AC losses in TF magnets during JT-60SA commissioning: experimental analysis and simulations

Alexandre Louzguiti[1], Benoît Lacroix[1], Quentin Le Coz[2], Sylvie Nicollet[1], Alexandre Torre[1], Louis Zani[1], Frédéric Michel[3], Christine Hoa[3]

[1]IRFM, CEA Cadarache, France / [2]Assystem, Pertuis, France / [3]IRIG, CEA Grenoble, France

CHATS on Applied Superconductivity 2021, 20-24 September

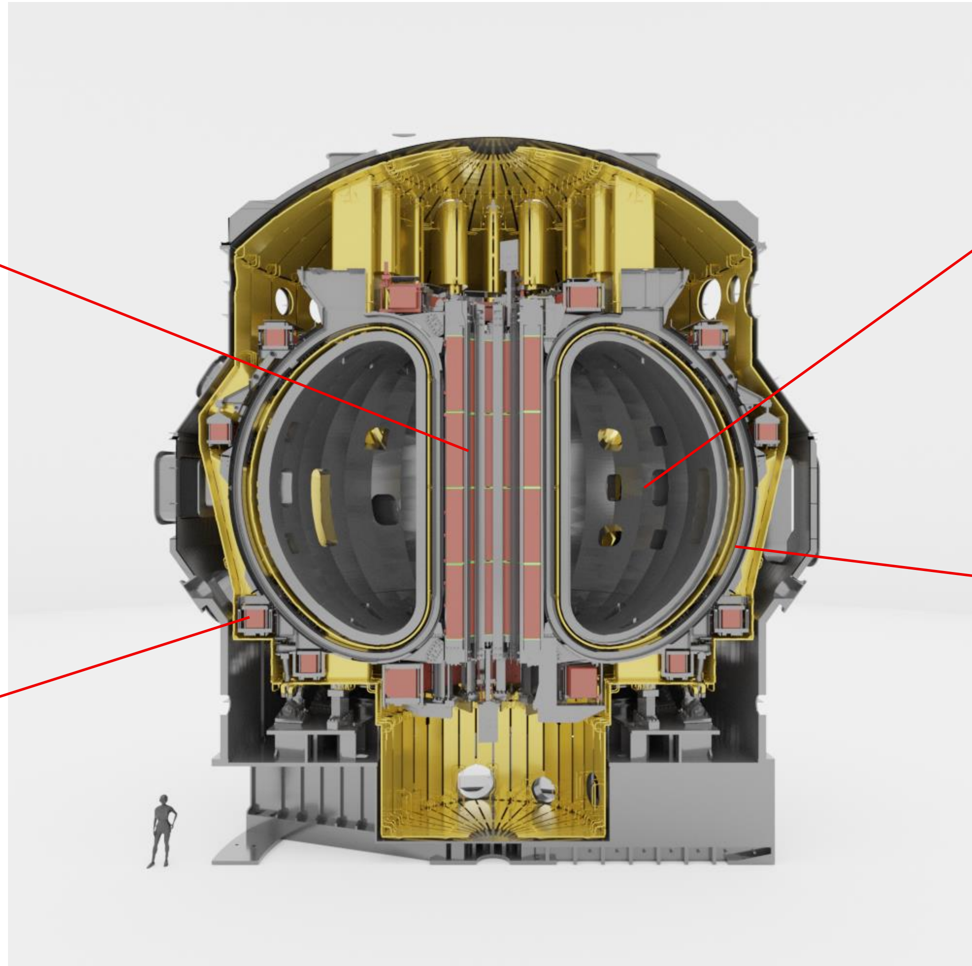
JT-60SA tokamak

CS magnet

- Nb_3Sn @ 4.5 K
- 4 modules
- 6.4m-high
- 100 tons
- 8.9T peak field

EF coils

- NbTi @ 4.8-5.0 K
- 6 coils
- 3.8 to 11.6 m-diameter
- 23-36 tons, total=178 tons
- 4.8-6.2T peak field



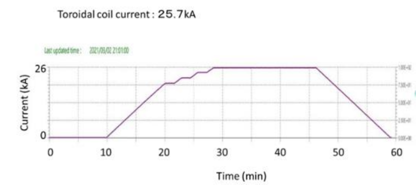
2.25 T nominal field at the middle of the vacuum vessel

TF magnet

- NbTi @ 4.4 K
- 18 coils
- 7.5m-high
- 420 tons
- 5.65T peak field
- 1 GJ (=ATLAS BT or 2xWEST)

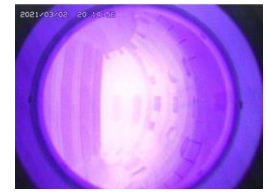
Pictures from https://www.jt60sa.org/
Data from M. Wanner et al., JT60SA Plant Integration Document (PID), 2020

JT-60SA integrated commissioning



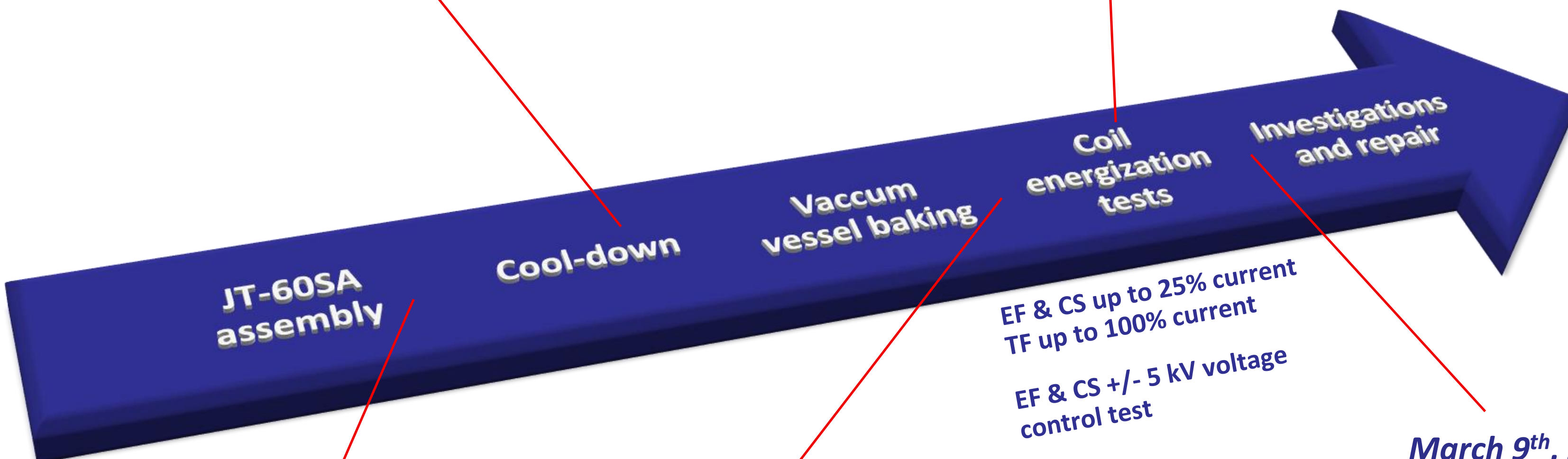
March 2nd, 2021

TF @ nominal current
+ ECR plasma



November 26th, 2020

All coils superconducting



March 9th, 2021

EF1 incident (electrical arcing+ cryostat vacuum loss)

January 13th, 2021

First coil energization (EF1 @ 1kA)

March 31st, 2020

End of assembly

Pictures from https://www.jt60sa.org/

Outline

- Experimental determination of AC losses in tokamak
- Theoretical calculation of AC losses in tokamak
- Comparison theoretical calculation vs experiment
- Comparison between tokamak and CTF experiments
- Experimental WP/Cas heat load distribution in tokamak

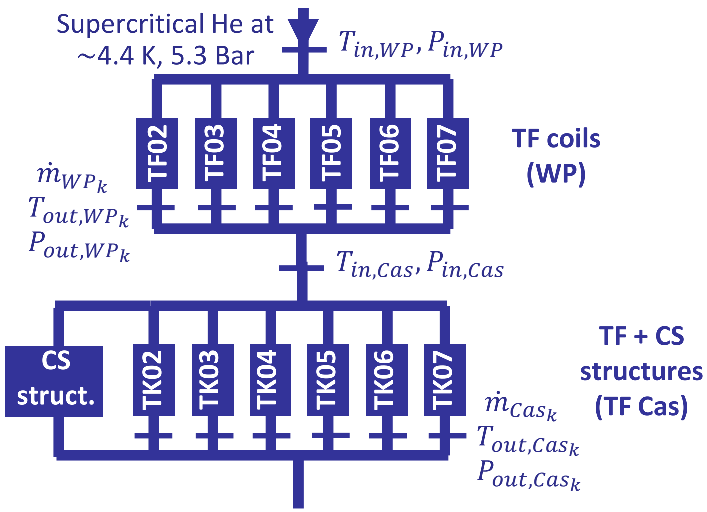
Experimental determination of AC losses in tokamak

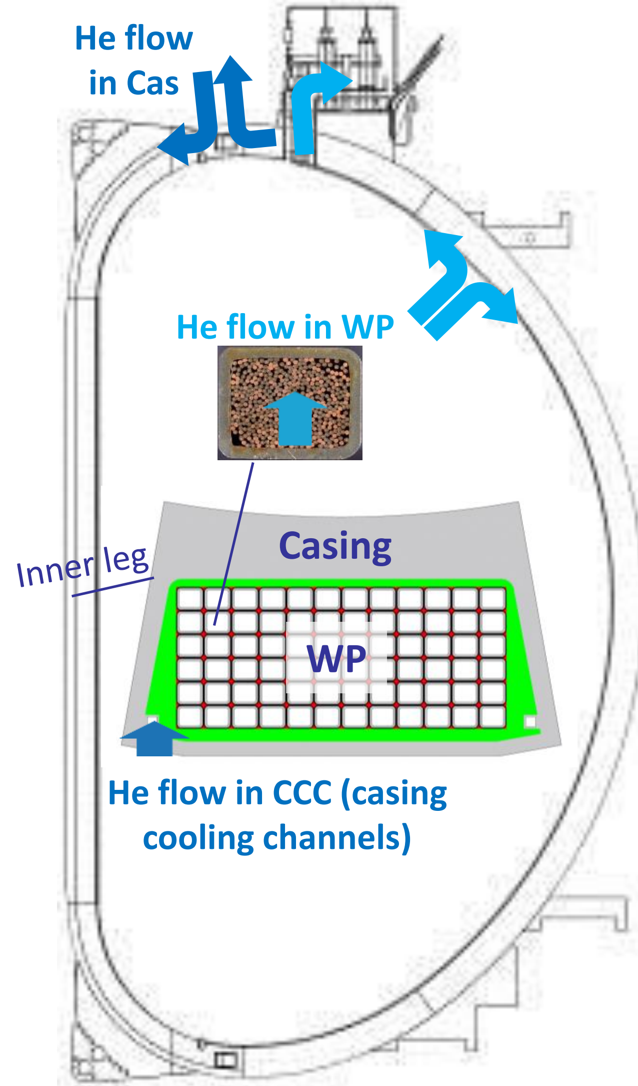
- During TF current tests (ramps and fast discharges), AC losses are generated
- AC losses=total transient heat loads generated during TF current tests
- Transient heat loads determined from enthalpy balances in casing and WP:

$$\begin{cases} \Delta H_{WP}[W] = \dot{m}_{WP}\left[h\left(T_{out,WP}, P_{out,WP}\right) - h\left(T_{in,WP}, P_{in,WP}\right)\right] \\ \Delta H_{Cas}[W] = \dot{m}_{Cas}\left[h\left(T_{out,Cas}, P_{out,Cas}\right) - h\left(T_{in,Cas}, P_{in,Cas}\right)\right] \end{cases}$$

Cryodistribution scheme

One TF group = 6 coils



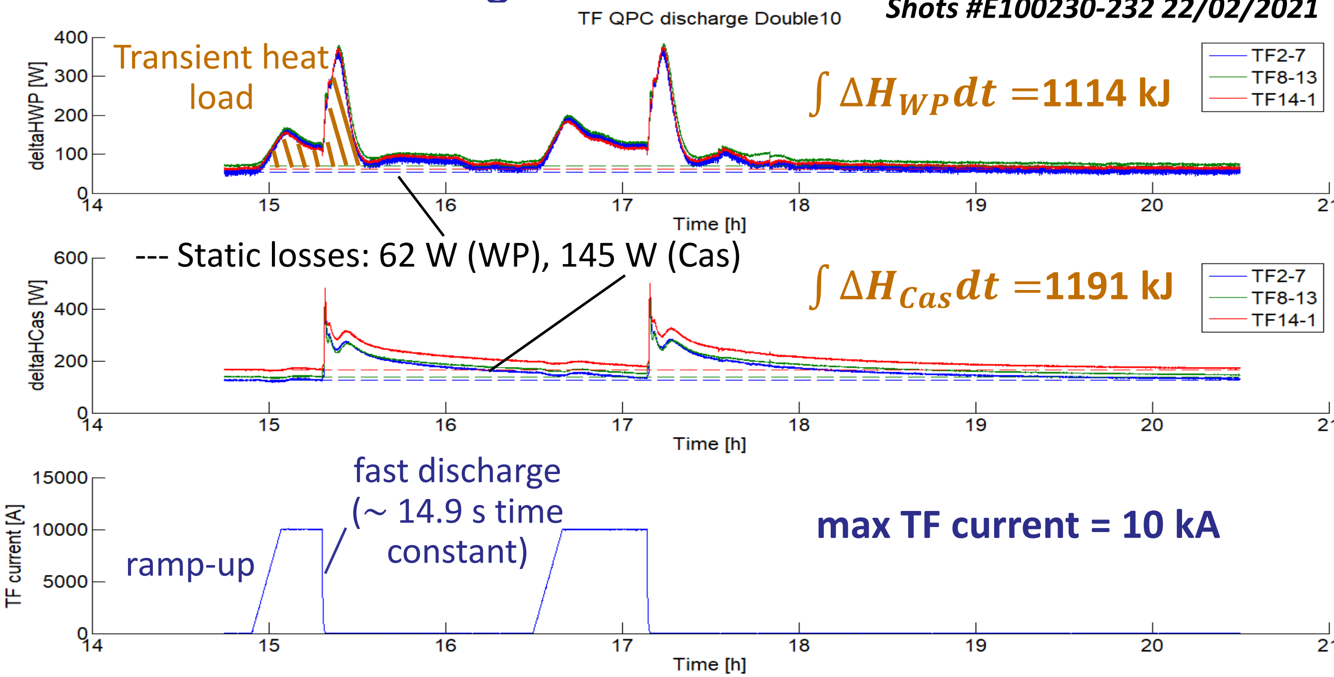


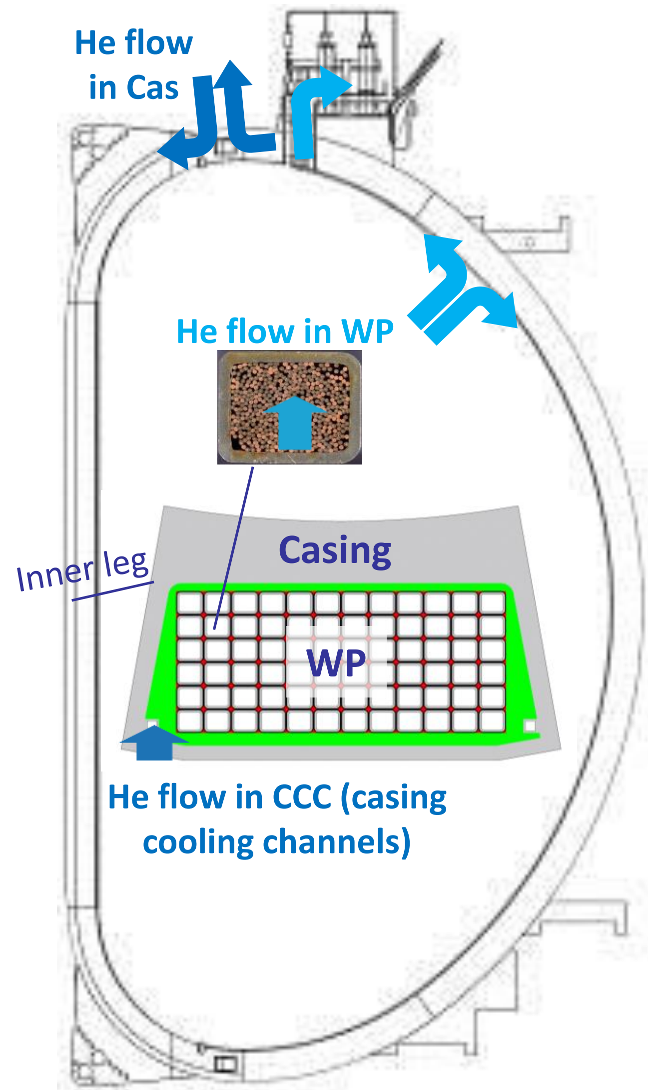
JT-60SA TF coil

Experimental determination of AC losses in tokamak

- During TF current tests (ramps and fast discharges), AC losses (hyst+coup in WP, EC in WP) are generated
- AC losses=total transient heat loads generated during TF currents
- Transient heat loads determined from enthalpy balances in casing and WP:

Shots #E100230-232 22/02/2021

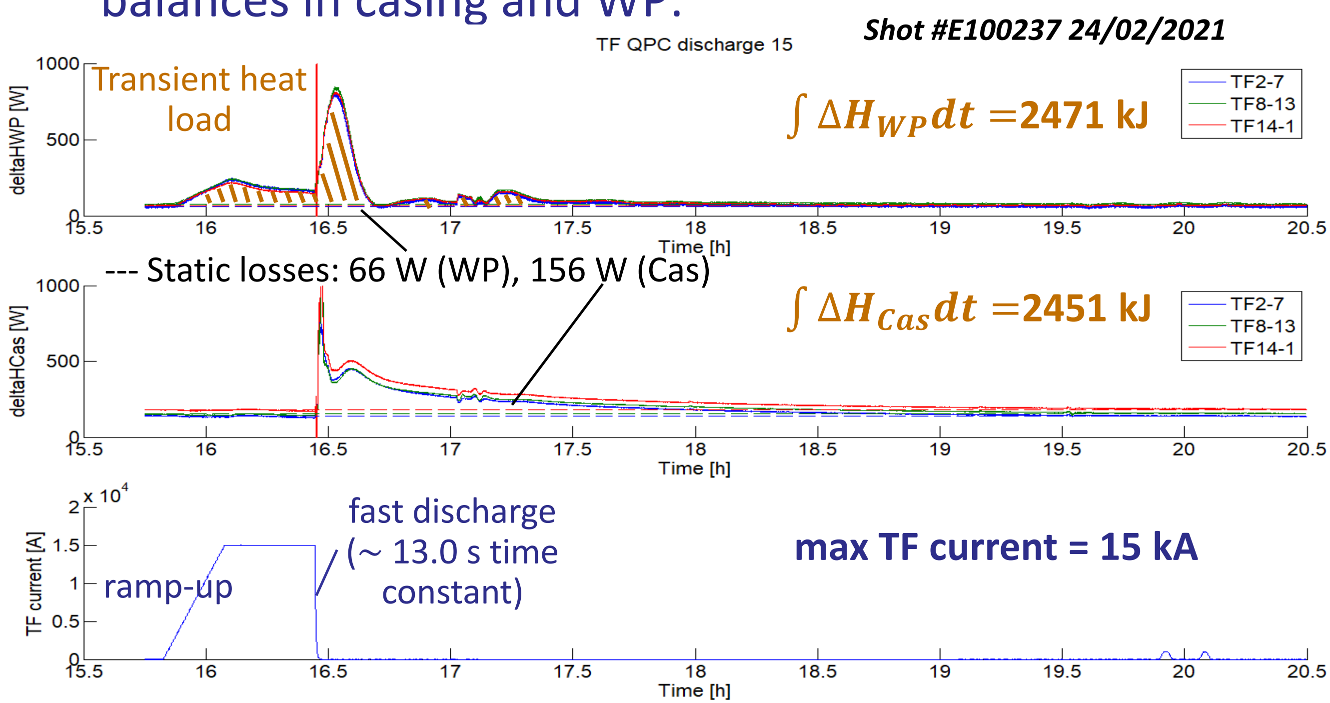


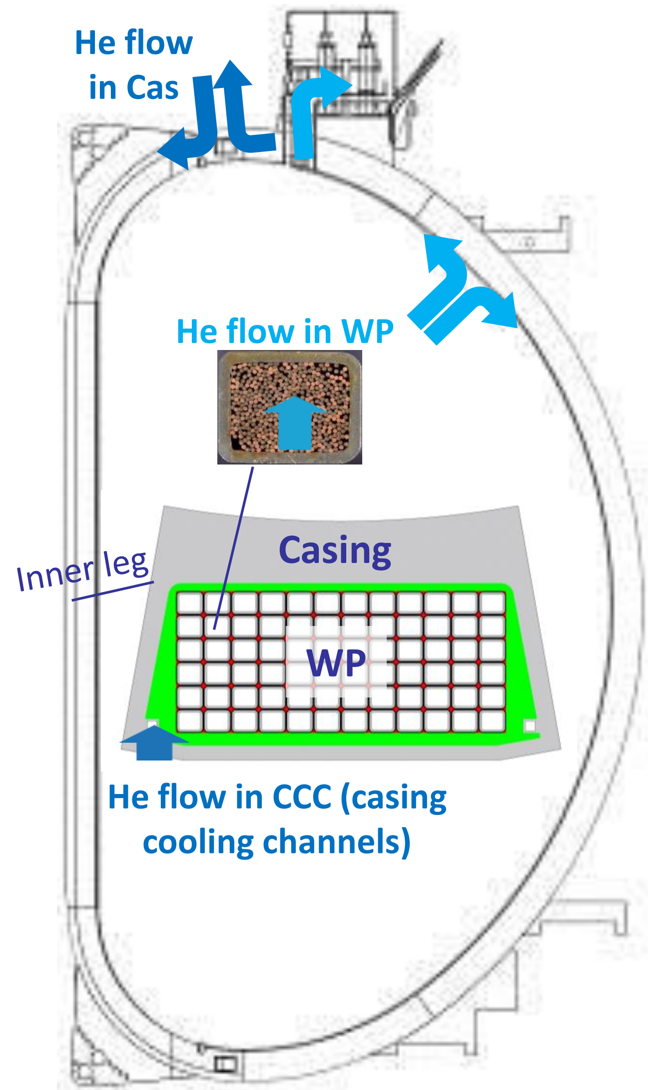


JT-60SA TF coil

Experimental determination of AC losses in tokamak

- During TF current tests (ramps and fast discharges), AC losses (hyst+coup in WP, EC in WP) are generated
- AC losses=total transient heat loads generated during TF currents
- Transient heat loads determined from enthalpy balances in casing and WP:



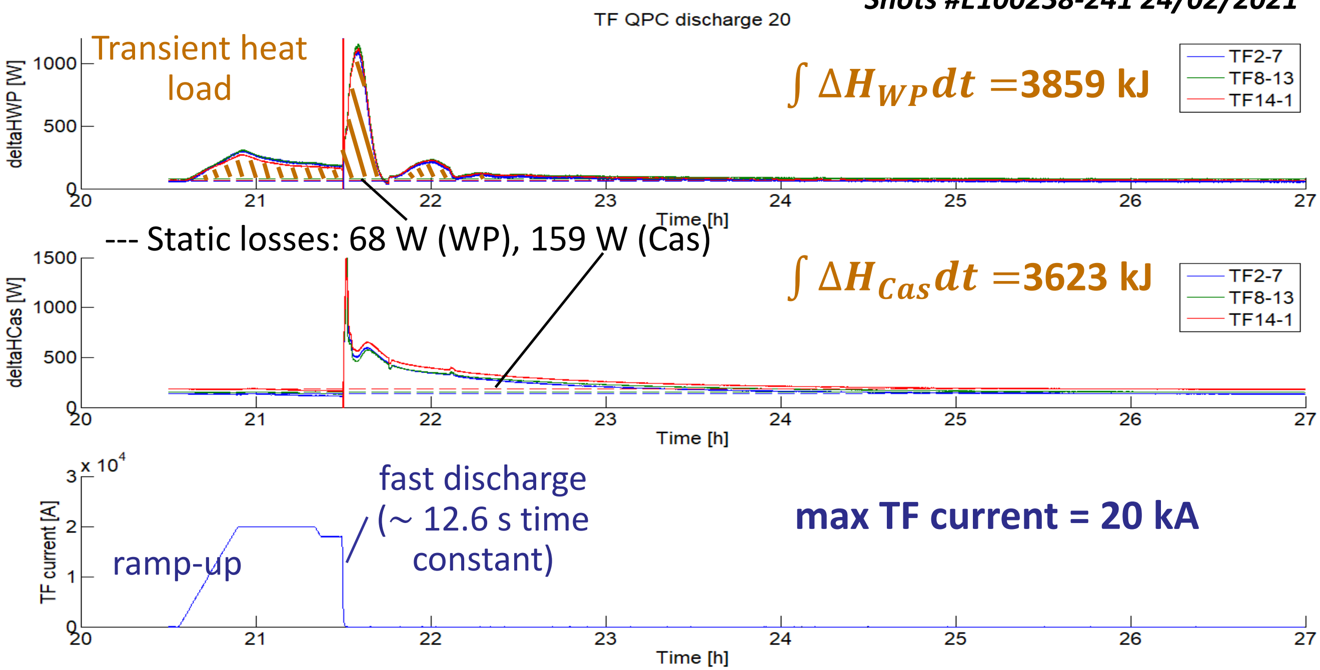


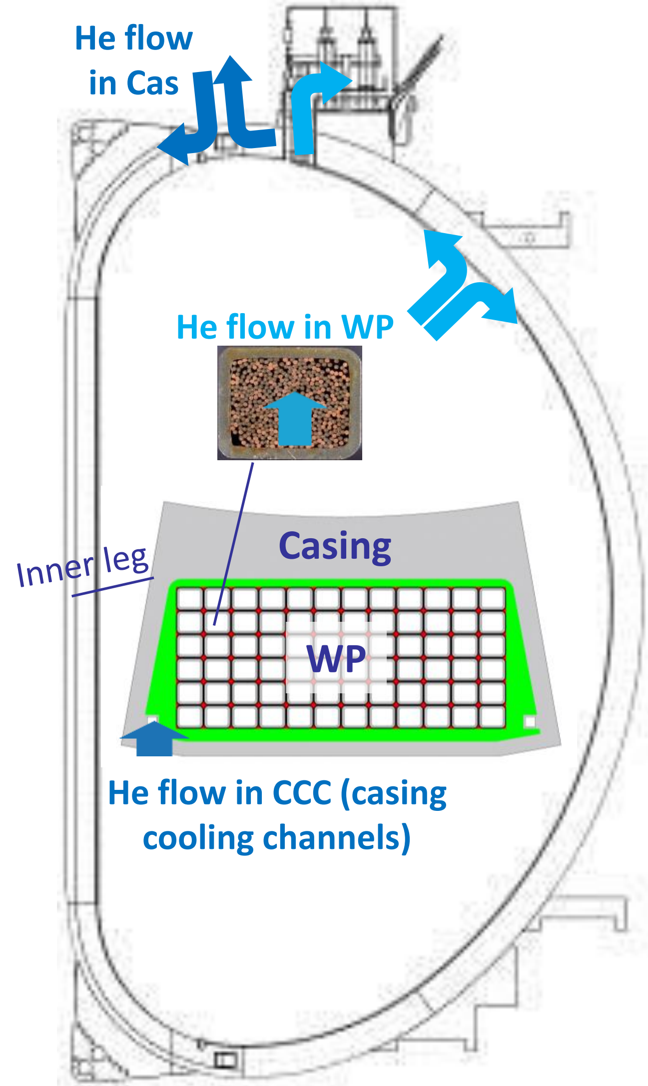
JT-60SA TF coil

Experimental determination of AC losses in tokamak

- During TF current tests (ramps and fast discharges), AC losses (hyst+coup in WP, EC in WP) are generated
- AC losses=total transient heat loads generated during TF currents
- Transient heat loads determined from enthalpy balances in casing and WP:

Shots #E100238-241 24/02/2021





JT-60SA TF coil

Experimental determination of AC losses in tokamak

❖ Summary of the experimental data analysis:

TF current [kA] (ramp-up + fast discharge)	Fast discharge time constant [s]	Static losses per TF group [W]		Transient heat loads [kJ]	
		WP	**Cas**	WP	Cas
10	**14.9**	**62**	**145**	1114	1191
15	**13.0**	**66**	**156**	2471	2451
20	**12.6**	**68**	**159**	3859	3623

Time constants are decreasing because:

- $\tau = L/R_d$
- effective R_d increases with I_{TF} (higher energy dumped → higher temperature → to higher resistance)

Average static loads deduced from enthalpy balances during 6 weekends of Jan & Feb 21 gives reasonable agreement:

- WP: 61 W (2-11% agreement)
- Cas: 141 W (3-13% agreement)

Transient heat loads seem equally shared between WP/Cas but knowing the heat sources is required before further analyzing this data (later in this presentation)

Theoretical calculation of AC losses in tokamak

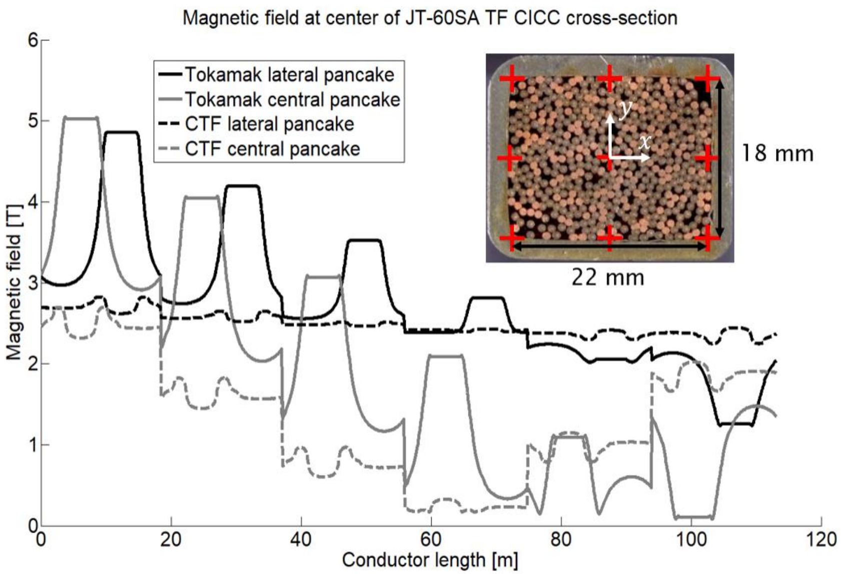
❖ Hysteresis losses in the TF winding packs

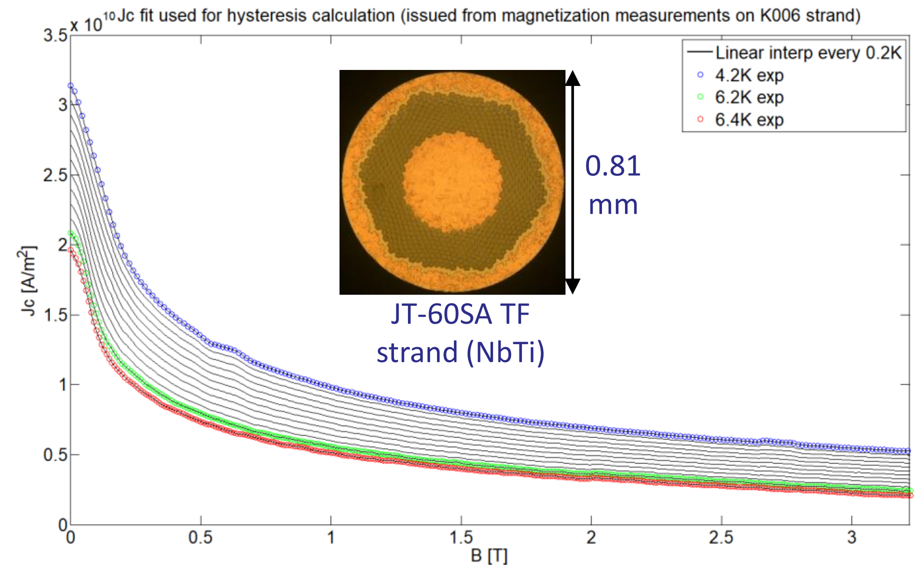
- Magnetic field map computed with TRAPS code [1] at 9 points of JT-60SA TF CICC along TF coil in tokamak
- Hysteresis losses computed with analytical formulae from [2]

$$P_h = \begin{cases} \frac{\pi|\dot{B}|\Delta B^2}{2\mu_0^2 J_c d_{eff}}\left(1 - \frac{\pi \Delta B}{3\mu_0 J_c d_{eff}}\right) \text{ if } \Delta B < B_{pen} \\ \frac{2 J_c d_{eff}|\dot{B}|[1+(I/I_c)^2+0.2056(I/I_c)^4]}{3\pi} \text{ if } \Delta B > B_{pen} \end{cases}$$

- $J_c(B,T)$ is measured in [3] and d_{eff} is measured in [4]

$$\text{with } B_{pen} = \frac{2\mu_0 J_c d_{eff}}{\pi}\left[1 - \frac{\pi^2}{8}\frac{I}{I_c} + \left(\frac{\pi^2}{8} - 1\right)\left(\frac{I}{I_c}\right)^2\right]$$





[1] P. Hertout et al., IEEE Trans. Appl. Supercond., 2002 / [2] B. Turck, CEA Technical note, 1985 /
[3] L. Zani et al., IEEE Trans. Appl. Supercond., 2013 / [4] M. Chiletti et al., IEEE Trans. Appl. Supercond., 2020

Theoretical calculation of AC losses in tokamak

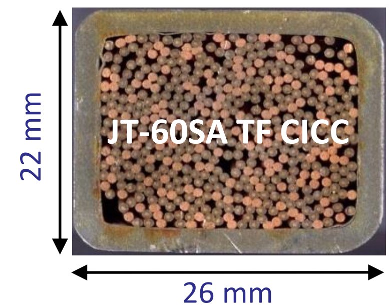
❖ Coupling losses in the TF winding packs

- Same magnetic field map than for hysteresis losses (average field on TF at I_{nom}=25.7 kA is $B_{TF\ avg}$=2.2 T)
- Power per unit volume of sc strands computed with MPAS model [1] using coefficients deduced from measurements at CEA [2] (performed at 0.5 T average field)

$$\begin{cases} P_c\ [W/m^3] = \sum_{j=1}^{N} \frac{nk_j \tau_j \dot{B}_{int,j}^{\ 2}}{\mu_0} \\ B_{int,j} + \tau_j \dot{B}_{int,j} = B_{ext} \end{cases}$$

nk_j	0.220	0.254	0.293	0.340	2.23
τ_j (ms)	6.02	14.6	42.8	85.9	250

- Since ramping times and fast discharges time constants of JT-60SA TF current tests (>10 s) are long compared to MPAS time constants (<0.25 s), the $n\tau$ approach is sufficient: $n\tau_{CEA} = \sum_{j=1}^{N} nk_j \tau_j$=**604 ms**
- To account for the effect of the high field in the tokamak on $n\tau$, we also use Sultan measurement [3] $n\tau_{Sultan} = \sum_{j=1}^{N} nk_j \tau_j$=**279 ms** and we linearly interpolate $n\tau(B_{TF\ avg})$ using $\begin{cases} n\tau(0.5\ T) = n\tau_{CEA} \\ n\tau(5.65\ T) = n\tau_{Sultan} \end{cases}$
- In the tokamak the field is majorly perpendicular the short side of the TF CICC while it was perpendicular to its broad one in the measurements at CEA and Sultan. So we correct the coupling losses formula with a factor 0.838 (this value is deduced from analytical formulae of demagnetization factor for rectangular prisms [4] as detailed in [5])



[1] B. Turck et al., Cryogenics, 2010 / [2] M. Chiletti, PhD Dissertation, 2021 / [3] L. Zani et al., IEEE Trans. App. Sc., 2013 / [4] Amikam Aharoni, J. Appl. Phys., 1998 / [5] A. Louzguiti et al., IEEE Trans. App. Sc., 2021

Theoretical calculation of AC losses in tokamak

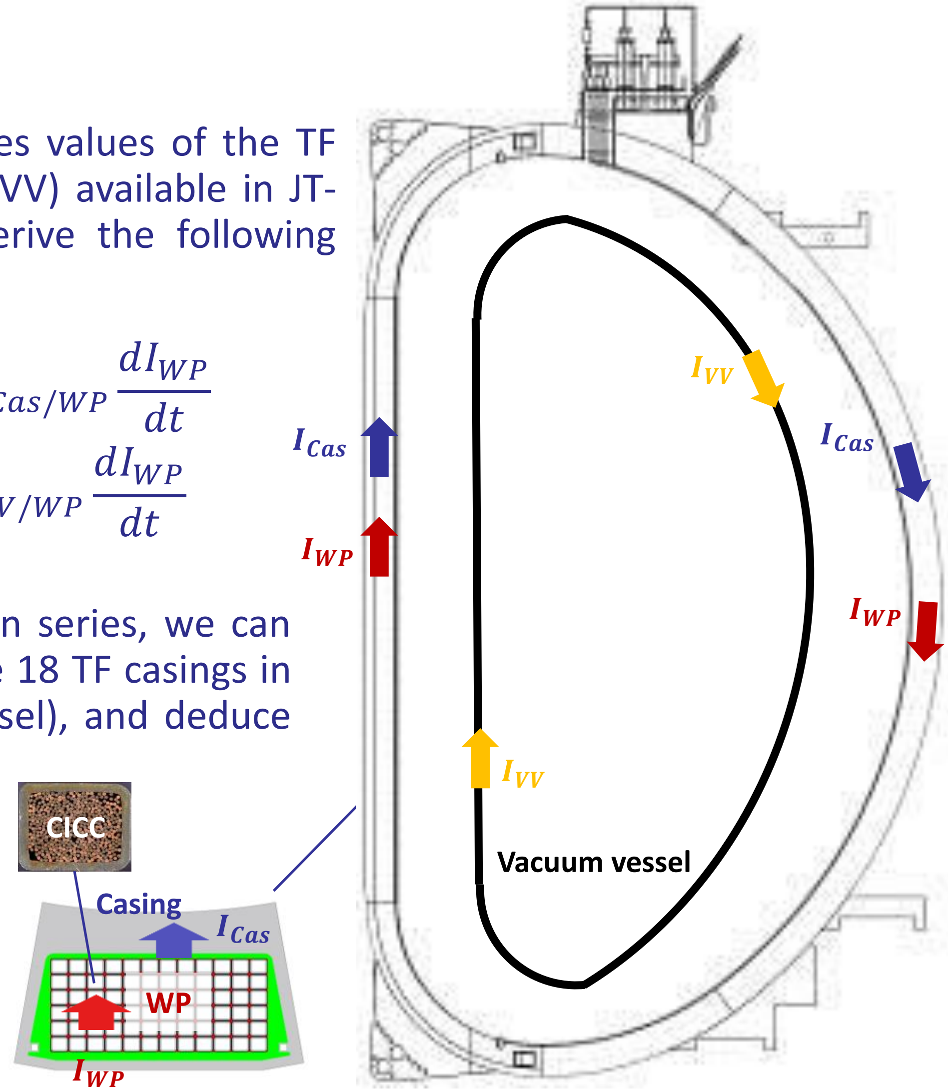
❖ Eddy currents losses in the TF casings

- From the resistances and self and mutual inductances values of the TF windings (WP), TF casings (Cas) and vacuum vessel (VV) available in JT-60SA Plant Integration Document (PID), we can derive the following system of equations:

$$\begin{cases} R_{Cas}I_{Cas} + L_{Cas}\dfrac{dI_{Cas}}{dt} + M_{Cas/VV}\dfrac{dI_{VV}}{dt} = -M_{Cas/WP}\dfrac{dI_{WP}}{dt} \\ R_{VV}I_{VV} + L_{VV}\dfrac{dI_{VV}}{dt} + M_{Cas/VV}\dfrac{dI_{Cas}}{dt} = -M_{VV/WP}\dfrac{dI_{WP}}{dt} \end{cases}$$

- Knowing the current I_{WP} flowing in the 18 TF coils in series, we can solve this system for I_{Cas} (total current induced in the 18 TF casings in parallel) and I_{VV} (induced current in the vacuum vessel), and deduce the heat load on the TF casings with

$$E_{Cas}[J] = \int P_{Cas}dt = \int R_{Cas}{I_{Cas}}^2 dt$$



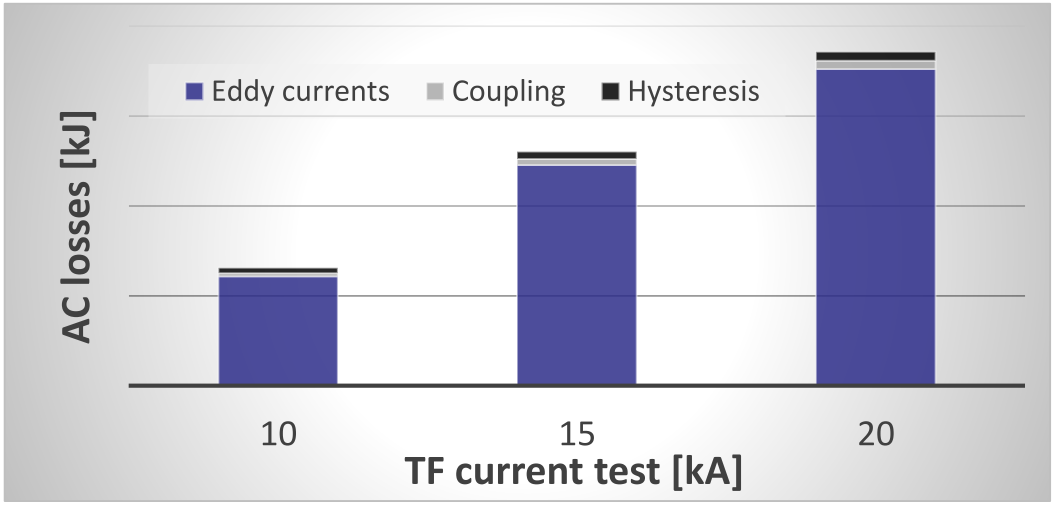
JT-60SA TF coil

Theoretical calculation of AC losses in tokamak

❖ Theoretical results for the selected 10/15/20 kA TF current tests

- Hysteresis losses represent less than 5% of the total AC losses
- Coupling losses represent less than 3% of the total AC losses
- Eddy currents losses in the TF casings represent **more than 90%** of the total AC losses
- Assuming a conservative value of 10 nΩ/coil for the total joints resistance, their Joule losses would represent less than 3% of the total AC losses

TF current test [kA] (ramp-up + fast discharge)	Hysteresis losses in WP [kJ]	Coupling losses in WP [kJ]	Eddy currents losses in Cas [kJ]	Total AC losses in WP+Cas [kJ]
10	123 (5 %)	71 (3 %)	2431 (92 %)	**2625**
15	165 (3 %)	132 (3 %)	4910 (94 %)	**5207**
20	200 (3 %)	185 (2 %)	7044 (95 %)	**7429**



Comparison theoretical calculation vs experiment

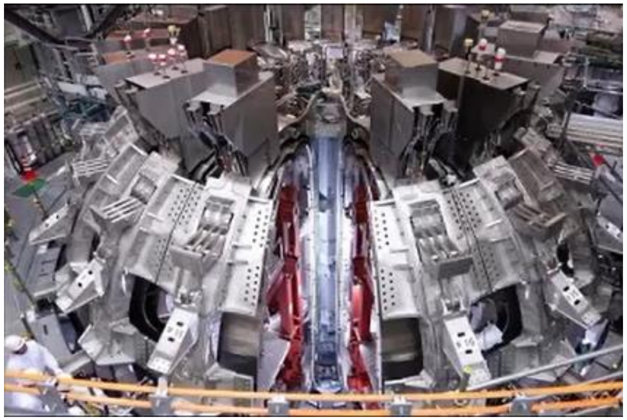
TF current test [kA] (ramp-up + fast discharge)	Total experimental transient heat loads [kJ]	Total AC losses calculation [kJ]
10	**2305**	**2625 (+14 %)**
15	**4922**	**5207 (+6 %)**
20	**7482**	**7429 (-1 %)**

- The **theoretical** AC losses calculations **are in line with the experiment**. Given the experimental uncertainties (e.g. static losses variations, unknown inlet mass-flow during transients, etc.), an agreement of the order of 10% is retained and is satisfyingly explaining the origin of the transient heat loads
- Since the **major contribution is from the eddy currents** (>90 %), TF hysteresis and coupling losses predictions are credible but cannot be assessed accurately from the tokamak experiment. A similar observation has been made during the analysis of the CTF experiment [1]

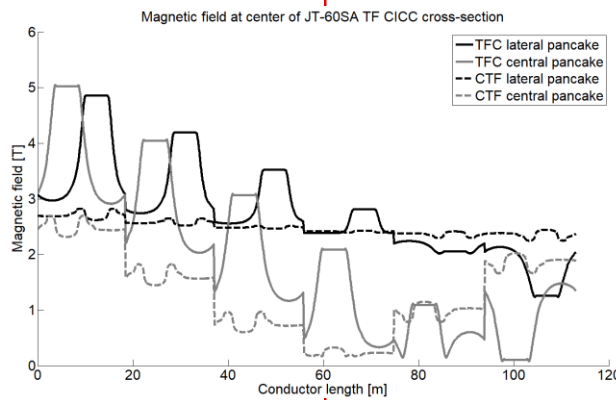
[1] A. Louzguiti et al., IEEE Trans. App. Sc., 2021

Comparison between tokamak and CTF experiments

JT-60SA tokamak, QST Naka, Japan



$B_{avg,tok}$=2.22 T | $B_{avg,CTF}$=1.79 T



Cold Test Facility (CTF), CEA Saclay, France

20 kA ramp-up + fast discharge (12.6 s time constant)

Hysteresis [kJ]	Coupling [kJ]	Eddy currents [kJ]	Total theoretical [kJ]	Total experimental [kJ]
11 (3 %)	10 (2 %)	391 (**95 %**)	412	416 (**+1 %**)

Values are for only one TF coil (i.e. total tokamak/18)

25.7 kA fast discharge only (8.1 s time constant)

Hysteresis [kJ]	Coupling [kJ]	Eddy currents [kJ]	Total theoretical [kJ]	Total experimental [kJ]
5 (3 %)	21 (11 %)	161 (**86 %**)	187	214 (**+14 %**)

Discrepancies with tokamak are due to different: time constants, TF currents, field in WP and enclosed by casings, VV presence

- For both configurations, the casing eddy currents are the largely dominant contribution in the AC losses and the theoretical calculations are in a **10% agreement** range with the experiment

Experimental WP/Cas heat load distribution in tokamak

❖ **Summary of the experimental data analysis:**

TF current [kA] (ramp-up + fast discharge)	Eddy currents losses in Cas [kJ]	Total AC losses in WP+Cas [kJ]	Transient heat loads [kJ]	
			WP	Cas
10	2431 (**92 %**)	2625	1114 (**48.3%**)	1191
15	4910 (**94 %**)	5207	2471 (**50.2%**)	2451
20	7044 (**95 %**)	7429	3859 (**51.6%**)	3623

- The major part of the AC losses is generated in the Cas by the eddy currents (>90%) and yet the transient heat loads are absorbed almost equally by the WP and the Cas → this indicates that the **Cas are transmitting a large part of their heat loads to the WP**
- In addition, the increase of the share absorbed by the WP with the TF current is consistent with the enhanced WP/Cas thermal contact due to **higher Lorentz forces**

Experimental WP/Cas heat load distribution in tokamak

- **Summary of the experimental data analysis:**

TF current [kA] (ramp-up + fast discharge)	Eddy currents losses in Cas [kJ]	Total AC losses in WP+Cas [kJ]	Transient heat loads [kJ]	
			WP	Cas
10	2431 (**92 %**)	2625	1114 (**48.3%**)	1191
15	4910 (**94 %**)	5207	2471 (**50.2%**)	2451
20	7044 (**95 %**)	7429	3859 (**51.6%**)	3623

- In a near future, we plan to use **TACTICS** (quasi-3D simulation tool developed at CEA coupling the 1D thermohydraulics code THEA with the 2D thermal one Cast3m [1]-[2]), to estimate the WP/Cas thermal contact resistance and its evolution with the TF current. We will perform a parametric study on the **thermal contact resistance** until the WP/Cas distribution of the simulated heat loads match the experimental ones.

[1] Q. Le Coz et al., Fus. Eng. Des., 2017 / [2] L. Zani et al., Cryogenics, 2020

Conclusions

- First experimental analysis on AC losses in JT-60SA tokamak, conducted on TF
- Theoretical AC losses predictions are in line with the experiment (limited accuracy on coupling+hysteresis)
- Major contribution comes from the eddy currents in the casing
- The casing redistributes a large part of its transient heat loads to the WP (stability?)
- Previous experimental AC losses analysis performed on CTF supports these results
- Upcoming TACTICS simulations to determine the WP/Cas thermal contact resistance will potentially help to better anticipate the magnet stability in future operations