Calorimetry in WEST: global power balance and local in-situ measurement on the lower divertor

J.Gérardin, R.Loux, P.Malard, G.Olive, F.Faisse, B.Salamon, S.Vives, WEST team, WPTE team



Summary

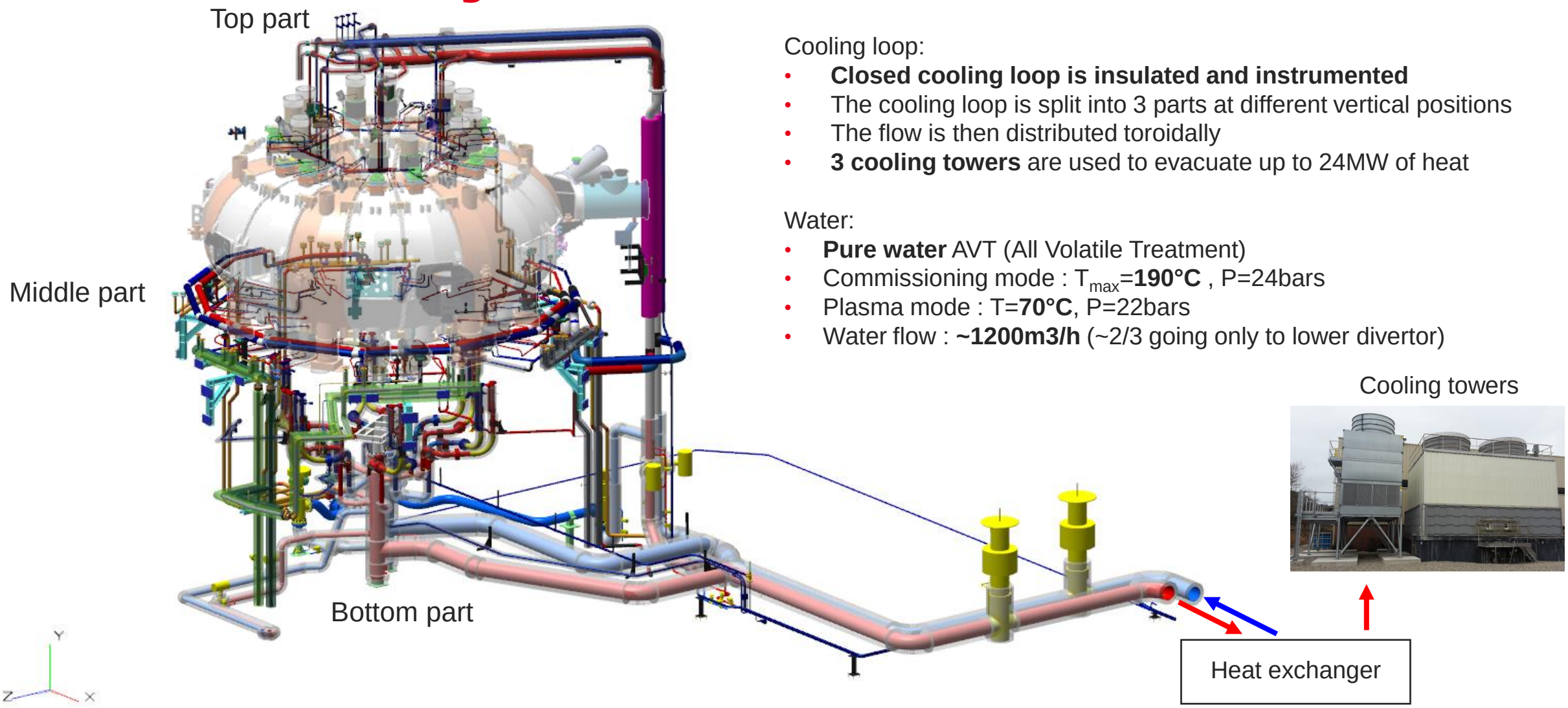
1. Calorimetry system of WEST

2. Power and energy balance from C7 (2023) to C13 (2026)

3. Magnetic ripple and in situ calorimetry

1. Calorimetry in WEST

WEST: Actively cooled tokamak



Cooling loop:

- **Closed cooling loop is insulated and instrumented**
- The cooling loop is split into 3 parts at different vertical positions
- The flow is then distributed toroidally
- **3 cooling towers** are used to evacuate up to 24MW of heat

Water:

- **Pure water** AVT (All Volatile Treatment)
- Commissioning mode : T_{max}=**190°C** , P=24bars
- Plasma mode : T=**70°C**, P=22bars
- Water flow : **~1200m3/h** (~2/3 going only to lower divertor)

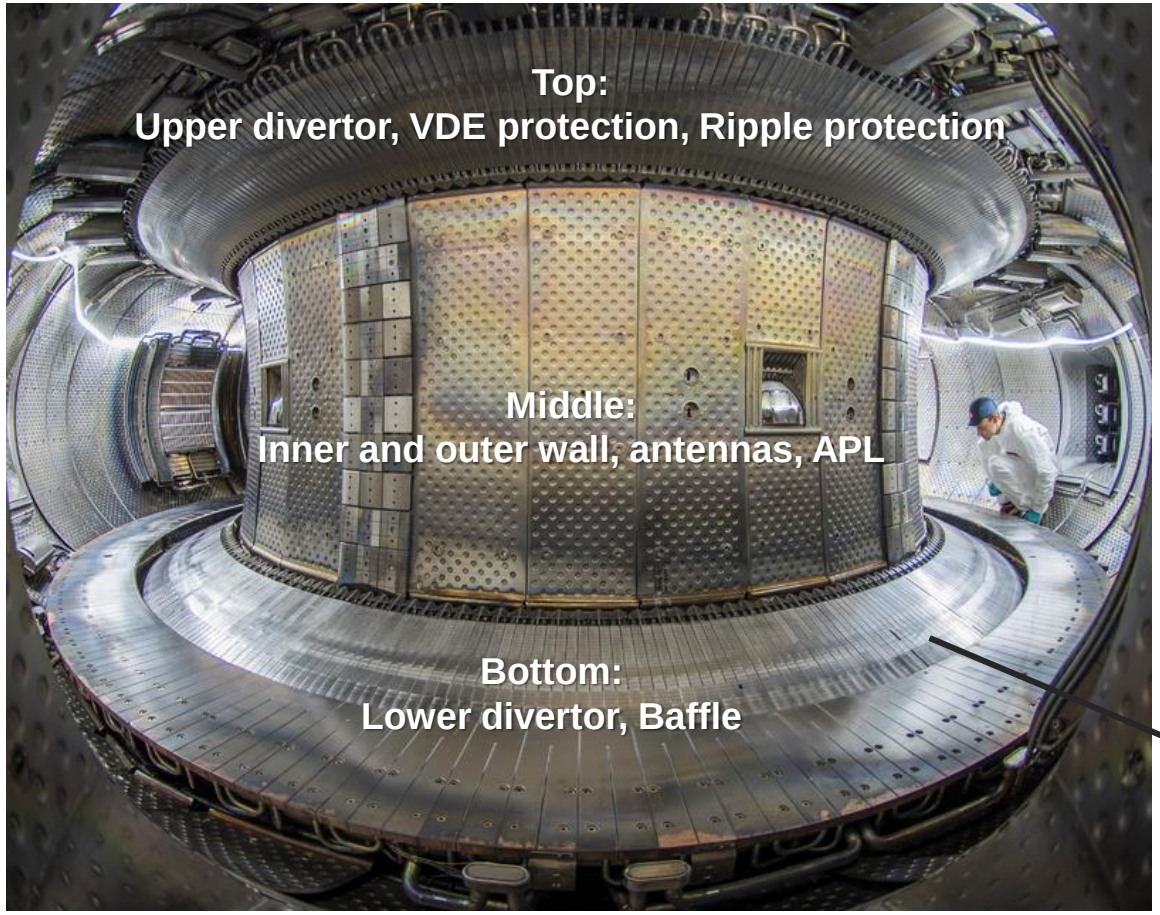
Cooling towers

Heat exchanger

Open cooling loop

Allow WEST to perform long pulse operation

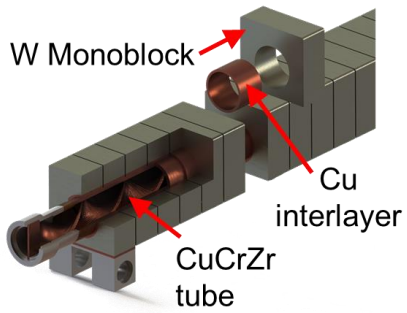
WEST: Actively cooled tokamak



Instrumentation of the cooling loop

- **172 sensors used**:
  - Resistance temperature detector PT100
  - Vortex type flowmeter
- **10 different components** instrumented
  - With toroidal discretization → **94 sub components instrumented**
- **Continuous data acquisition** during the day:
  - Different frequency of acquisition (in pulse, not in operation…)

→ Around 115,000 data points per sensor per day for **a total of 20M data points per day.**

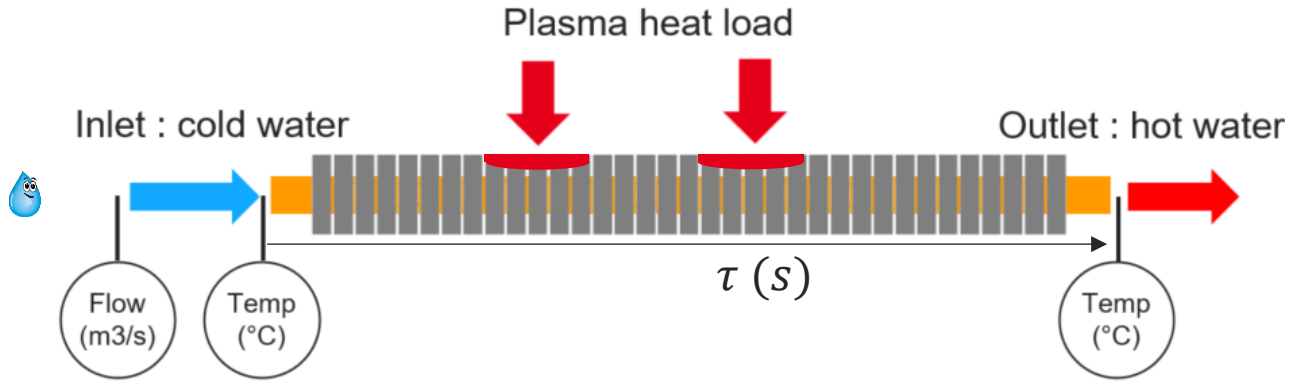


ITER technology

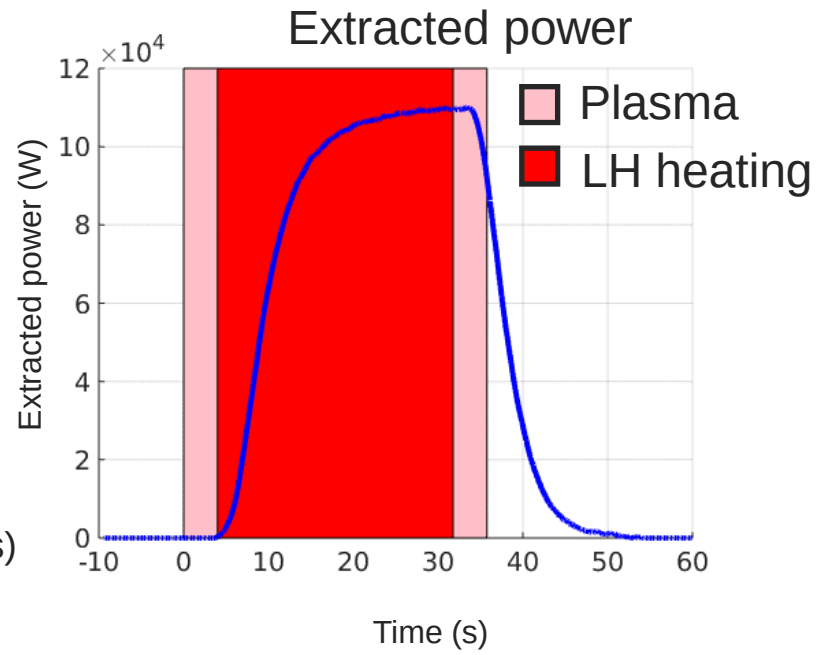
Monitoring of the water cooling and calorimetric measurement

Calorimetry

On a water cooled tokamak, the calorimetry can be done by measuring the heating of the water flowing through each group of components.



$$P(t) = Q_v(t)\rho C_p\left(T_{Out}(t) - T_{In}(t-\tau)\right)$$



ρC_p: water density (kg/m^3) and specific heat (J/m^3/°C) Q_v: volumetric water flow (m^3/s)

T_{In}, T_{Out}: inlet and outlet water temperature (°C) τ: flowing time between inlet and outlet (s)

Actively cooled tokamak	Inertial tokamak
Heating of the water coolant	Heating of localized tile
1 measure can cover large area	1 measure cover 1 tile
Steady state reachable	Transient measurement
Small heating (bad Signal Noise Ratio)	Large heating (good SNR)
Real time estimation of power and energy	Post pulse analysis

At steady state, the extracted power by the water on a component is mainly equal to the plasma heat load on this component.

The total extrated energy is the integral of the extracted power.

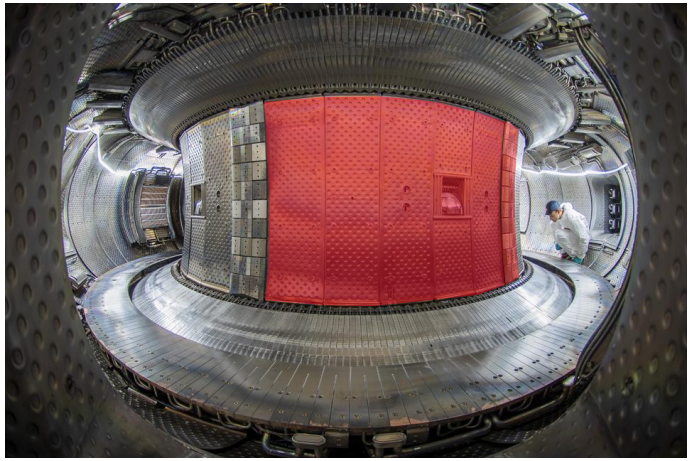
Usage for:

- Plasma physics (power and energy balance)
- Plasma Facing Component (PFC) safety

Fusion power plant needs continuous operation and knowledge of the power distribution

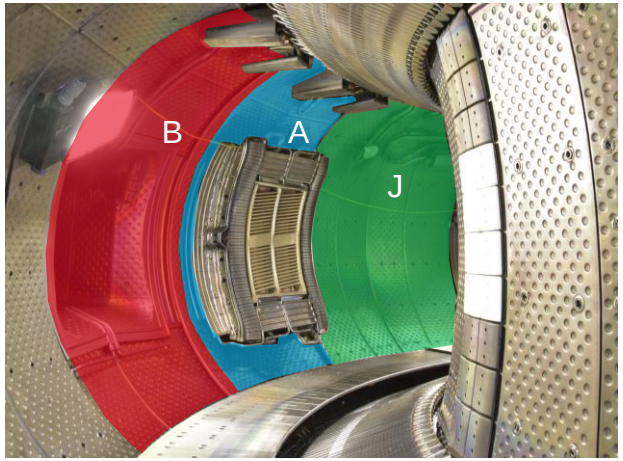
Group of components monitored by calorimetry

Inner wall



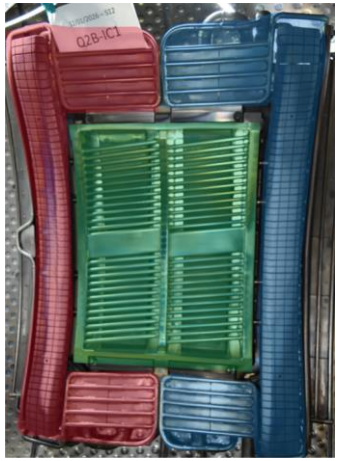
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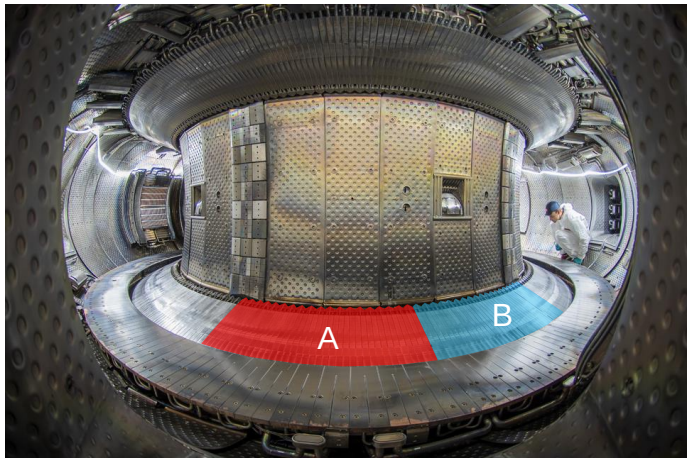
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LH / ICRH antennas



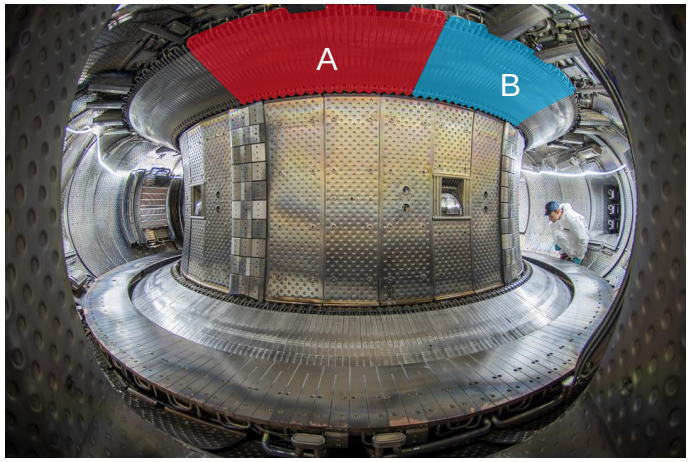
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Right lateral protection
Grill / Faraday screen

Lower divertor



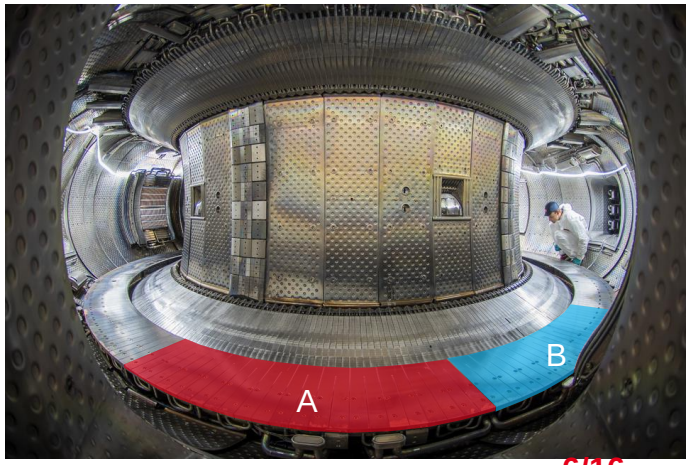
12 sectors of 30°

Upper divertor



12 sectors of 30°

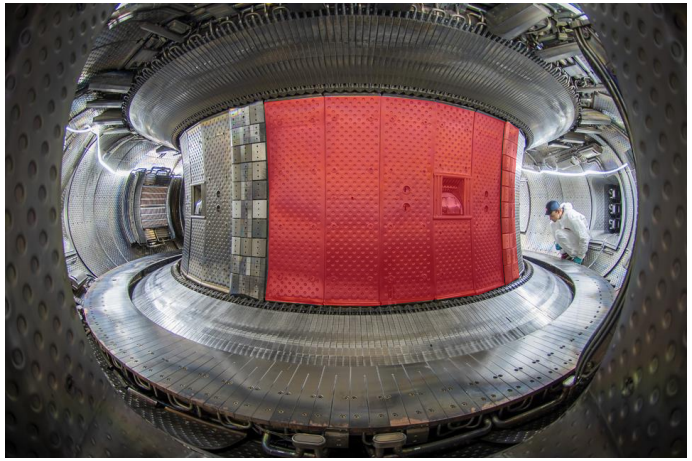
Baffle



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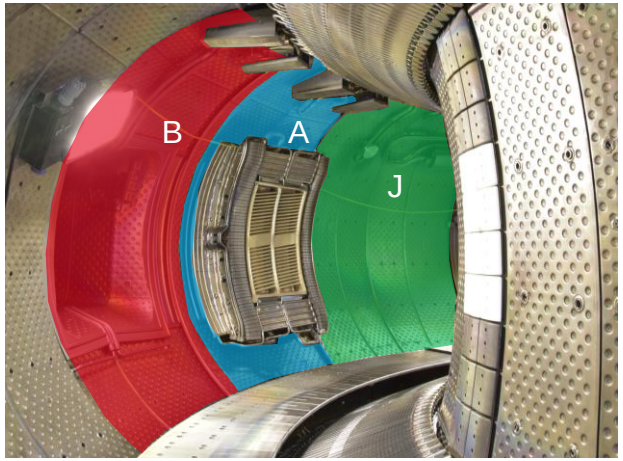
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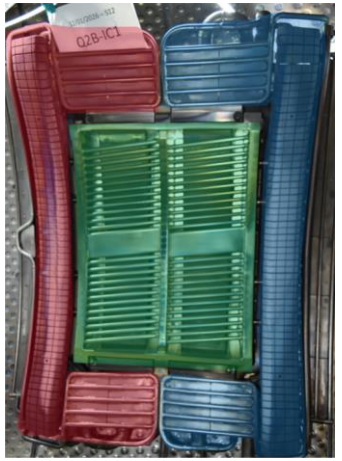
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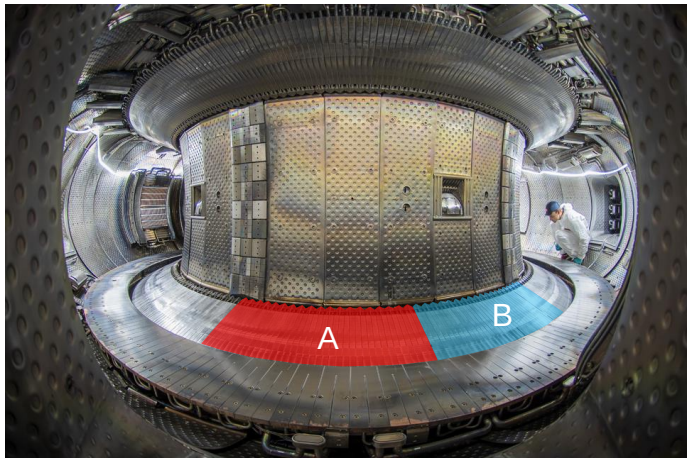
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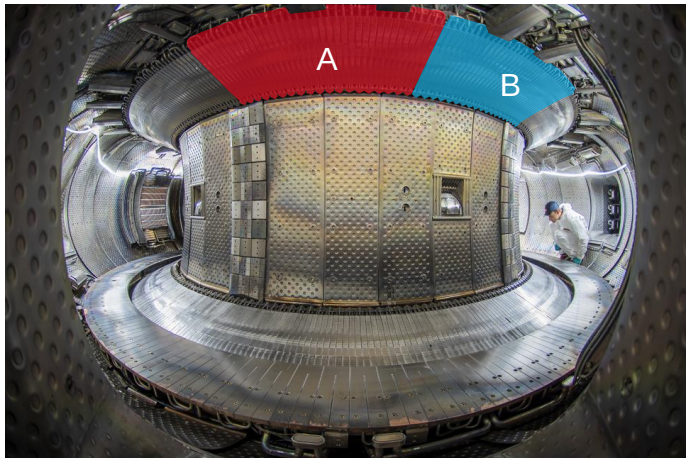
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Lower divertor



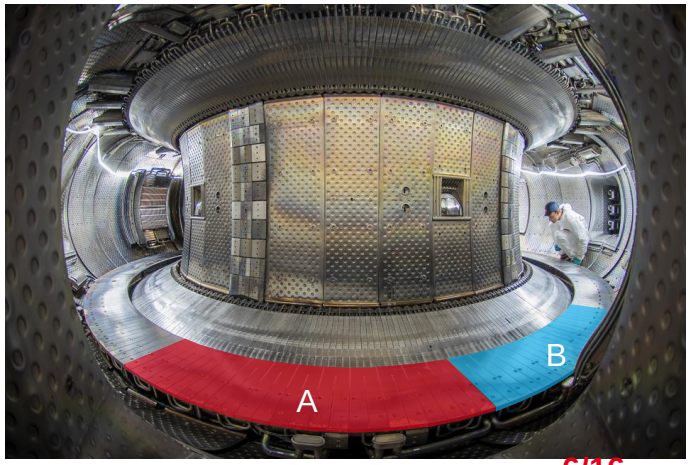
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Upper divertor



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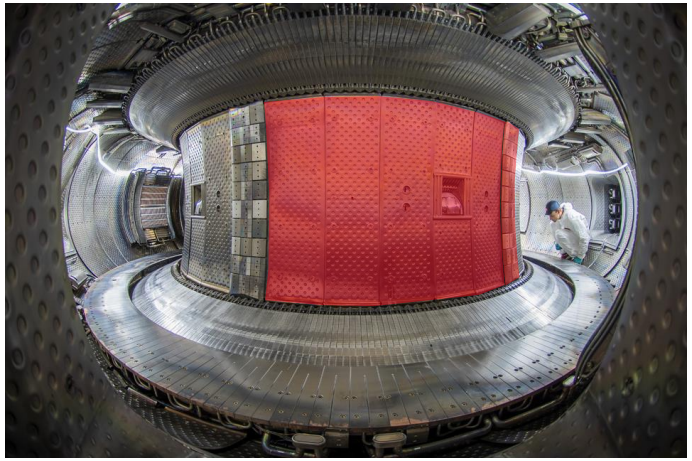
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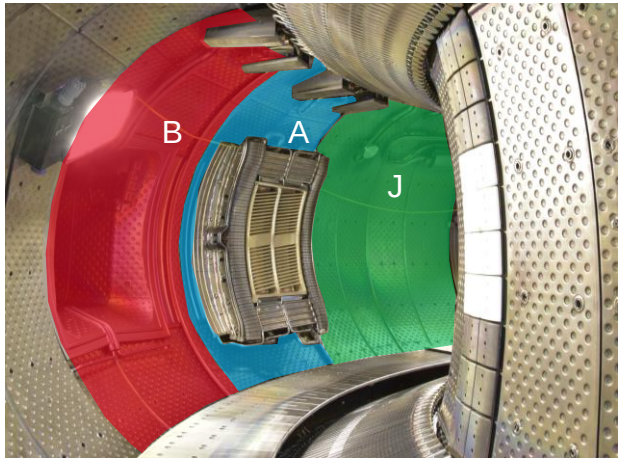
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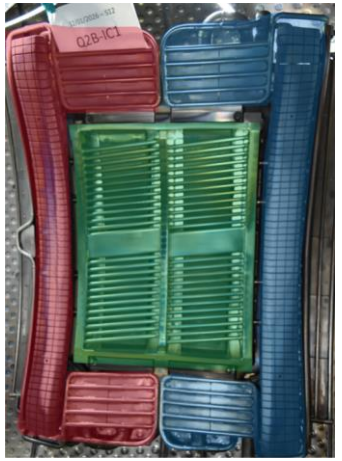
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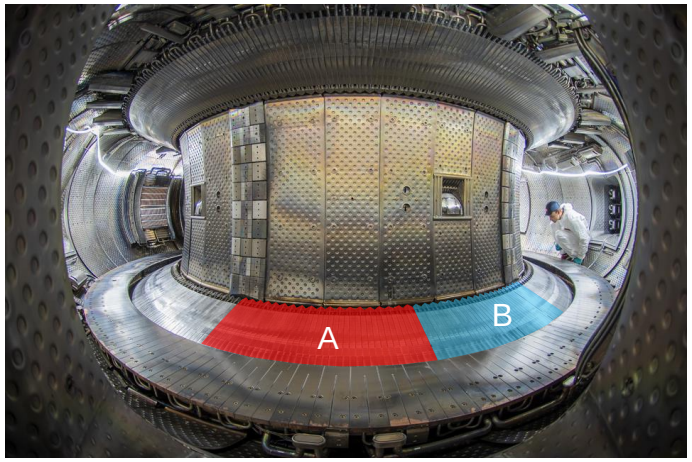
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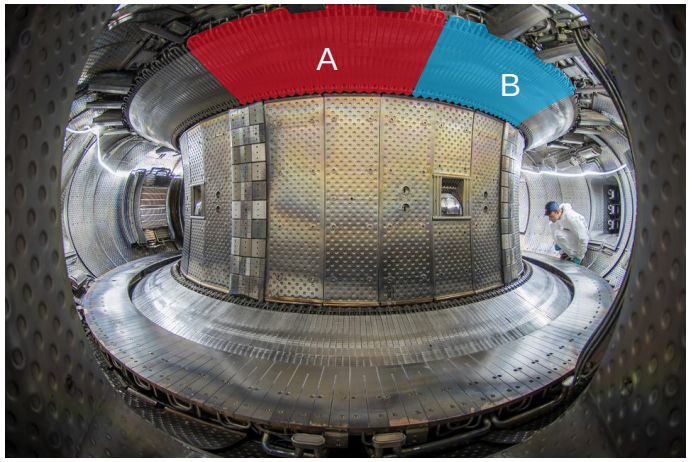
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Lower divertor



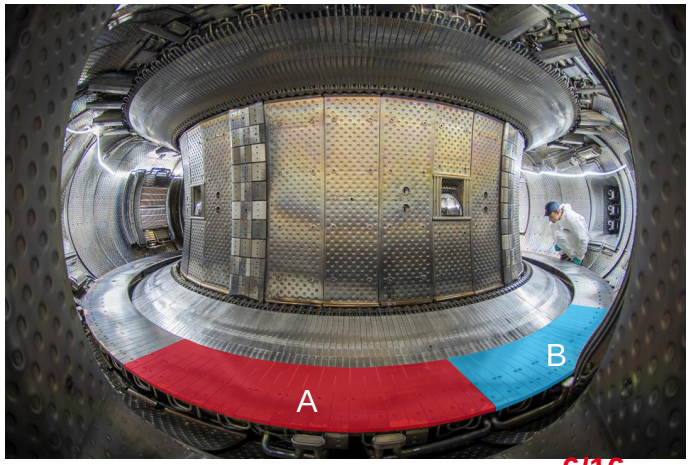
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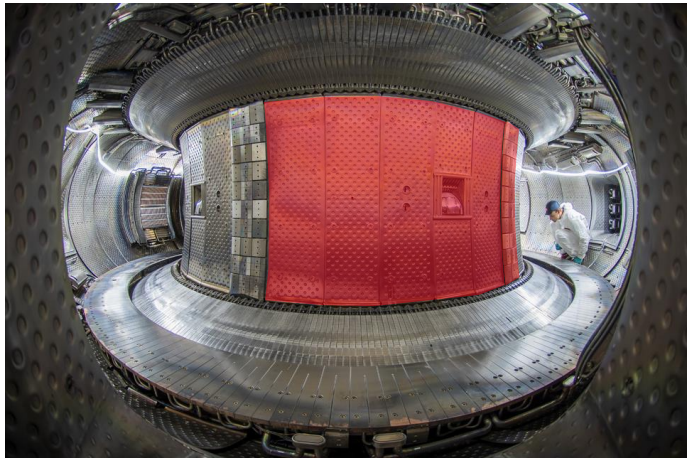
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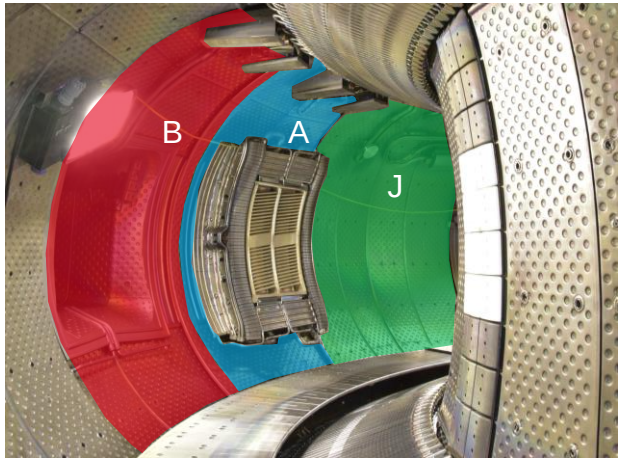
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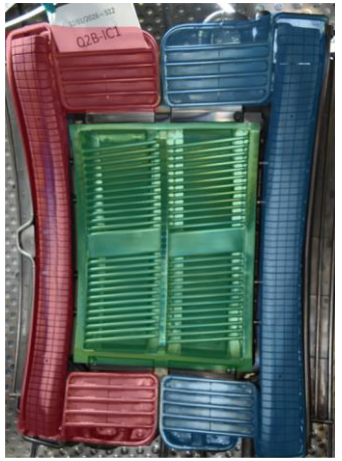
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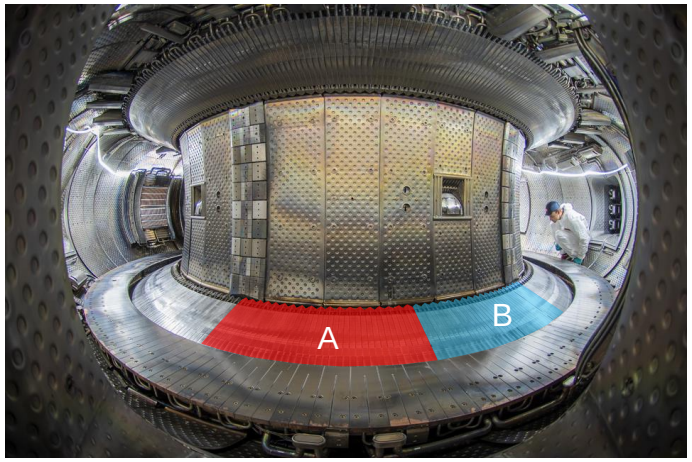
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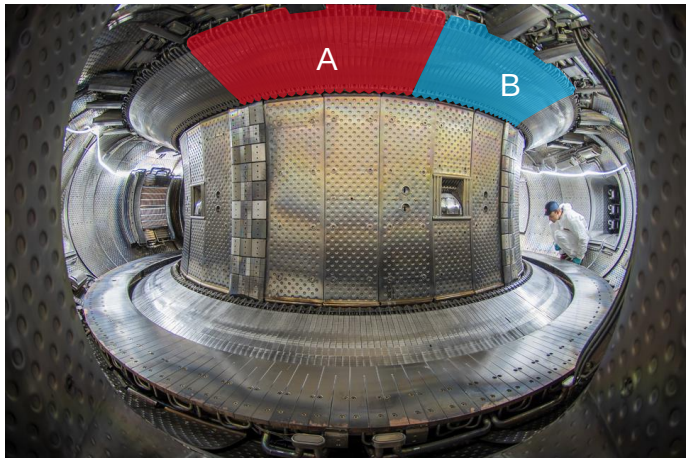
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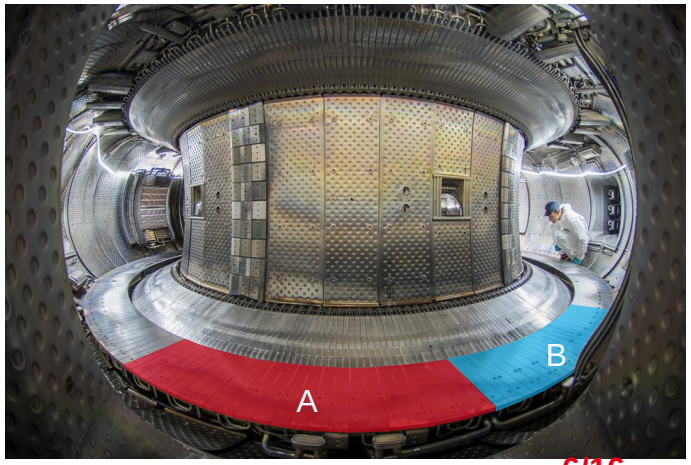
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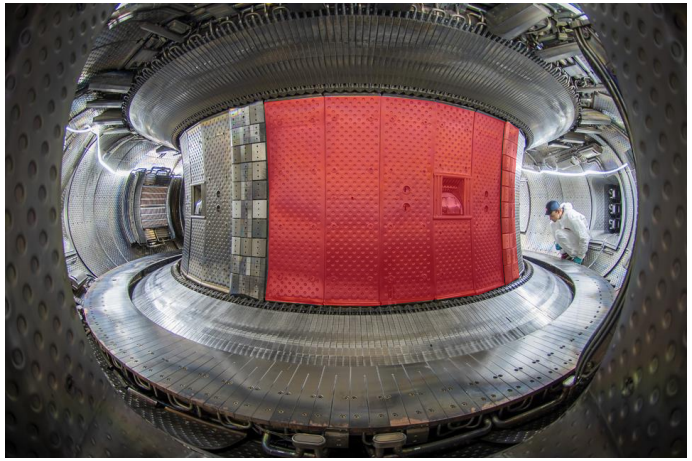
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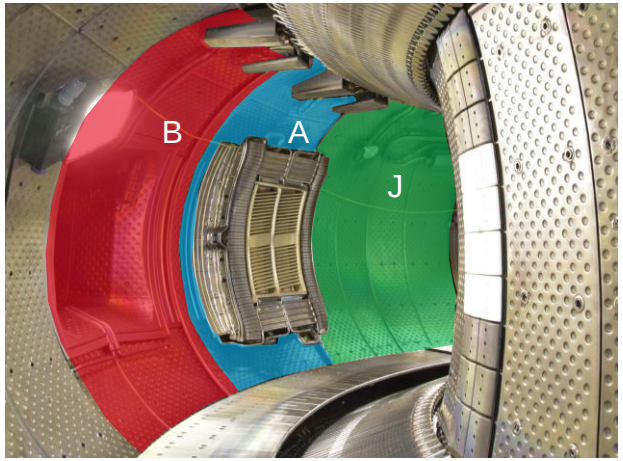
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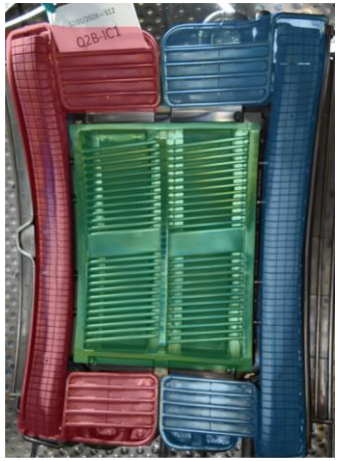
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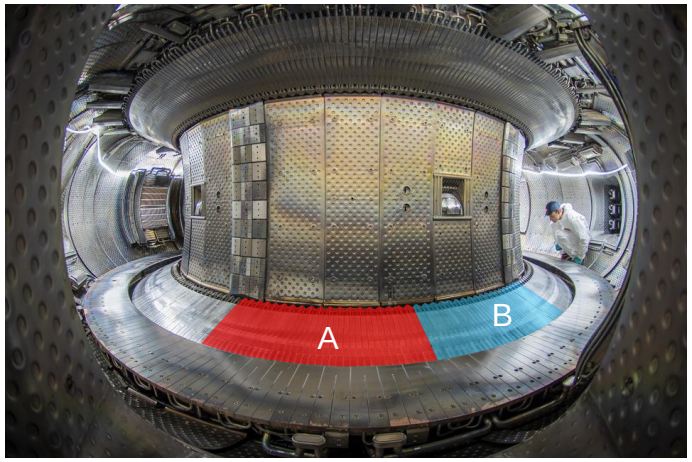
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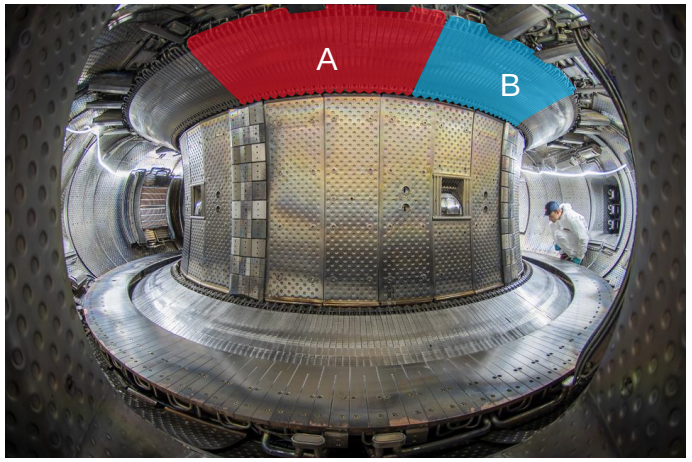
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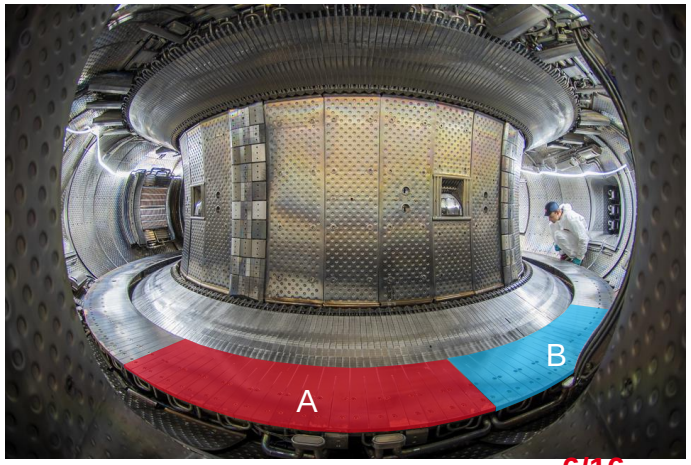
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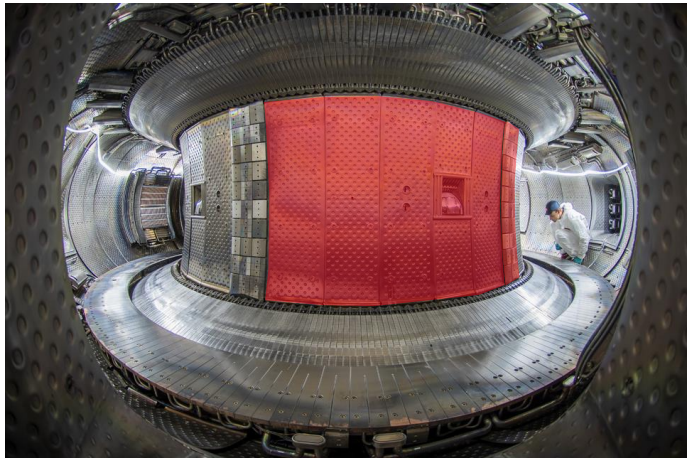
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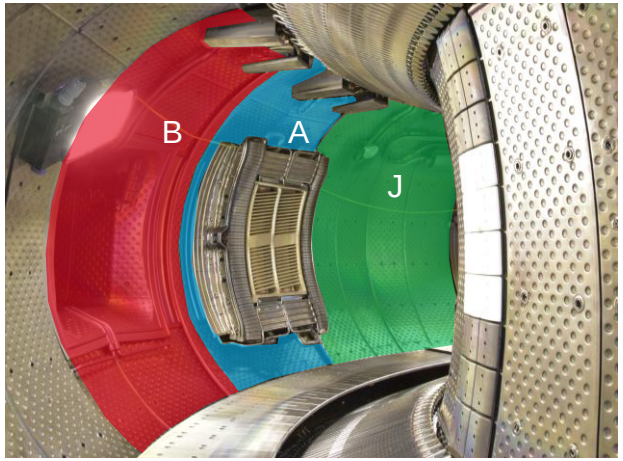
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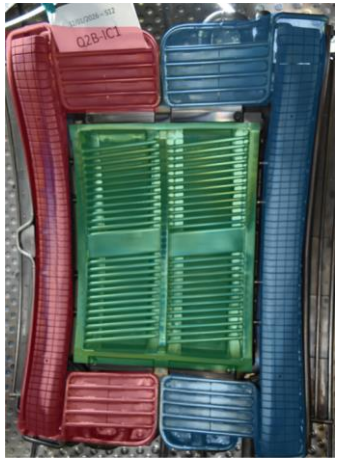
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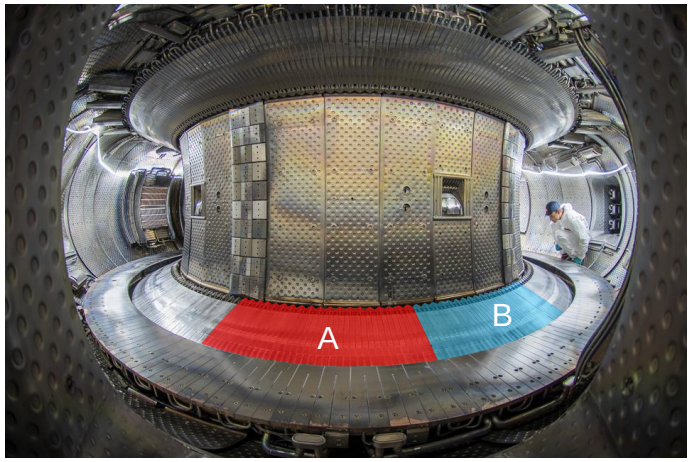
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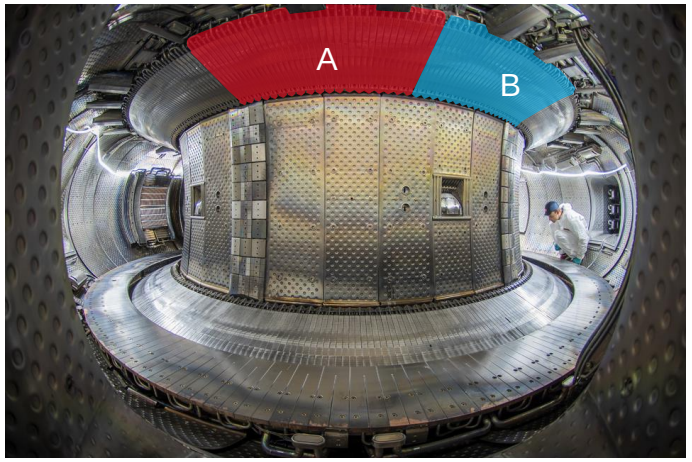
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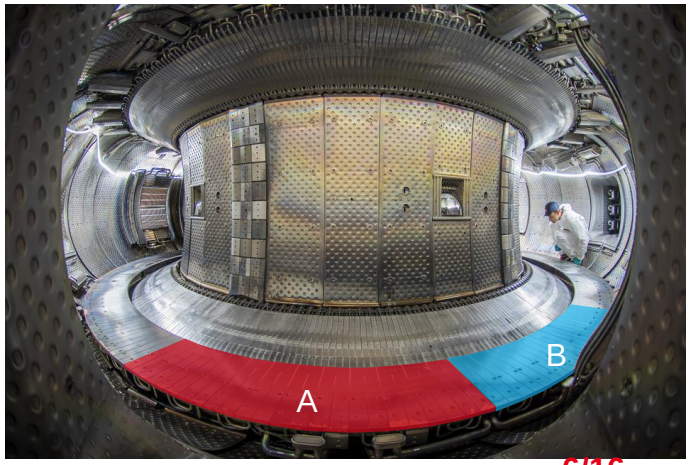
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Upper divertor



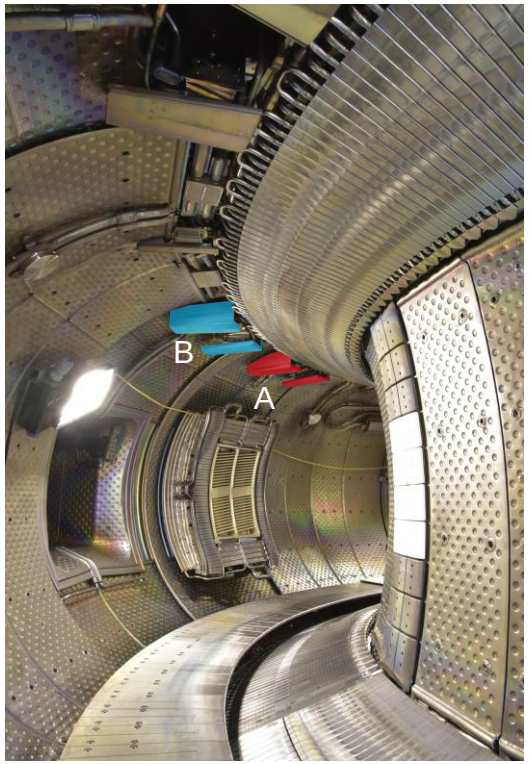
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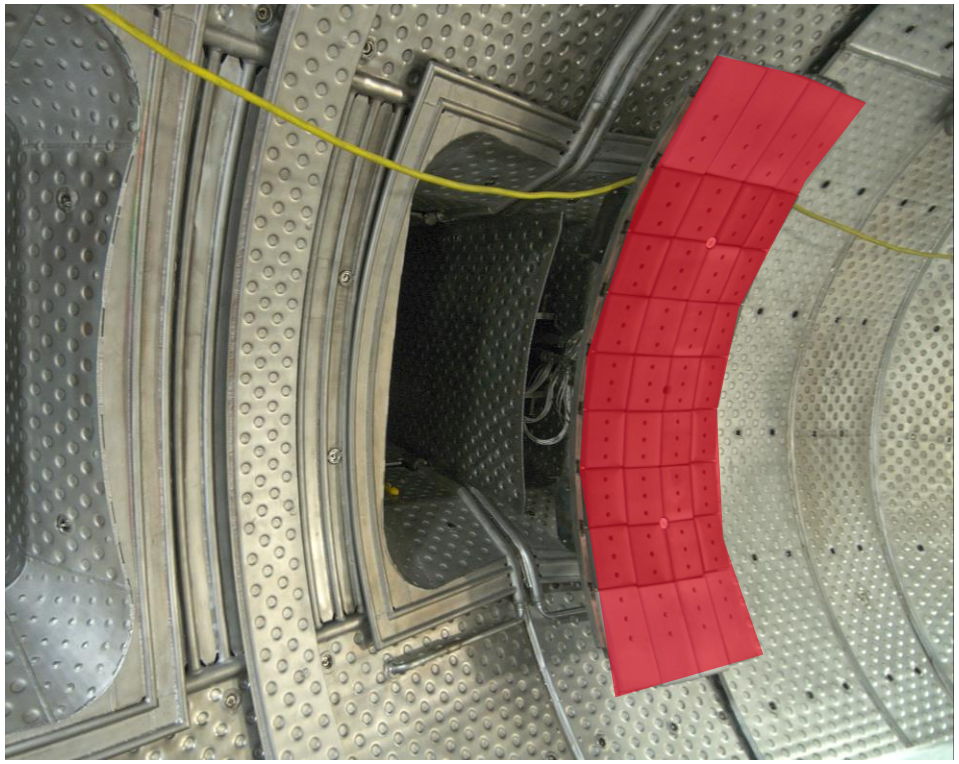




18 upper protection every 20°

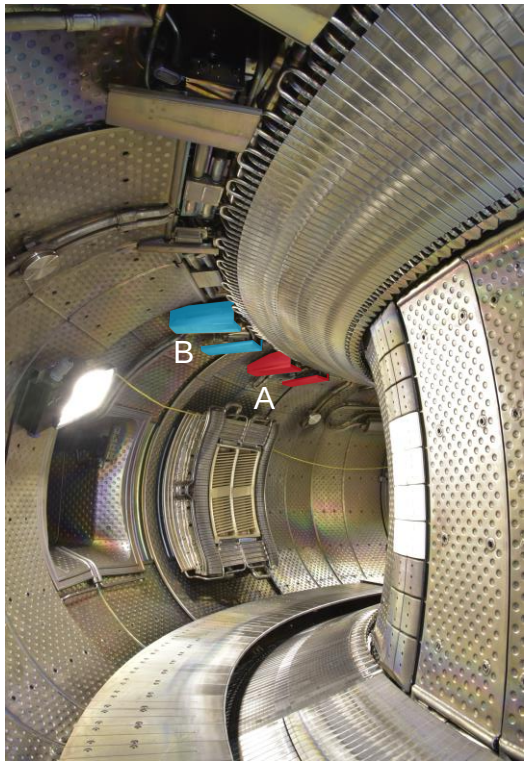
12 VDE protection

6 electronic ripple protection every 60°



1 Antenna Protection Limiter (APL)

Group of components monitored by calorimetry

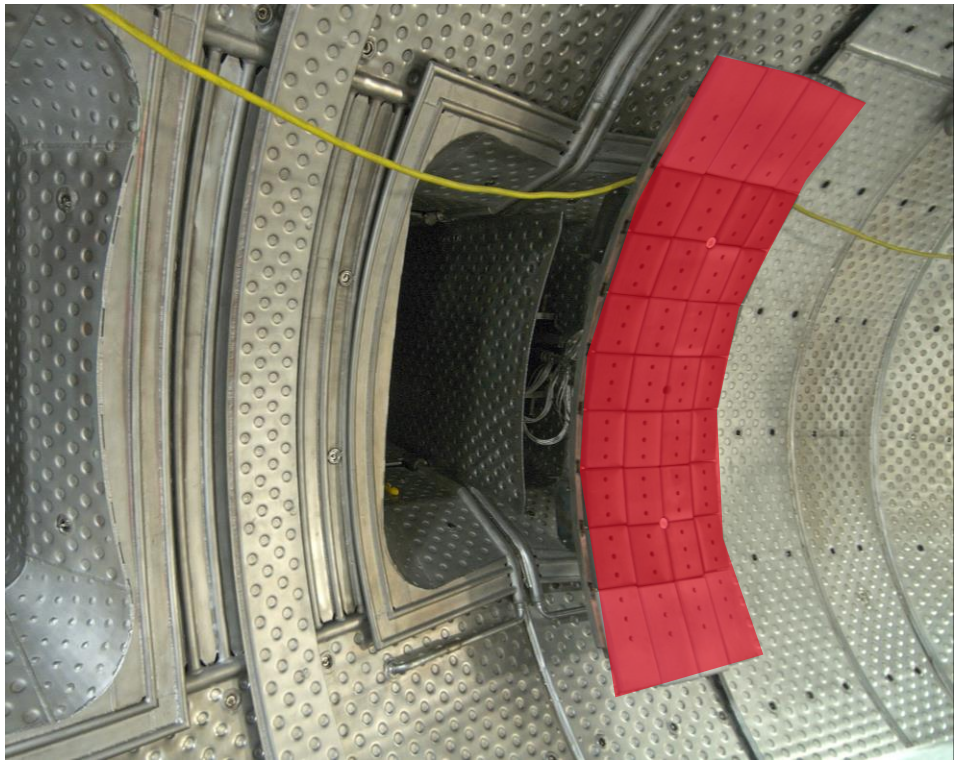




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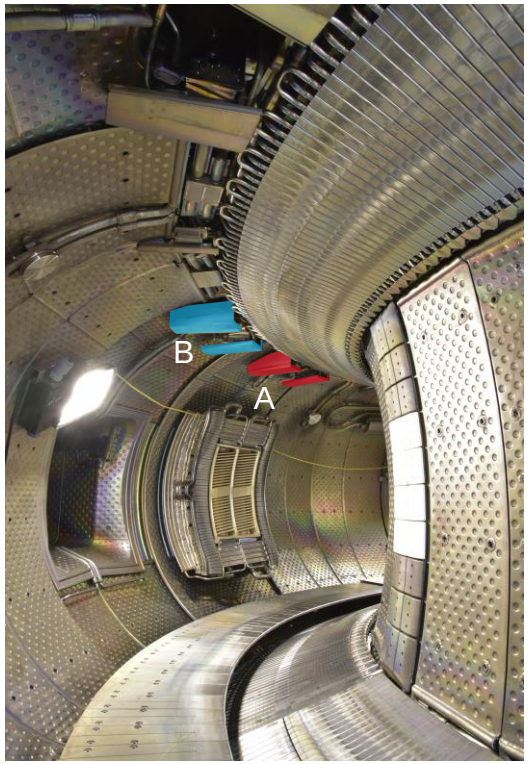
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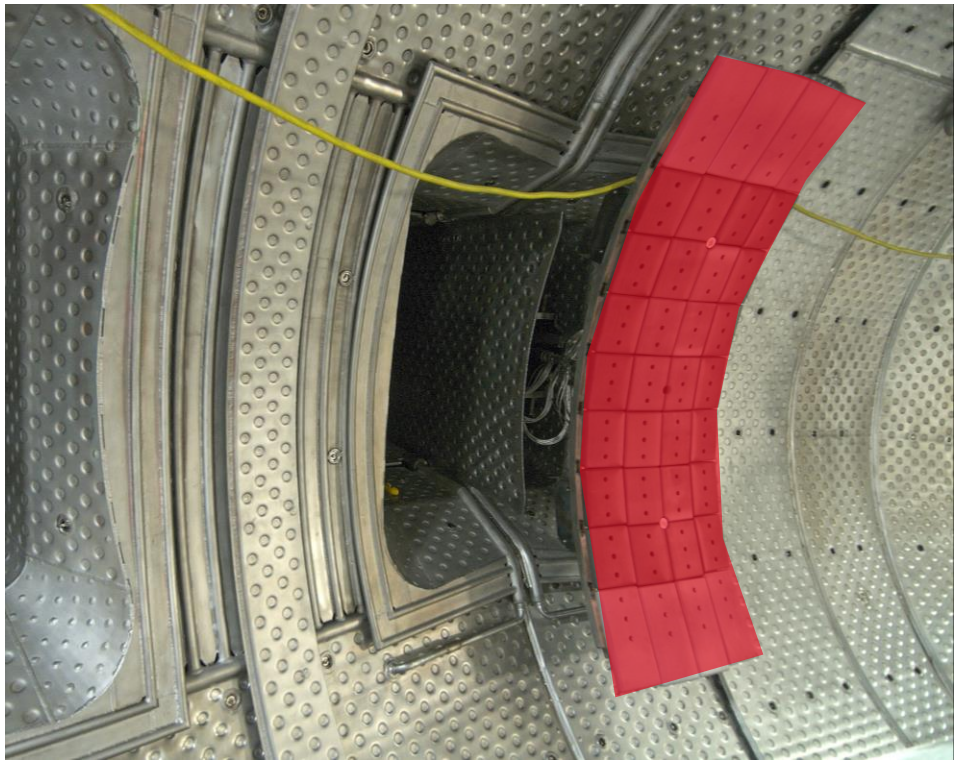




18 upper protection every 20°

12 VDE protection

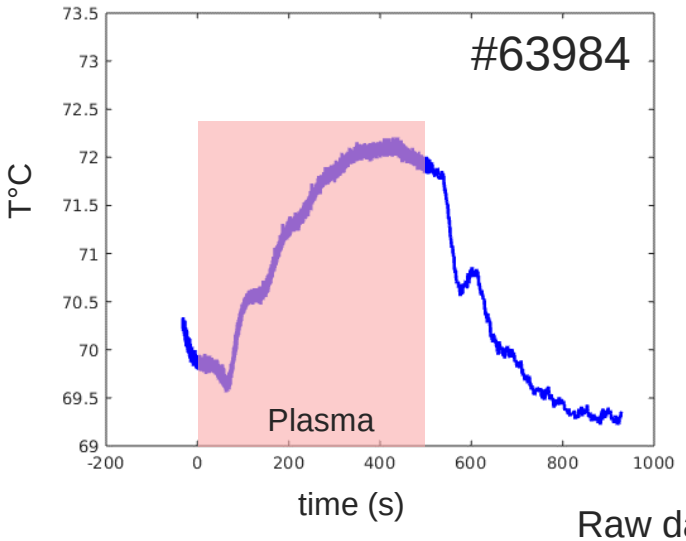
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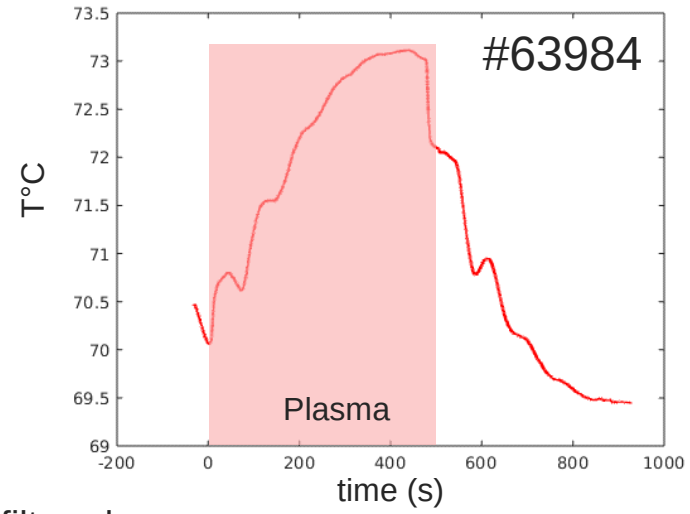
Typical temperature measurement of calorimetry

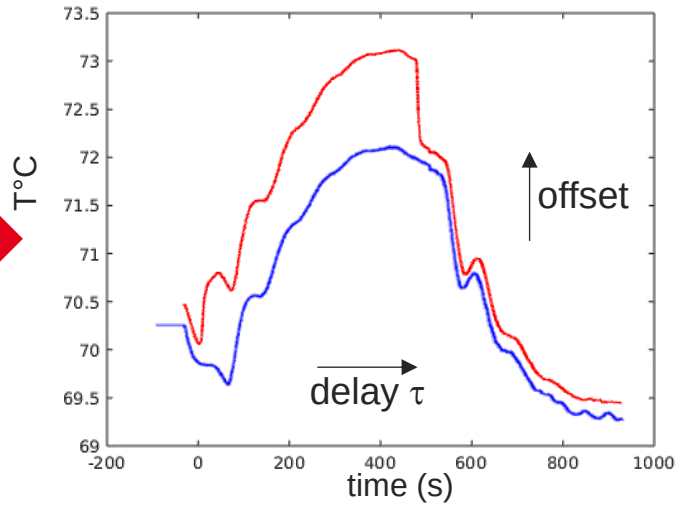
Global inlet temperature



+

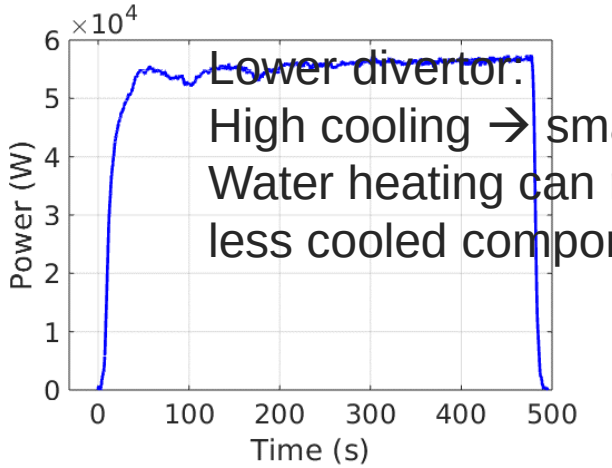
Lower divertor Q5A outlet temperature





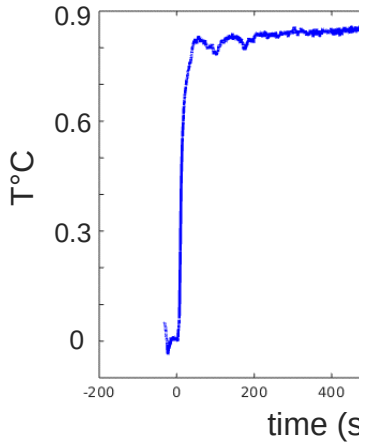
Raw data are filtered.

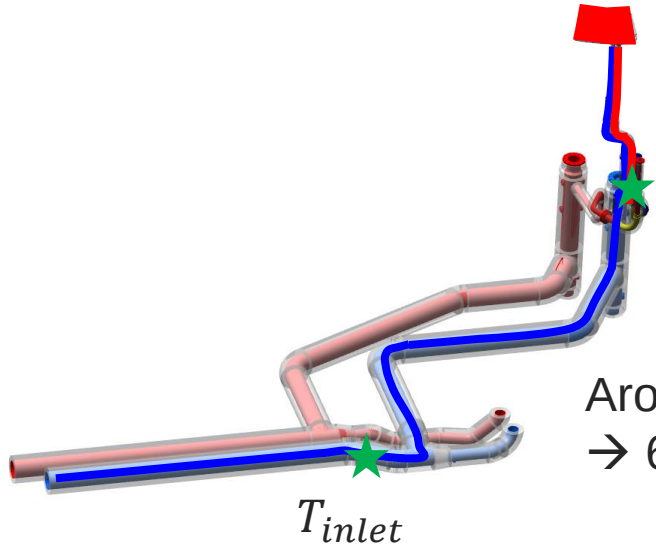
Need to adjust the delay and the offset on the inlet temperature to match the outlet temperature before and far after the pulse.



Lower divertor:
High cooling → small heating.
Water heating can reach 5-10°C on less cooled component.

Resulting power



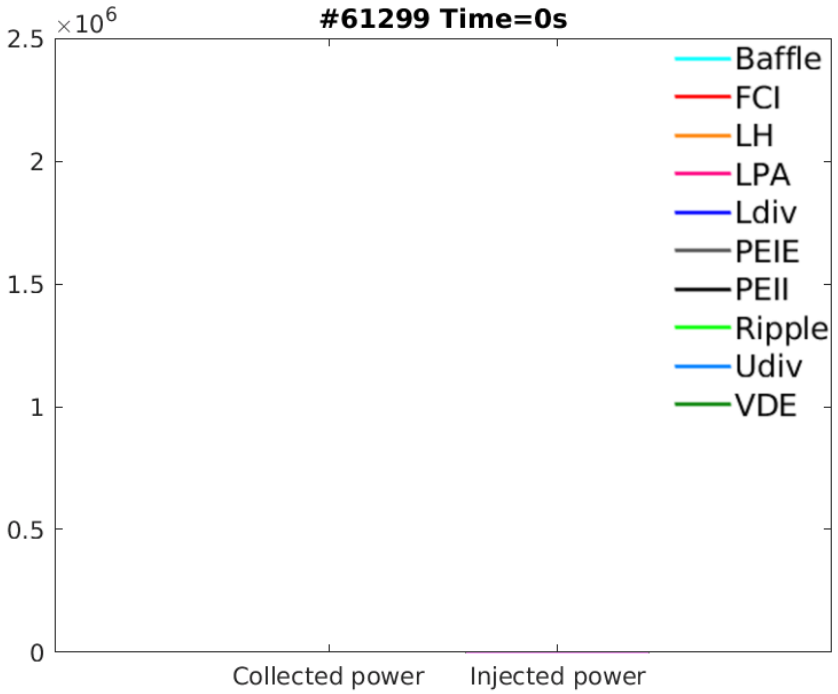


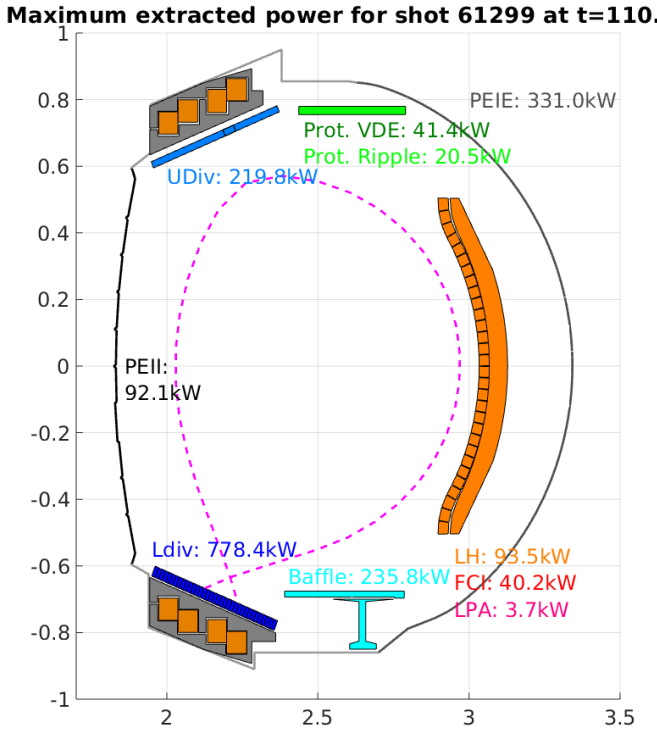
Around 17m
→ 6s delay

2. Energy and power balance from C7 (2023) to C13 (2026)

Power balance on long pulse

#61299 on 02/2025: 2MW LHCD **1337s** → 2.2GJ collected on 2.6GJ injected





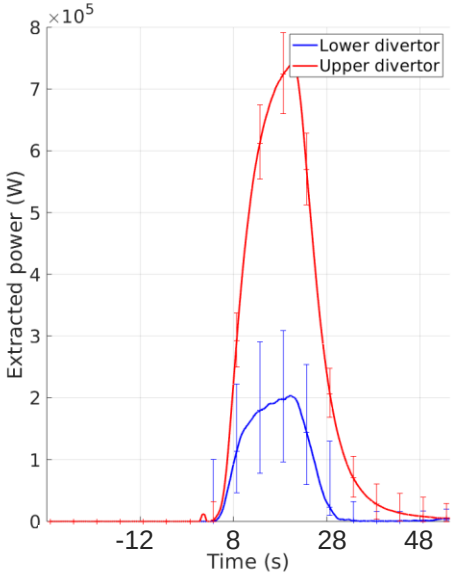
For this long pulse, the lower divertor received around 33% of total energy.
At steady state, the collected power is close to 800kW on the lower divertor.

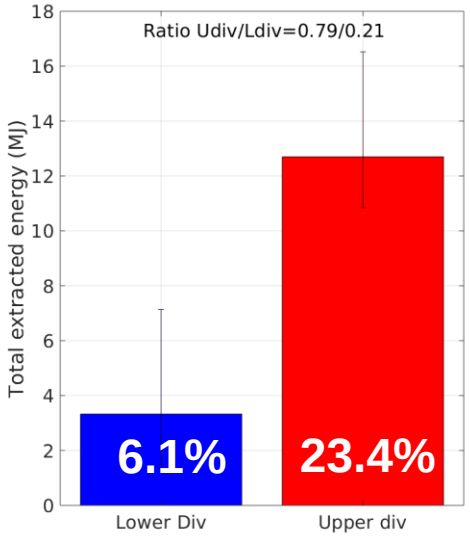
Power balance obtained for long pulse.

Energy balance for different magnetic configuration

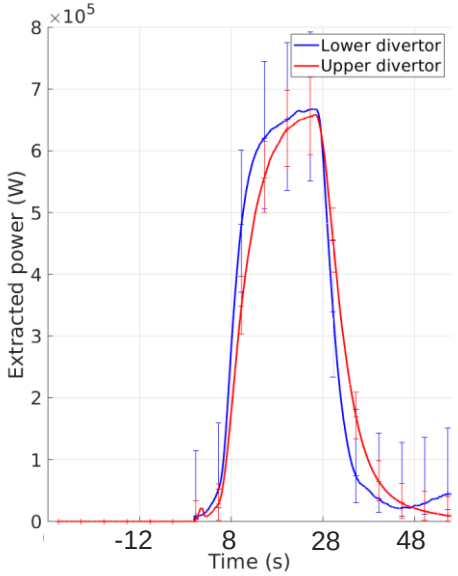
Calorimetry is used to compare energy collected on both divertor for different magnetic configuration

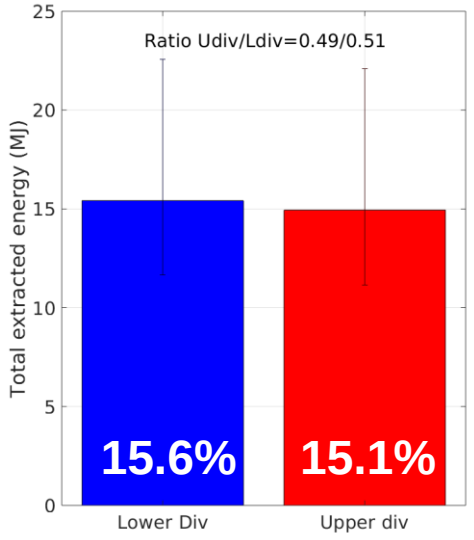
Upper Single Null





Double null



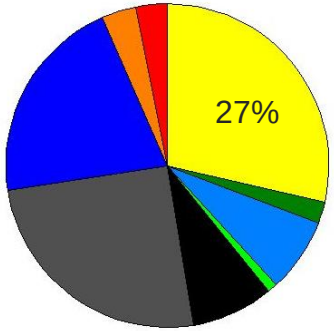


The power and energy in double null configuration are equally distributed between both divertor.
The fraction of energy going on both divertor remains in the same order of magnitude for both configuration.

Perspective: use the calorimetry system to adjust the plasma magnetic configuration

Energy balance over campaign

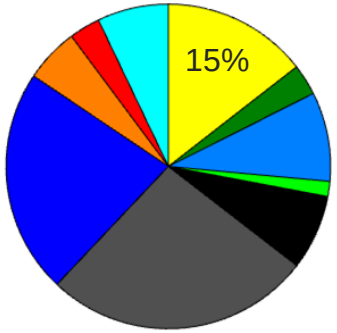
C7 (01/23-04/23)



1105 pulses
5.4h
48.4GJ

No baffle measurement
Lower divertor fully actively cooled

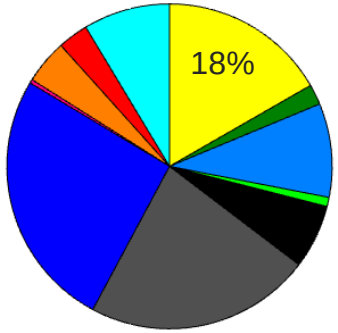
C8-C9 (12/23-04/24)



1277 pulses
5.7h
43.9GJ

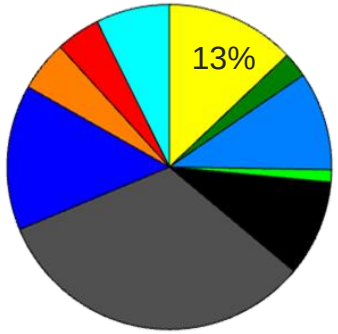
Baffle actively cooled

C10-C11 (11/24-04/25)



1608 pulses
7.3h
47.1GJ

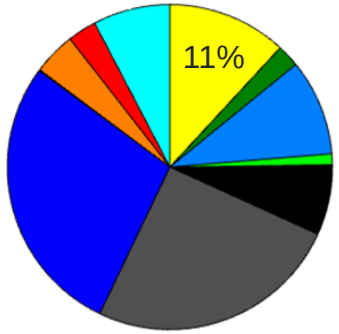
C12 (11/25-12/25)



862 pulses
4.6h
46.2GJ

Improvement of the inlet temperature measurement
XPR campaign

C13 (05/26-07/26)



779 pulses
2.6h
15.4GJ

Baffle Ldiv Udiv
ICRH Out. wall VDE
LH Inn. wall Undertermined
APL Ripple

Non negligible part undetermined:

- **Inaccuracies of measurement** (bad SNR)
- **Missing data** (approximated from equivalent ones)
- **Few components not monitored**

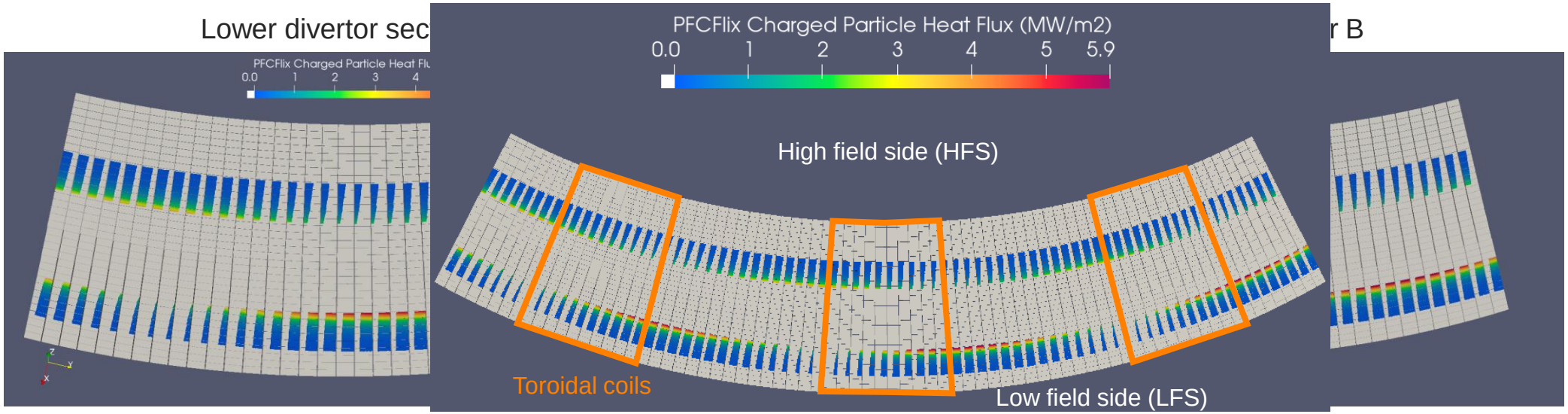
Perspective : improve energy balance and add more local intrumentation

3. Magnetic ripple and in-situ calorimetry

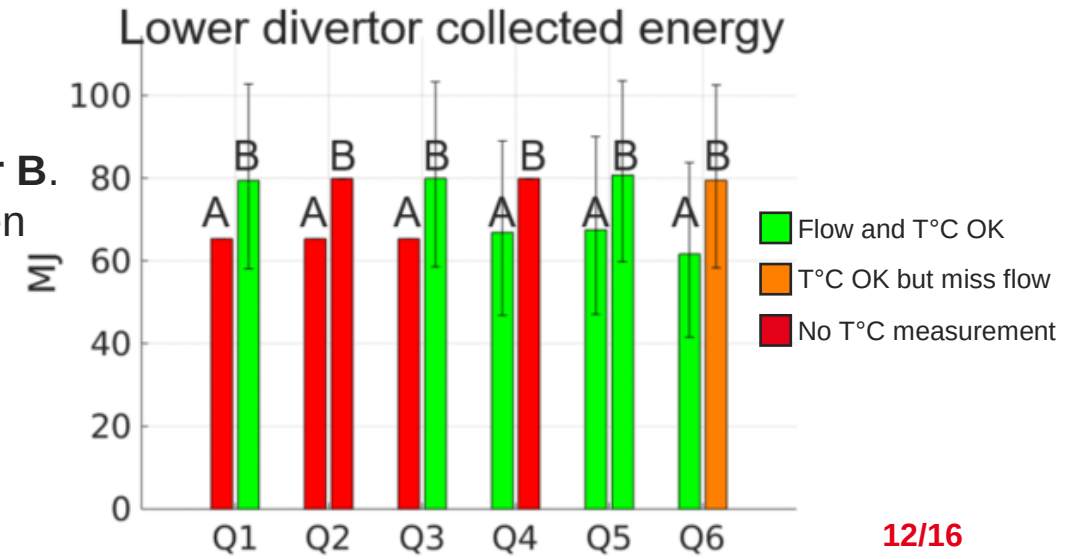
Ripple effect on lower divertor

Simulation of the heat flux on the lower divertor by field line tracing code (PFCFlix)

see poster Aumeunier Wed 23/09
Multi-Physics Simulations for Advanced Thermal Protection of Tokamaks…



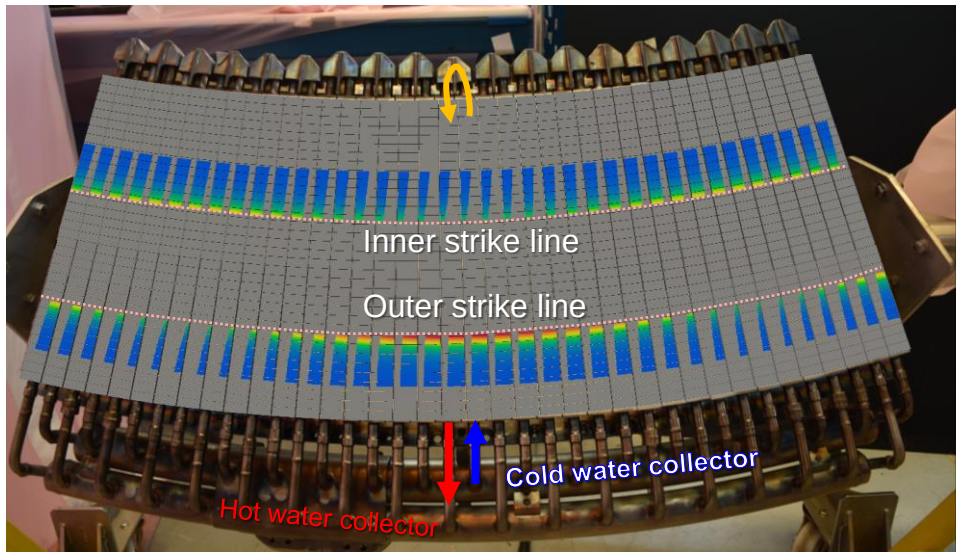
Due to the coils position, a **strong ripple** is present on the lower divertor.
Asymmetry of the heat load between HFS and LFS.
→ The **heat flux is not toroidally constant** and follow a pattern every 20°.
Sector are 30° large: the **pattern is different between sector A and sector B**.
Asymmetry between HFS and LFS makes integrated power different between sector A and B

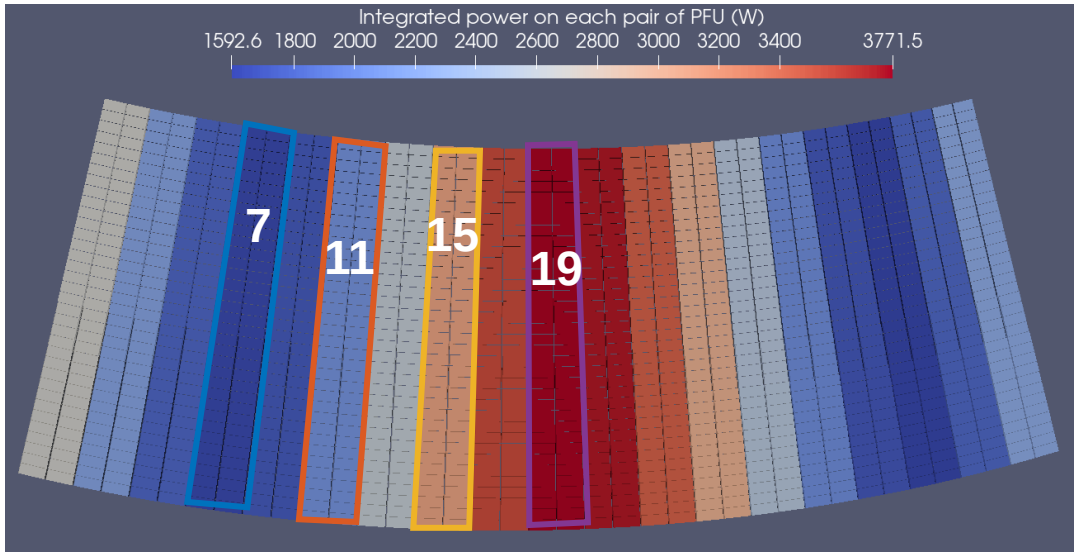


This effect is visible on the calorimetry system with sector B receiving more energy than sector A

Ripple effect on lower divertor

The ripple modulation create some discrepency between the different pairs of PFC

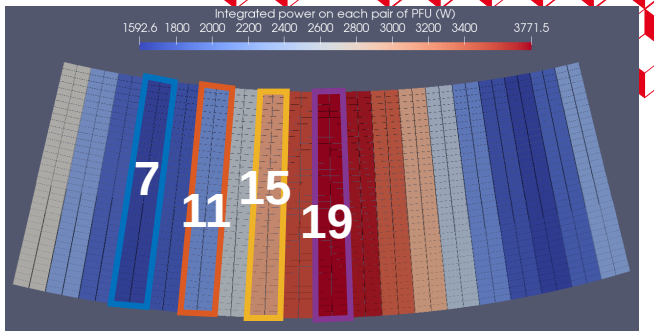




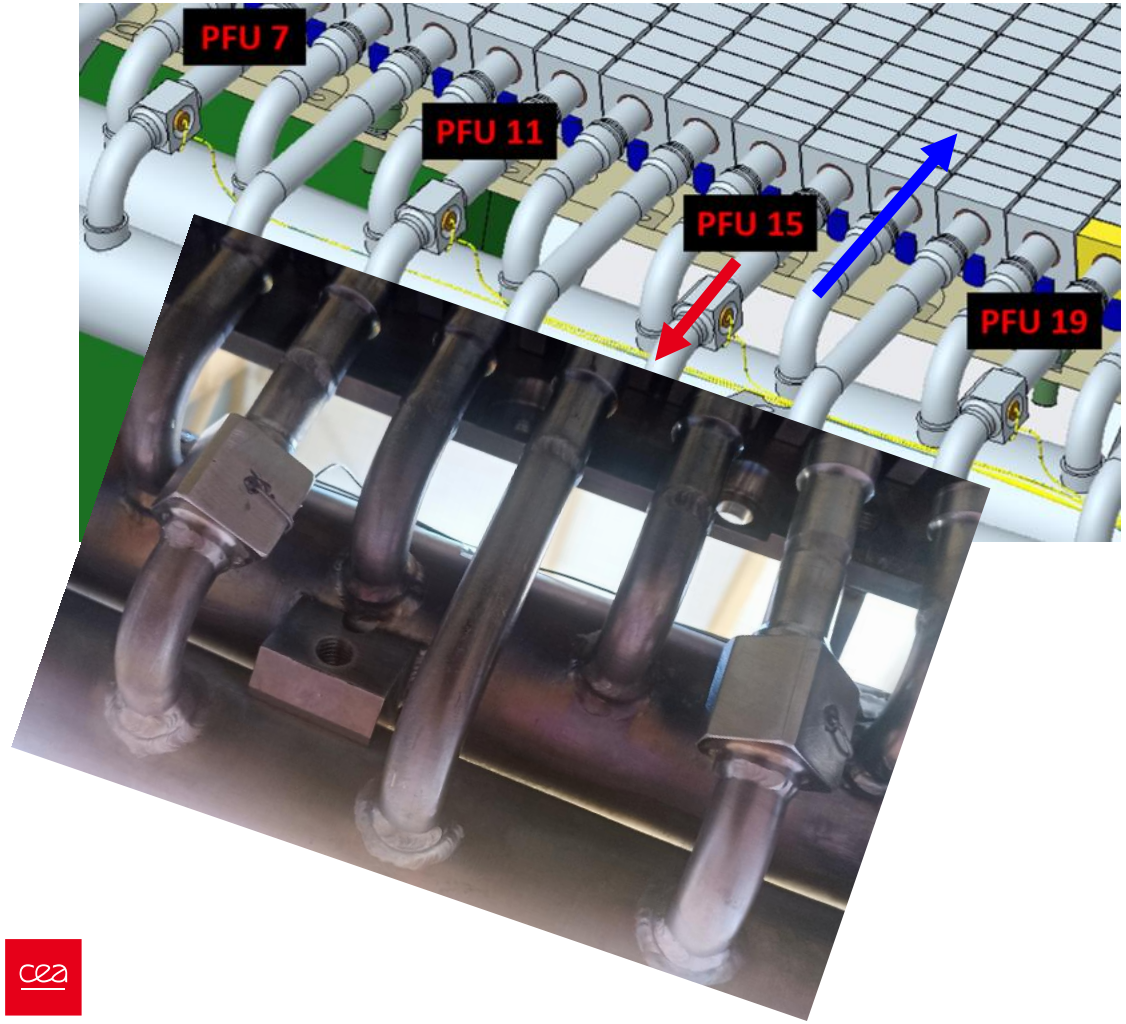
The amplitude of the magnetic ripple depends on some plasma parameters (Ip, X-Point height)

To measure the ripple modulation, an in-situ calorimetry system was installed on the lower divertor of WEST.
This extends the capabilities of the calorimetric system to measure extracted power on isolated components.
→ Can detect misalignment of component
→ Link with current measurement at monoblock and sector scale.

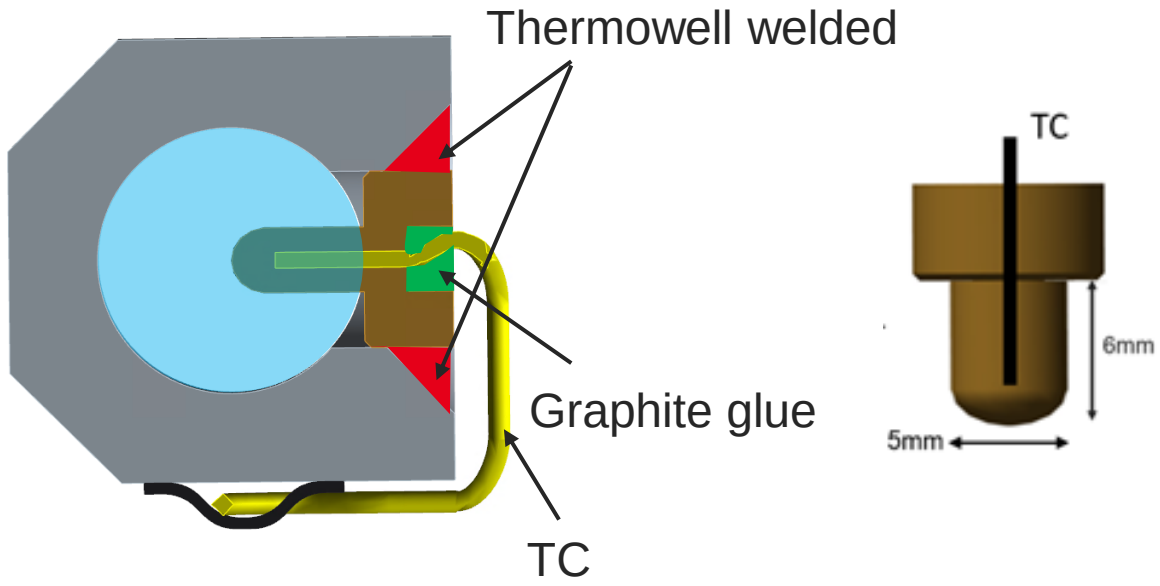
In situ calorimetry sensors



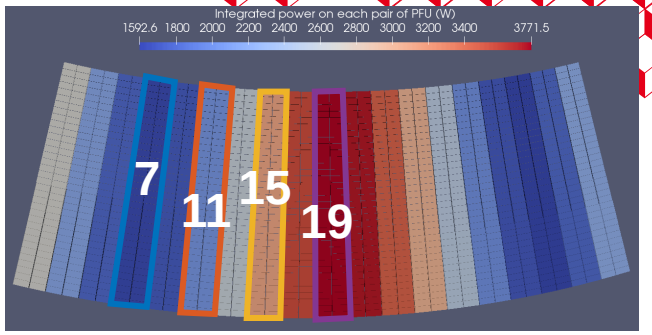
4 sensors positioned on the outlet of 4 pairs of lower divertor PFCs, covering from minimum to maximum of ripple amplitude



To prevent water leak, stainless steel thermowell was used. 1mm thermocouples (TC N type) are used to measure the temperature at the bottom of the thermowell

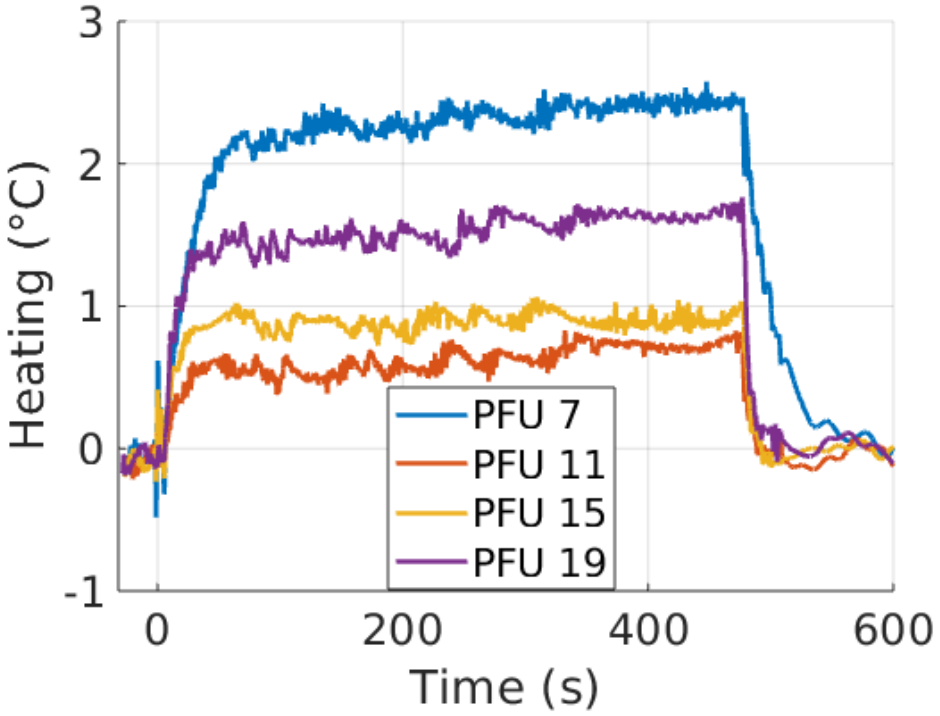


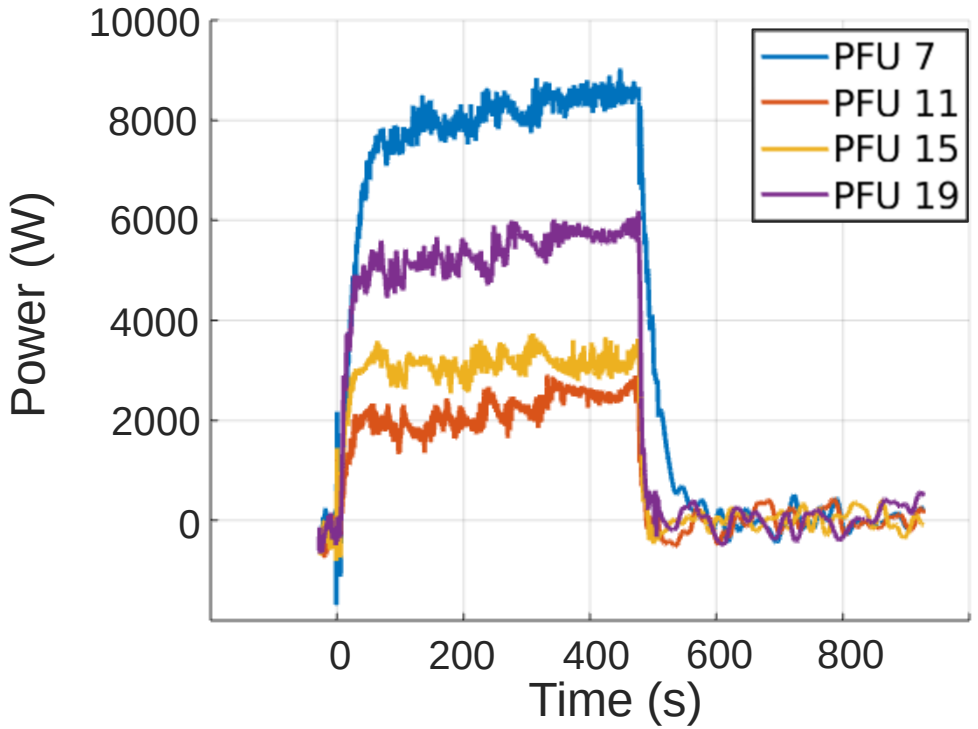
First result of the in situ calorimetry



First results are promising.

#63984 475s 220kA 2.4MW LHCD

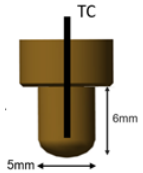




Water heating from 0.7 to 2.2°C

Leading to extracted power from 2kW to 8kW par pair of PFU

But, PFU7 should be at the minimum ripple… → TC not at the back of the thermowell?



Need to implement more sensors for redundancy and improve the TC fixation

Conclusion

- **Tokamak actively cooled** → allow to monitor the extracted power and energy on each component by calorimetry (by water heating).
  - Usage for plasma physics and protection
- The **energy balance is not close** due to uncertainties of measurement, missing data, few components not monitored.
- The **lower divertor and outer wall are the most loaded area**.
- **Power balance doable for long pulses** with stationnary condition.
- Magnetic ripple modulation on the lower divertor affect the collected energy on each lower divertor sector and locally between each pair of PFC.
- In situ calorimetry system was tested to measure the ripple effect.
  - Promising results but need redundancy for more accurate results.
  - To be compared with simulation.

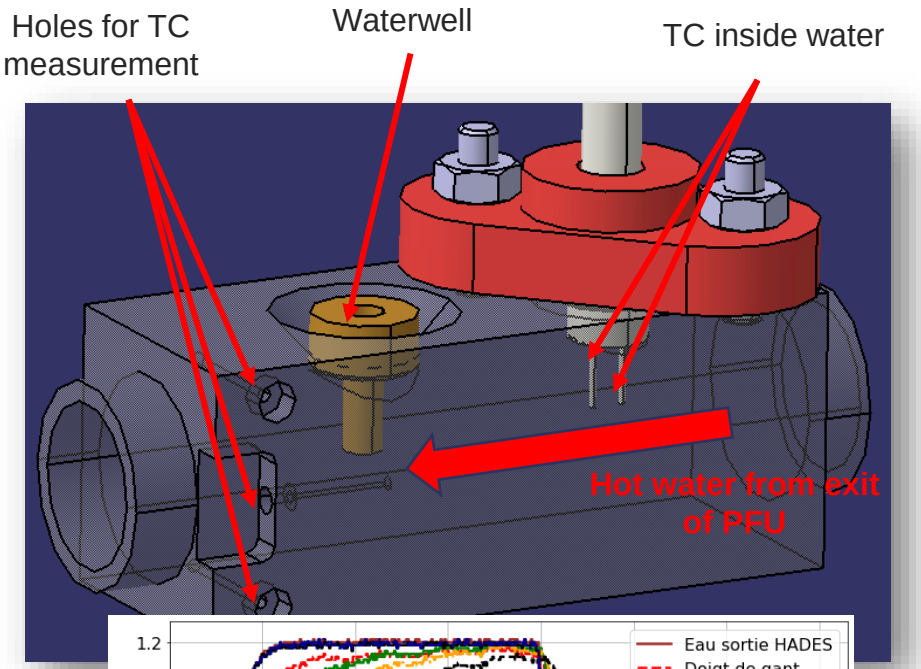
Thank you for your attention

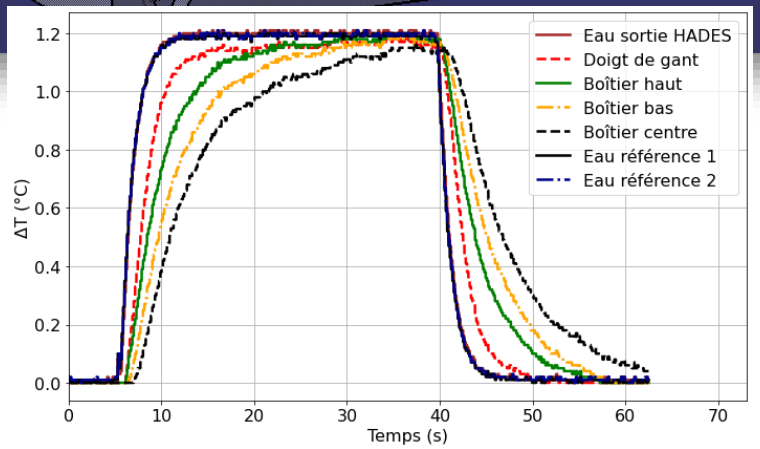
Jonathan.gerardin@cea.fr

Thank you for you attention

Jonathan.gerardin@cea.fr

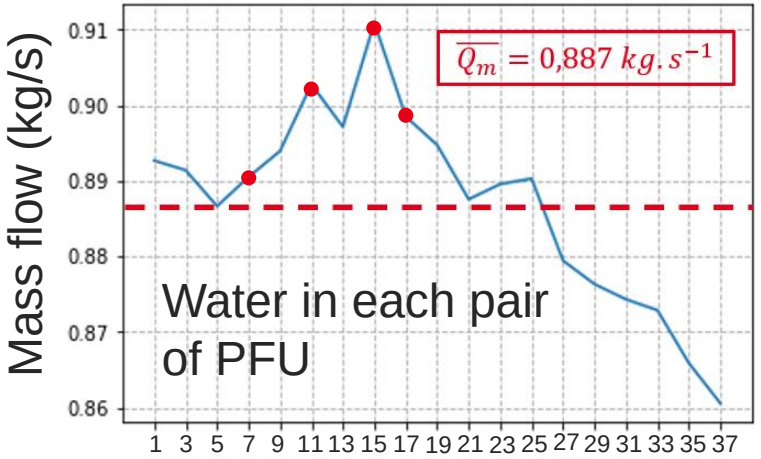
In situ calorimetry

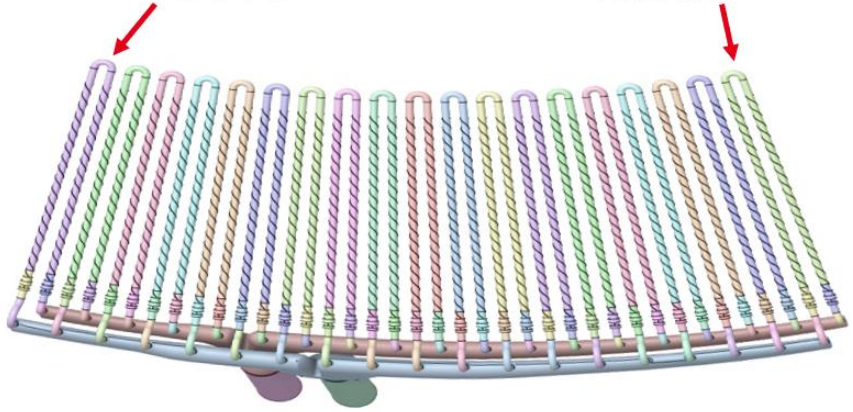




Waterwell gives similar results to thermocouple inside water. Need a slight larger delay to reach the steady state

ANSYS Fluent water flow simulation

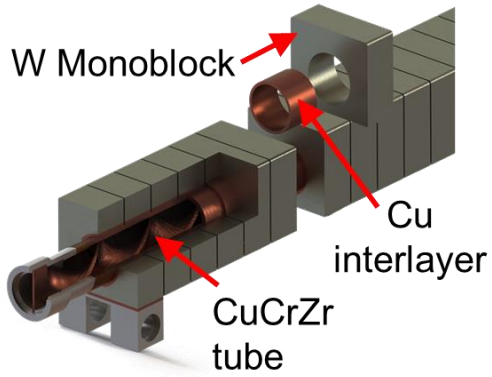


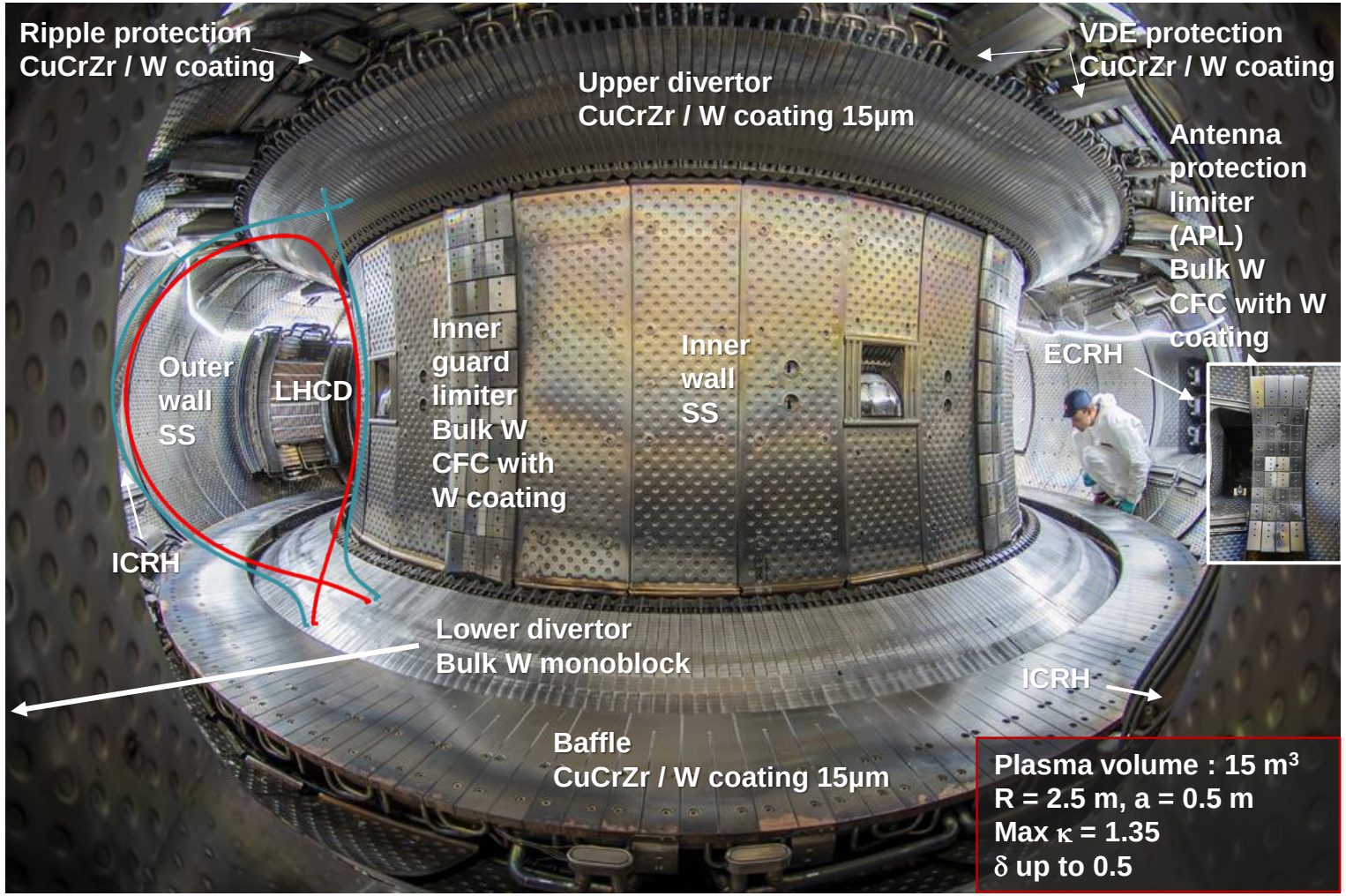


Maximum 2.5% of discrepency with respect to the average mass flow.

WEST: Tungsten (W) Environment Steady-state Tokamak

- Superconduct. toroidal field coils (3.7 T)
- W environment
- Upper and lower divertor
- D_2/H_2 fueling
- Fully actively cooled (70°C)
- 2x LHCD antennas (7MW)
- 2x ICRH antennas (4MW)
- 1x ECRH (1MW)

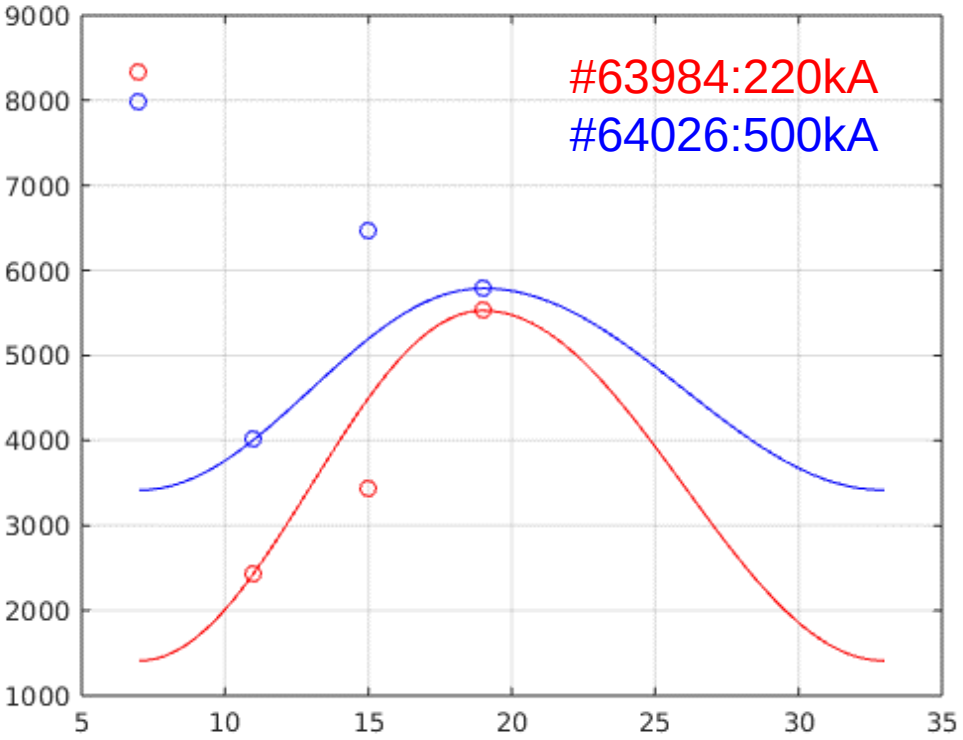


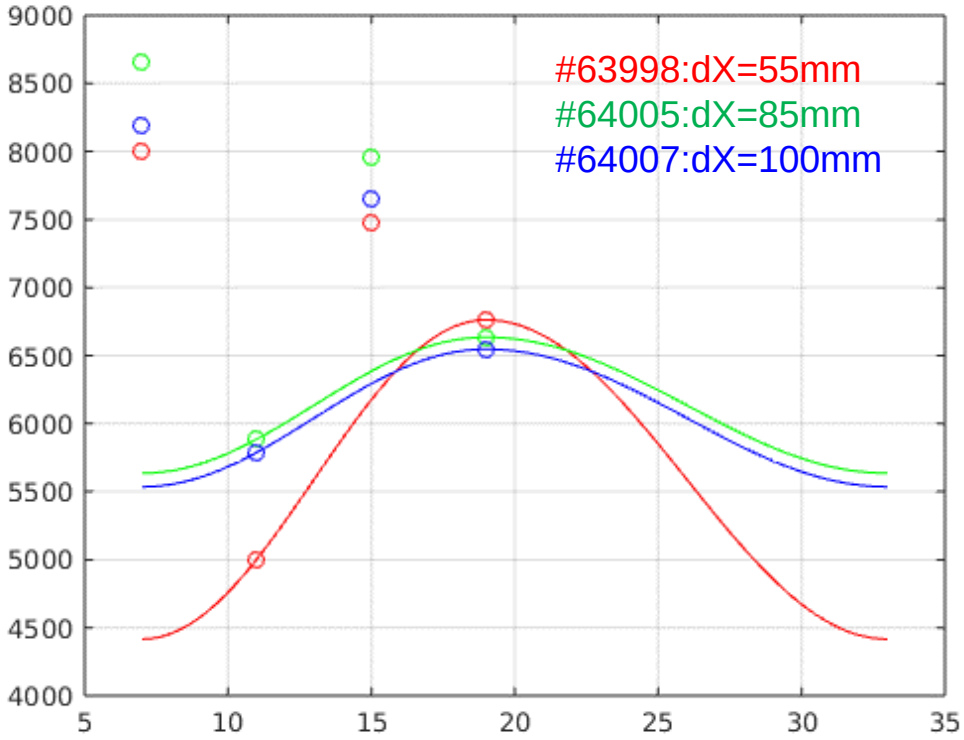


ITER-grade W-monoblock
- Pressurized water (15-20 bars)
- High power exhaust capabilities : 20 $MW.m^{-2}$
- Cooling temperature : 70°C

Ripple modulation by in situ calorimetry

First result are promising.





Estimation of the ripple modulation based on PFU11 and PFU19 only.
Consistant with expectation.
Need to be compared with heat flux simulation.
Require more redundancy for the sensors.

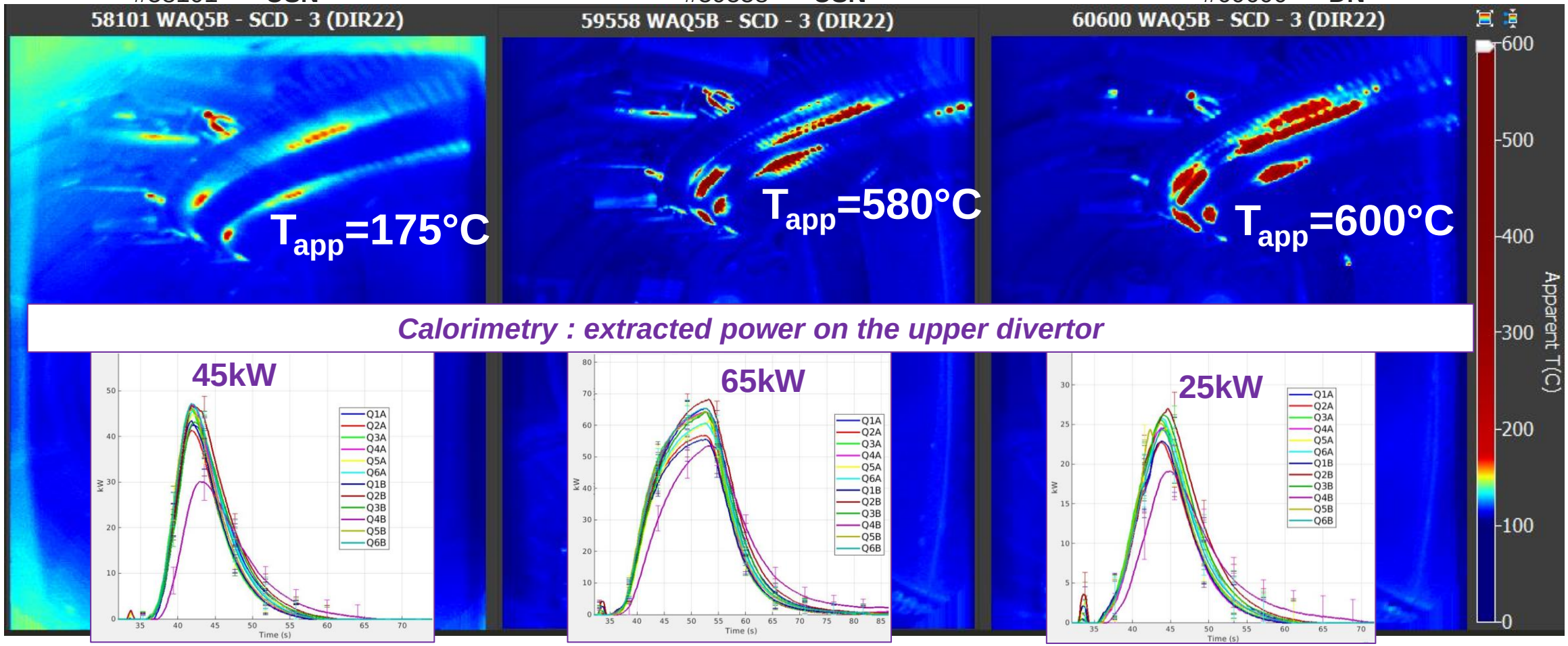
Other usage of calorimetry : PFC protection

Support to the InfraRed protection

C7 (before high fluence campaign) #58101 **USN**

C9 #59558 **USN**

C10 #60600 **DN**

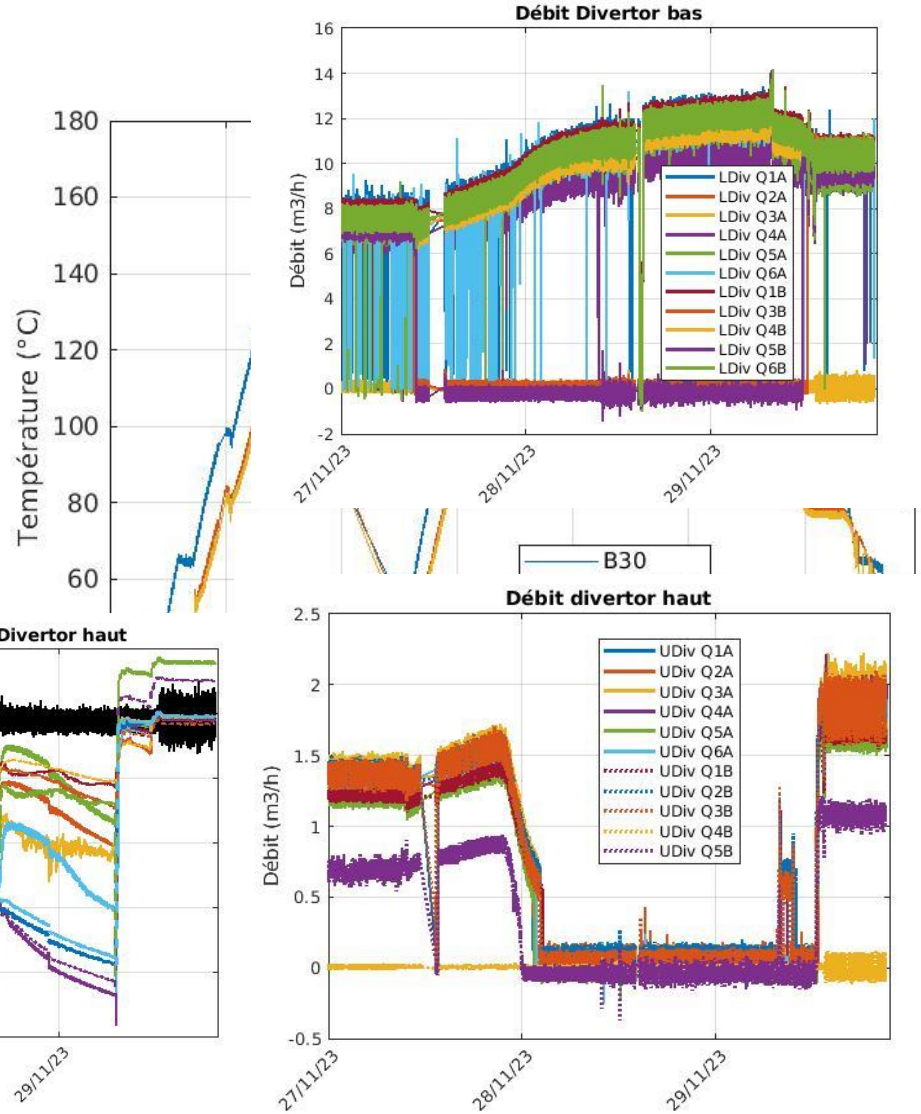


Other usage of calorimetry : baking monitoring

Water temperature is monitored during conditionning phase to ensure that the water is circulating everywhere.

During the baking before C8 campaign, a water flow problem has been detected on 4 subsector of the lower divertor (Q4A,Q4B,Q5A,Q5B). Water temperature data were also confirmed by embeded measurement (TC/FBG).

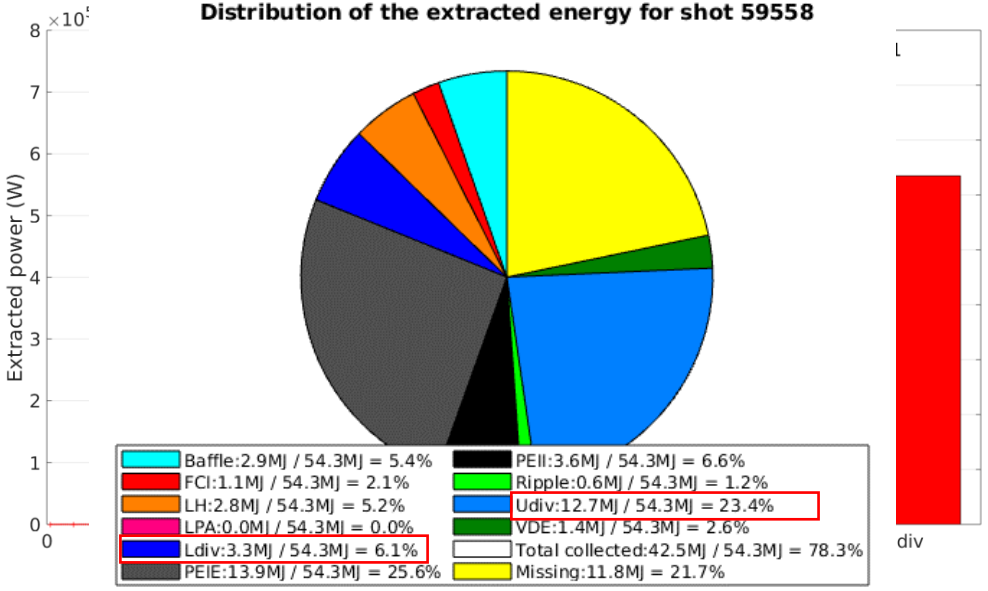
An issue with the flow on the top part of the machine was also detected. The water flow decreased on top of the machine, leading to a decrease of temperature, while the water flow increased on the bottom part



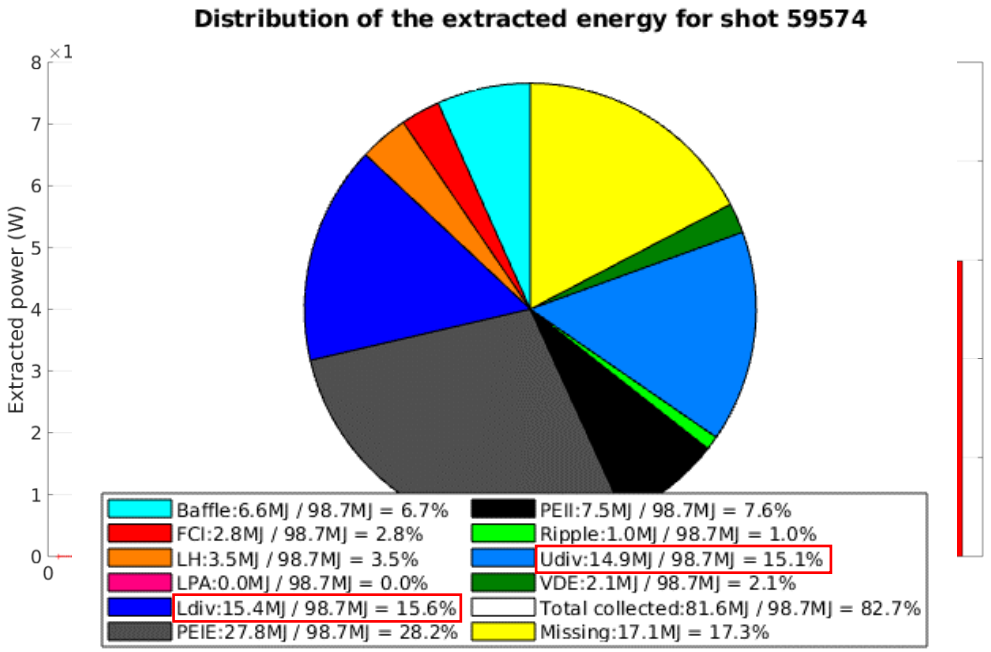
Energy balance for different magnetic configuration

Calorimetry is used to compare energy collected on both divertor for different magnetic configuration

USN



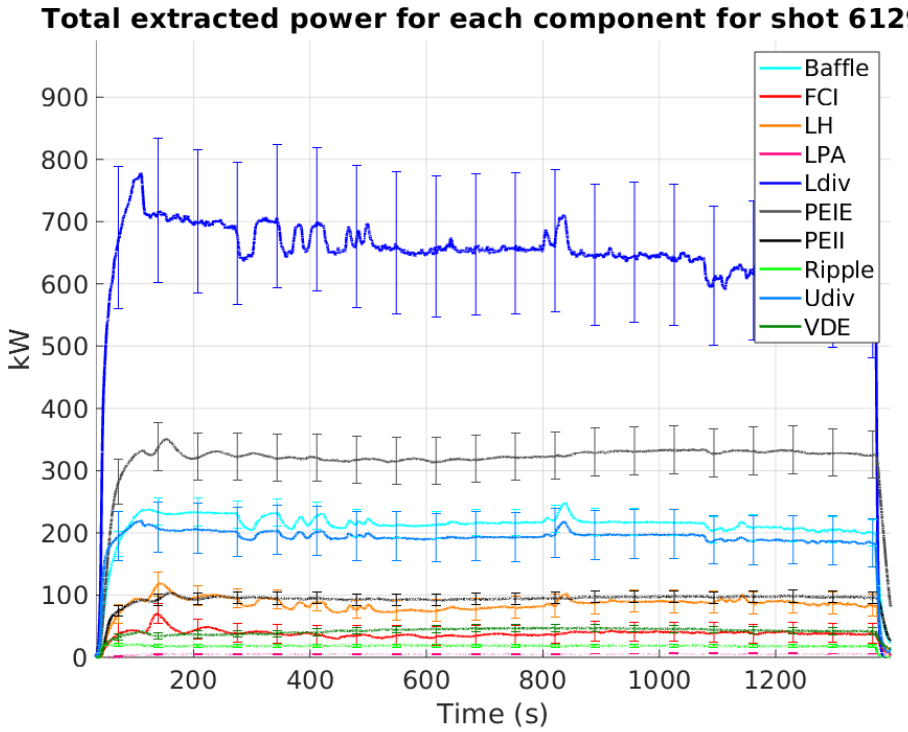
Double null

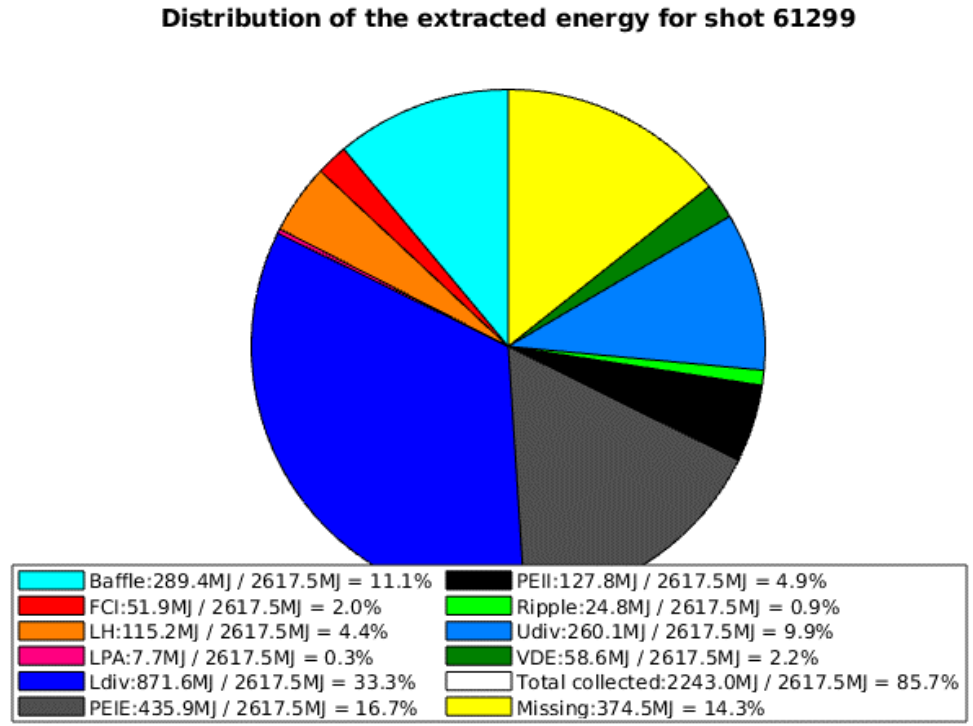


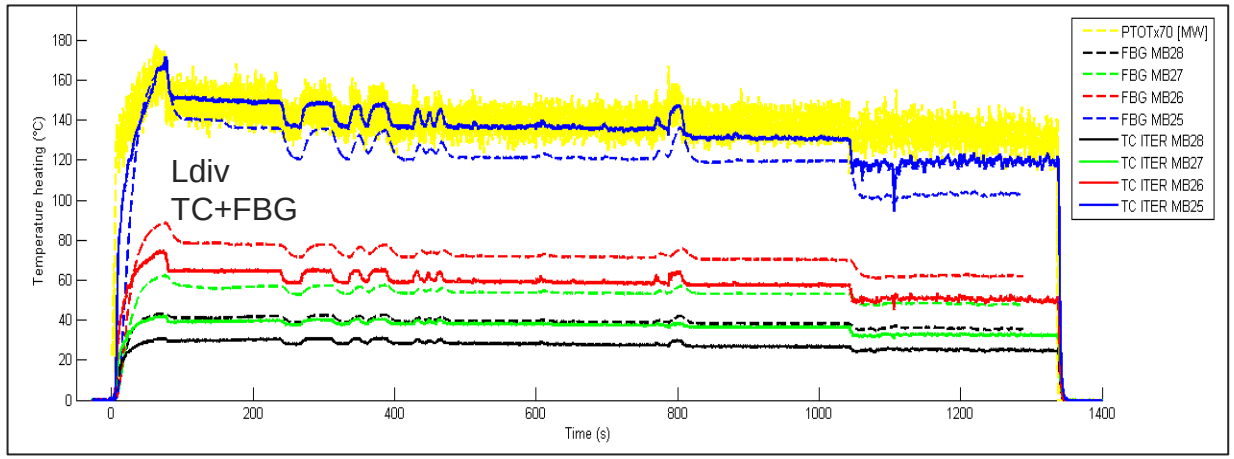
The power and energy in double null configuration are equally distributed between both divertor.
The fraction of energy going on both divertor remains in the same order of magnitude for both configuration.
More uncertainties of measurement for Upper Single Null (small water heating on lower divertor)

Perspective : use the calorimetry system to adjust the plasma magnetic configuration

Pulse #61299

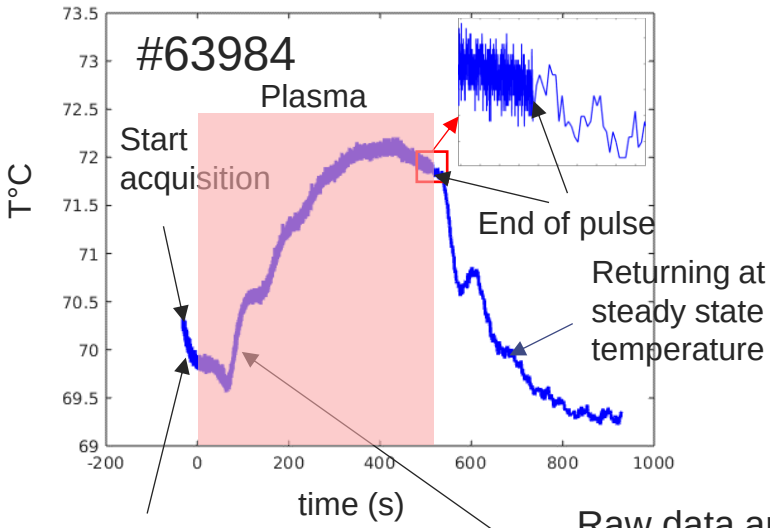

Total extracted power for each component for shot 61299
Baffle
FCI
LH
LPA
Ldiv
PEIE
PEII
Ripple
Udiv
VDE
kW
Time (s)


Distribution of the extracted energy for shot 61299
Baffle:289.4MJ / 2617.5MJ = 11.1%
FCI:51.9MJ / 2617.5MJ = 2.0%
LH:115.2MJ / 2617.5MJ = 4.4%
LPA:7.7MJ / 2617.5MJ = 0.3%
Ldiv:871.6MJ / 2617.5MJ = 33.3%
PEIE:435.9MJ / 2617.5MJ = 16.7%
PEII:127.8MJ / 2617.5MJ = 4.9%
Ripple:24.8MJ / 2617.5MJ = 0.9%
Udiv:260.1MJ / 2617.5MJ = 9.9%
VDE:58.6MJ / 2617.5MJ = 2.2%
Total collected:2243.0MJ / 2617.5MJ = 85.7%
Missing:374.5MJ = 14.3%


Ldiv
TC+FBG
Temperature heating (°C)
Time (s)
PTOTx70 [MW]
FBG MB28
FBG MB27
FBG MB26
FBG MB25
TC ITER MB28
TC ITER MB27
TC ITER MB26
TC ITER MB25

Typical temperature measurement of calorimetry

Global inlet temperature

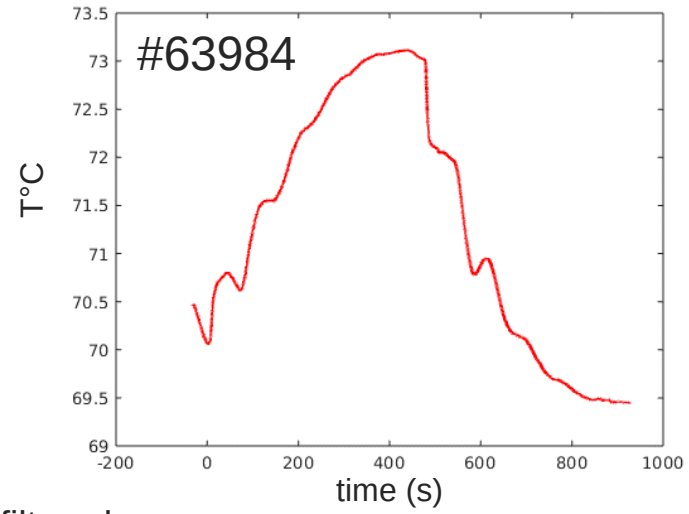


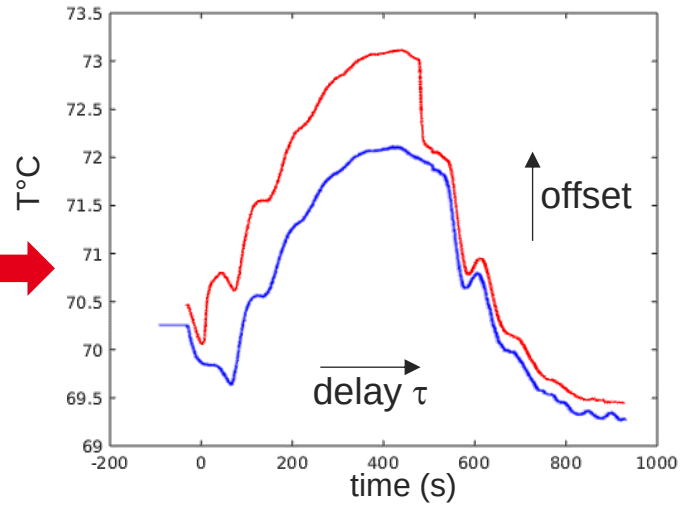
Inlet temperature 70°C mixed with another cooling loop at 50°C

Raw data are filtered.

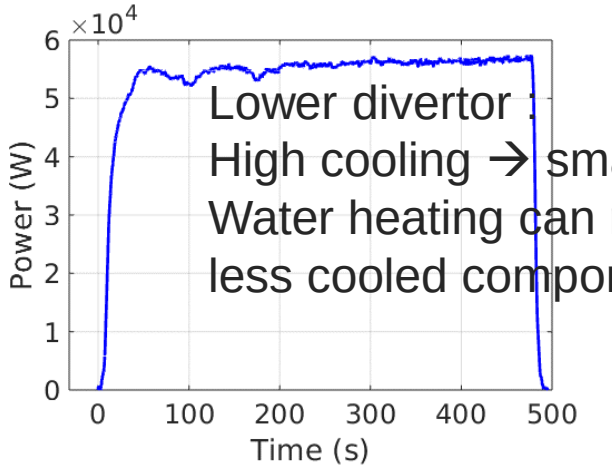
After ~60s, the water enters for the second time inside the tokamak. Hotter

Lower divertor Q5A oulet temperature



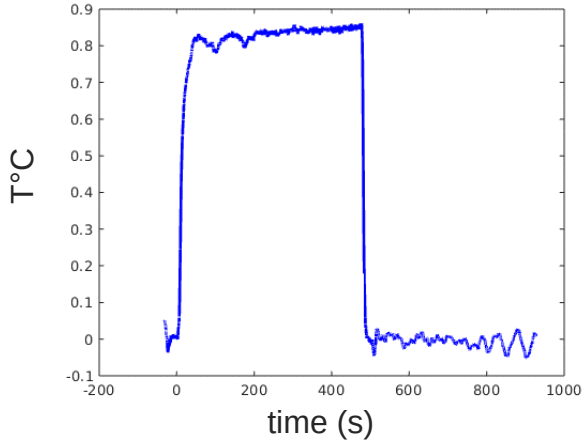


Need to adjust the delay and the offset on the inlet temperature to match the outlet temperature before and far after the pulse.



Lower divertor :
High cooling → small heating.
Water heating can reach 5-10°C on less cooled component.

Resulting power



Resulting heating