Operating the WEST Superconducting Long Pulse Tokamak

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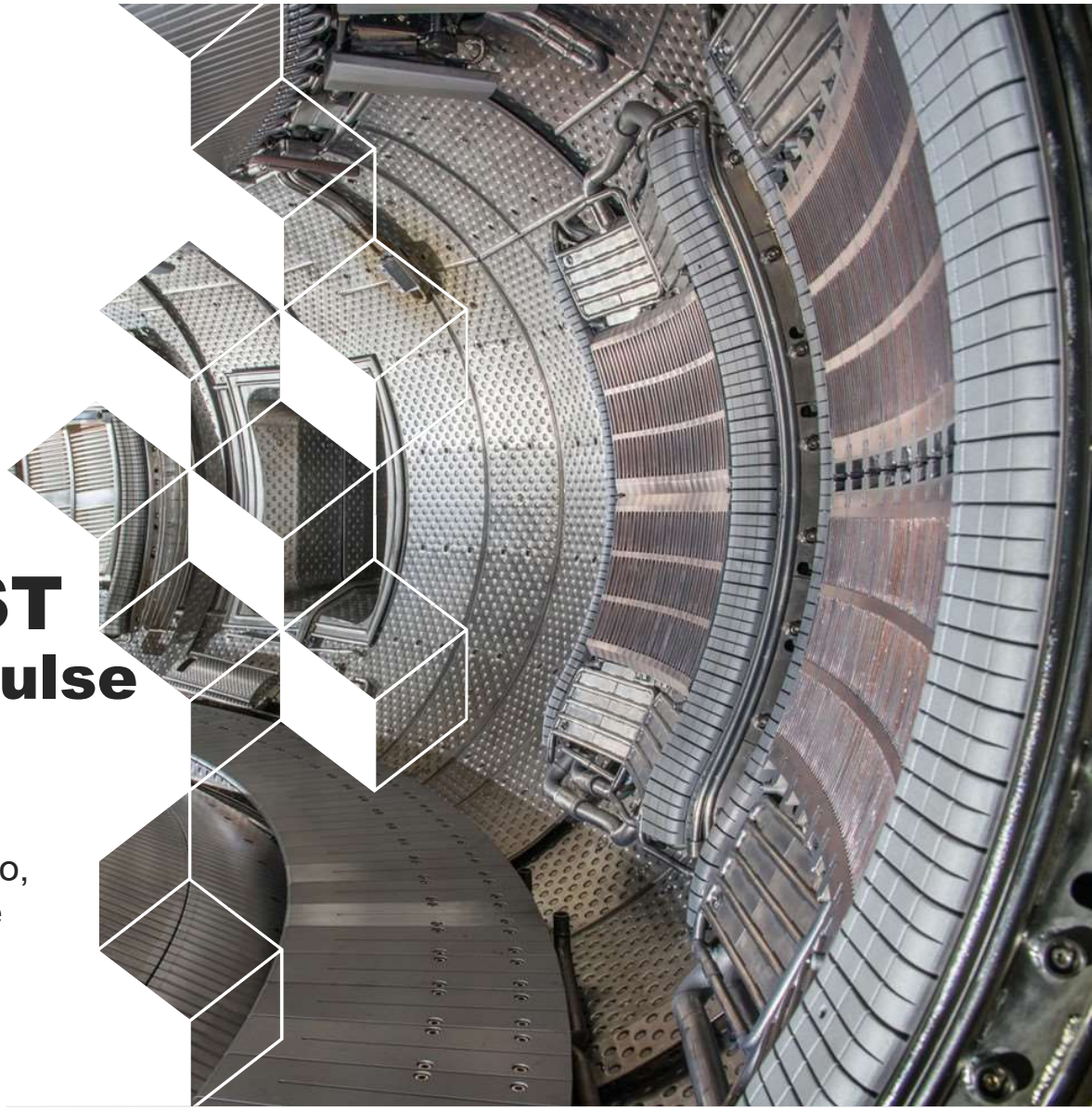

OUTLINE

1. Introduction on WEST Superconducting Tokamak & Ancillary Systems
2. WEST Achievements, Operation, Availability since December 2022
3. Two Highlights specific to Long Pulse Operation Tokamak
   - Infrared protection for plasma facing components
   - Actively Cooled Components & Water Leaks management

1. Introduction on WEST Superconducting Tokamak and Ancillary Systems

WEST: a MA class superconducting tokamak

- Full tungsten actively cooled environment
- Flexible magnetic configuration (LSN, USN, DN)
- Large current drive capability
- **Long pulse operation ➔ 1000 s**

I_p (q_{95}~2.5)	1.0 MA
B_φ	3.7 T
R	2.5 m
a	0.5 m
A	5-6
Max κ	1.35
δ	Up to 0.5
V_p	15 m^3
n_{GW} (1MA)	1.5 10^{20} m^{-3}
P_{ICRH}	9 MW
P_{LHCD}	7 MW
P_{ECRH}	3 MW (2024 - 2025)
$T_{flattop}$	1000 s

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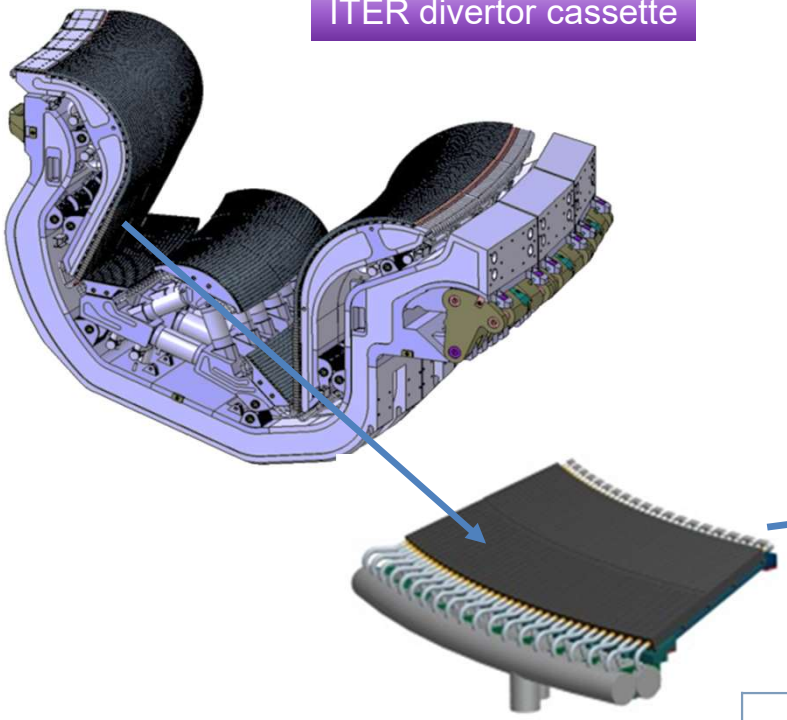
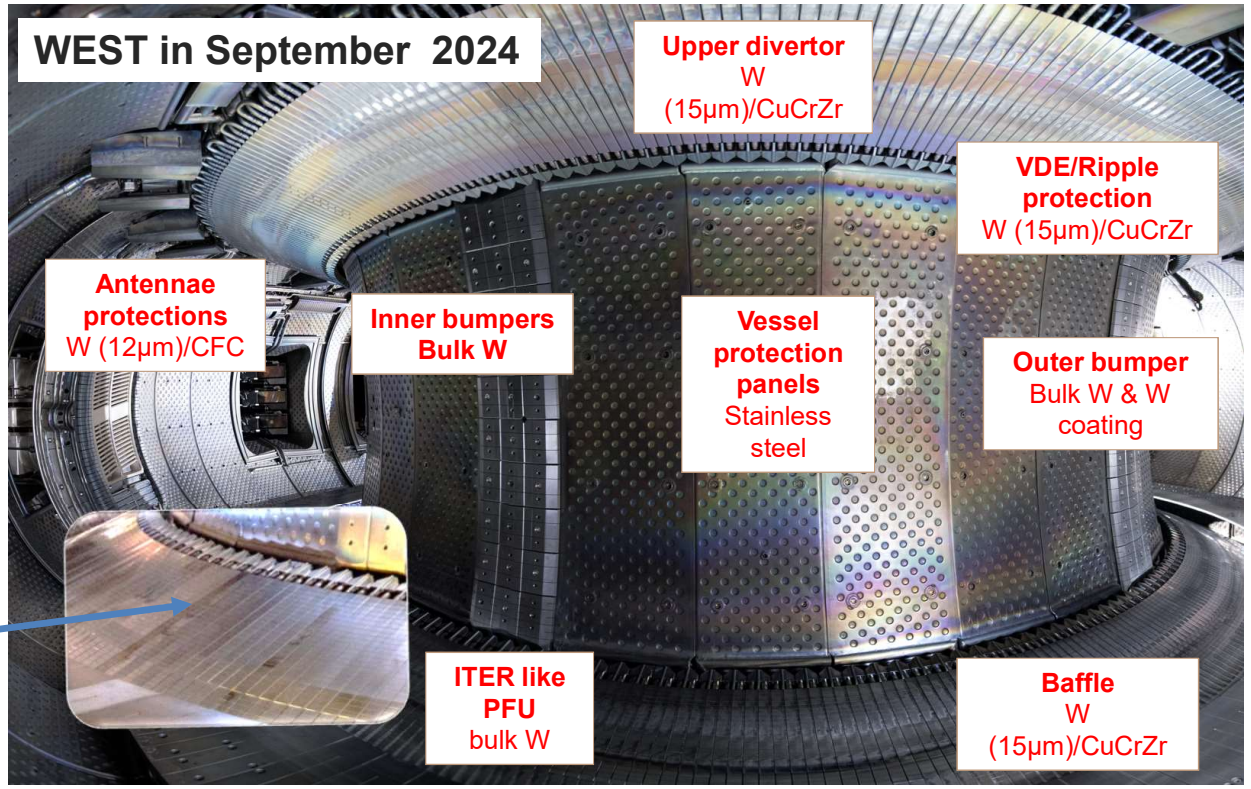
WEST: a Tungsten divertor, superconducting & actively cooled tokamak

ITER divertor cassette



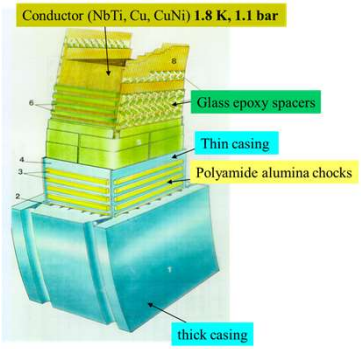
ITER-like WEST divertor

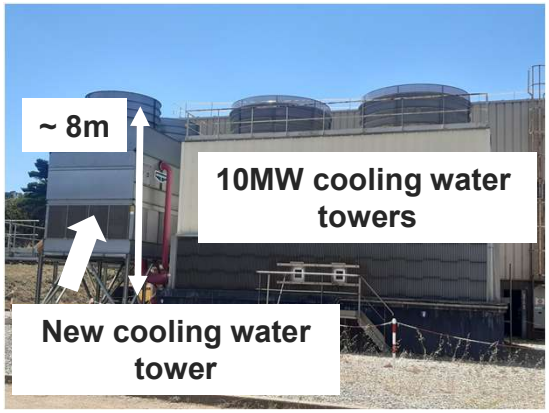


Phase 1 (Dec 2016 – Jan. 2021)	Phase 2 (≥2021)
Actively cooled + W coated inertial divertor elements	**Completely actively cooled ITER grade divertor prototypes and baffles**

WEST Ancillary Systems

- **Magnetic system**
  - **18 TF Superconducting NbTi magnets (160 tons), Thermal Shields (20 tons)**
  - 9 CS/PF water cooled Copper Coils
  - Upper and Lower water cooled Copper Divertor Coils
- **Cryoplant to cool down magnets**
  - **3kW @ 4.5K (1/3 of JT-60SA cryogenic system)**
  - 3.5 tons of helium inventory
  - Gas helium (200 bar) and Liquid helium storage
- **Water cooling system to remove heat loads from Plasma Facing Components (PFC) and continuous systems**
  - **15MW** (upgrade of additional 5MW for 1000s plasma)
  - Dedicated high pressure and temperature water loop
- **Electrical Power Supplies**
  - 400kV: Pulsed power Electrical Network
  - 2 x 15kV: Steady state Electrical Network
- **Heating systems**
  - Lower Hybrid: 7MW, 1000s
  - ICRH: 9MW, 30s; 3MW, 1000s
  - ECRH: 3MW, 1000s






400kV


2 x 15kV

2. WEST Achievements, Operation, Availability since December 2022

Main achievements since December 2022

- **C6&C7 plasma campaigns**

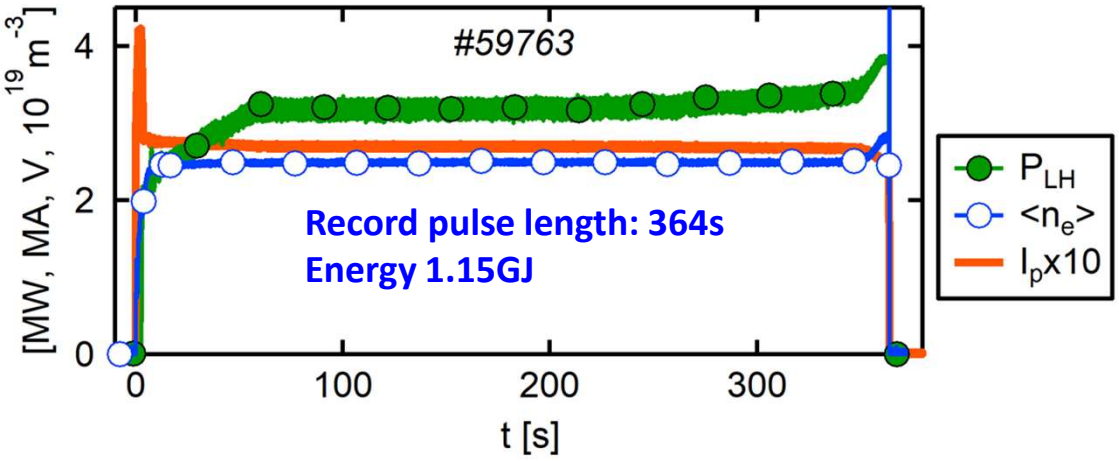
  Dec. 2022-April 2023
  - 3.5 months
  - **5h30 plasma cumulated duration**
  - 44GJ injected energy
  - Max Lower hybrid 5MW, max ICRH 4MW
  - 100s plasma pulses

- **C8&C9 plasma campaigns**

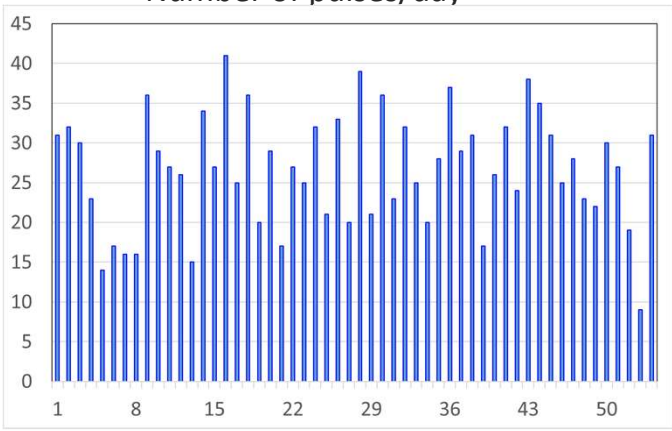
  Dec. 2023-April 2024
  - 4 months
  - **5h45 plasma cumulated duration**
  - 38GJ injected energy
  - Max Lower hybrid 5.8MW, max ICRH 4.5MW
  - **Plasma pulse > 6min achieved**

- **Plasma pulses**

Plasma pulses	Total	Failed	Commissioning plasmas	Physics program
C6&C7	1420	13%	15%	**72%**
C8&C9	1478	9%	14%	**77%**



Number of pulses/day



- 30 pulses/day (shift up to 9:00pm)
- 22 pulses/day (shift up to 6:00pm)

WEST Operation

Yearly operation target

- 2 campaigns of ~3 months
- Shutdown for maintenance and evolutions of 4.5-5 months
- Commissioning of 1 month before campaign

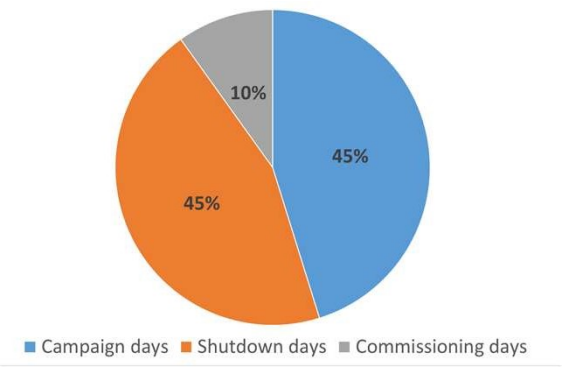
Week operation

- Monday dedicated to Maintenance/Boronisation
- 4 operation days in two shifts
  (2 days 8:45am-6:00 pm + 2 days 8:45am-9:00pm)

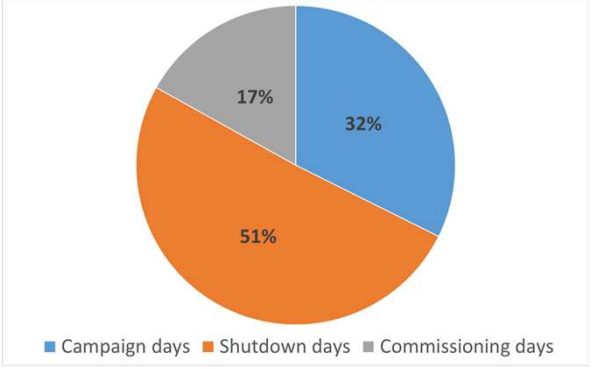
2023												2024											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
S6	C7			S7							C8	S8	C9			S9						C10	

- **WEST availability > 70% since 2019** during plasma campaigns
- Shutdown and commissioning phases longer than expected

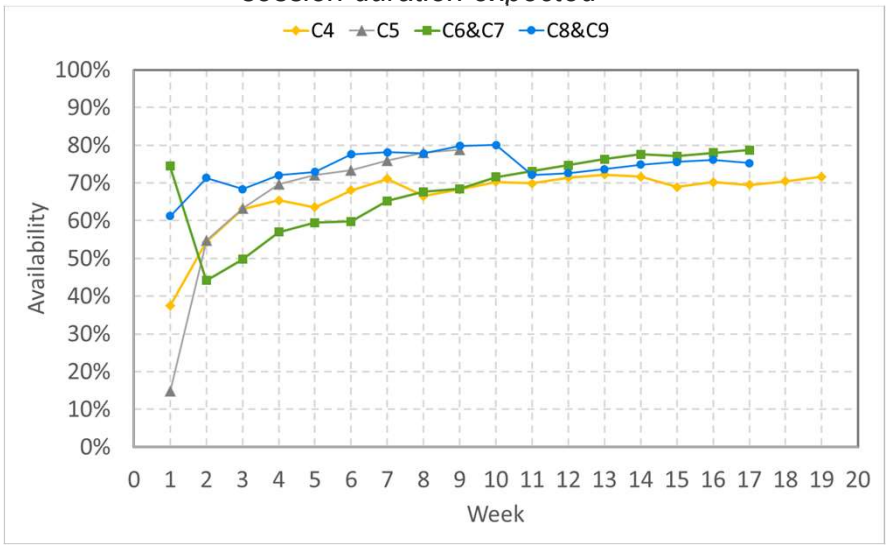
Expected



Performed



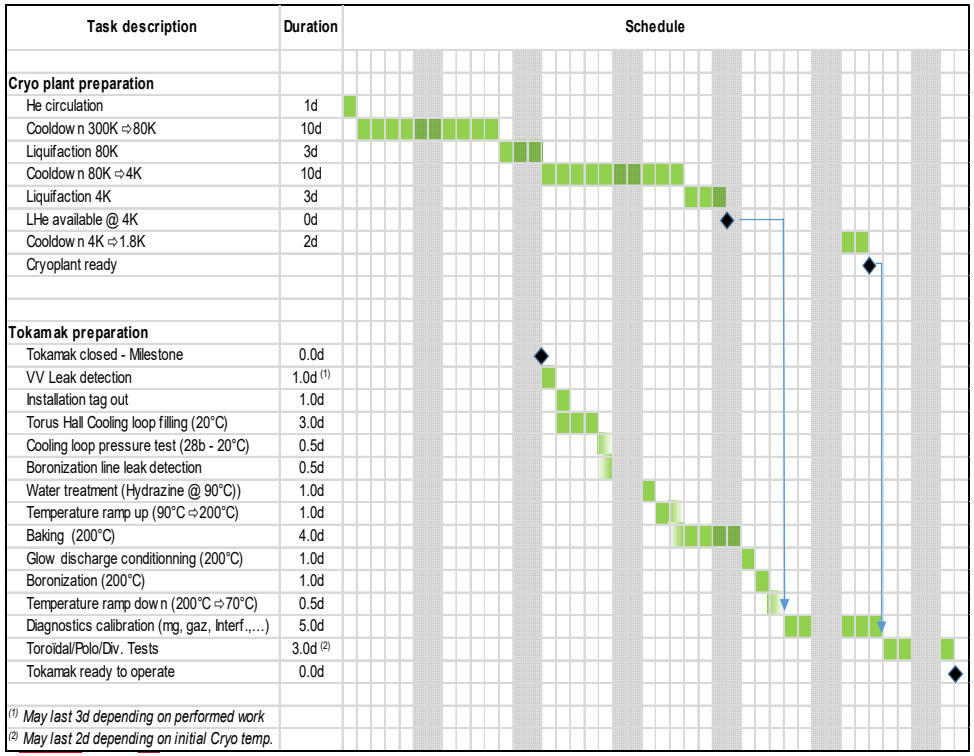
$$Availability = \frac{[\text{session duration achieved}] - \text{downtimes duration}]}{\text{session duration expected}}$$



Commissioning before campaign

After Shutdown, commissioning duration is about 1 month:

- **Cool-down of the magnets**
- Helium leak detection on vaccum vessel
- **Water Cooling loop filling (30m^3), High-pressure leak test, Chemical Treatment of water**
- Baking at [200°C, 35bar] of the vaccum vessel



Task description	Duration
Cryo plant preparation	
He circulation	1d
Cooldown 300K ⇨80K	10d
Liquifaction 80K	3d
Cooldown 80K ⇨4K	10d
Liquifaction 4K	3d
LHe available @ 4K	0d
Cooldown 4K ⇨1.8K	2d
Cryoplant ready	
Tokamak preparation	
Tokamak closed - Milestone	0.0d
VV Leak detection	1.0d (1)
Installation tag out	1.0d
Torus Hall Cooling loop filling (20°C)	3.0d
Cooling loop pressure test (28b - 20°C)	0.5d
Boronization line leak detection	0.5d
Water treatment (Hydrazine @ 90°C))	1.0d
Temperature ramp up (90°C ⇨200°C)	1.0d
Baking (200°C)	4.0d
Glow discharge conditionning (200°C)	1.0d
Boronization (200°C)	1.0d
Temperature ramp down (200°C ⇨70°C)	0.5d
Diagnostics calibration (mg, gaz, Interf.,...)	5.0d
Toroïdal/Polo/Div. Tests	3.0d (2)
Tokamak ready to operate	0.0d

(1) *May last 3d depending on performed work*
(2) *May last 2d depending on initial Cryo temp.*

Magnets cool down ~ 3 weeks from 300K to 1.8K

~ 4 weeks from Tokamak closure to first plasma

→ Incident on cryogenic system results in a long time delay (~ 2months) for plasma operation mostly due to warm-up and cool down of the magnets

→ Leak detection may take time due to the huge number of flanges on the machine and the number of work performed during shutdown

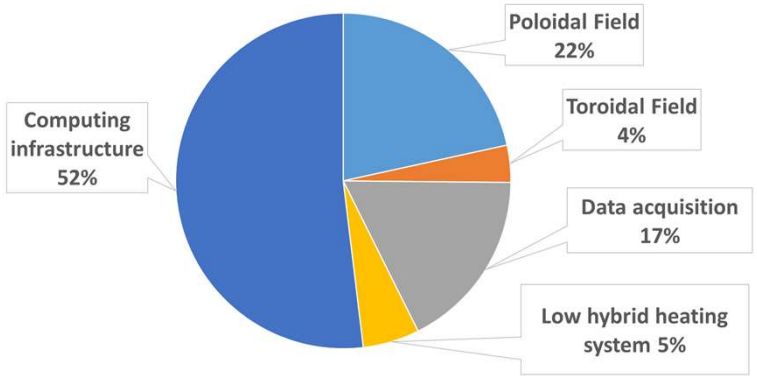
→ In-vessel water leak: Typical duration 5 weeks

During Campaign: Systems availability

All unavailability are reported in a dedicated database during plasma campaign

Operation downtimes: Time contributions (%) of systems

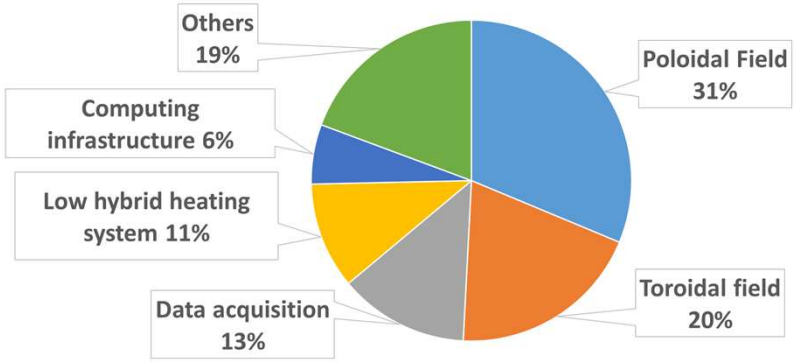
C6&C7 (2023)



CODAC upgrade performed due to obsolescence

- Central database migration
- Data storage during experiments
- Data access to ARCAD
- Acquisition units configuration
- Operation software suite

C8&C9 (2024)



Magnetic system

- Default electronic components
- Loss of continuous data monitoring

Data Acquisition : long pulse data strategy

LH heating system : klystron loss, power supply

- Distribution of operation downtimes varies from one campaign to another
- **Analysis of operation downtimes: identification of more frequent failures or delays**

→ Completion of maintenance plan

3. Two Highlights specific to Long Pulse Operation Tokamak

Real time protection implemented for Long pulse operation

IR diagnostics (7 endoscopes) installed on the WEST tokamak covering 52% (45m^2) of the 1st wall, 85% of the lower divertor

IR monitors the surface temperature of critical PFCs in order to prevent damages during long pulses : **definition of Regions Of Interest and associated temperature threshold**

❑ **Two-stage protection**

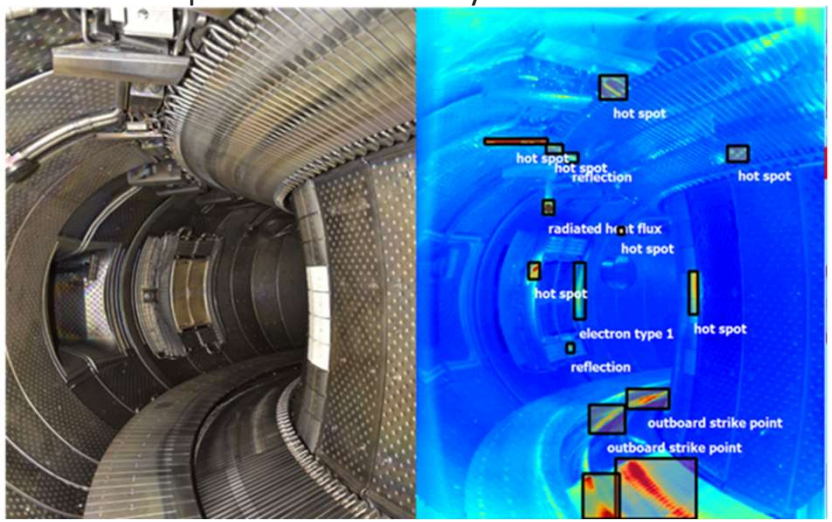
- Limit avoidance: **Real time feedback control acting in a proportional way on the injected power** → only 3% of the feedback controls cross the threshold and lead to triggering an interlock (soft plasma landing)
- Interlock: Identification temperature threshold and deliver an alarm leading to plasma soft landing

❑ First demonstration of inverse IR Neural Network (NN) to **remove reflections and determine accurate surface temperature** from IR images

❑ Additional diagnostics

- **VUV** (Vacuum Ultra Violet) on cooper wavelength: Real time feedback control acting in a proportional way on the injected power
- **Calorimetry diagnostic** (~200 sensors & flow meters implemented) with automatic Data processing tool → Thermal Energy

Spatial resolutions from 2mm/px to 0.1mm/px
temperature uncertainty of 6% at 1000°C



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Actively Cooled Components & Water Leaks management

- Validation of active cooled components before integration in the vacuum vessel

→ Specific test: Pressure (45 bars) and temperature (200°C) cycling with helium tightness test

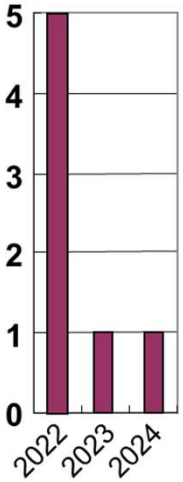
Water leak can occur and involve impact on operation

Tore Supra (24 years): 19 in-vessel water leaks during plasma campaign → ~33 days lost

WEST (2016-)

7 events

1 week of plasma campaign lost



3 leaks due to design issue

4 leaks due long operation components

- Leak localisation by presurization - depresurization of water circuits
- Leak detection by sniffing inside the vacuum vessel
- Leak detection by glow decharge (in progress)

Leak localization faster and eased by isolation of hydraulic sub-circuits

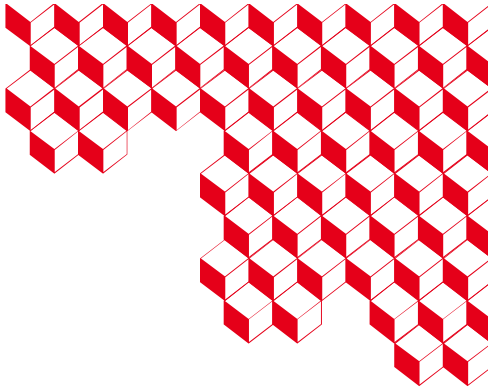
→ Improvement of water circuits configuration with the implementation of sets of valves and bottom drains

Summary & Perspectives

- WEST is a superconducting long pulse tokamak that involves complex systems (superconducting magnets, cryogenic system, water cooling system, heating systems, power supplies …)
- WEST achievements
  - Plasma duration of 364s
  - The WEST availability is > 70% since 2019
  - > 70% of plasma rated as meeting physics program requirements
  - Operation downtimes monitoring is essential to complete the maintenance plan
- IR Real time protection
  - 52% of the first wall of the vacuum vessel, 85% of the lower divertor monitored by IR diagnostic
  - 97% efficiency of real time feedback control for real time protection
- Water leak management detection to improve reactivity
  - Typical duration (localization, repair) of an in-vessel water leak: 5 weeks
  - Water network configuration: leak localization faster and eased by isolation of hydraulic sub-circuits

New capabilities for next campaigns

- Bulk W-tiles (instead of W-coated & BN) on inner and outer start-up limiters
- ECRH, 1 MW available end 2024, 3 MW in 2025
- New diagnostics (Thomson scattering, collector probes, …)
- Acquisition system compatible with long pulse > 1000s (large flow rate & large amount of data)



Thank you for your attention