ongoing development and validation are required before deployment for operational use

V. Gorse et.al. (2026)



WEST IR thermography

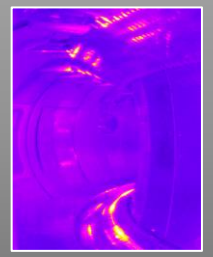
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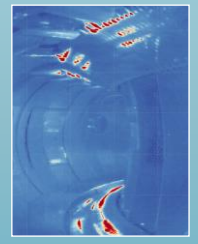
Post-Pulse analysis is essential !
but It is too late to protect the on-going pulse

Thermal Scene



Endoscope & Acquisition system

Image in Apparent Temperatures



Archiving/Storage

Visualization

Image in Digital Level (Luminance)



Post processing

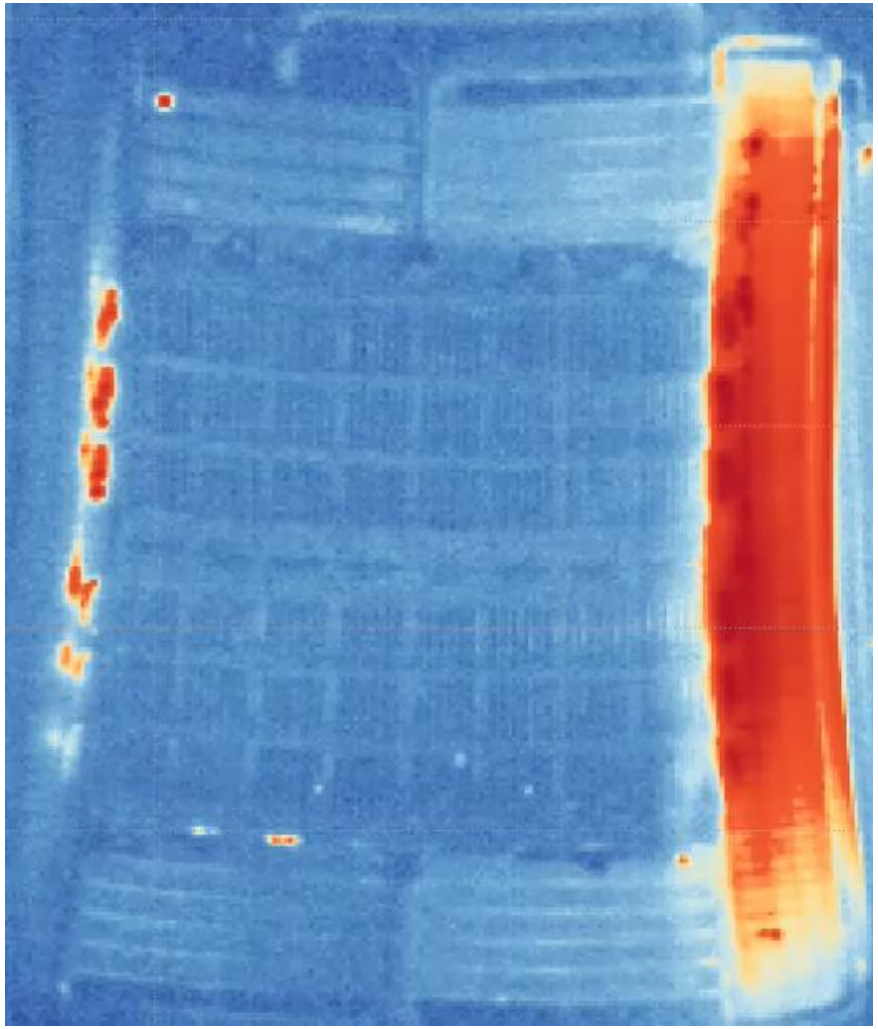
PCS

Real-Time Basic or advanced Post processing

Human analysis In Control Room

Electric Arc Detection

- Operational on WEST since 2024, the arc detector
  - Identifies electric arcs on Lower Hybrid antenna grills
  - Interfaces directly with the heating protection loop
- Lightweight CNN (~104k parameters)
  - Running on CPU at ~125 Hz for a 50 Hz acquisition rate
  - Fully compatible with real time
- Tuned for machine protection
  - Prioritizing missed-event reduction over false positives
  - All arc events in the validation set were detected



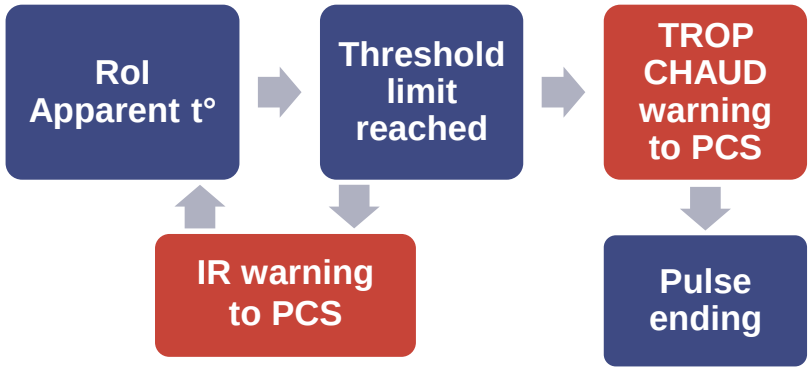
E. Grelier et.al. (2026)

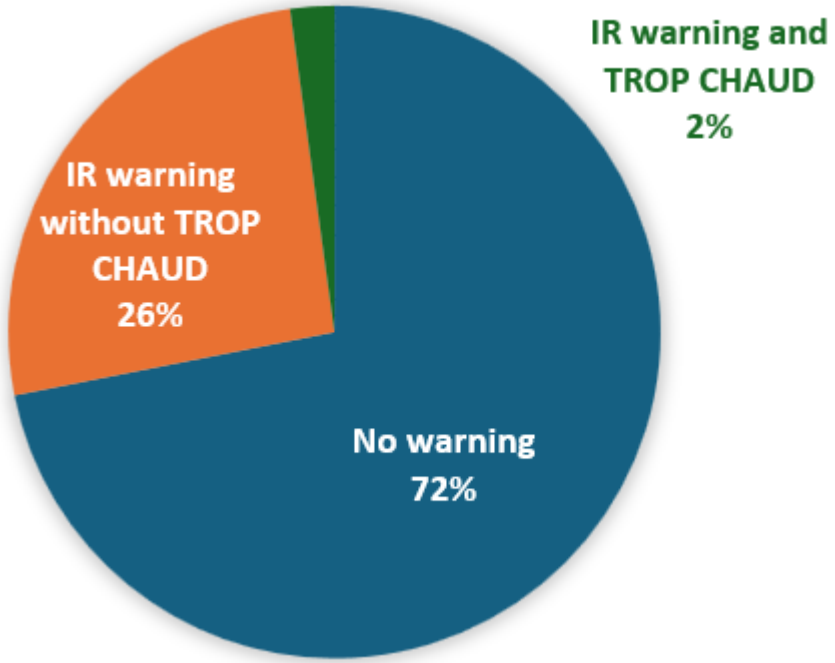
Deterministic real time Machine Protection

- Predefined Regions of interest (RoIs) are monitored in real time using the maximum apparent temperature
- Two protection levels are transmitted to the WEST PCS:
  - “IR warning” → LHCD power feedback
  - “TROP CHAUD warning” → controlled discharge termination

- Since 2023 (C7 to C13 experimental campaigns)
  - 26% triggered heating-power feedback
  - 2% were eventually terminated despite a preceding IR warning

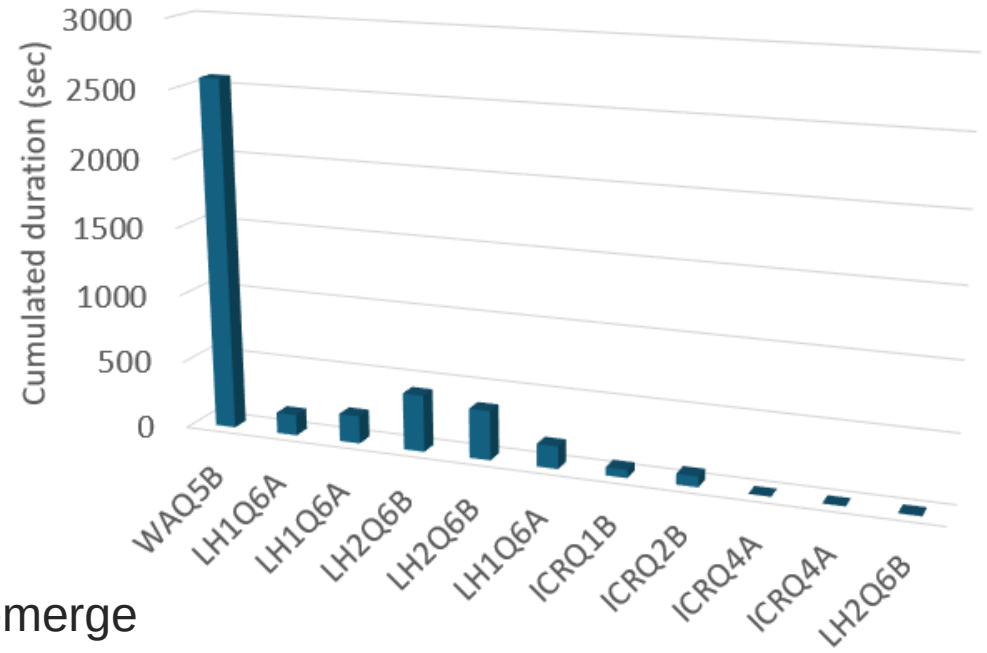
- **WEST operates close to its thermal limits, making active IR feedback essential**

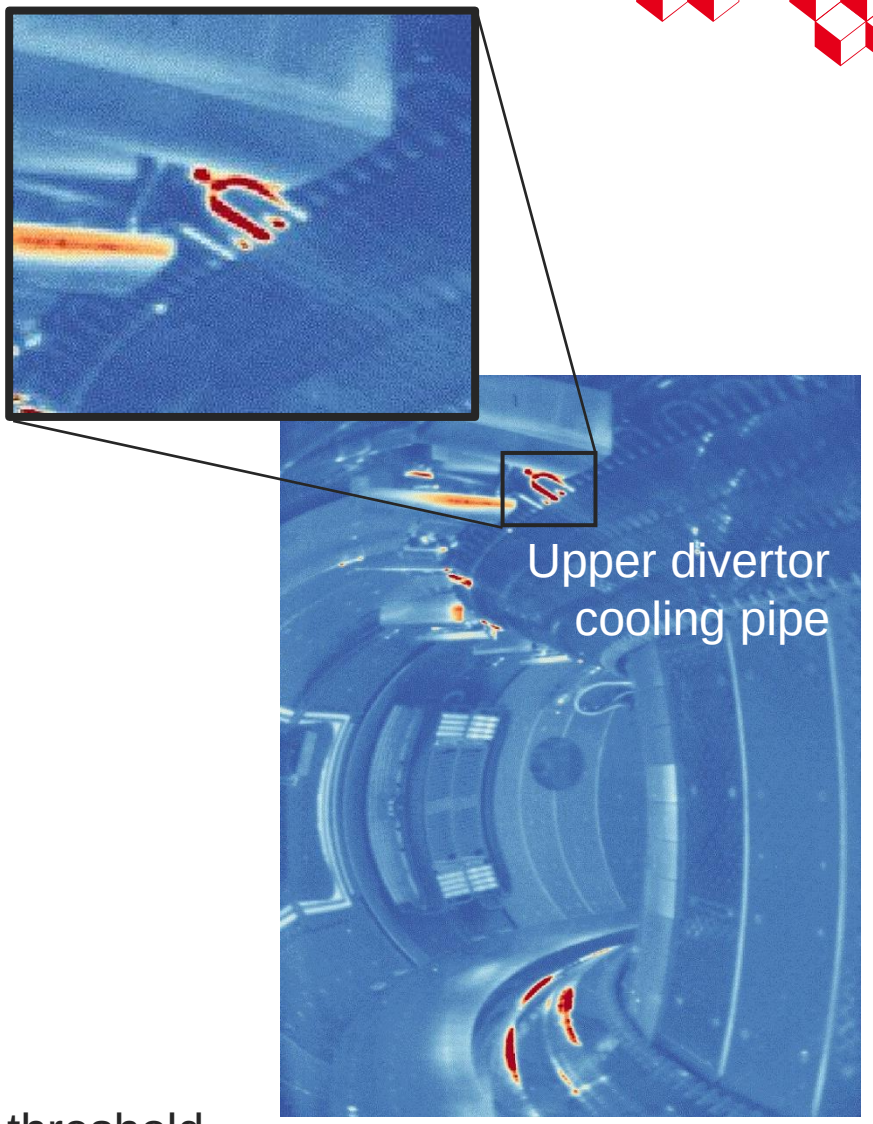




Limits of RoI-Based Protection

- A single component can significantly constrain the operating domain
  - Upper-divertor cooling pipes dominated the feedback
    - More than 2500 seconds of feedback since C7 (2023)





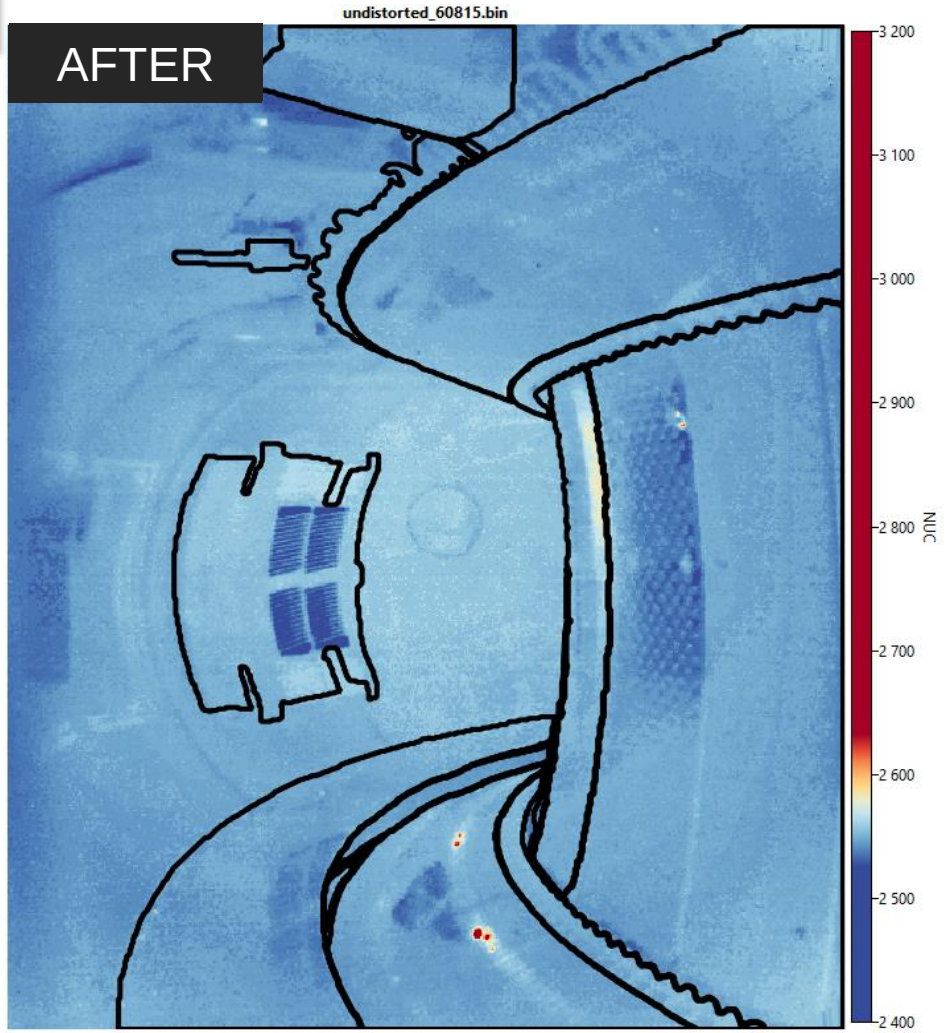
- Two key limitations emerge
  - Emissivity changes affect apparent temperature and the regulation threshold
  - RoI must remain accurately aligned with the physical component

Improving the Robustness of RoI-Based Protection

E. Grelier - This conf. S1-031

- Geometrical robustness with TOKIRA
  - Deep-learning-based automatic frame registration
  - Corrects translation, rotation and zoom
  - Automatically transfers reference RoIs to each incoming frame
  - Offline qualified during C13; real-time implementation under development
- Thermal robustness
  - Apparent temperature remains sensitive to surface emissivity
  - Current emissivity estimates rely on:
    - in-situ measurements between campaigns
    - PPO expertise
  - Emissivity may evolve significantly during a campaign
    - New approach combining in situ measurement of the emissivity during a campaign with photonic calculations

J. Gaspar - This conf. S1-033



WEST IR thermography

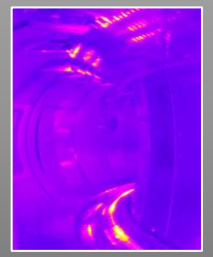
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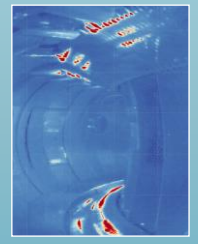
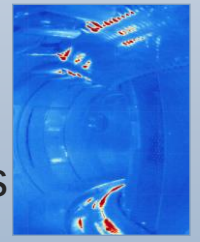


Image in Absolute Temperatures



Archiving/Storage

Visualization

Image in Digital Level (Luminance)



Post processing

PCS

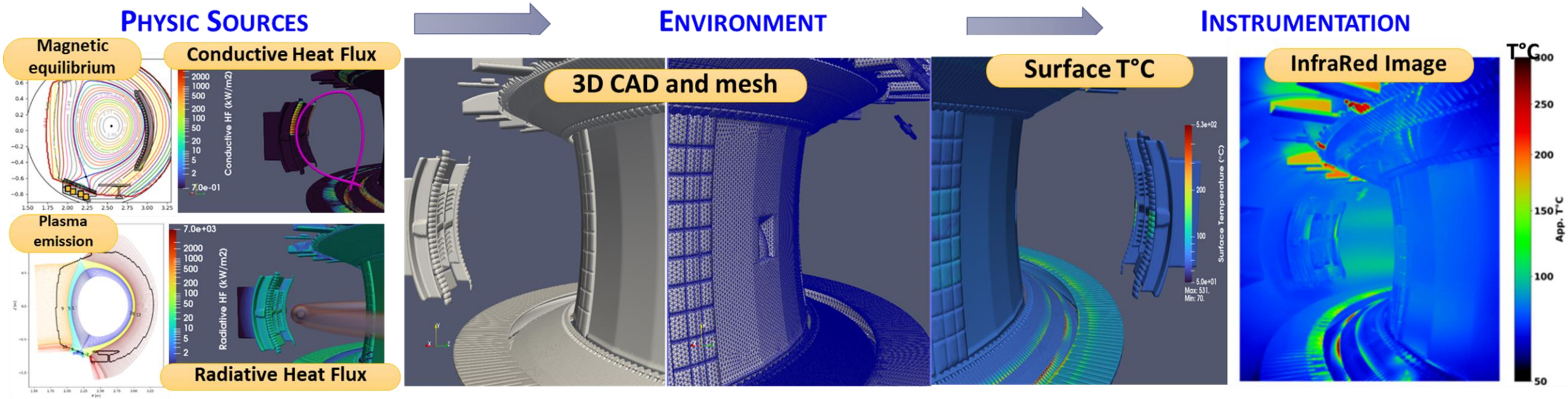
Real-Time Basic or advanced Post processing

Human analysis In Control Room

Quantitative IR Thermography and Wall Protection

- IMPACT (IR-Digital Twin) from specified plasma scenarios to IR images
  - End-to-End Simulation: capable of managing complex geometries and material properties, as well as infinite sources.
  - Multiphysics Numerical Platform: heat loads, thermal, photonic, and optical models
  - High-Performance Computing

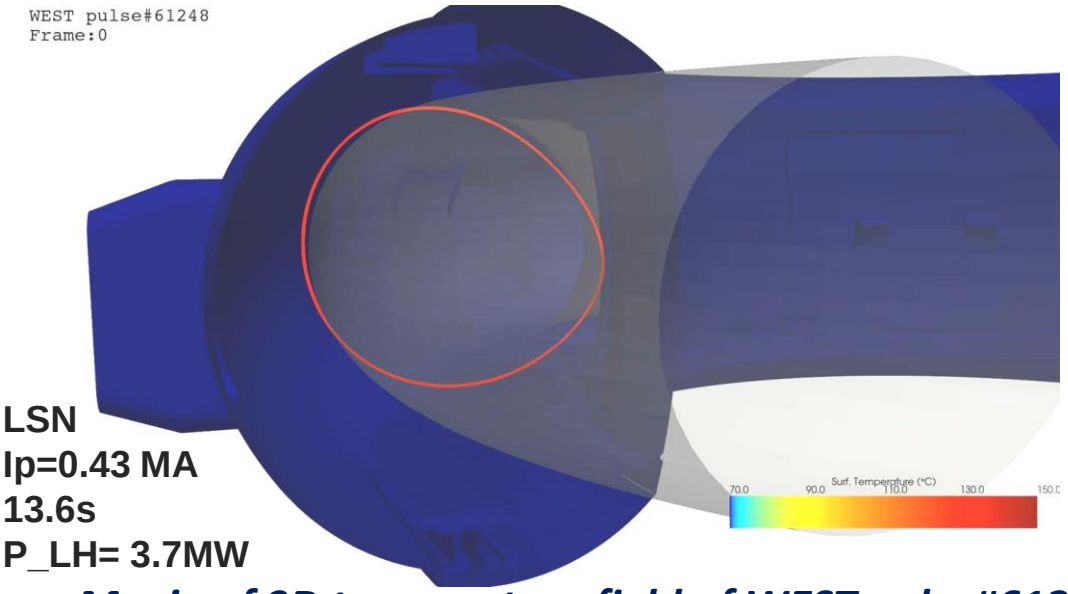
MH. Aumeunier - This conf. S1-035



Quantitative IR Thermography and Wall Protection

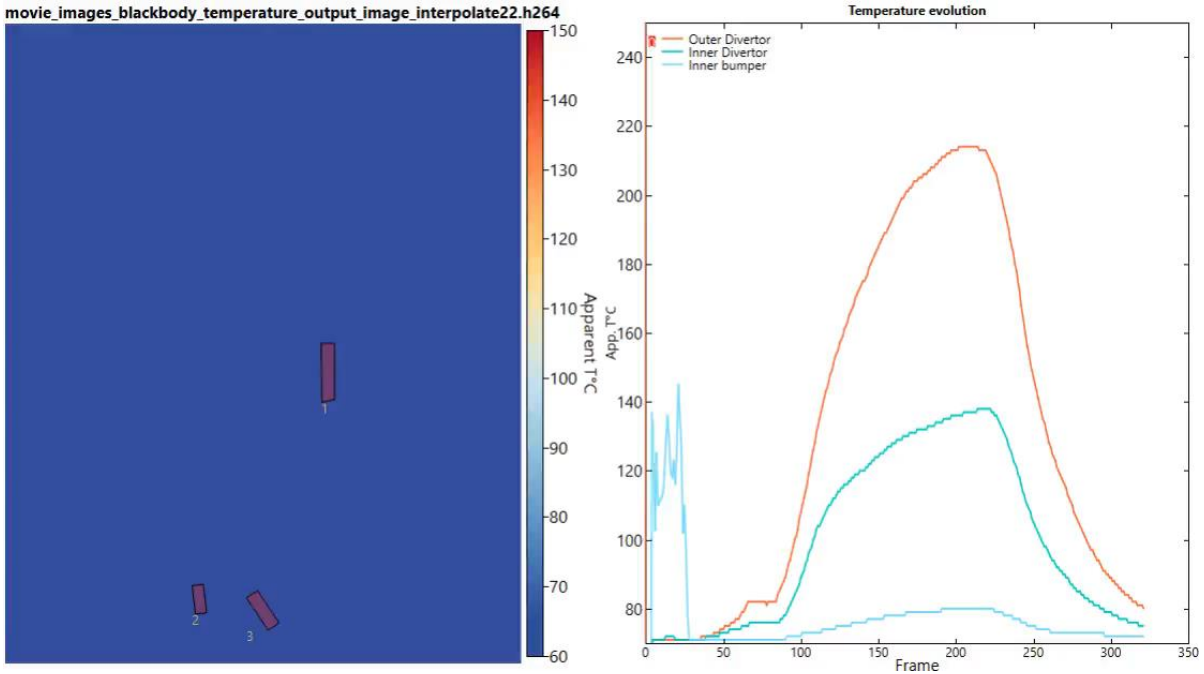
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MH. Aumeunier - This conf. S1-035



LSN
Ip=0.43 MA
13.6s
P_LH= 3.7MW

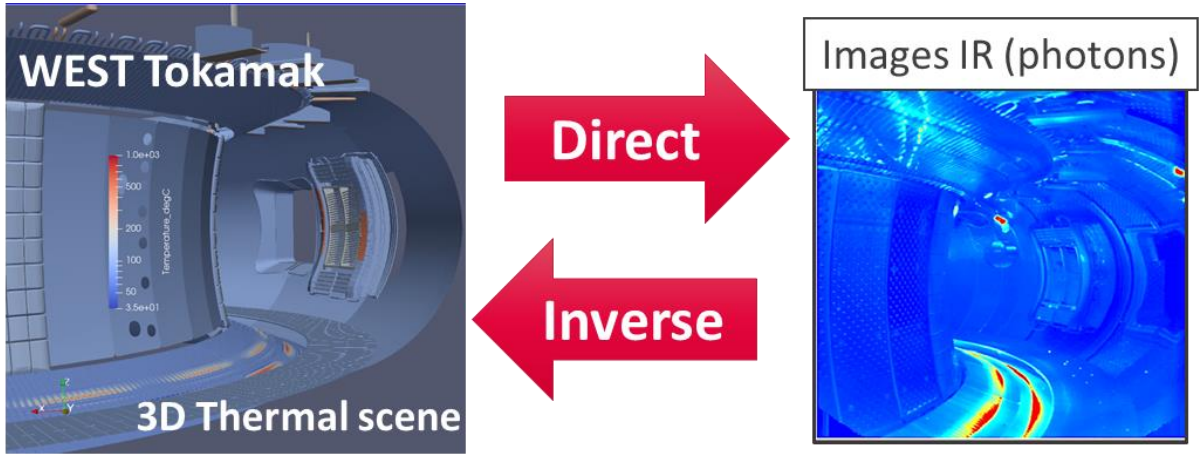
Movie of 3D temperature field of WEST pulse#61248



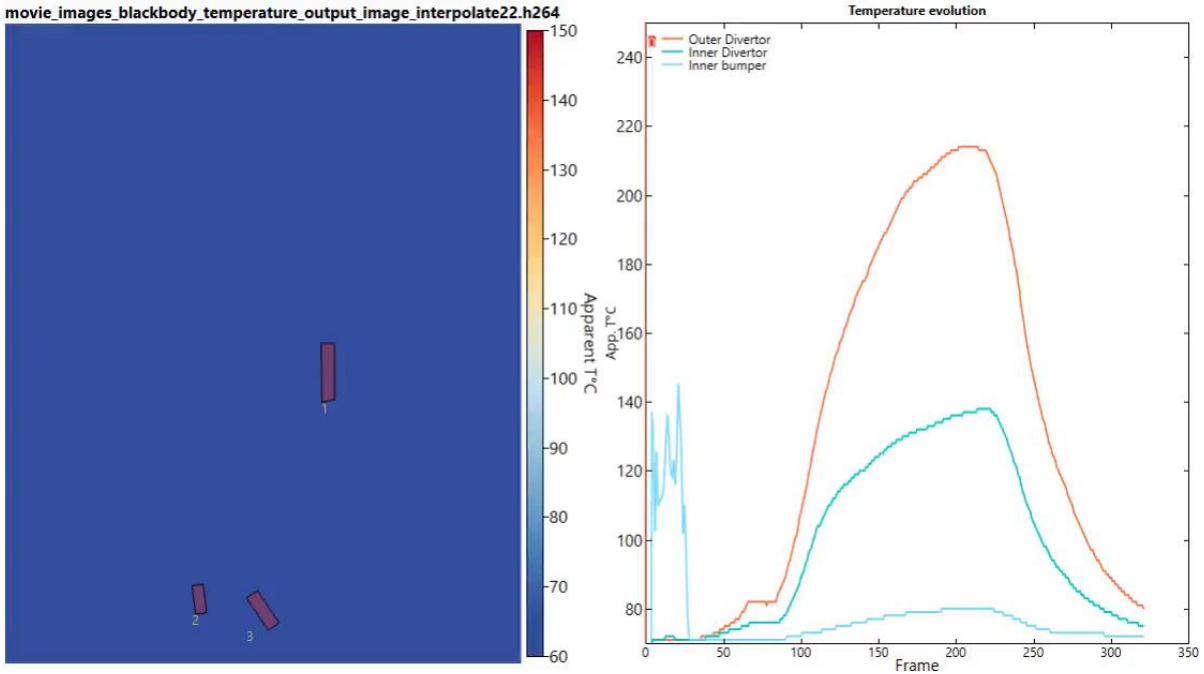
Simulated IR movie of WEST pulse #61248

Quantitative IR Thermography and Wall Protection

- IMPACT is used to IR quantitative inversion to predict thermal scene parameters (t°, emissivity)
  - A significant advancement in building realistic and exhaustive synthetic databases for ML/AI learning, enabling temperature prediction and heat load reconstruction



MH. Aumeunier et.al. (2024)
A. Juven et al. (2024)

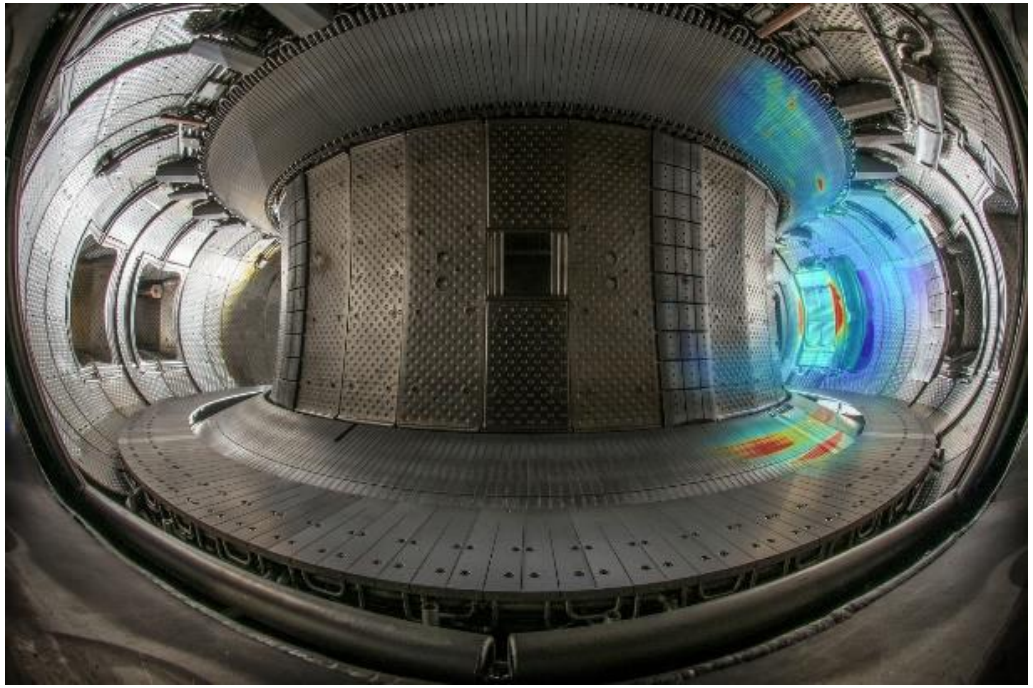


Simulated IR movie of WEST pulse #61248

Conclusions

- Infrared thermography is now a key element of machine monitoring and protection on WEST
  - It has evolved from a diagnostic into an integrated wall-protection ecosystem
  - It provides reliable protection, supports expert decisions between pulses, and contributes to automatic protection during plasma operation

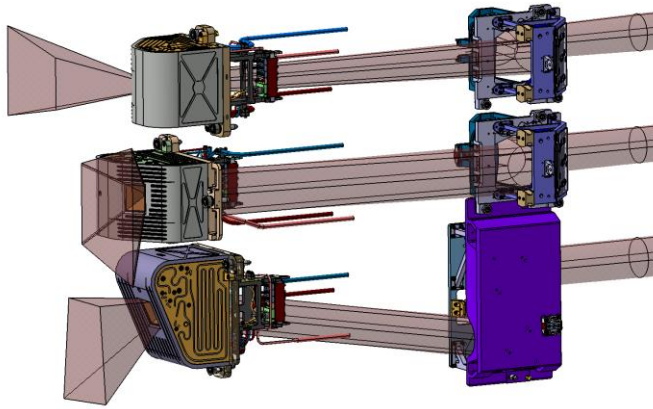
- WEST is a powerful testbed for technologies relevant to future fusion devices
  - Its protection ecosystem enables new hardware, processing methods and real-time algorithms to be tested under operational conditions

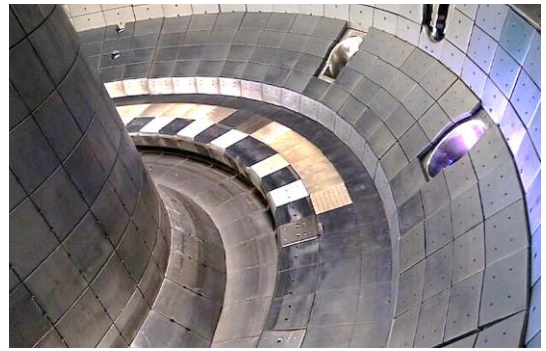


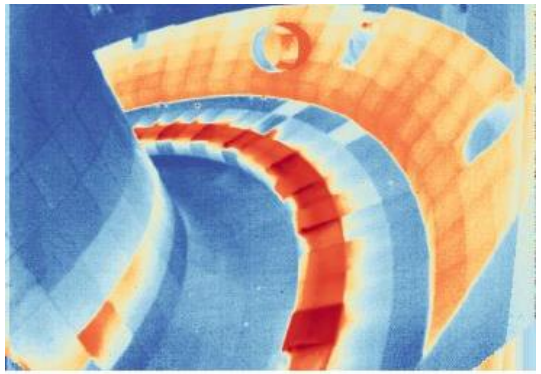
Conclusions

Part of this ecosystem is already mature enough to be deployed on other fusion devices through collaborations

- Long-standing collaborations with ITER and F4E
  - IR viewing system (Equatorial WAVS), common IR calibration strategies, performance assessments, analysis tools (Thermavip)
- Development, installation and operation of a Wide-Angle IR endoscope
  - On DIII-D in July 2026
- Cross-machine developments
  - such as the arc detector jointly developed with EAST (ASIPP)
- Open-source tools and common standards available to the community







“MERCI !