2nd Calibration Workshop for Microwave Diagnostics

ITER, Cadarache, France

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Absolute Calibration Procedure of the ECE Radiometer at WEST

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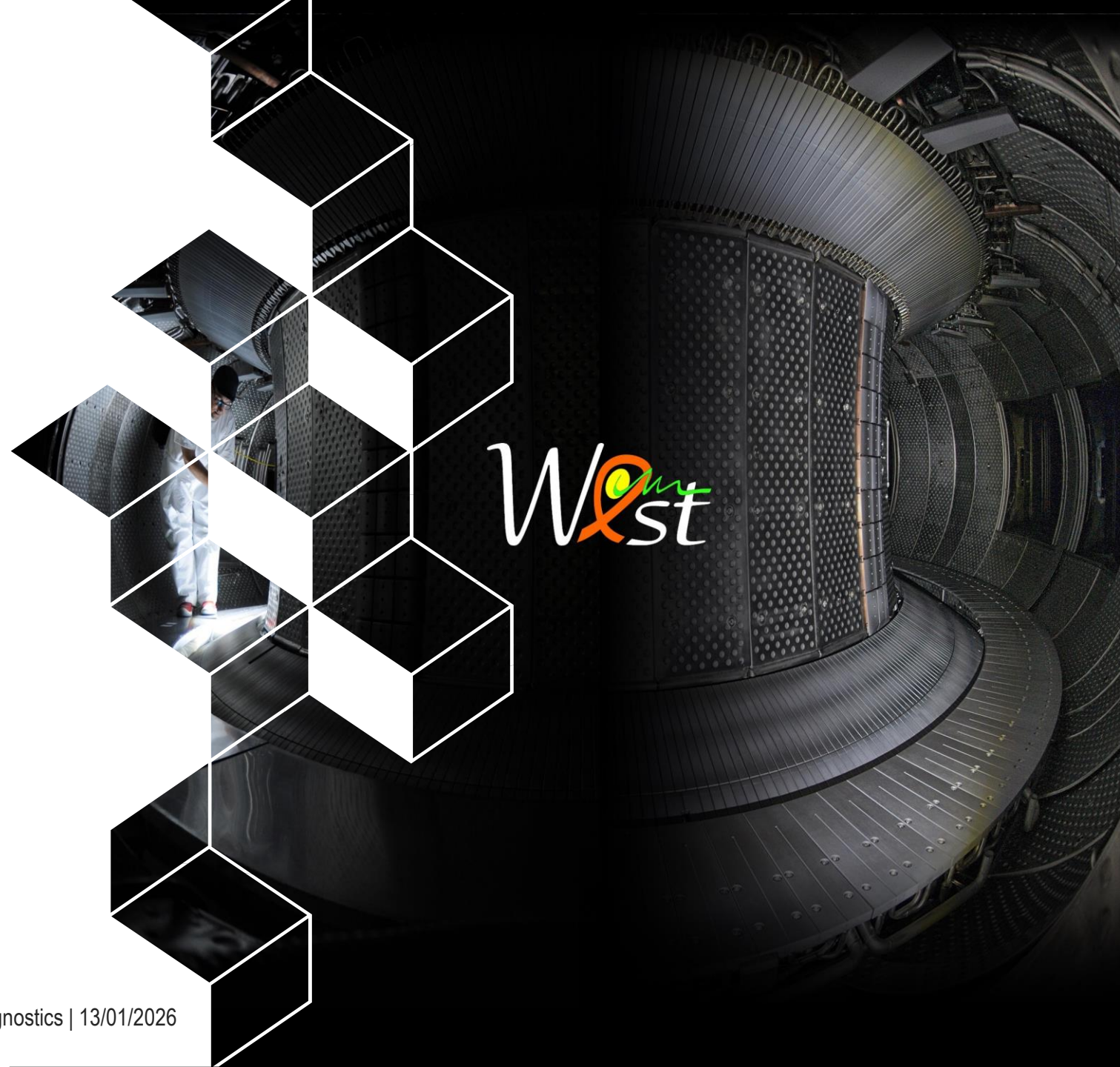
Outline

- *ECE @ WEST*
  - Technical characteristics
  - Result summary
- Absolute calibration procedure
  - Setup & technical components
  - Results & result expectations
  - Principal issues
- Perspectives



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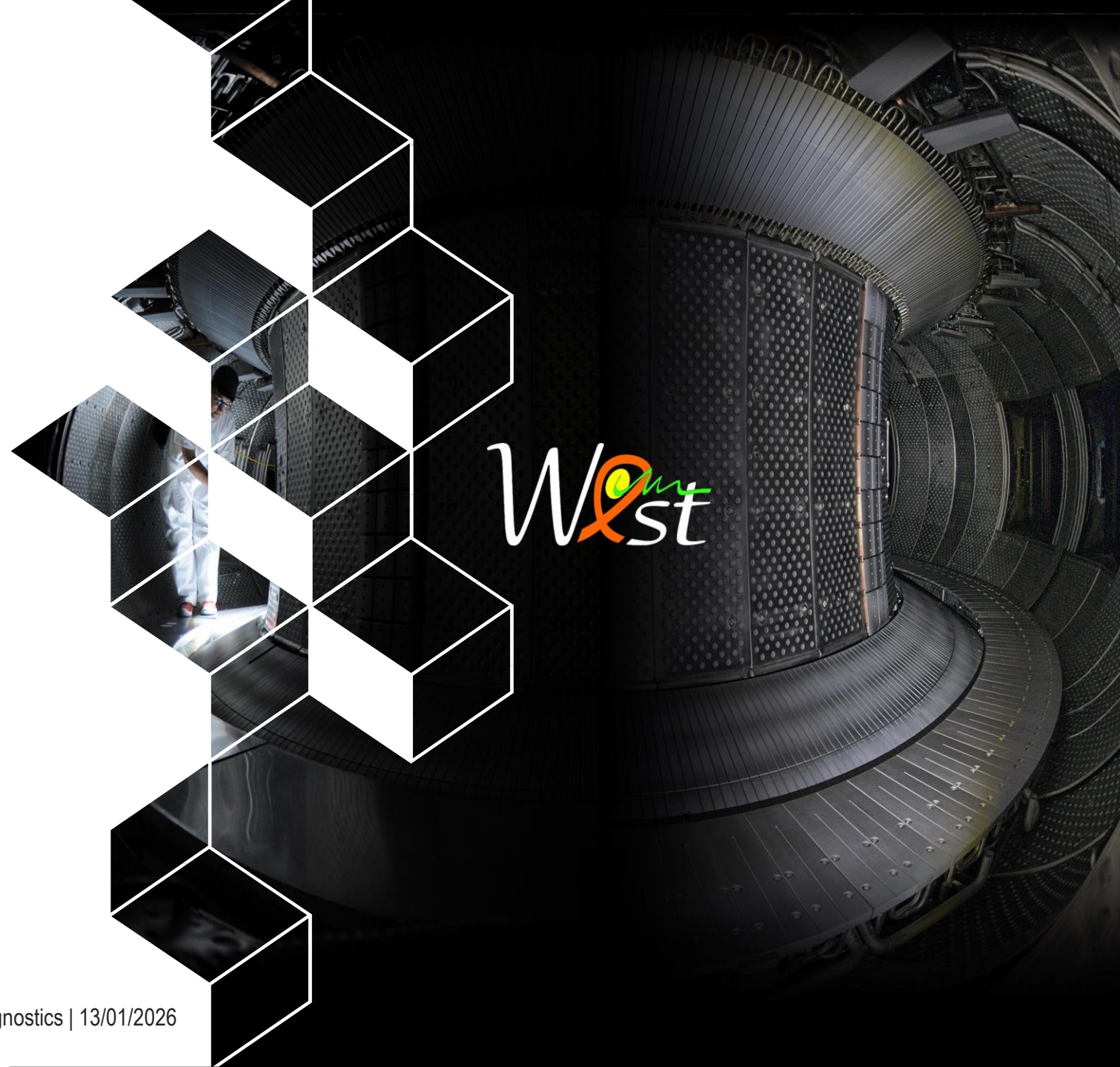
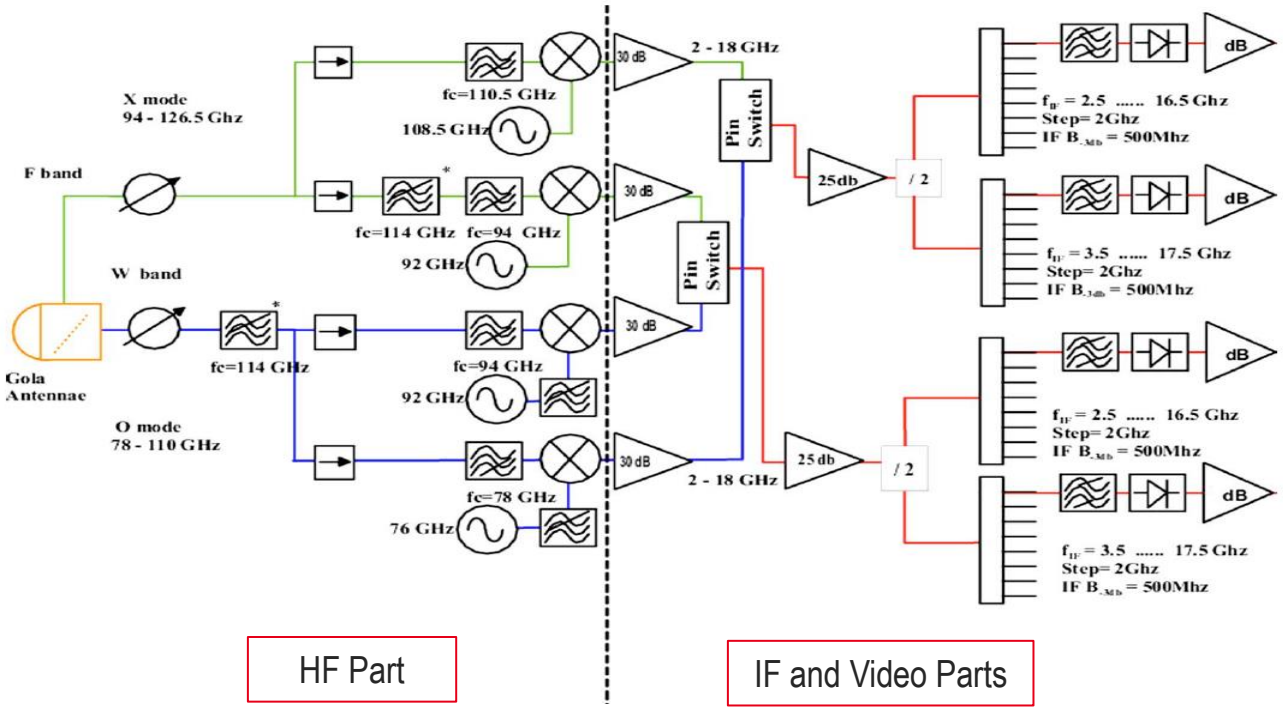


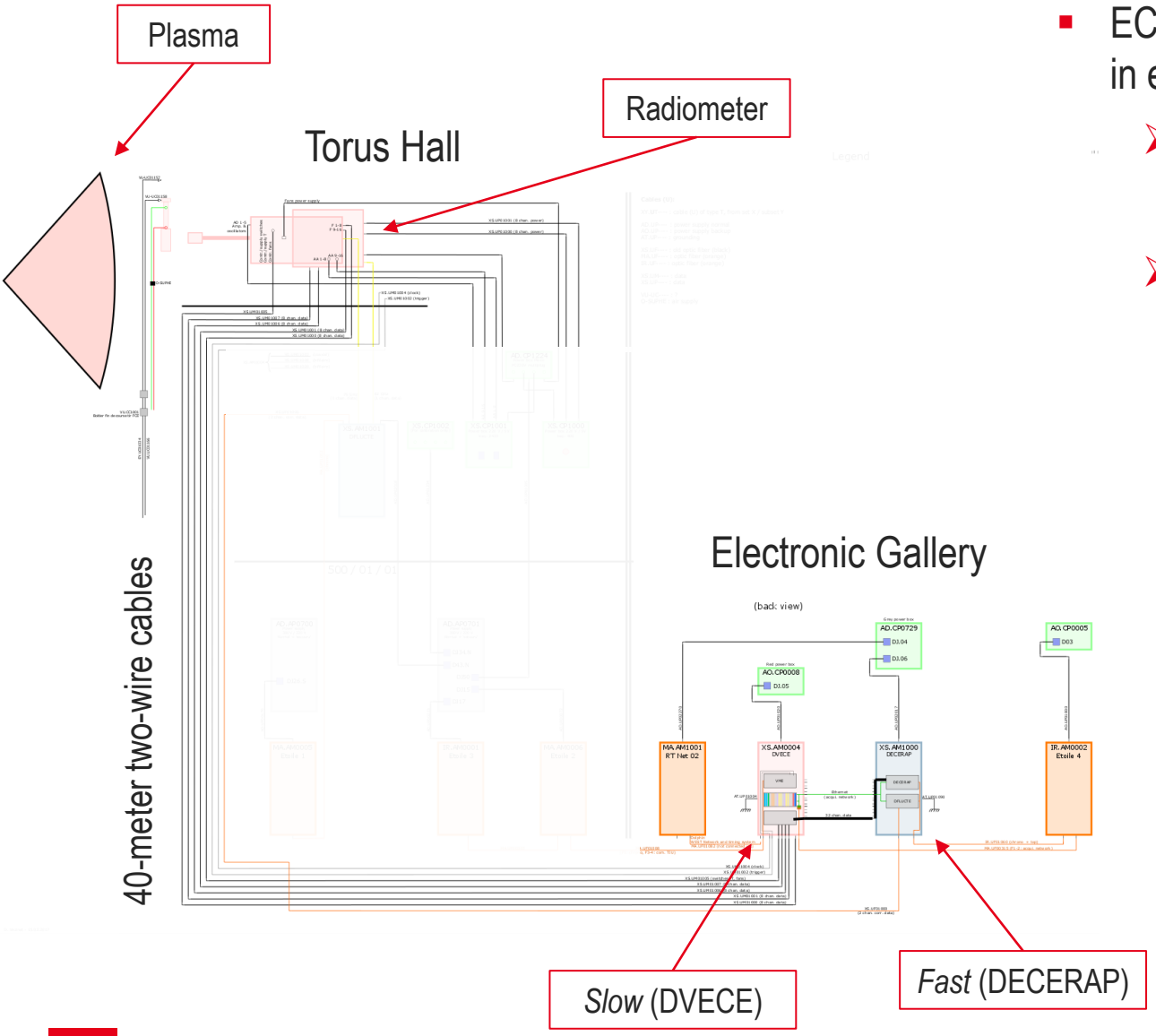
ECE @ WEST: Global System Introduction

- Electron Cyclotron Emission (ECE) heterodyne radiometer at WEST:
  - 32 channels, 1 GHz spaced, 500 MHz bandwidth (±250 MHz)
  - Horizontal (and ⊥) line-of-sight (with very low beam width)
  - Dual-polarization antenna for non-simultaneous measurements:
    - 1st harmonic O-mode for $B_t > 2.2$ T (78-110 GHz)
    - 2nd harmonic X-mode for $B_t \leq 2.2$ T (94-126 GHz)



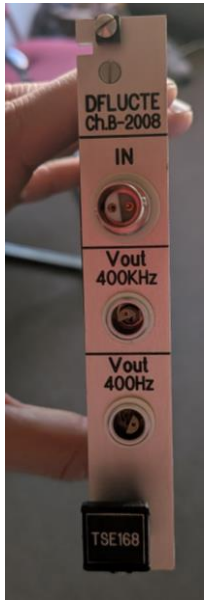
[J.-L. Segui *et al.*, *Rev. Sci Instrum.* 76, 123501 (2005)]

ECE @ WEST: Acquisition System Introduction

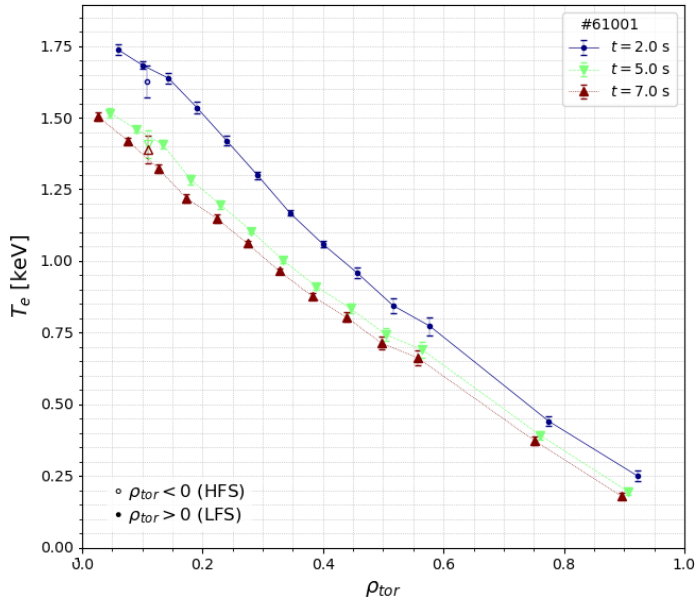


- ECE radiometer linked to 2 independent acquisition systems (placed in electronic gallery 40-meter away from Torus Hall):
  - 1 kHz (*slow*) → Up to ~2000 s of acquisition
    (Absolutely calibrated – See next slides)
  - 1 MHz (*fast*) → Multiple triggers with up to 1 s of acquisition each
    (Uncalibrated)

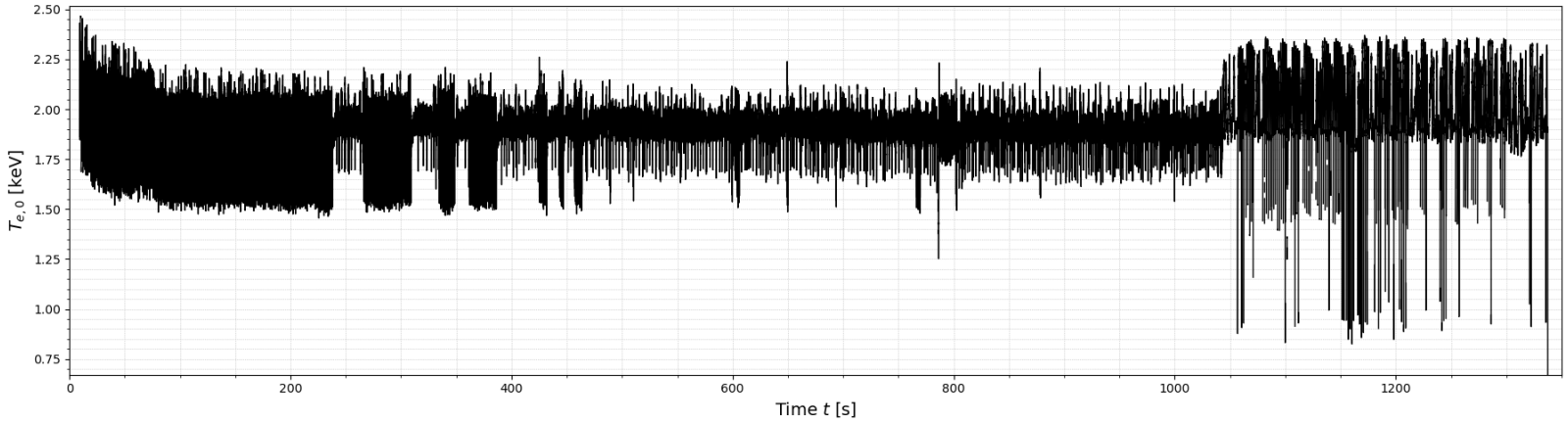
[K.-W. Chen *et al.*, *to be submitted to Rev. Sci Instrum.* (2026)]



ECE @ WEST: Summary



WEST #61299



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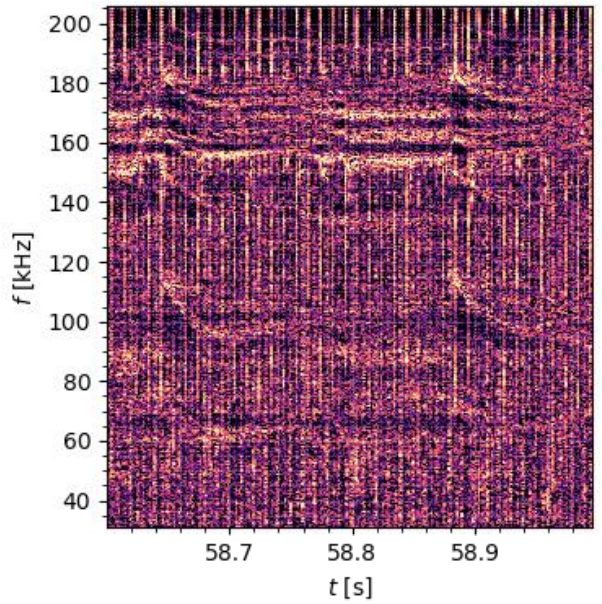

- ECE currently in operation at WEST:
  - Principal diagnostic for electron temperature evaluation
  - Good radial coverage
  - Capable of *slow* temperature evaluation in long-pulse operations
  - Triggered *fast* acquisition characterizing high-frequency activity in the whole radial domain
  - Real-time T_e provided to PCS from 2026 [K.-W. Chen *et al.*, *to be submitted to Rev. Sci Instrum.* (2026)]

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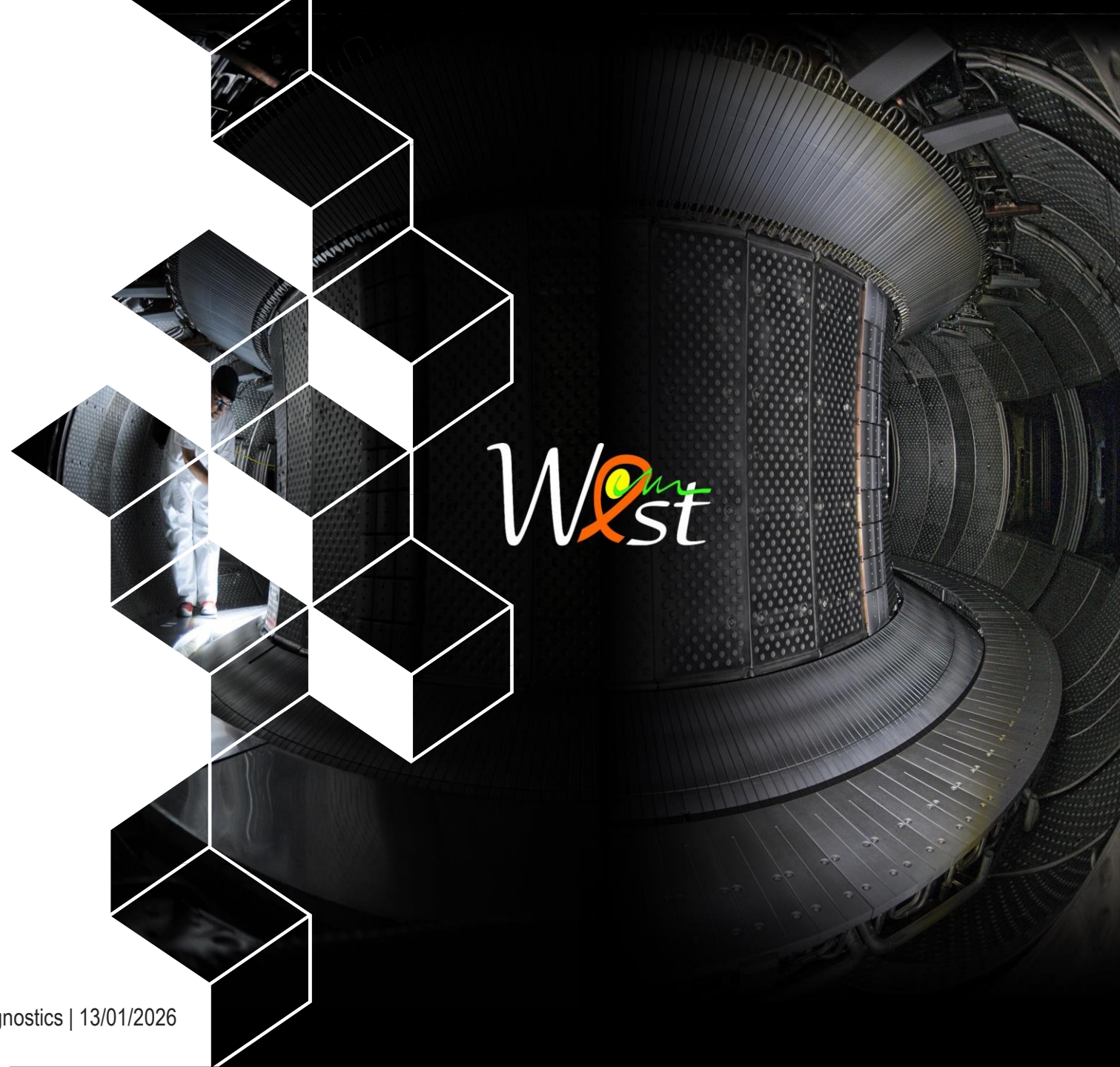
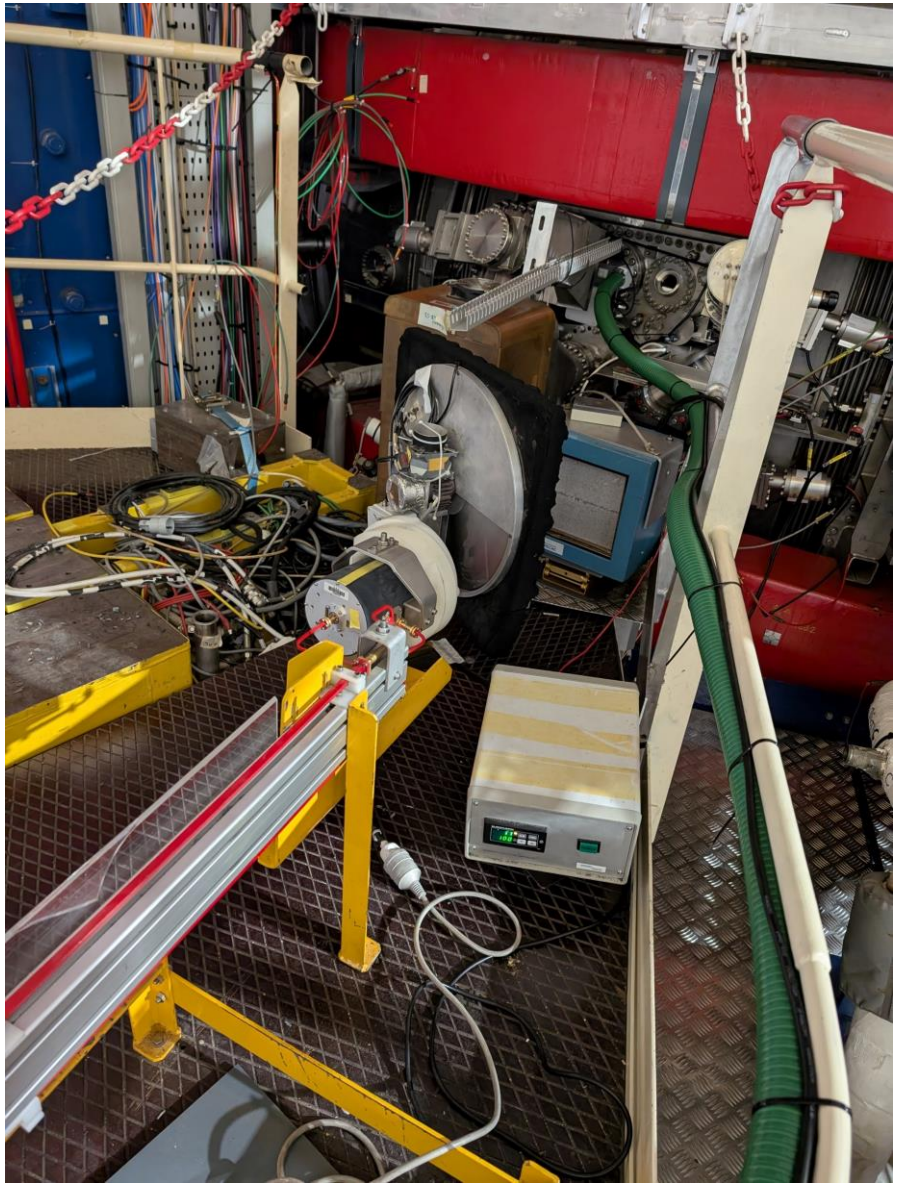


Calibration Setup

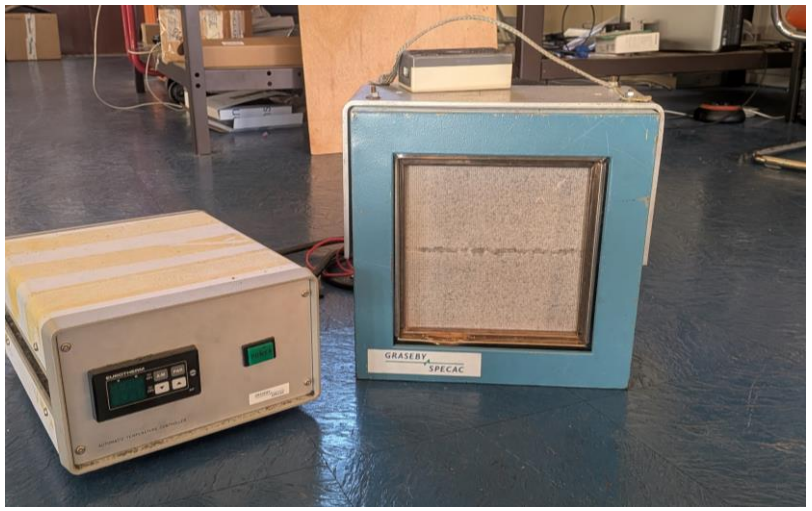
- Dedicated calibration procedure developed more than 30 years ago
  - More recently optimized in the acquisition procedure

- Performed **outside the vacuum vessel** but inside the tokamak hall
  - Sessions **before / after** the campaigns
  - Possibility of **intra-campaign** sessions (during maintenance days) but risky…

- Tools to be prepared / steps to be undertaken
  - Move the radiometer over the platform to allocate tools
  - Black-body source (SPECAC P/N 40.110) with $T_{BB,max} = 600$ °C
    - Low power for each channel → Dedicated gains (×1000) are added to the acquisition chain
  - Rotating chopper (~10 Hz)
    - Alternating phases at T_{amb} and T_{BB} → Linear dependence
    - Possibility of conditional average over statistically large set of samples
  - Vacuum vessel window mock-up

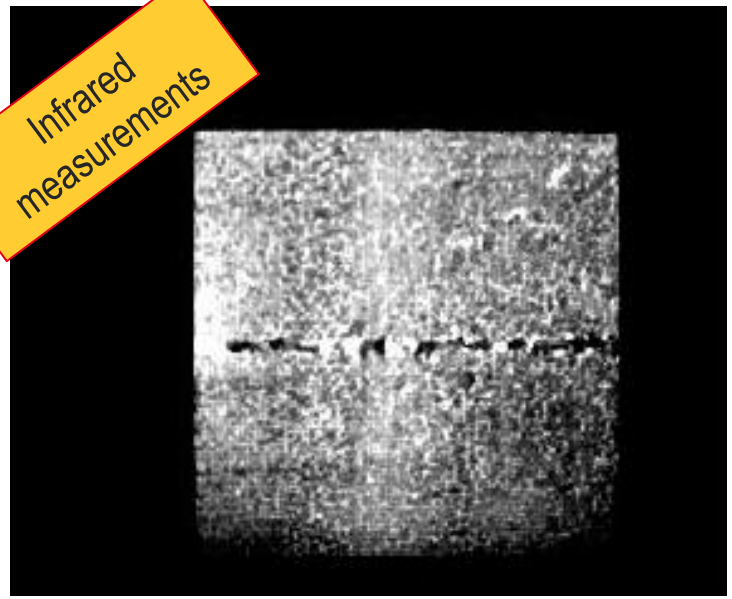


Black-body Source: Fundamental & Fragile



- High-temperature **black-body source**: SPECAC P/N 40.110
  - $T_{BB,max} = 600\ (\pm 2)$ °C
  - Active area: 195×195 mm — Overall size: 315×315×210 mm
  - Frequency range: $75 < f < 1000$ GHz
  - Emissivity $\varepsilon > 0.87$

Specs on manual…

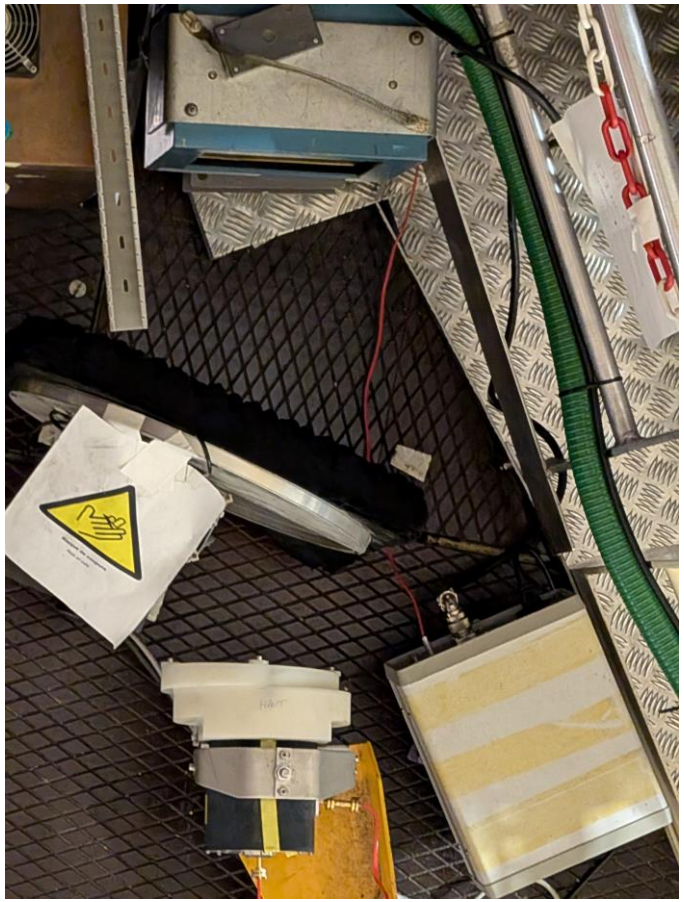


Infrared measurements

- Quite old and fragile tool → Many relevant issues in the last few years…
  - Reduced uniformity of the emission
  - Fragility of the filtering surface
  - *Recurring* resistance breaking
  - Difficult to determine the emitted temperature
  - …

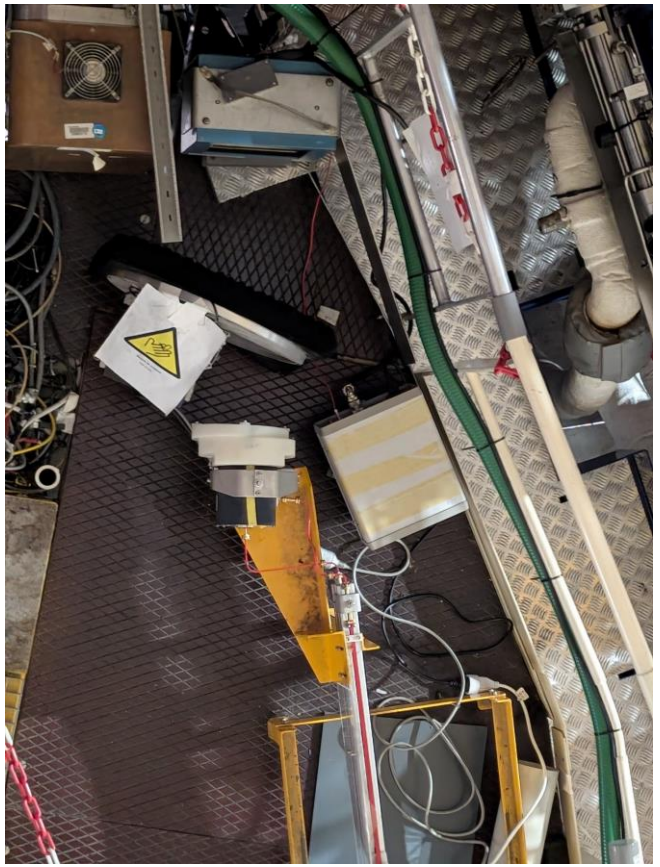
Chopper: Setup Information

- **Two-blade chopper** rotating at 11 Hz interposed between black-body and radiometer antenna
  - Assuming linear dependence of the calibration (using 2 points at different temperature)
  - Generating statistically relevant modulated black-body signal to radiometer → Decorrelating noise by conditional averaging over 50k samples in reasonable time (~2h)
- Tilting chopper to avoid rebounding radiation from black-body



Calibration Sessions: Organization

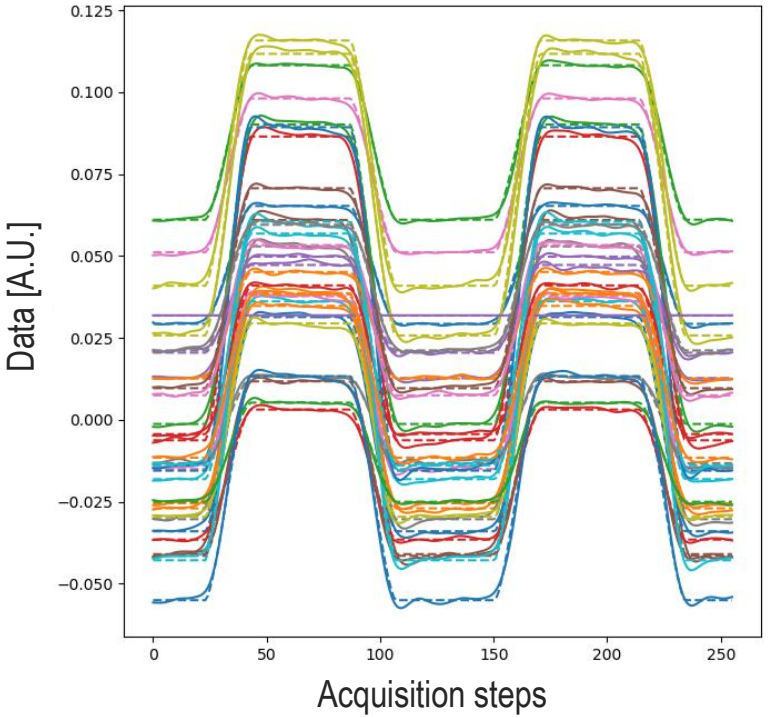
- Calibration sessions organized before and after each experimental campaign
  - Need to access Torus Hall
  - Need time to prepare setup (> 2h):
    - Moving all instruments in the torus hall (on the platform)
    - Retracting radiometer over rails
    - Positioning and aligning black-body source with antenna
    - Changing attenuators position in video part
  - ≤ 3 calibration sessions per day (for O-mode) – X-mode requires larger sampling set

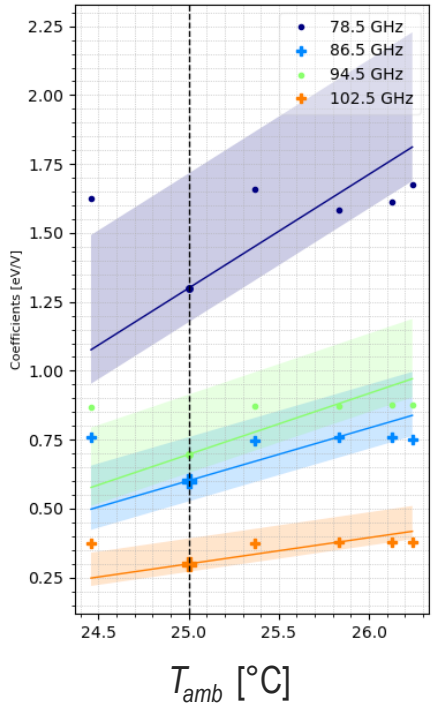


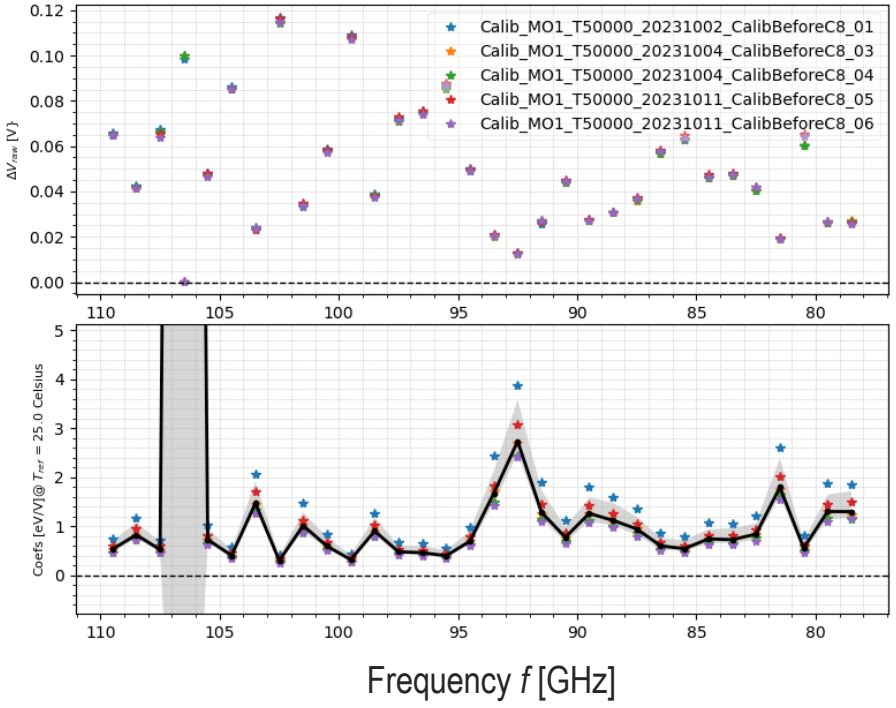
- Radiometer acquisition chain very sensitive
  - Calibration in maintenance days possible but risky → Possibility of losing previous calibration accuracy by breaking acquisition cards (occurred quite few times…)

- Duration of one calibration campaign: ~1 week
  - Generate enough calibration sessions for both O-mode and X-mode
  - Discard calibration sessions with issues

Result Summary of Calibration Campaign





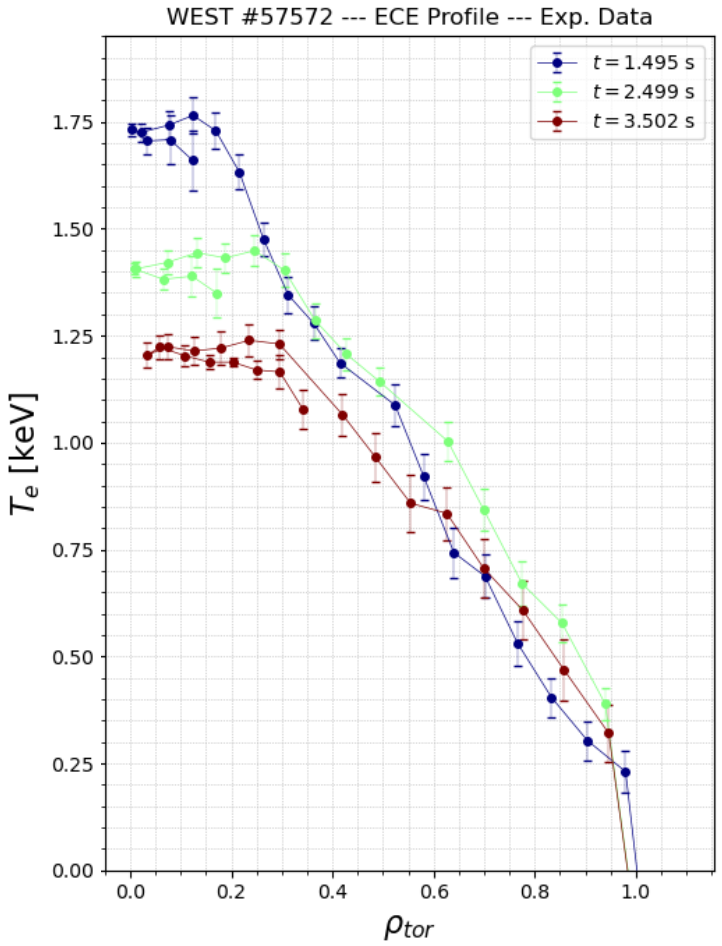


- Calibration sessions *generally* give consistent results among the same calibration campaign
  - Before vs. After experimental campaign sessions are generally **consistent**
- The calibration coefficients are computed as average among all the *good* calibration sessions
  - Different average method:
    - Considering manufacturing specifications of the dependence of the Schottky diode on T_{amb}
    - Minimizing the fitting error between the prescribed and the real dependence on T_{amb} → Generally used

Calibration Session Outputs: Main Issues & Found Solution

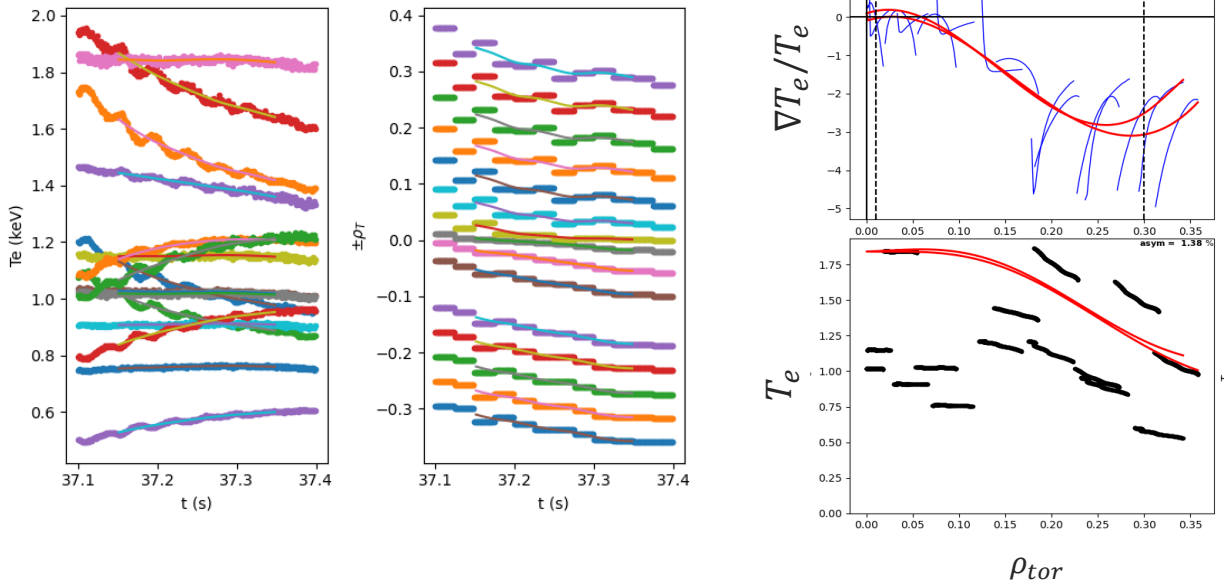
Main issues

- Not always good covering between HFS & LFS
- Large sensitivity to wave-guide band type with strong nonlinear behaviour



Solution

- Cross-calibration sessions are usually performed on dedicated ohmic plasma pulses
  - Rapid (~100 ms) plasma movement by > 5 cm
  - Assuming steady-state plasma → Correcting each channel calibration coefficients for smoother profiles
  - Allowing to multiply by a corrective factor



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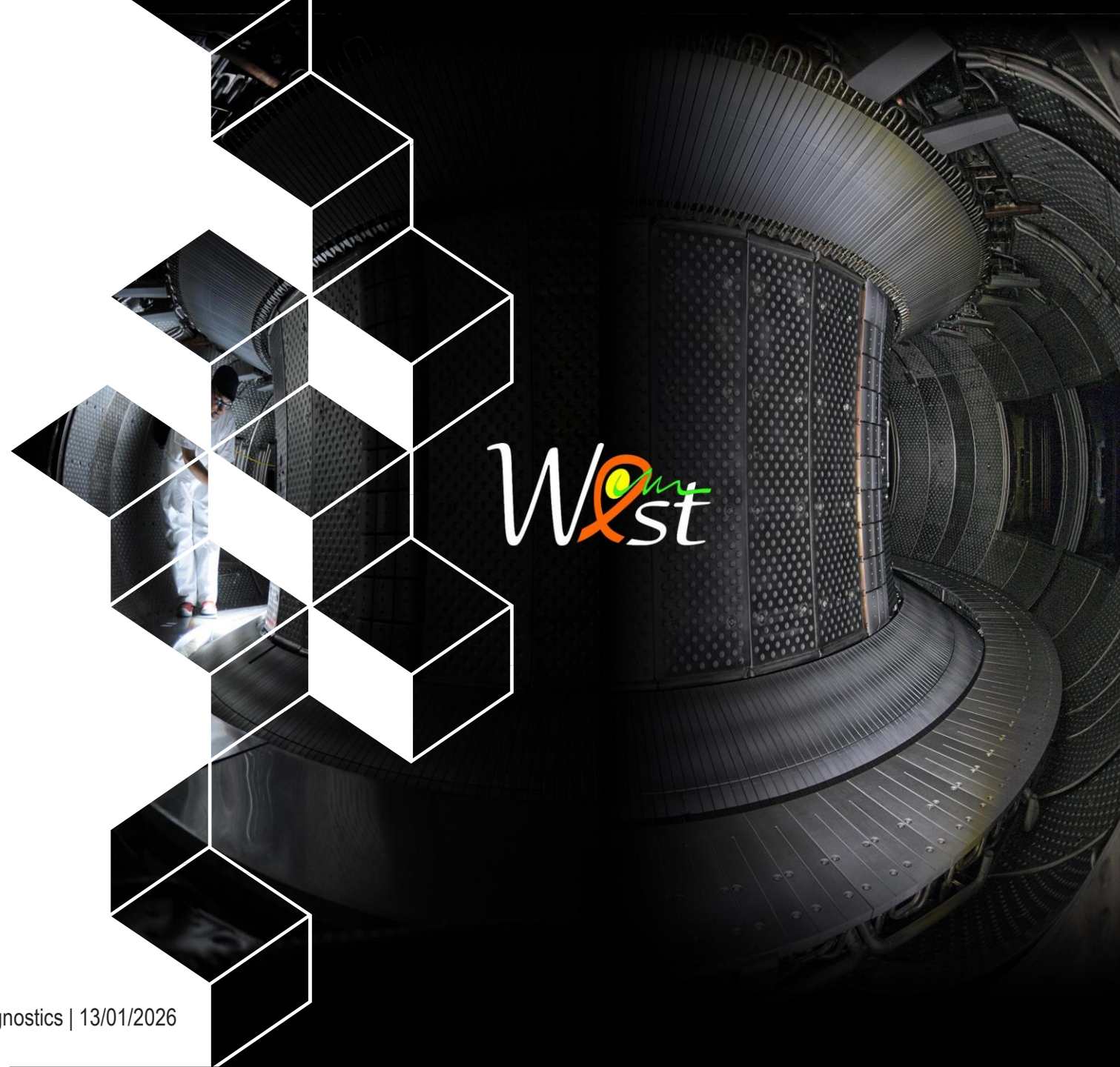

(Long-term…) Perspectives: Black-body Source

- Black-body source verification to be crucially done → Main source of uncertainty for ECE calibration @ WEST
  - ➢ French national laboratory for calibration (LNE) cannot check this type of instrument → Others in Europe?
- Upgrading calibration procedure by adding He/N Eccosorb cold source at known *T*
- Purchasing (/ fabricating) new black-body source
  - ➢ Proficient discussion with M. Hirsch and his group (W7-X, Greifswald, Germany)

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Backup Slides

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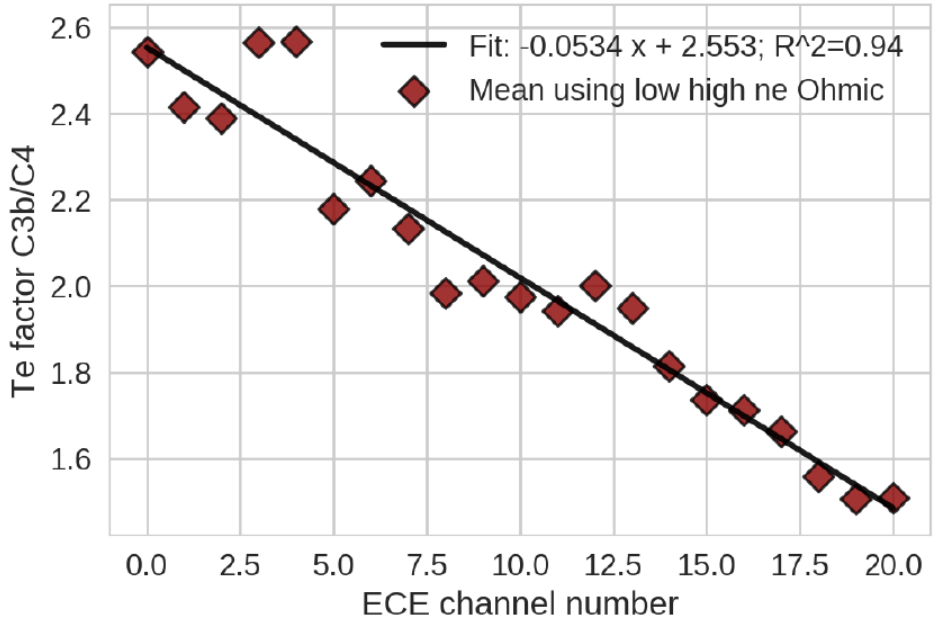
Sensitivity of Calibration to Wave-guide Type

- During previous campaign: systematic error in temperature measurements but not in calibration coefficient
  - Very similar coefficients between two campaigns
  - T_e too low by a factor of ~2 (after statistical and cross-diagnostic comparisons)

Issue in high power measurements!



- Solution found: attenuators in front of radiometer entrance inverted between O- and X-mode (band W vs. band F)
  - Nonlinearity introduced in the measurements