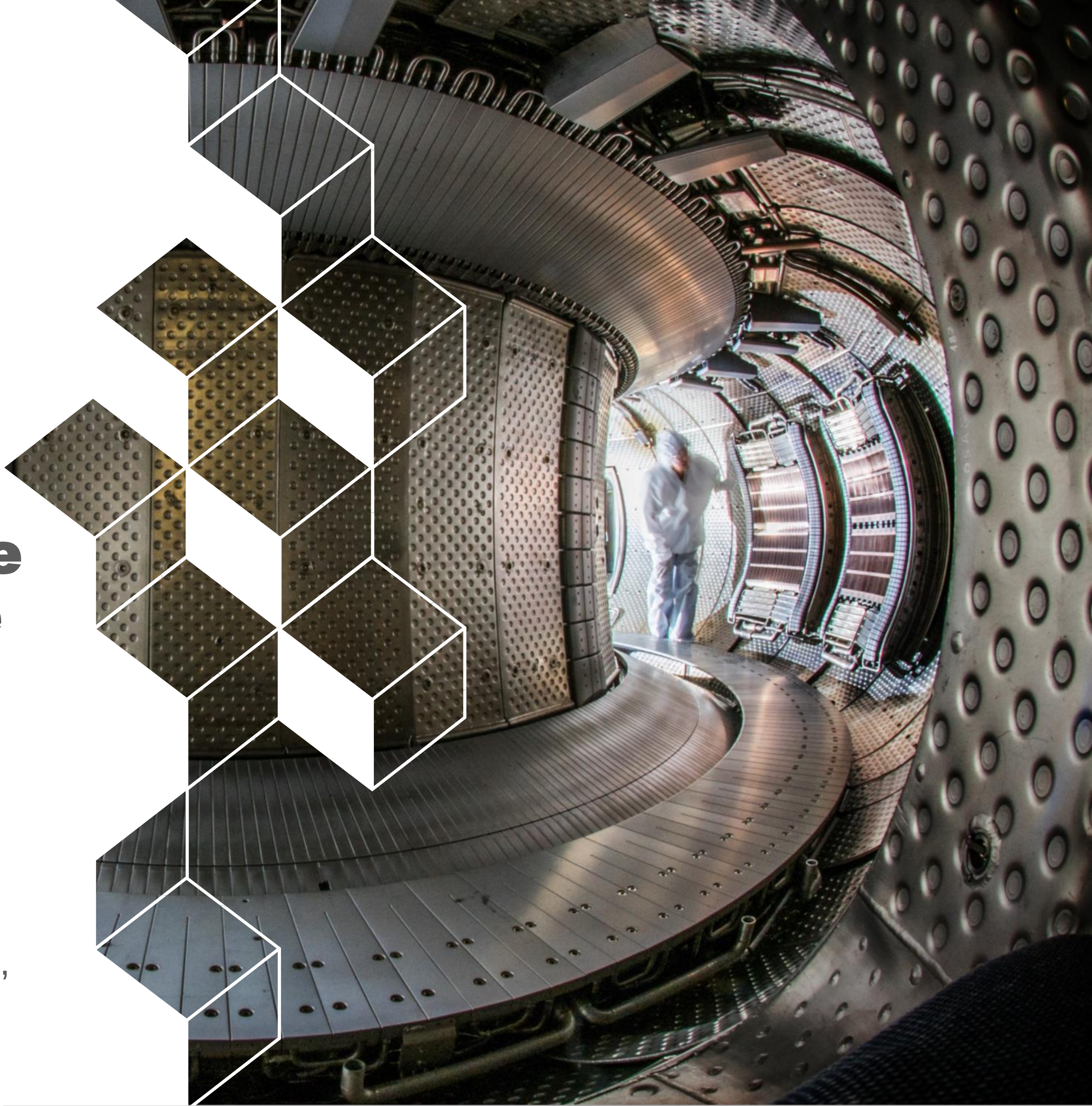
Lower Hybrid current drive long pulse operation state of the art on WEST



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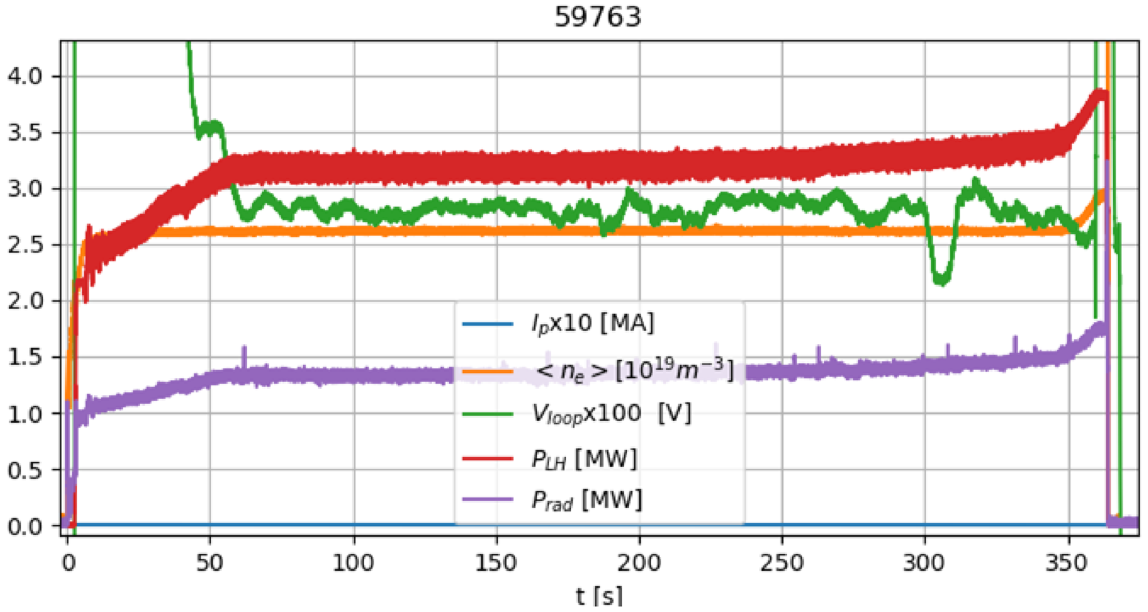
The LHCD system of WEST: a key system for high power and long pulse operation

- **World-leading class Lower Hybrid Current Drive (LHCD) system installed on WEST :**
  - Maximum LH power currently installed on a tokamak (9 MW/CW @generator)

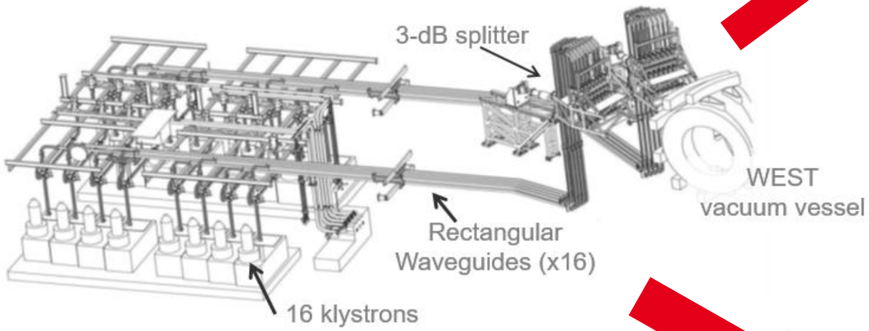
- Key system for:
  - **High fluence experiments** and characterizations of ITER-grade plasma facing units (divertor tungsten tiles, etc)
    - **WEST record** :
      - Maximum coupled LH power 5.8 MW

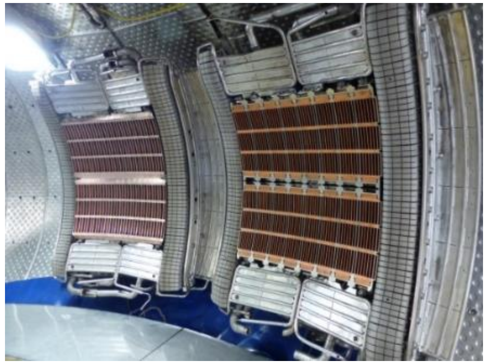
  - **Long pulse operation**:
    - **WEST record** :
      - 364 s with LHCD
      - 1.15 GJ
      - 3.2 MW injected



The LHCD system of WEST: a key system for long pulse operation

- The LHCD system is necessary to replace the inductive current in long pulse operation in WEST





▶ **2 launchers 7 MW/1000 s**

Each powered by 8 klystrons

- **Strong expertise of long pulses operations :**
  - System designed to support power for 1000 s
  - Fully **water cooled**
  - Real time **Cooper Impurity** and **IR monitoring interlocks** with power control loopback
  - Launchers position adjustable (~100 mm range) regards plasma boundary position

LHCD klystrons plant

▶ **Standard WR284 waveguides**
- Actively cooled (25-30 m)
- N2 pressurized @2 bar

▶ **16 klystrons @ 3.7 GHz with 620 kW/1000 s power capability each for plasma operation**

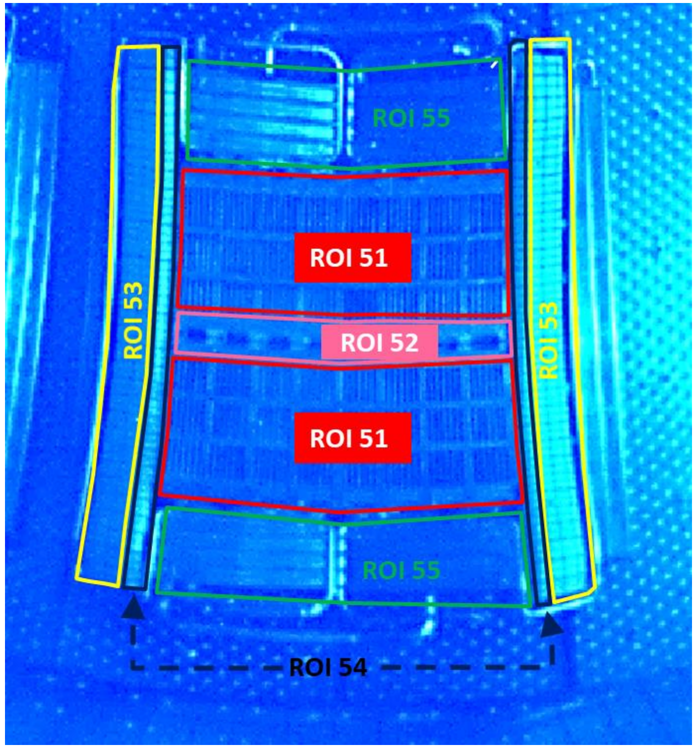
Still challenging! What can be improved:

To reach high-power long pulse operation up to 1000 s?

To better monitor the LH system and to further improve its reliability?

Interlocks for the safety of the LHCD system

- **Real-time protection of in-vessel components, including LHCD launchers:**
  - Feedback controlled LH power
    - Threshold on:
      - Copper impurity content from spectroscopy
      - Temperature on predefined Regions of Interest (ROI) from IR camera
    - New safety system for the LHCD launchers:
      - Automatic IR-based arc detection algorithm implemented for the next campaign, trained on previous campaigns

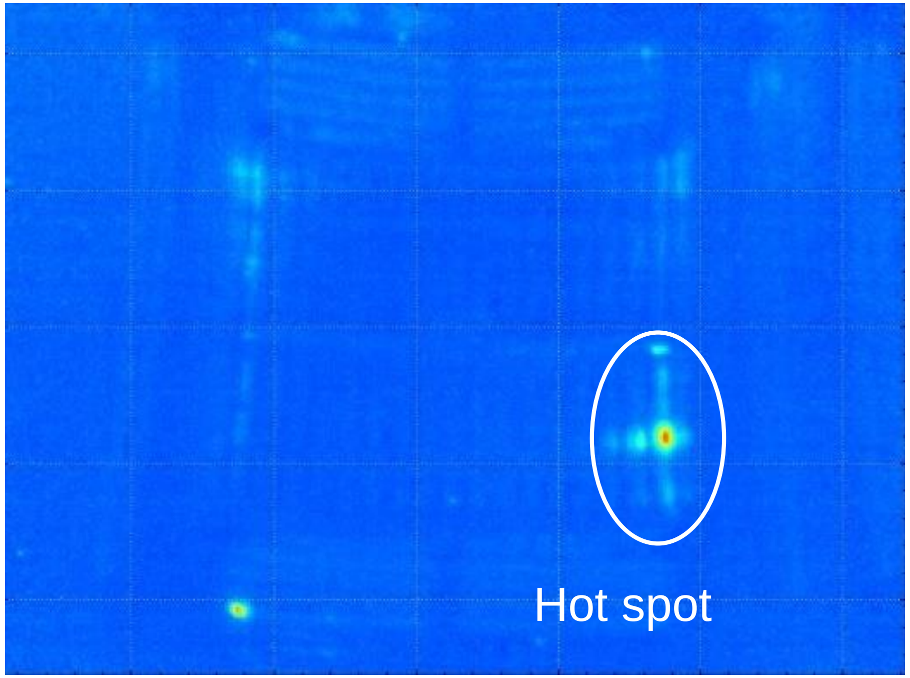


- **LHCD Power plant protection :**
  - Real-time control of the injected power interlock ⇒ threshold on reflected power
    - @ launcher level
    - @ klystron level
  - Arcs, vacuum, water flow rate, temps, filaments, focusing coils,… (**PLCs** for slow response security and electronic cards based on **EPLD for fast response** securities).

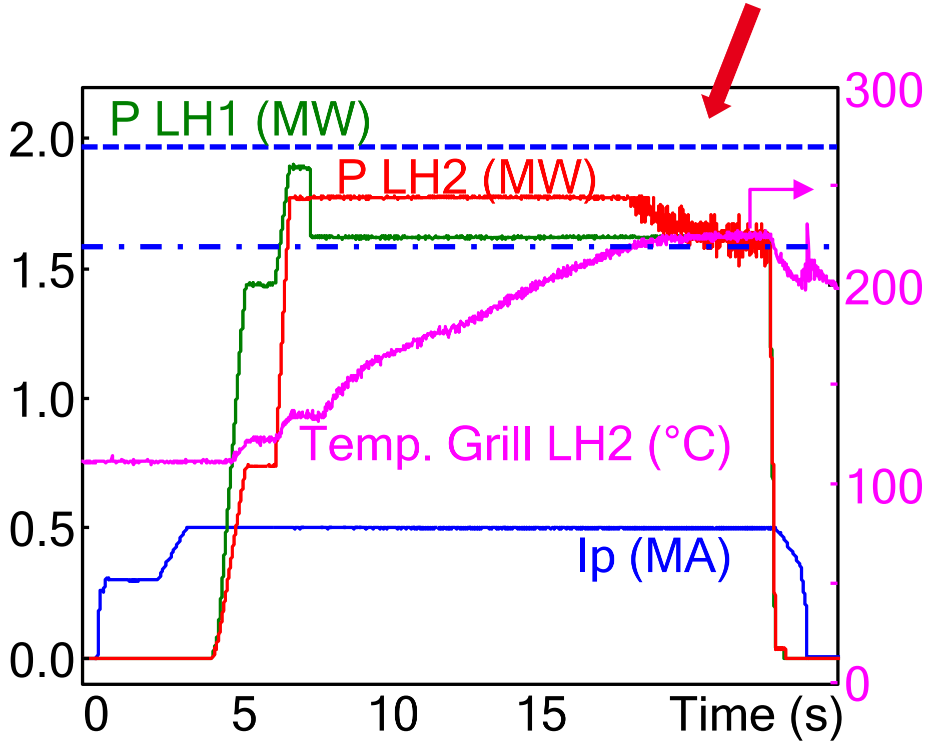
Interlocks for the safety of the LHCD system

- Example of **real-time protection** of the LH launcher (connected to the PCS) triggered by **IR measurement**

Reduced power to ensure T_{Grill} below threshold



IR view of the launcher grill



Content

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Optimization of the LHCD system for long pulse operation

- 3 main focusing points

Maintain full performance of the klystrons

Optimize the cooling water system

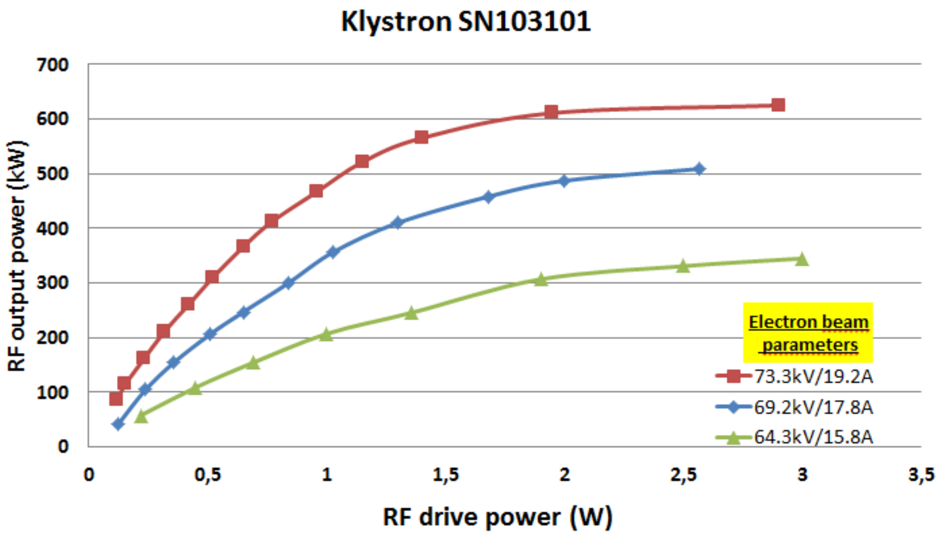
Improve the power plant reliability

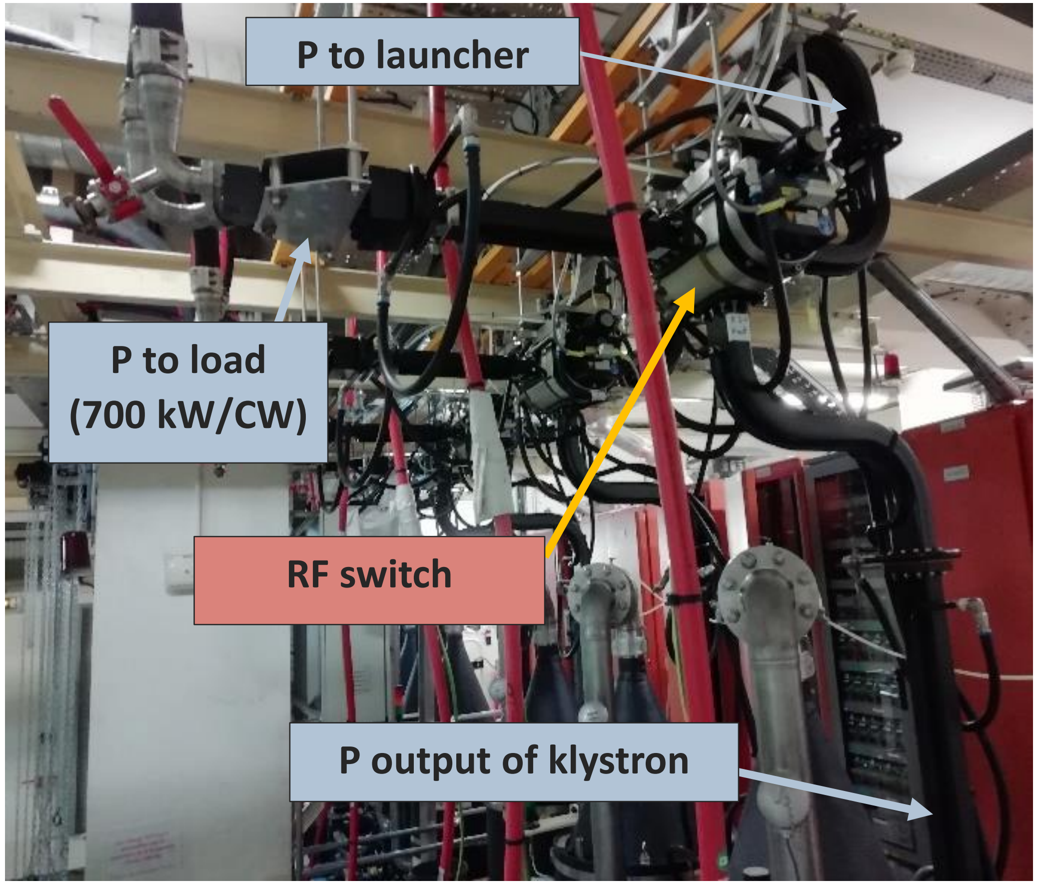
Maintain full performance of the klystrons

- **Maintenance during WEST shutdown**:
  ⇒ Regular RF calibrations, tests of klystrons on matched load (pulse duration up to 500 s)

- **RF switch allow selecting the klystron operating mode:**
- *Tir sur plasma* : power is directed to the Tokamak
- *Tir sur charge* : power is directed to an actively cooled load (250 l/min) - only one klystron is tested at a time in this mode

- **Load cooling circuit** is equipped for **calorimetric power measurements** (flowmeter, load inlet and outlet temperatures)
  ⇒ Characteristic curve for each klystron:

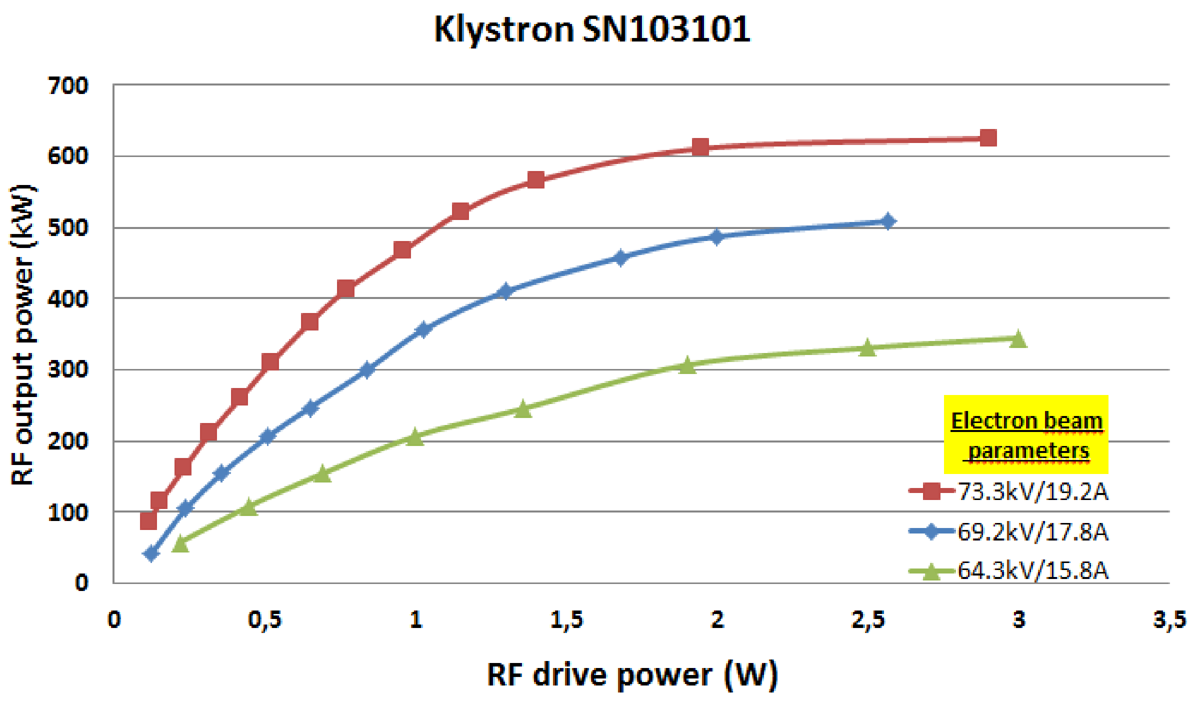




Optimize the cooling water system

- **Challenges to go to 1000 s**
- **Cooling water loop optimization:**
  - Minimize the dissipated power for each klystron:

⇒ minimize cathode voltage of klystron at the lowest value possible with respect to the max power requested



Example : 4 MW request of LH power

⇒ 250 kW x 16 klystrons

- **Power dissipated in water loop (per klystron):**
  - Vk = 65 kV ➔ 1 MW
  - Vk = 70 kV ➔ 1,2 MW
  - Vk = 73 kV ➔ 1,4 MW

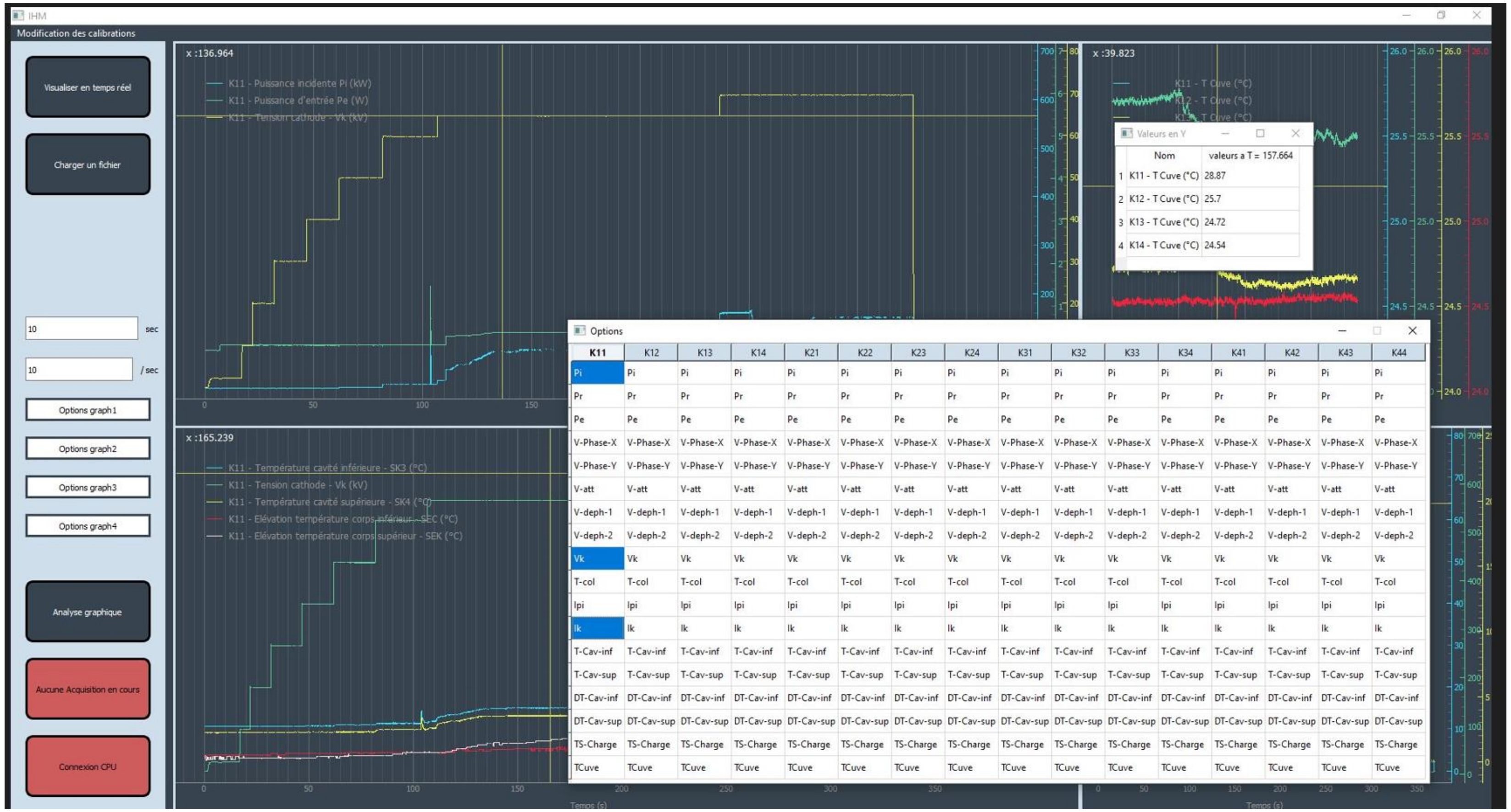
➔ **Saving up to 6.4 MW !**

Improve the klystron plant reliability

- New klystron plant **data acquisition system** (288 channel @1KHz)

- In the **control room**:
  - Monitoring klystron performance
  - Monitoring klystron safety signals
  - Better post-pulse analysis

- Between experimental campaigns:
  - Build a complete multi-parameter database for long-term klystron proctoring
  - In the future: AI database analysis for klystron failure prediction



- Examples:
  - Cavity temperature ➔ Beam focus issue
  - Ionic pump current ➔ vacuum quality /tube integrity
  - RF input power ➔ Gain evolution
  - Collector temperature ➔ Calorimetric measurement

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Conclusion

- LHCD is a complex system requiring constant monitoring of klystrons and installation to ensure :
  - performance, availability and reliability on plasma experiments
  - Expertise and knowledge of the technical team

- Local acquisition system improvement will allow us to :
  - monitor in real-time the safety-relevant parameters of the 16 klystrons
  - Record automatically all klystrons parameters. The analysis of theses data should be helpful to anticipate and predict some issues or performances degradation of klystrons in the future.

- System ready for the next campaign and for moving towards the 1000 s pulse.
  (Winter is coming : best condition for the water cooling loop efficiency with lower temperature outside ☺ !)

Thank you for your attention

The LHCD klystron plant

- **LHCD klystron plant :**
  - **16 Klystrons reparted in 4 modules** equiped with :
    - HV solid state switch (open 100 kV/25 A in ~5 µs)
    - Dummy load 700 kW/CW
    - RF switch
  - **4 HVPS** 80 kV/100 A (32MW !)
  - **Dedicated cooling water loop**
    - 27 MW exhausting capacity (@540 m^3/h)

- **Klystron TH2103C :**
  - Frequency : 3,7GHz
  - RF Gain > 50 dB
  - Pmax RF: 700 kW/1000 s
  - Efficiency < 40% (Pelec = 1.7 MW)

TH2103C klystrons: operating principle

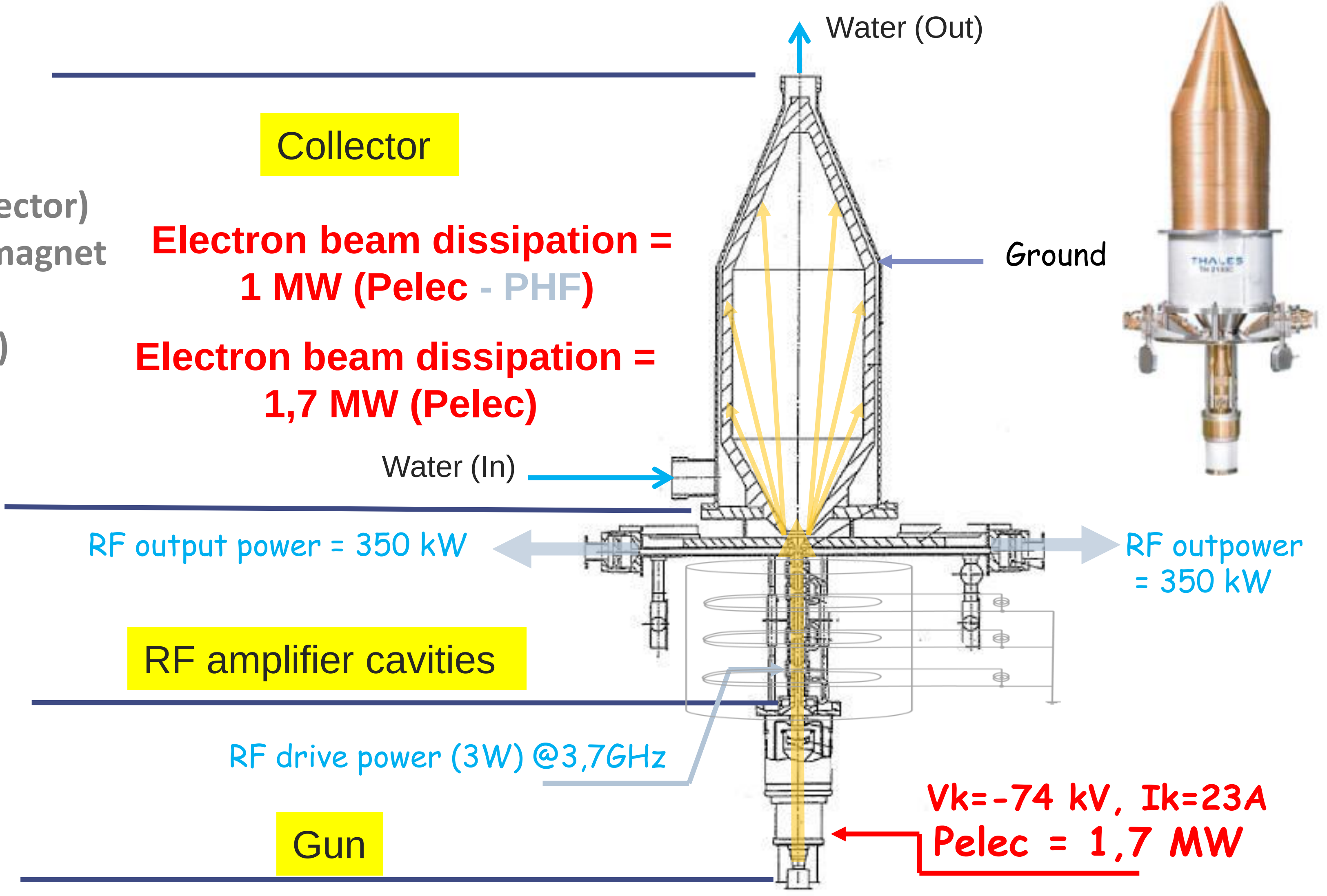
High Frequency amplifier

- Filament heating: electron emission
- Electron acceleration (between Vk - collector)
- Beam focusing (magnetic field - electromagnet around cavities)
- Gain Amplification HF > 50dB (cavity x 4)
  - Efficiency ~40%

Performances TH2103C :

- HF Frequency : 3,7GHz
- Pmax HF: 700 kW / 1000 seconds

~ 900 ch…



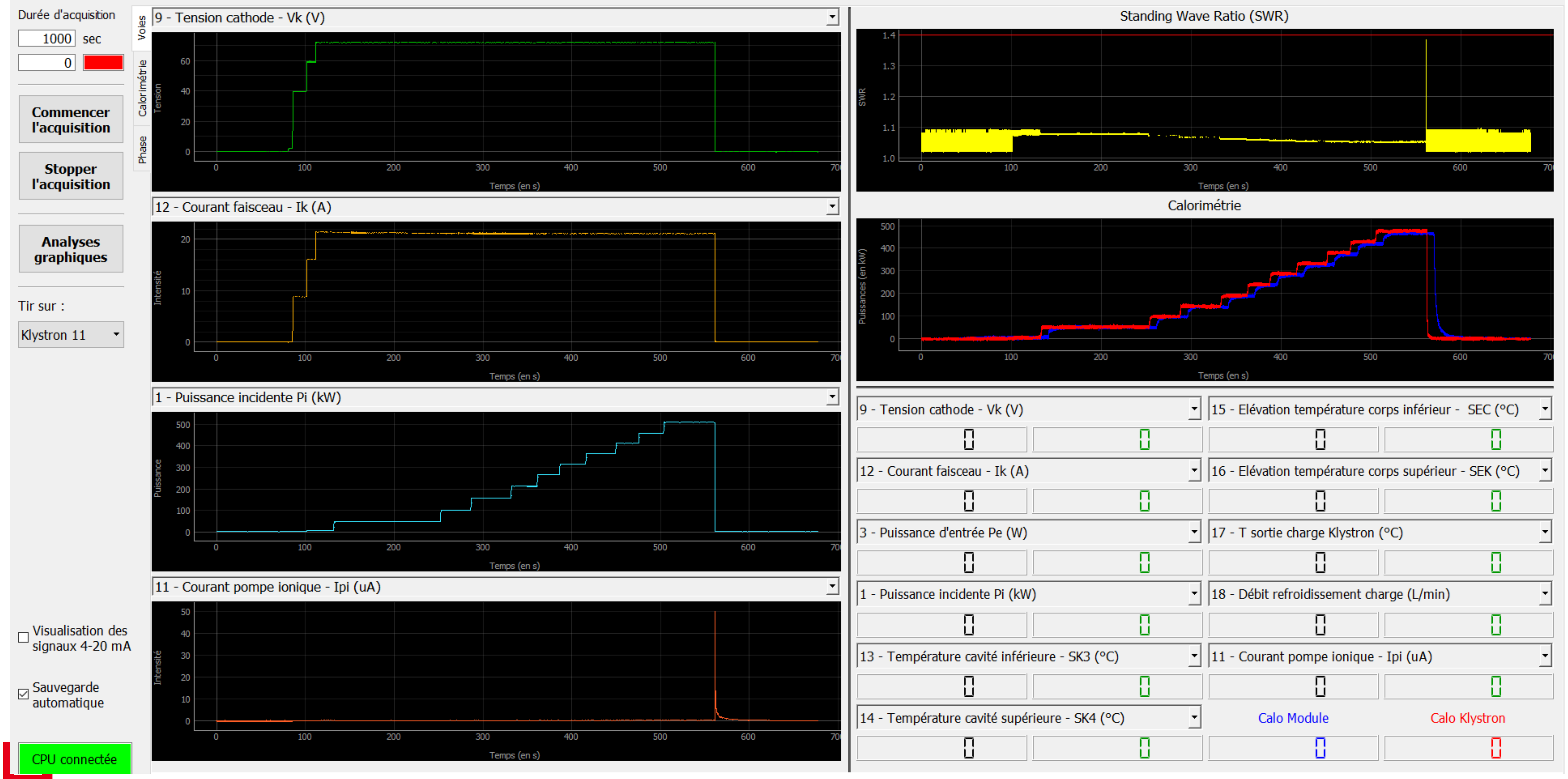
LHCD System power plant

Sub-assemblies required for klystron operation :

- Power supplies (coils, filament)
- High Voltage Fast switch HT (toff < 3µs)
- HF racks: 3.7GHz source, regulation, preamplification
- Fast security (based on EPLD)
- Sensors (PHF, t°, flow, U, I,…), arcs detectors, conditioners
- PLCs

Racks for one module of 4 klystrons

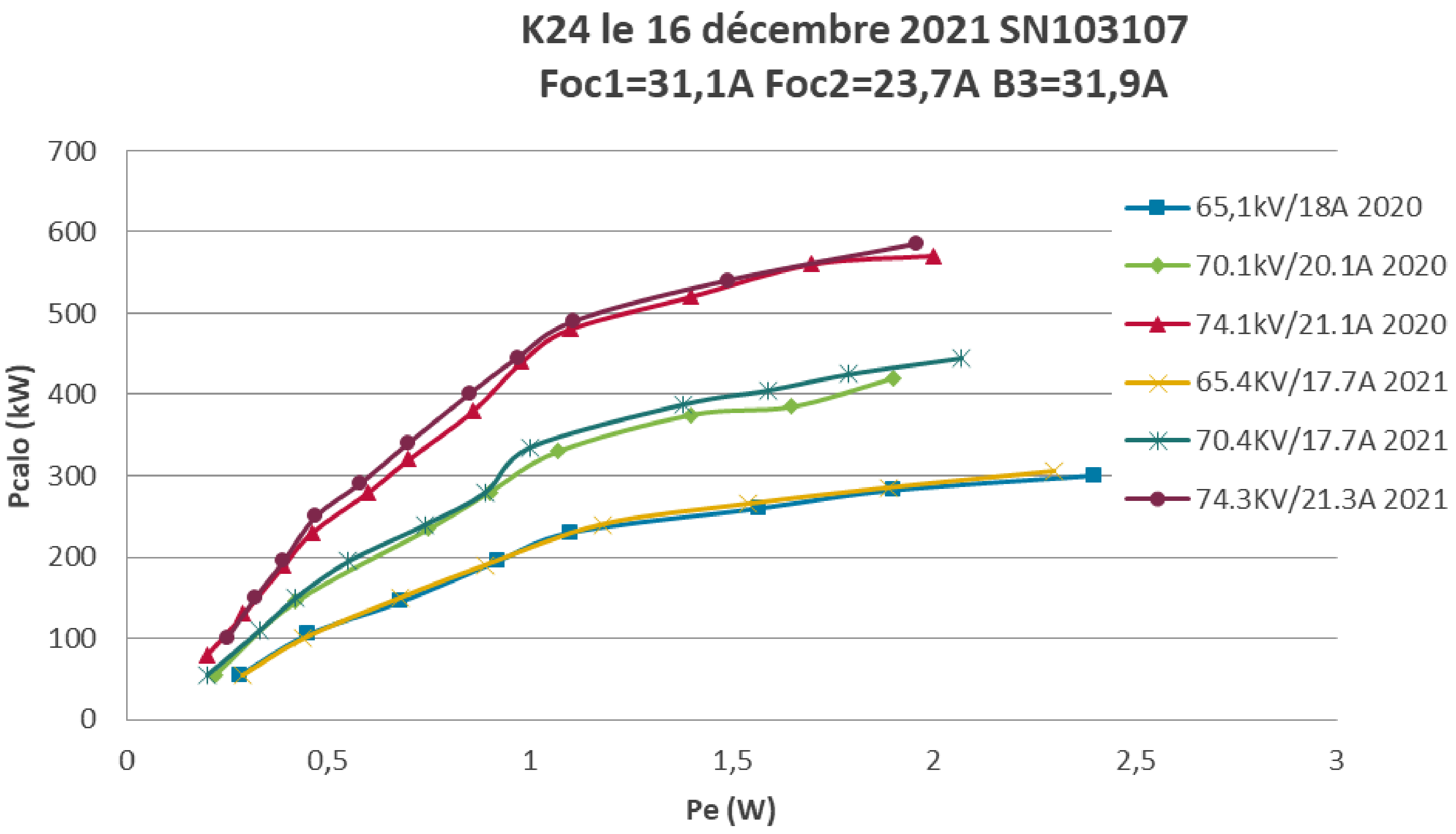
Data acquisition for a test on matched load during 500 s



Tests on matched load

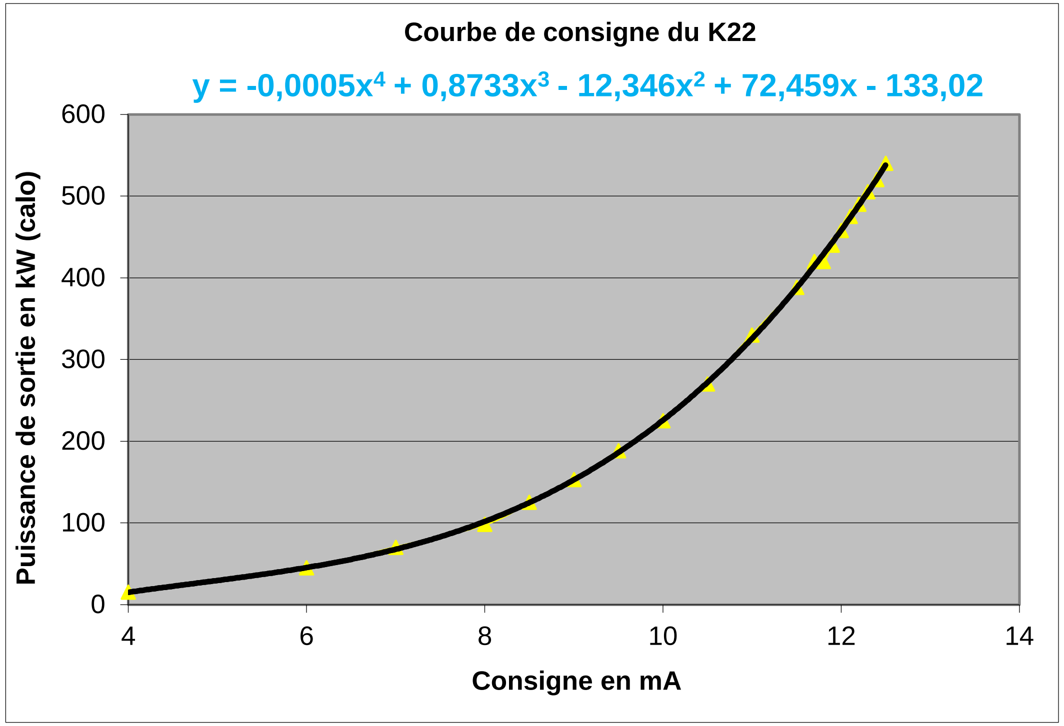
- **Klystron gain curves:**

  - changes compared with previous years
  - determining the maximum output power available on plasma



Tests on matched load

- calibration: power setpoints vs. actual power measured by calorimetry.



- Update calibration coefficients :
  - in DHYB diagnostics (for plasma mode)
  - In PLCs source code (for matched load mode)

On plasma (HF measurements and setpoints sent from DHYB) :

- The klystron output power (blue) corresponds to the setpoint sent by Plasma Control System (red).
  - in green: power coupled to plasma -10% losses (lines and reflected power).