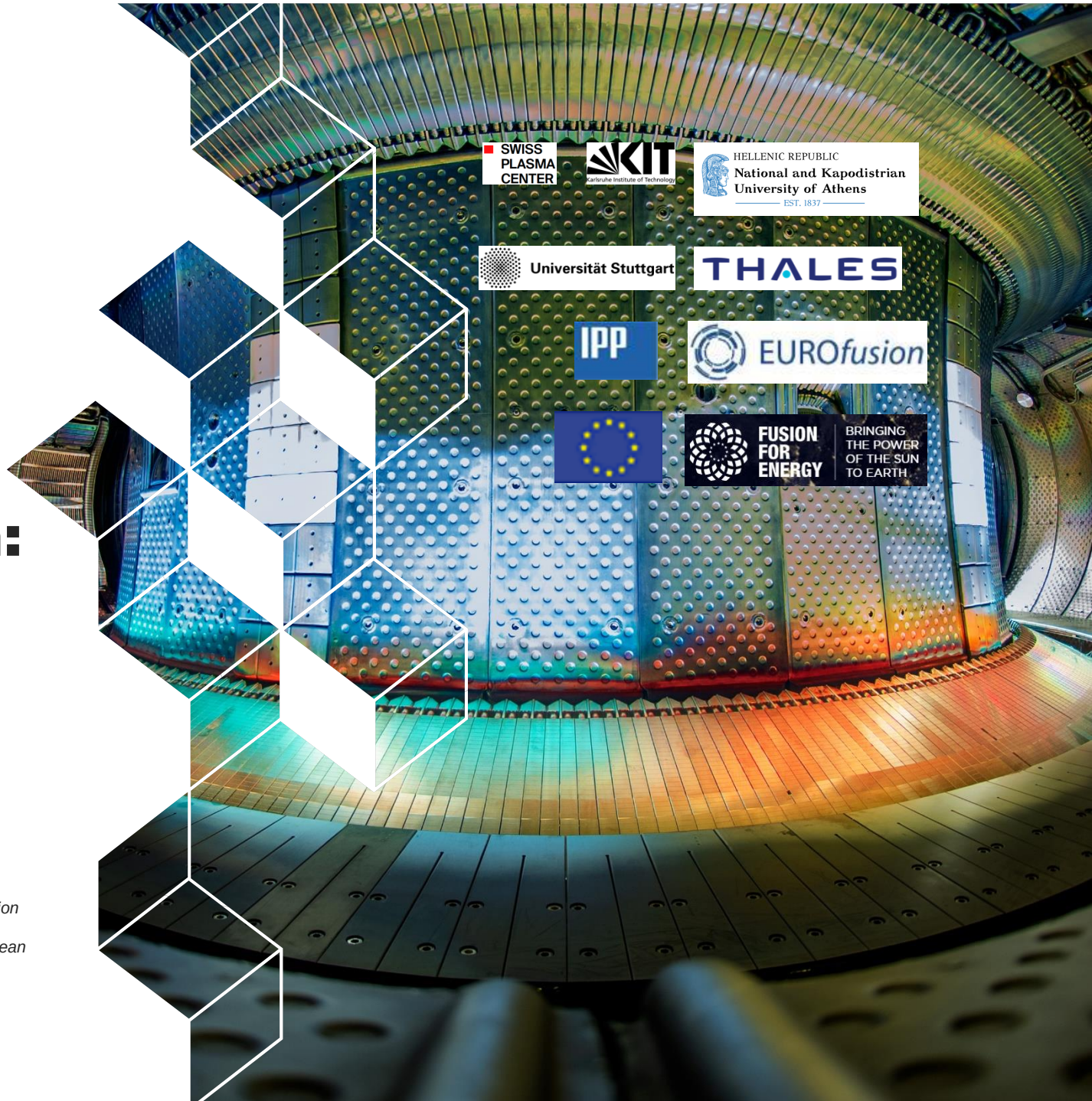
Deploying the WEST Electron Cyclotron System: Performance, Challenges and Lessons Learnt

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* see http://west.cea.fr/WESTteam

Special thanks to WEST partners
KIT, Swiss Plasma Center, IPP, F4E, ASIPP

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Outline

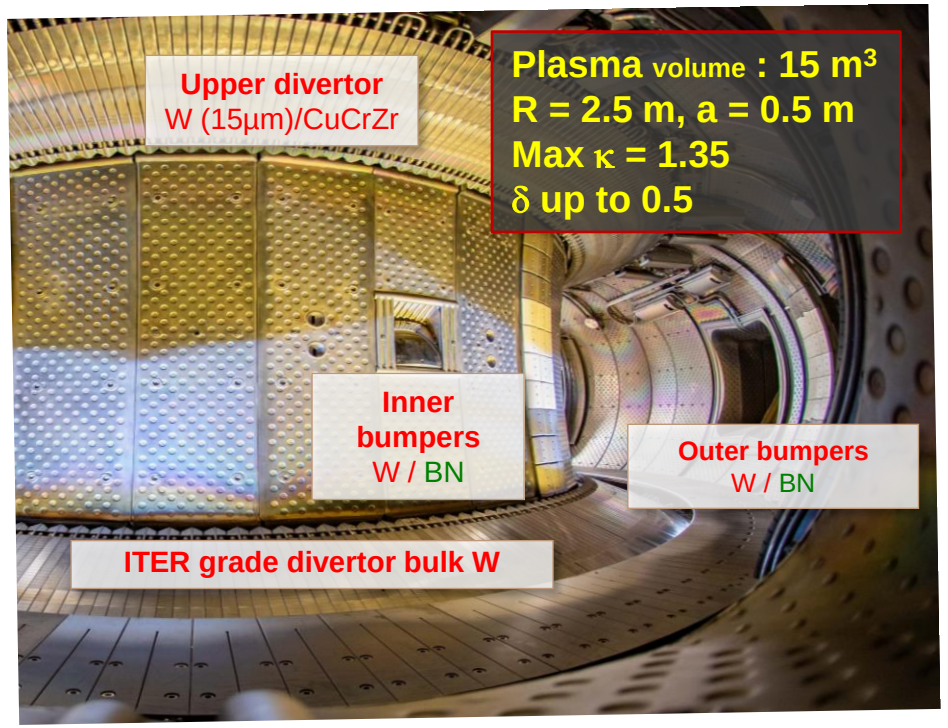
1. EC project for WEST
2. Deploying and commissioning the platform
3. Test of WEST gyrotrons
4. Recent plasma experiments with EC
5. Conclusions

1. EC project for WEST

Why an EC system for WEST ?

WEST is a long pulse operation tokamak

- Superconducting magnets, nominal magnetic field 3.7 T
- Fully actively cooled plasma facing components (W monobloc, W coated components)
- Heating & CD: RF sources only long pulse operation compatible



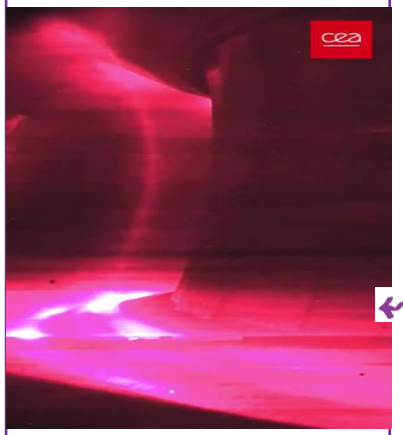
A new EC system for WEST will

- Secure ramp up phase, increase T_{e0}
- Control W tungsten accumulation
- Give margin for H-mode operation (more RF power)
- EC wall conditioning and EC assisted start up (in vessel component protection to be improved)
- Broaden WEST operational domain

[J. Bucalossi 2026 This conference]

EC for WEST

Plasma



- Electron heating
- Current drive
- Control W impurities

Launcher

Steerable mirrors
3-lines



Transmission line

63,5 mm corrugated
transmission line
+ Valve VAT

Distribution/Switches

Long pulse dummy load

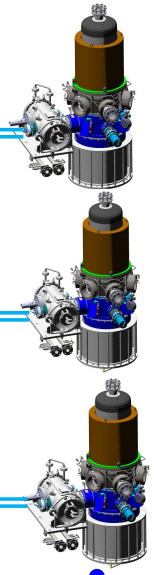
Sw4

Sw3

Sw2

Sw1

Gyrotrons



GYRA1

GYRA2

GYRB3

CODAC
Control/Command, Data acquisition
Fast interlocks

HVPS
2 High Voltage Power Supplies
(-55 kV/90A)

3 EC injection lines into the plasma

Up to 3 MW 105 GHz

4 operating modes

Integrated cooling, vacuum, power supplies systems, auxiliaries

WEST gyrotron specifications

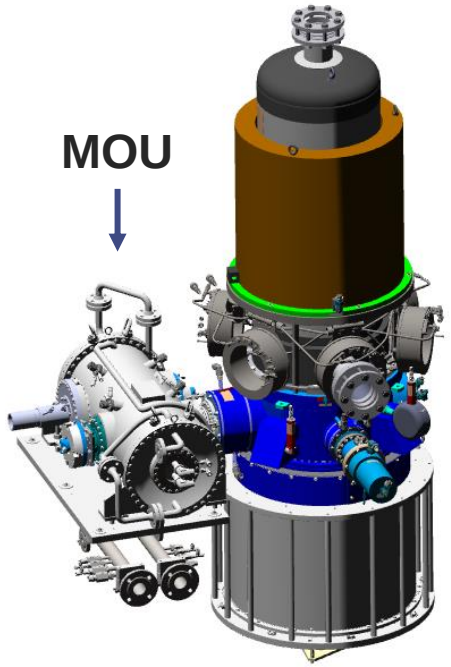
Gyrotron design by KIT & NKUA

Adapted from existing TH1507U W7X gyrotron

Gyrotron Parameters	
Parameter	***Design Value***
Operating frequency	**104.92 GHz**
Operating cavity mode	$TE_{-20,8}$
Magnetic field	4.13 T
Cathode voltage	-55 kV
Body voltage	+23 kV
Efficiency	> 40 %
Beam current	45 A
RF power	**1 MW**
Gaussian mode content	98.85%
Pulse duration	**1000 s**

O-Mode P_{abs}/P_0= 95,7%
ρ~ 0,1

Gyrotron TH1511



[L.Delpech 2023, FED 186]

EC project

- Three gyrotrons
- One dummy load
- Two HVPS

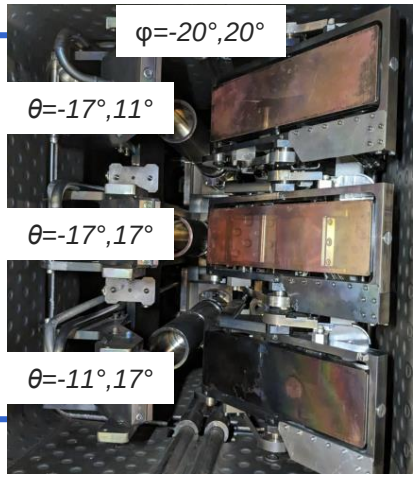
⇨ Constraints

- Assembly start : Nov 2023
- Integrated commissioning start : Nov 2024

WP1
Platform
3 gyrotrons

WP2
Launcher
3 steering mirrors

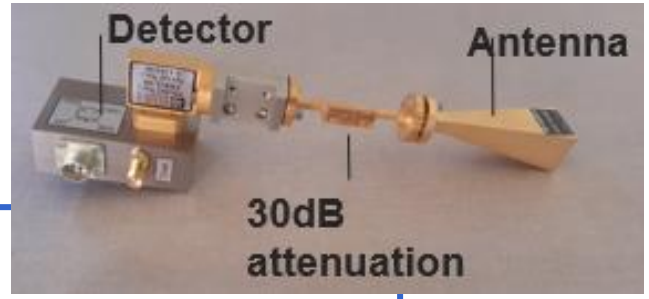
- Water cooled steering mirrors
- Limited to 1MW/10 s per line
- ECRH and ECCD possible
- **In operation since April 2025**



WP3
Safety
Security

- Gyrotron = X-Ray generators
- Documentation for French Nuclear operator (ASN) : Jan 2022
- **Agreement from ASN for detention and use of 3 gyrotrons March 2024**

WP4
Tokamak protection



- Three sniffers installed to protect microwave diagnostics
- **In operation since April 2025**

2. Deploying and commissioning the platform

Design of the WEST Gyrotron Test and Operation CODAC system

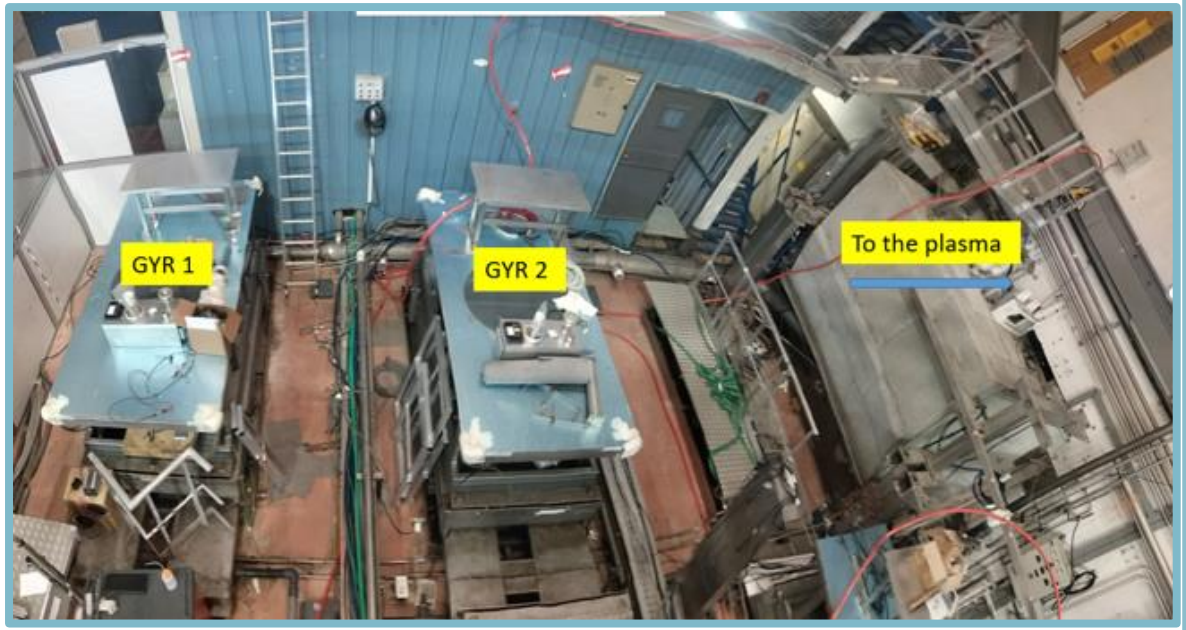
CODAC designed for 4 operating modes

Objectives	*Operating mode and functions*
Gyrotron qualification	**Filament off** (1 Gyrotron): test the voltage withstand, test the HVPS sequence **Open space** (1 Gyrotron): gyrotron qualification in short pulse operation (< 15 ms) No transmission line connected **Dummy load** (1 Gyrotron): gyrotron and MOU conditioning, long pulses 1MW/1000s
Plasma Experiments	**Plasma** (1 to 3 Gyrotrons)

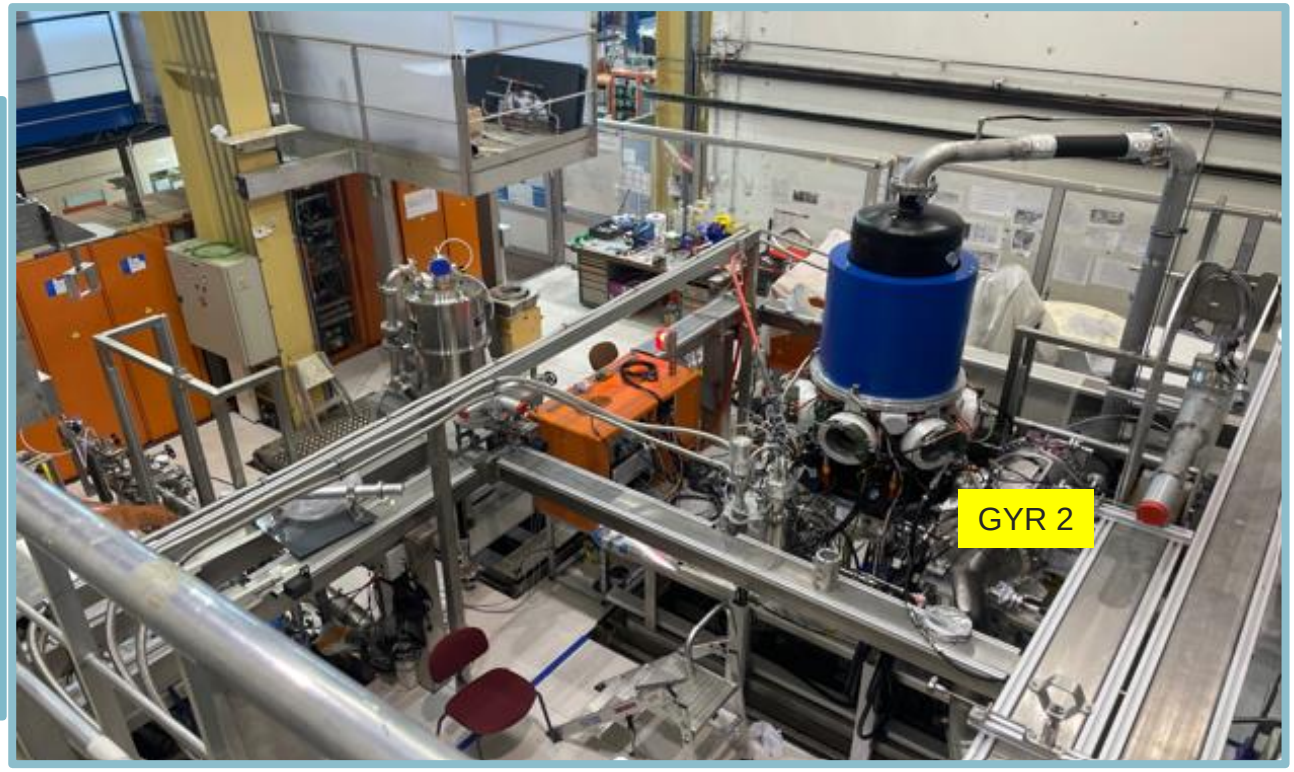
All gyrotrons operated in the same mode	**> 3500 variables Programmable Logical Controller**	**1H00 to change operating mode**

Evolution of the platform

November 2023



November 2024



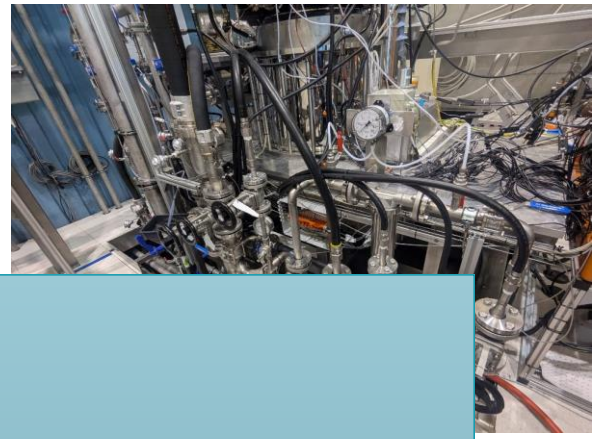
12 months from scratch to a gyrotron qualification ready position

Commissioning of the EC platform

Sep 2024
- Integration of the gyrotron SN001

Oct 2024
- MOU and cooling pipes connexion





Nov 2

Jan 2

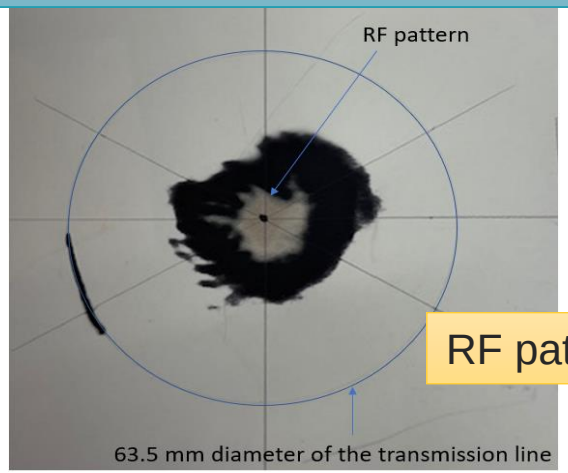
Feb 2

4 months to fully validate the first gyrotron position

Mar 2025
- Tests in open space

  First RF pulse

20th march
t = 3.7 ms
$V_{cathode}$ = *49.6 kV*
V_{body} = *17.7 kV*
I_{beam} = *34 A*



RF pattern



TL alignement

April 2025: First EC pulses on plasma few ms

Commissioning of the WEST EC platform

Lessons learnt

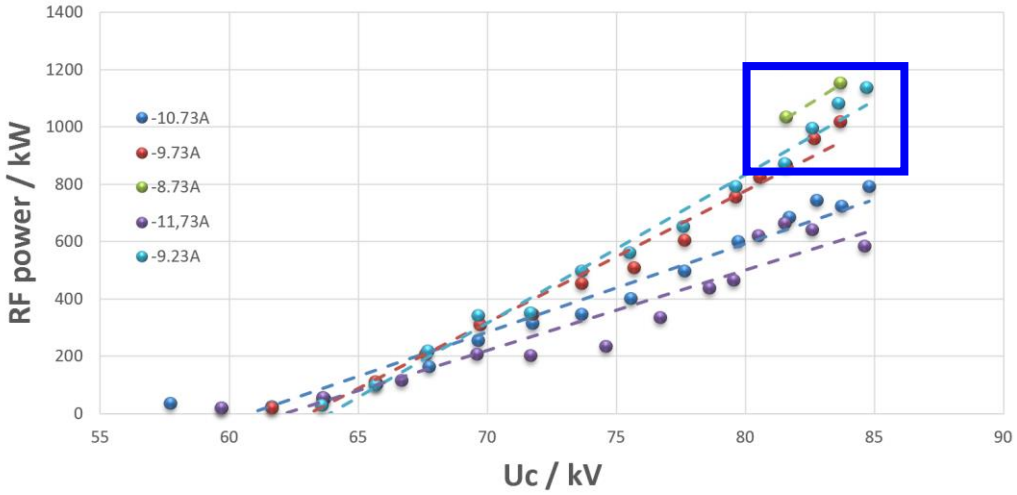
- Time to commission complex systems is always underestimated
- Improve efficiency during commissioning implies
  1. Maximize intermediate validation tests before integrated commissioning: identify issues
  2. Optimize measurement points to support failure analysis and built a valuable data base
  3. Low turn over team from design to commissioning ensures strong systems knowledge
  4. Ensure the core team remains involved throught the commissioning phase
  5. Maintain close contact with experts to avoid repeating known mistakes
- WEST EC platform - Commissioning phase (TRL 8) **VALIDATED**
- WEST EC platform - Consolidation phase (TRL 9) **ON GOING**

A mature system still needs a consolidation phase before entering routine operation

3. Tests of WEST gyrotrons

Validation of the gyrotron Radio Frequency (RF) design in KIT–FULGOR SN001- *Jun 2024*

Optimisation of the magnetic field profile to reach 1MW



***Courtesy** T. Rzesnicki*

TH1511 FULGOR
KIT test bed



Validation optical parameters

- Beam waist diamond-disk window: ~ 20 mm
- Beam pattern: centered on the diamond window

Validation in long pulse operation

- Max. Efficiency (P_{RF}/P_{elec}) ~ 46% 1 MW RF power)
- Operation in depressed collector compatible with WEST HV PS (max. V_k=-55 kV, I_{beam}= 45 A)

1MW/5s – Repetitive pulses validated → **Manufacturing of two gyrotrons triggered**

Qualification of SN002 in WEST platform
(Nov 2025-Feb 2026)

Validation of SN002 short pulse

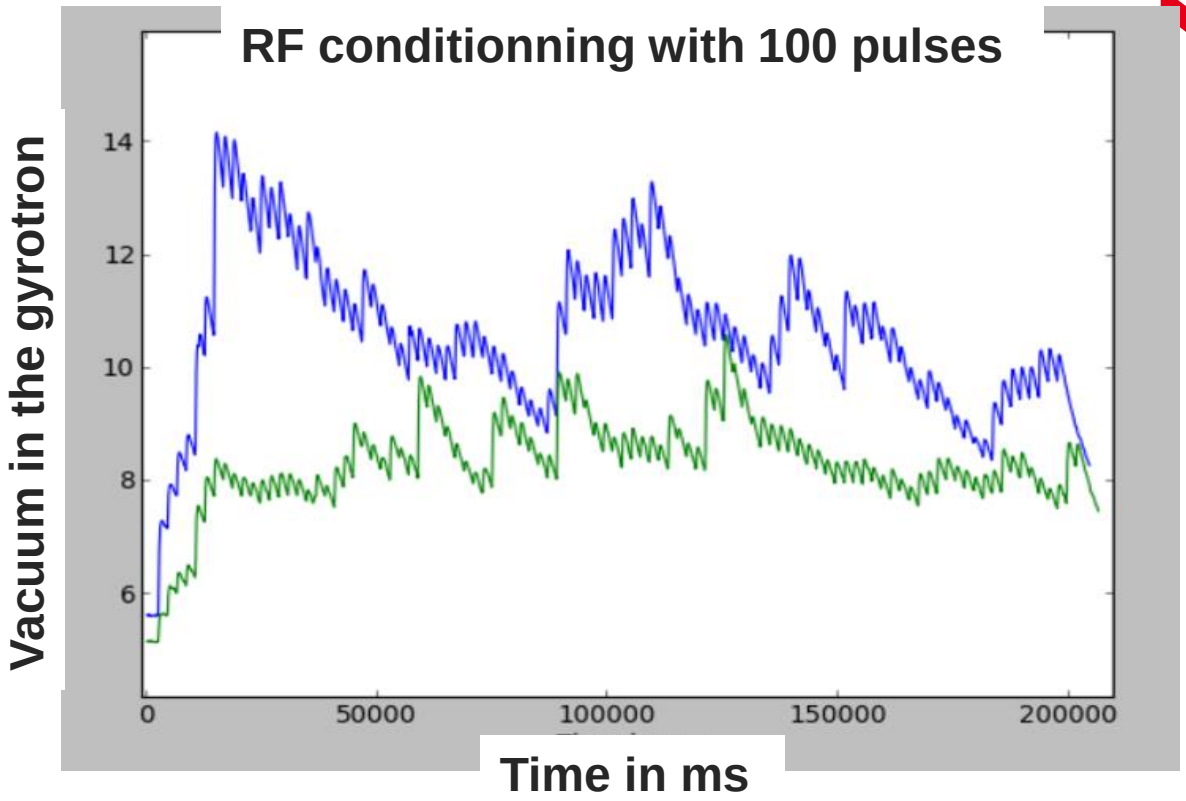
- Conditioning the cathode (5 d)
- Mapping in short pulse (3 d)
- Beam content and deviation analysis (2 d)
- Adjusting MOU, Assembly + Beam Pattern (5 d)

3 weeks

Validation of SN002 long pulse (Dummy load)

- RF Conditioning (Multi-pulsing mode)
- Mapping (Imain, Igun)
- Power balance cross check (300 kW/40s)
- Diode mode 900 kW/1000 s
- **10 repetitive pulses 900 kW/5s**

4 weeks



NUMBERS

- 3273 pulses
- 5658 seconds of pulse duration = 94 mn
- **2893 seconds of RF pulse = 48 mn to reach 900 kW/5s**

Failure of the Diamond Window SN002

Failure conditions

- 900 kW/4.8 s (after 10 pulses)
- No outgassing in the gyrotron/ No pressure increased in the MOU/TL
- No arc interlock on the diamond window

Consequences

- Pollution with silicon oil in the MOU, pumping system, transmission line and gyrotron → THALES switched the coolant for the windows (Diamond and Saphire) from silicone oil to water

Platform Checks

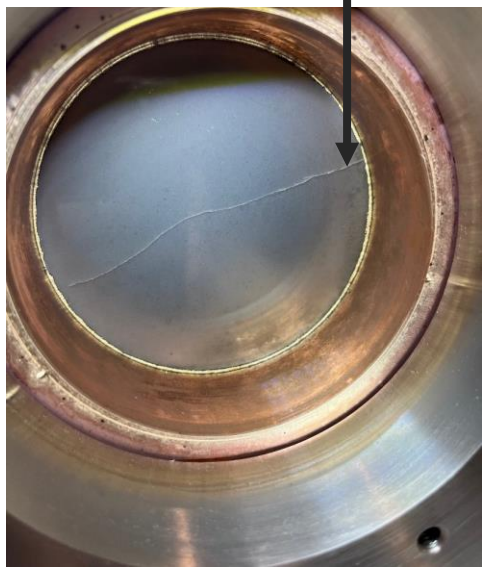
- Interlocks ✅
- Visual checks MOU ✅

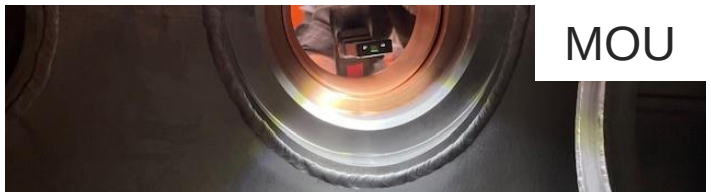
Supplier analysis

- Visual check of the disk : no arcs
- No sign of local overheating on flanges

Root cause unknown
Fragility if the DW
External cause

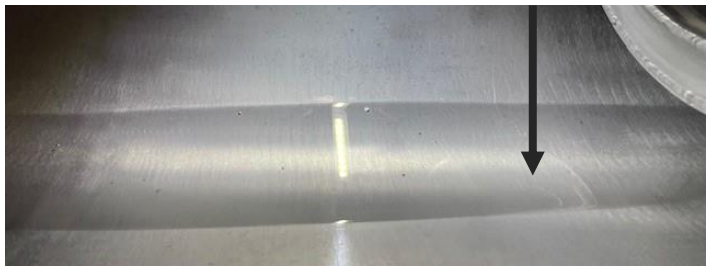
Large crack on the disk





MOU

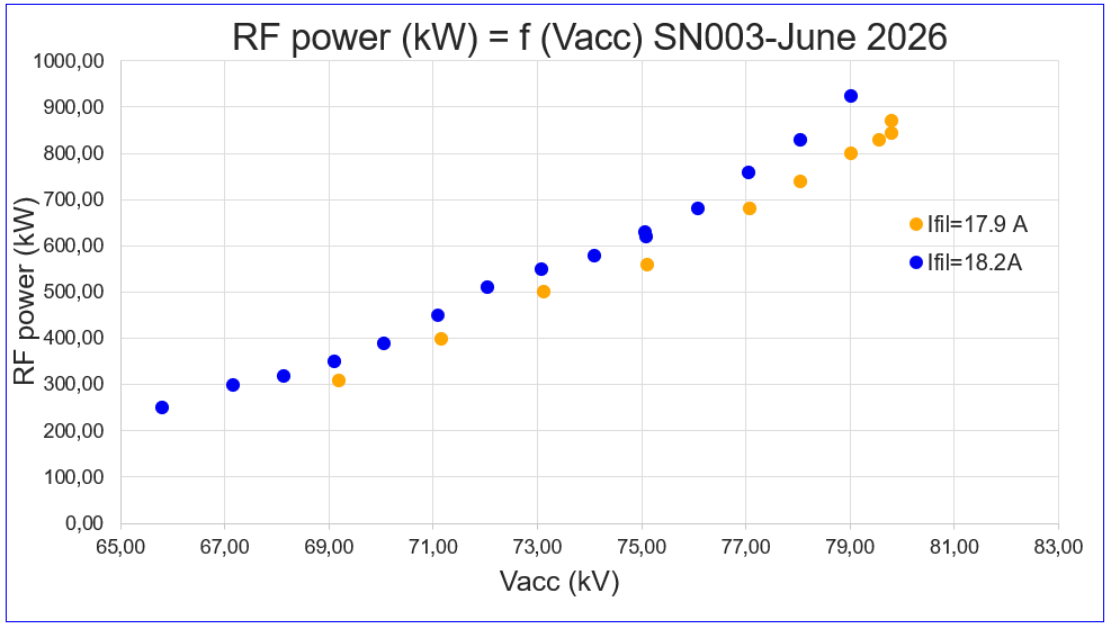
Loss of coolant circuit tightness



Results with SN003 FULGOR/WEST

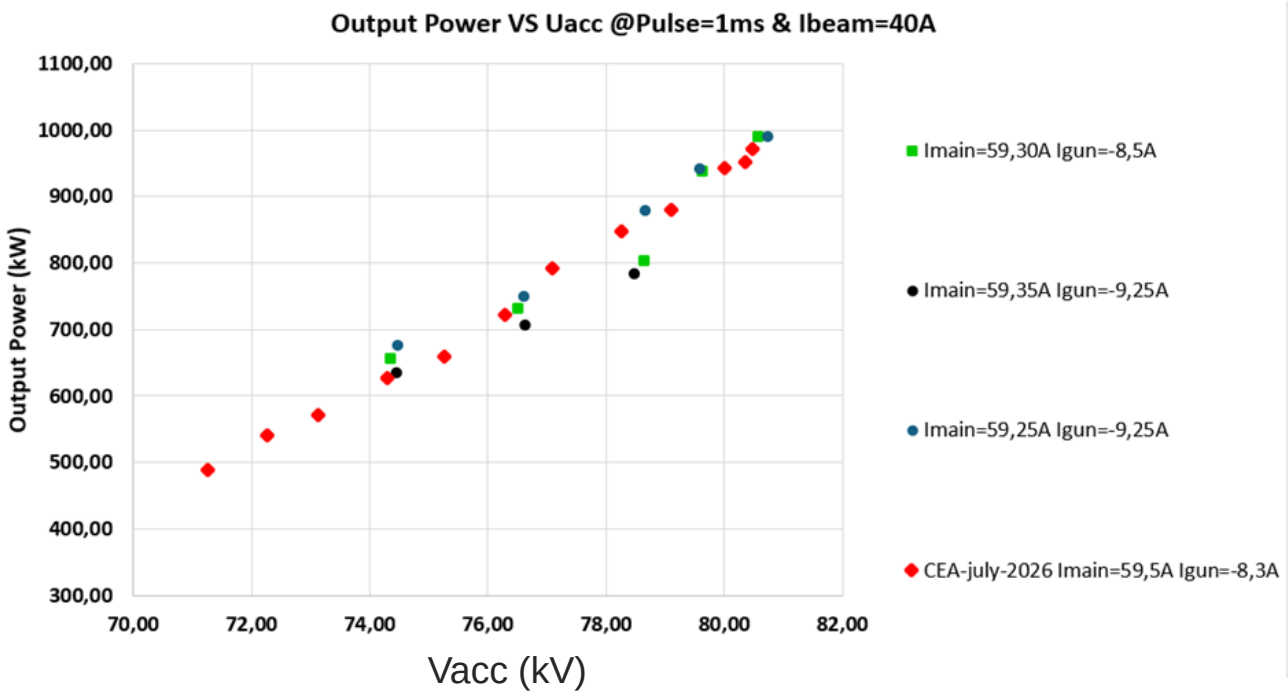
Validation of SN003 in FULGOR

- Mapping (Ifil, Imain, Igun)
- **Repetitive pulses 1MW/60 s achieved** (June 2026)



SN003 in WEST

- Mapping SP (July 2026): results close FULGOR
- Connexion transmission line to launcher
- Plasma experiments 28th-30th July 2026



WEST gyrotrons: Tests and Milestones achieved

1st Gyrotron

- Validation the **RF design** : **1MW/5s**
- Validation of FULGOR test bench
- Validation of WEST platform (Sep 2024-Oct 2025)

2nd Gyrotron (Nov 2025-Feb 2026)

- Full qualification a of gyrotron in WEST platform
- **1MW/5 s** achieved

3rd Gyrotron (Since July 2026)

- Qualification of the gyrotron in FULGOR: **1MW/60s**
- Integration in WEST platform/short pulse commissioning/connexion to the launcher (1 month)

WEST platform: 5 gyrotron installations/4 gyrotron removals completed in 2 years
Build strong hand-on experience

Gyrotron status on WEST sep 2026

Gyrotron validation

- 3 gy
  Der
  Sta
  Bea
- Stro
  Loa
  com
  THA
  of S
- Ess

SN003: ready for plasma operation

SN001: ready to start qualification

SN002: under reparation in THALES



4. Recent plasma experiments results with EC

Recent results: EC plasma experiments

Settings:

Upper mirror line

Pure ECRH

$\theta_L = -10°$, $\phi_L = 0°$

Best polarization (April 2025)

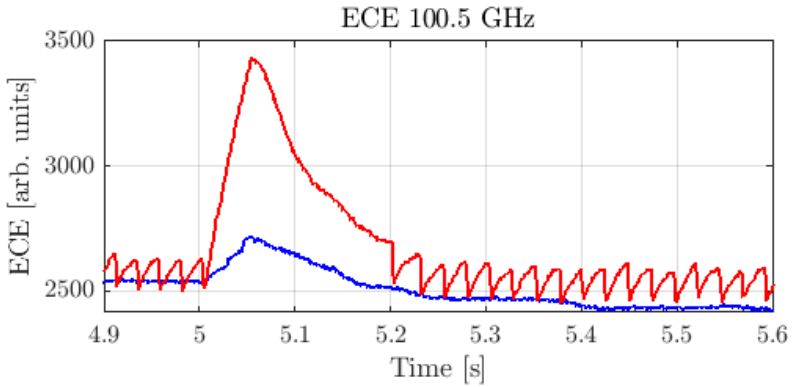
O-mode: $\phi_1 = 76°$, $\phi_2 = 92°$

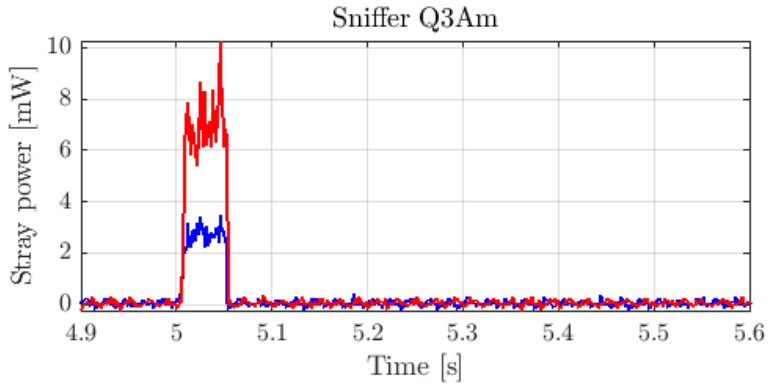
Results:

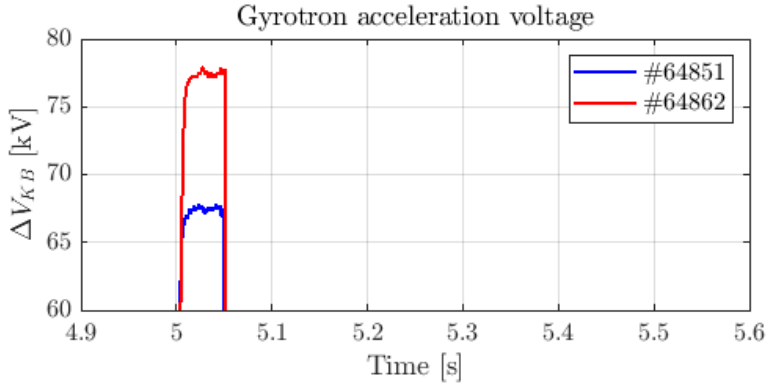
Increase power up to 800 kW

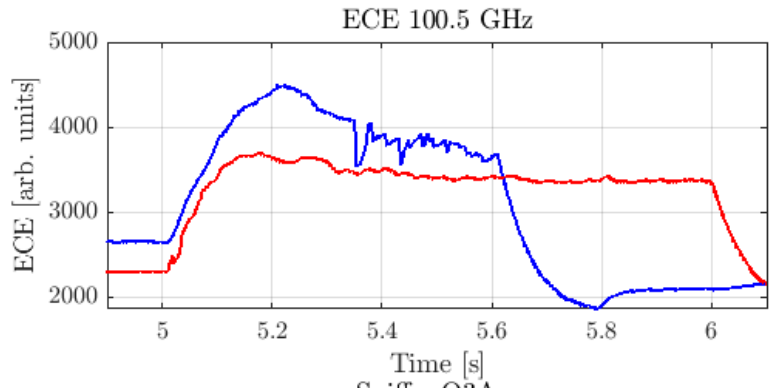
T_e increased by factor 2

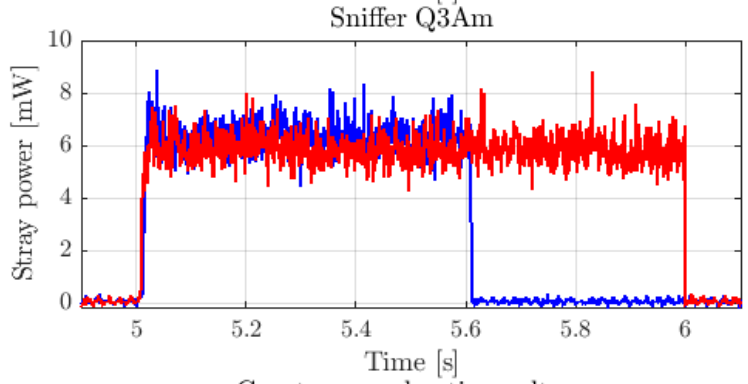
Increase pulse length

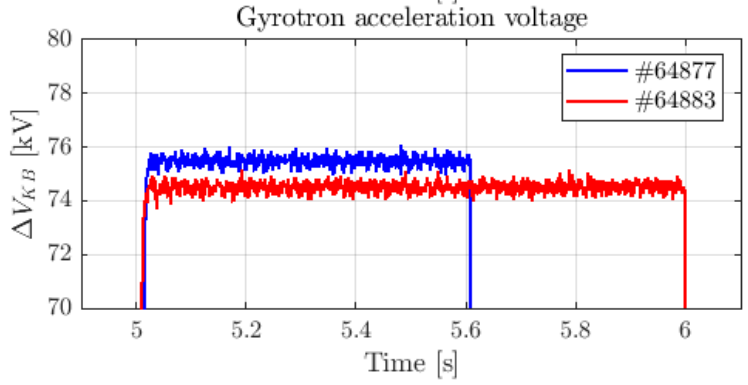












5. Conclusions

Summary and outlook

EC system is now operational on WEST

- Two gyrotron positions validated/4 modes of operation
- The WEST EC team has built a strong experience in gyrotron integration, qualification as well as in platform design and commissioning

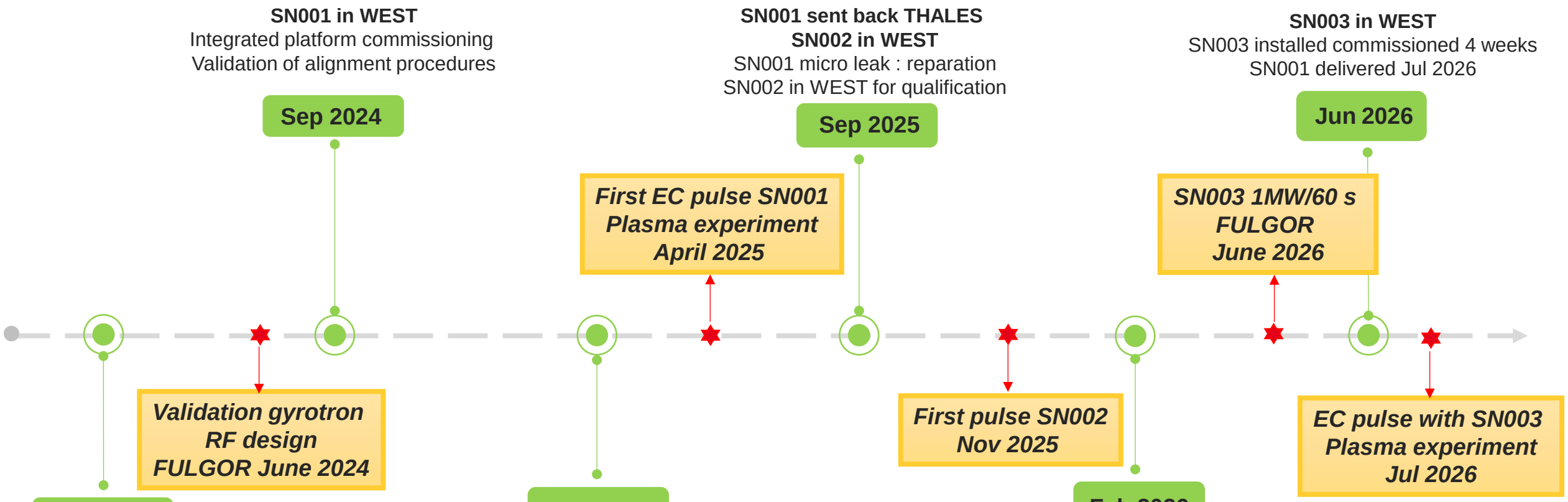
Next steps in WEST

- Finalize integration and validation of the 3rd gyrotron
- Consolidation platform for gyrotron qualification and plasma experiments is on going (TRL 9)
- Increase pulse length (includes also modifications or replacement of some components as the EC launcher, TL components: WEST phase 3)
- Improve launcher steering mechanism for real time control of mirror angles
- Explore possibilities for EC wall conditioning/EC start up

Main lessons learnt

- **Commissioning phase often underestimated**: an experienced team is a key to optimize the schedule and overcome the unexpected technical issues
- **Consolidation phase is essential** to ensure system reliability and enable a safe transfer of operational responsibility to less experienced operators

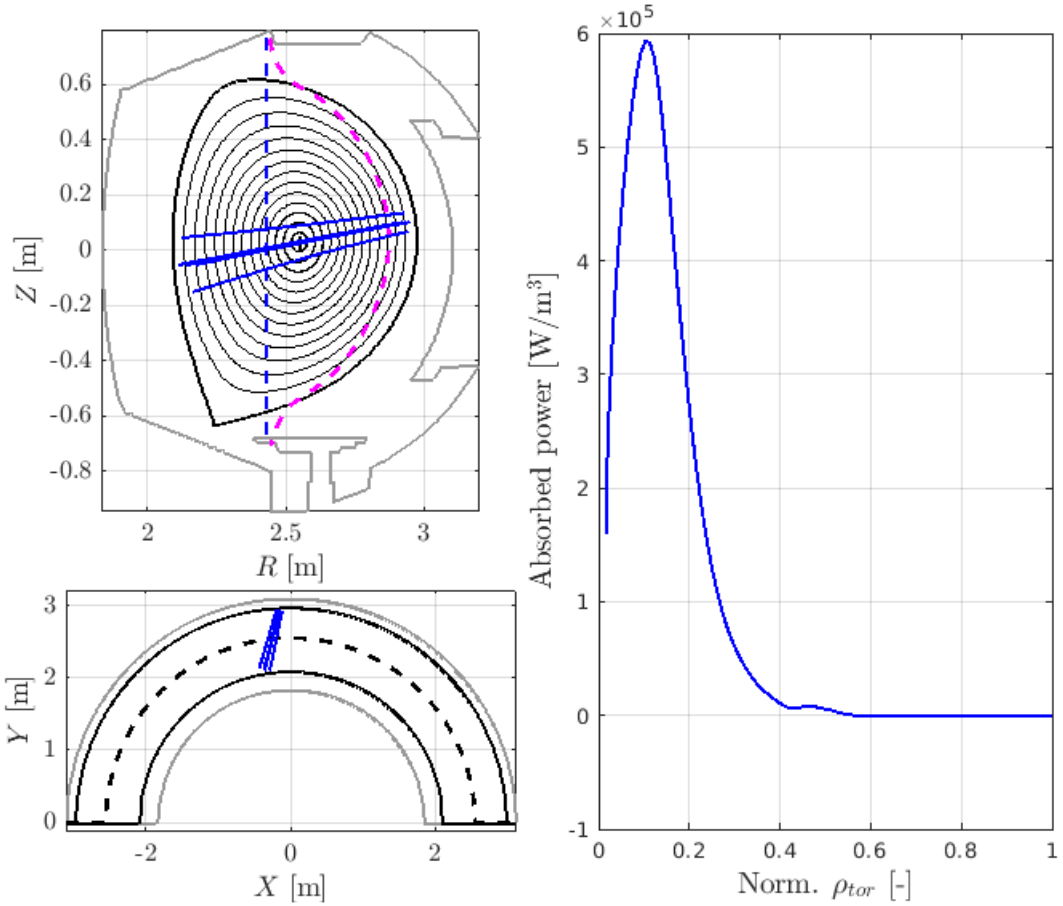
WEST gyrotrons: Tests and Milestones summary



5 gyrotron installations and 4 gyrotron removals completed in 2 years
Build strong hand-on experience

6. SPARE MATERIAL

Information sur simulation absorption EC



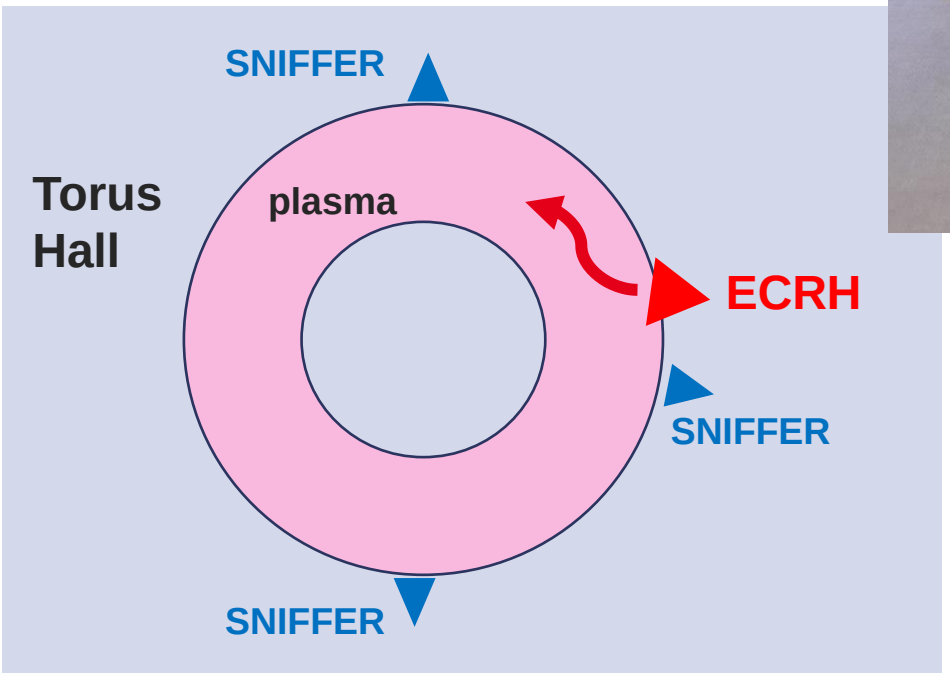
Parameters:

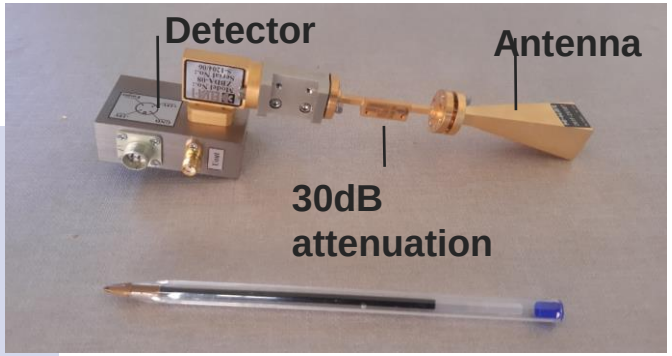
- Ray-tracing: TORBEAM
- Equilibrium: CHEASE
- Reference: #64416 @5s
- $\theta_L = -10°$
- $\phi_L = 15°$
- Transmission line 1, O-mode
- n_e and T_e from IMAS `core_profiles`, with $T_e \times 1.75$ to account for calibrations with soft X-rays
  - $n_{e0} = 3.88e19$ m^{-3}
  - $T_{e0} = 1.35$ keV
  - $P_{abs}/P_0 = 95.7\%$
  - Norm. $\rho_{tor}^{abs} = 0.1$

O-Mode P_{abs}/P_0= 95,7%
ρ~ 0,1 (TORBEAM, CHEASE)

First RF pulses on plasma: results

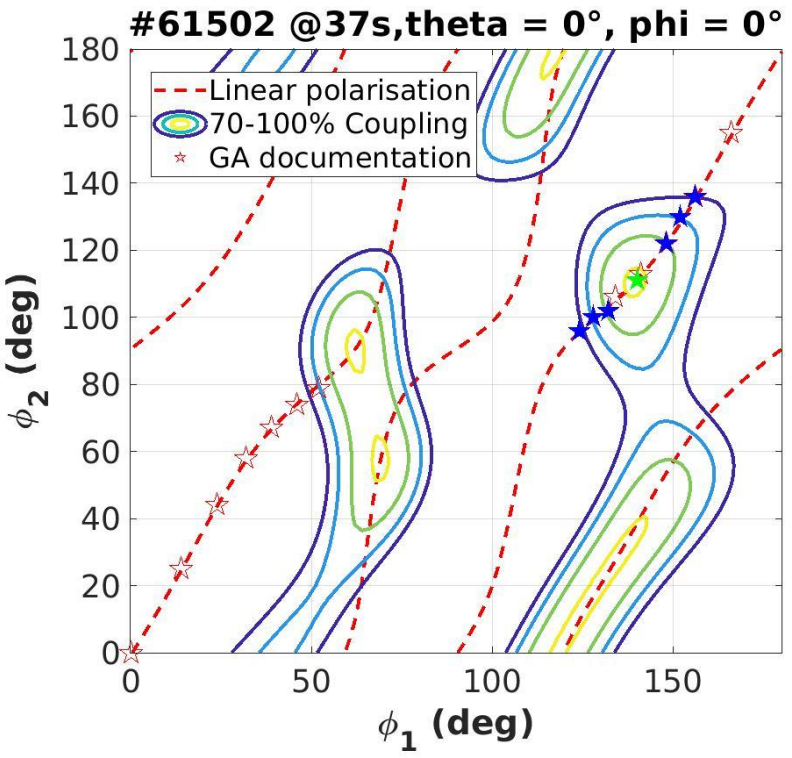
- Measure the non-absorbed power with Sniffers
- Three Sniffers around and outside the torus
- Simulations with ECPOL to get to optimized polarization





SNIFFERS to protect the diagnostics and measure the non absorbed power

Courtesy T.Fonghetti



Scan of polarization with ECPOL

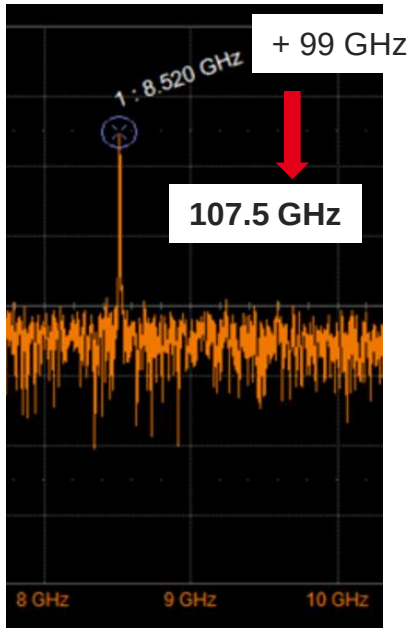
SWISS PLASMA CENTER

First RF pulses on plasma: preparation

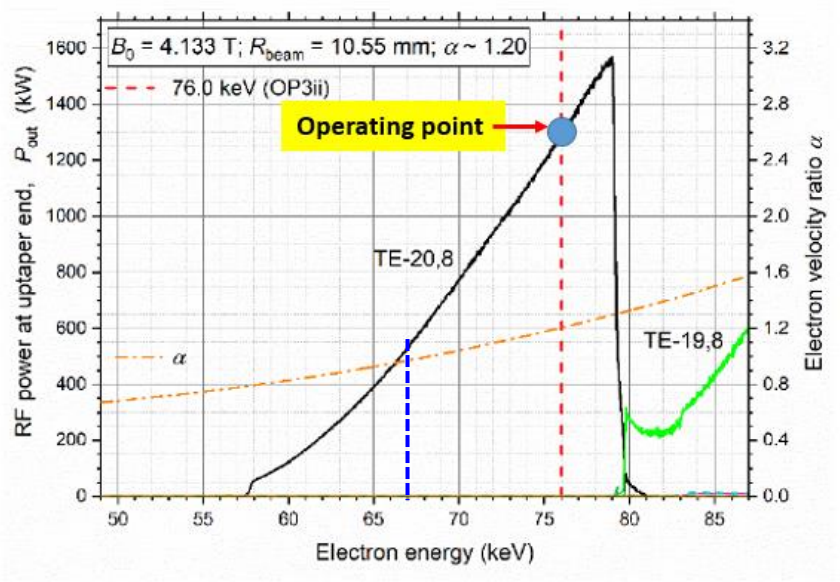
- **Three sessions to commission the EC system on plasma**
- **Short pulse operation up to 100 ms (Mode loss interlock to be validated)**
- **Scan of polarization pure heating performed**
- **Frequency measurements**

Frequency Measurements
(Super Heterodyne) local oscillator 99 Ghz

Frequency (Oscilloscope) measured during ramp up phase ~ 5 ms



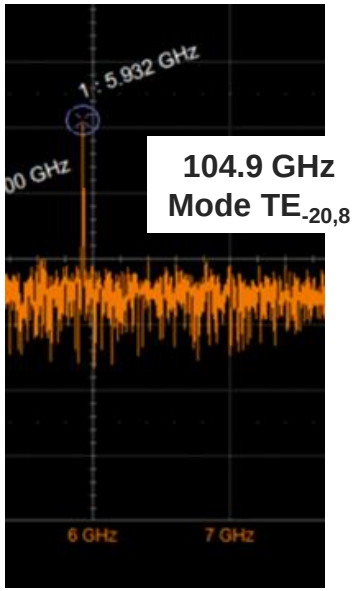
R_{beam} = 10.55 mm;
67% neutralisation (long-pulse)



107.5 GHz
Competitive mode
During ramp up

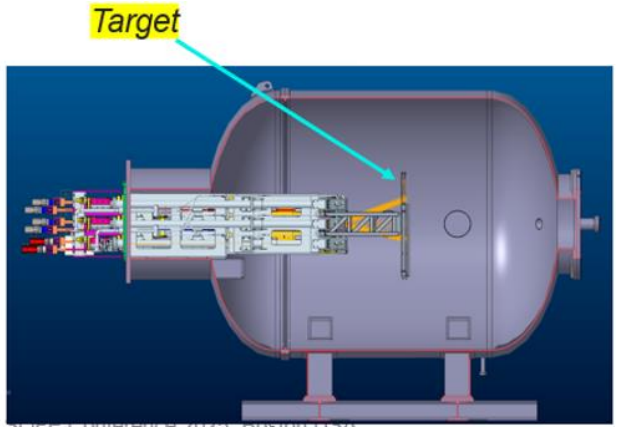
104.9 GHz
Mode TE$_{-20,8}$ established

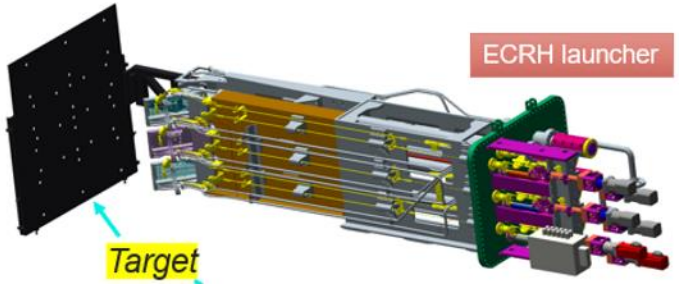
Frequency measured at operating point

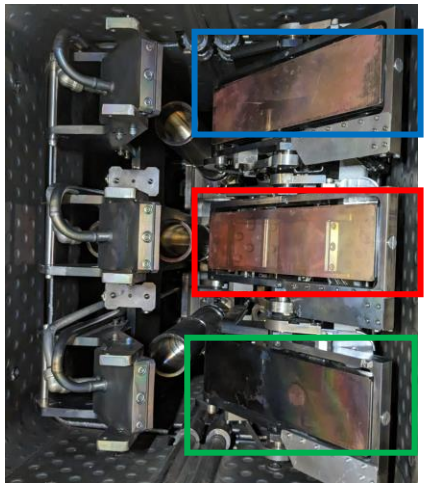


Antenna validation, installation and alignement

- Three steering mirrors (moveable in both poloidal and toroidal directions)
- Launcher calibrated (mirror mouvements) in a vacuum tank at ambient temperature and 70°C
- Leak tests at 220°C and 70°C

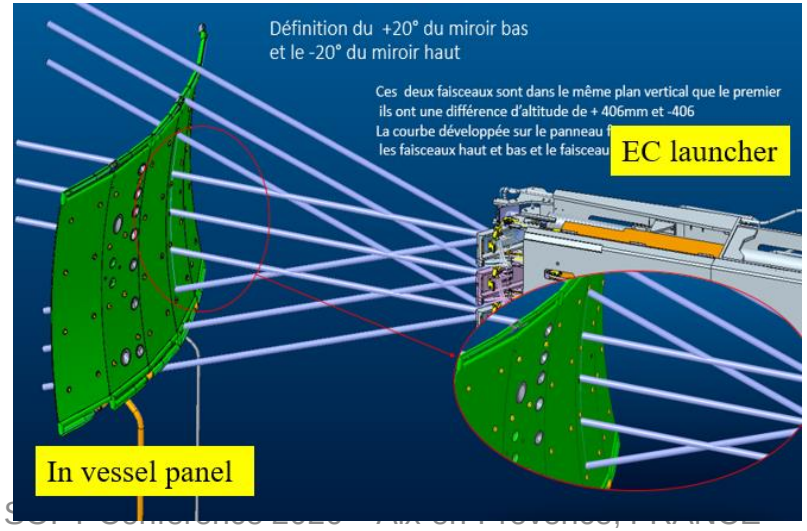




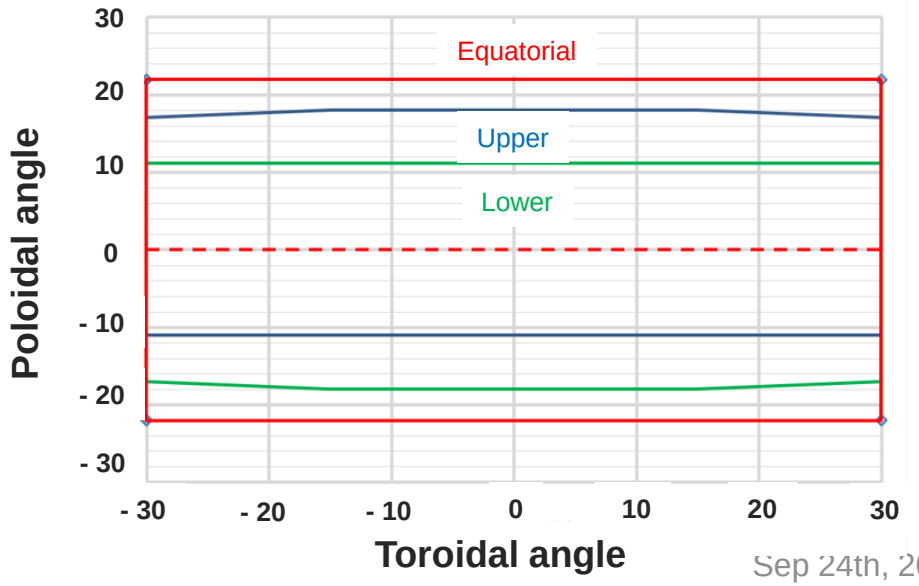


ECRH launcher
In WEST with three steering mirrors

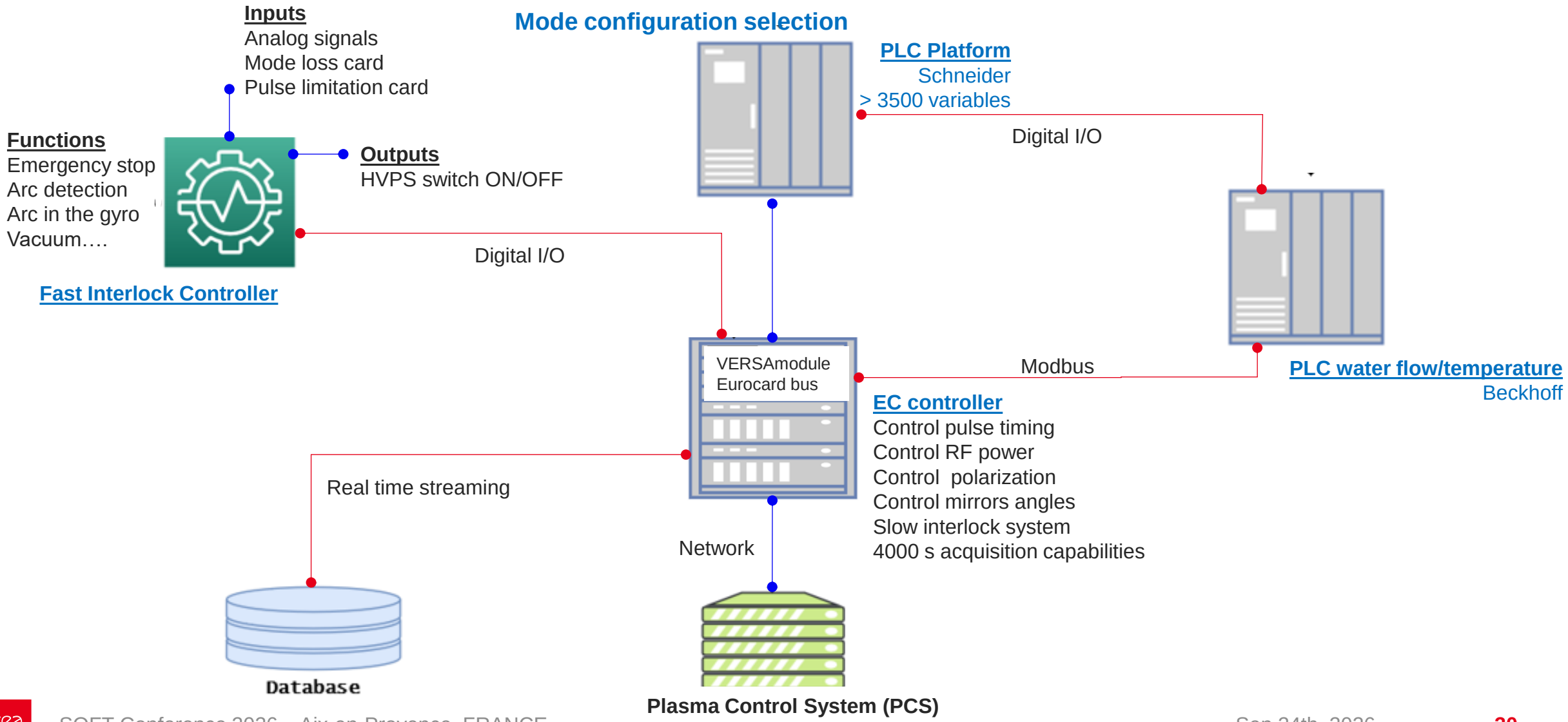
- Installation in the tokamak and alignement



Limitations of mirror angle



Design of the WEST Gyrotron Test and Operation CODAC system



CODAC system: lessons learnt

Fast Interlock Controller
Field Programmable Gate Array (FPGA) board

Built in-house



Interlock number

Watch dogs

Modes

HVPS status

- **Step 1** : Prove of concept + tests in lab ✅
- **Step 2** : Validation of the prototype integrated in the platform with a gyrotron ✅
- **Step 3** : Validation of serie cards ✅
- **Step 4** : Consolidation and reliability **ON GOING**

Failures found:

- Programming issue (Step 1)
- Parasitic signals due to environment (Step 2)
- Overheating of the cards (Step 3)

Lessons learnt

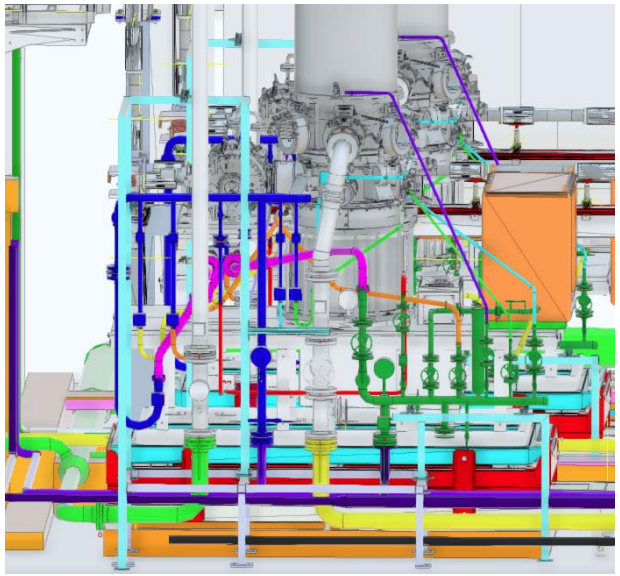
POC and tests are necessary:

- To prevent and correct issues before integration in the platform
  Time saving during integration/commissionnig
- To train and transfer knowledge to operators
  Optimize integration and commissioning

Design the WEST Gyrotron Test and Operation Cooling system (3 gyrotrons in parallel)

Collector cooling loop

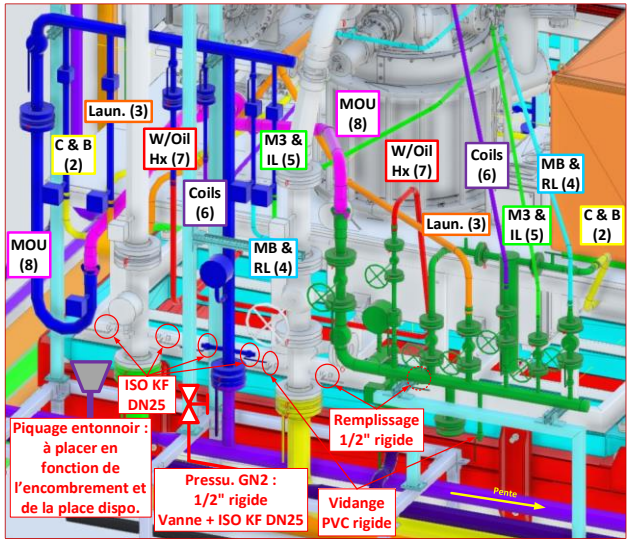
- Low pressure drop
- Highest flow rate
- Desionized water
- Total minimum water flow : 1500 l/mn
- Max T_{in} = 36 °C



Auxiliaries cooling loop

- Highest pressure drop
- Desionized water
- 5 circuits in parallel
- All interfaces are differents
- Total min water flow :
- Max T_{in} = 36 °C

Diamond/Saphire Windows cooling loop



Magnet cooling loop

- High pressure drop
- The highest flow rate
- Non desionized water
- Max T_{in} = 28 °C

Design the WEST Gyrotron Test and Operation Cooling deployment

Cooling system studies (7 months)

Includes the gyrotron connexions
Includes sensors, protection system
Regulation valves
Adjust design to the required flow rates
14 meetings
3D measurements of the platform

Procurement, manufacturing (4 months)

Procurement launched ASAP
Manufacturing in factory

Integration in the plateform (3 weeks)

Commissioning

Without Gyrotron
2 weeks

Testing
Controlling the sensors and acquisition

With 1 Gyrotron
1 week

Integrated validation
Control the cooling loops
Compliant to THALES specifications

Commissioning of the ECRH platform

INSTALLATION OF COMPONENTS

Interface adaptation → **Anticipate and simplify interfaces from the early design phase and keep an interface document up to date**

3D model compliance did not fully prevent integration rework →
- **Intermediate dimensional checks to increase confidence in the 3D model**
- **On-site work-shop : time saved**

COMMISSIONING

Difficult filling & draining Gyrotrons/auxiliaries → **Design for easy filling, draining and purging from the outset**

Cooling system with limited operational margins → **Define sufficient operational margins and validate them early** 

Leaks detected during commissioning → **Introduce intermediate testing**

Design of the WEST platform for gyrotrons

Four cooling loops

- Differents requirements (Pressure drop, Max inlet pressure, Water quality)
- Gyrotron, Magnet compressor, Transmission line components, HVPS Regulator, Dummy Load

3D models

- Supporting structures, transmission line arrangements, gyrotron connexions
- Handling and supporting tools

Vacuum systems

- Transmission line
- Dummy load
- Supra conductiong magnets



HVPS

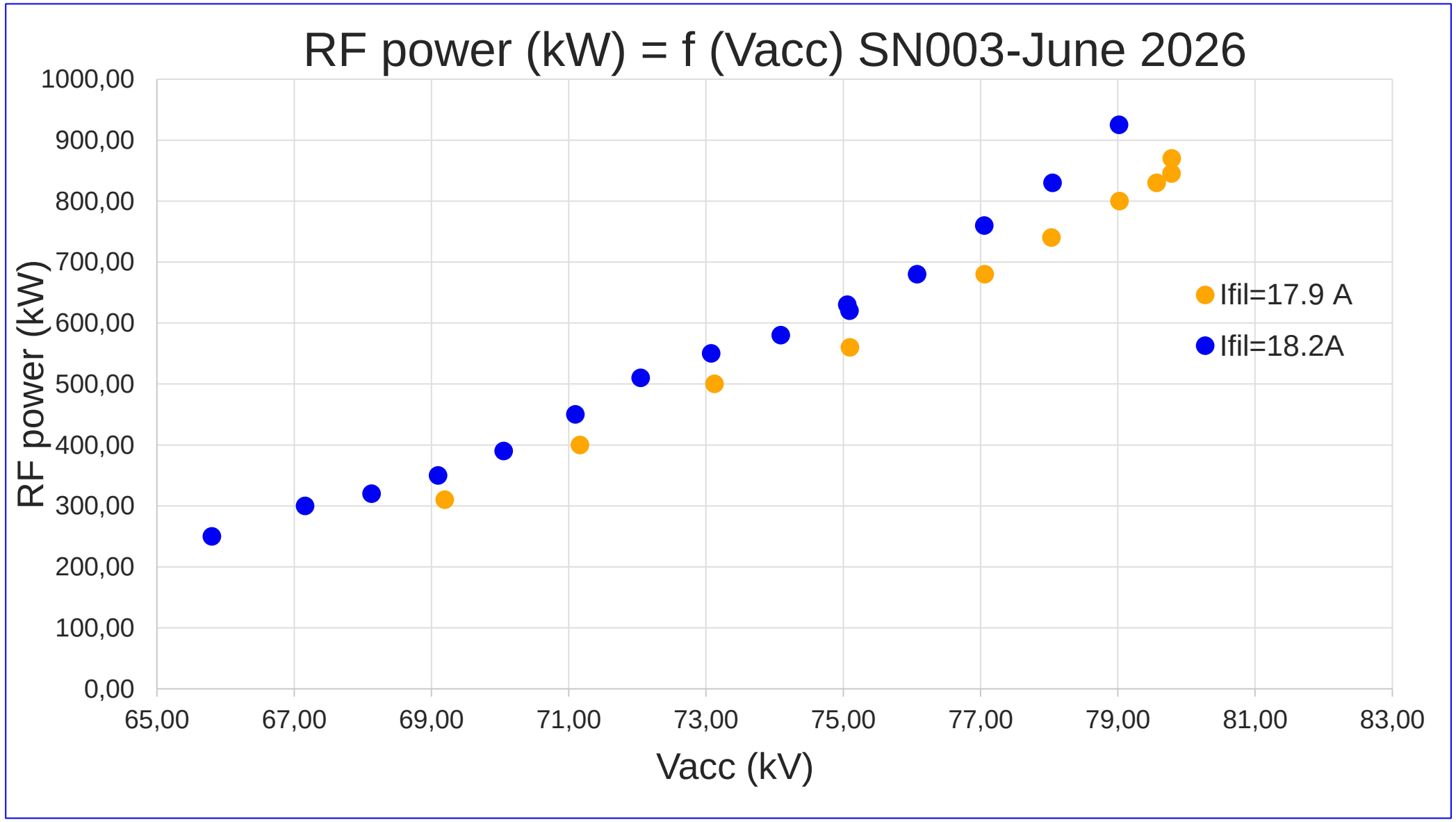
- Cathode Voltage (-55 kV/90 A)
- Body Voltage (30 kV/150 mA)
- Ripple, rising time, duty cycle
- Fast interlocks protection (< 10 µs)

CODAC/Fast interlocks

- New 2 Programmable Logical Controller (PLC)
- New Fast Interlock system (SSR)
- New CODAC system (compatible with Plasma Control System)

Auxiliaries

- Power supplies
- Arc detection
- Sensors (water flow, temperature, current, voltage, vacuum in the gyrotron, RF measurements, calorimetry)


RF power (kW) = f (Vacc) SN003-June 2026
RF power (kW)
1000,00
900,00
800,00
700,00
600,00
500,00
400,00
300,00
200,00
100,00
0,00
65,00
67,00
69,00
71,00
73,00
75,00
77,00
79,00
81,00
83,00
Vacc (kV)
Ifil=17.9 A
Ifil=18.2A