AC losses in JT-60SA TF magnet during commissioning: experimental analysis and modeling

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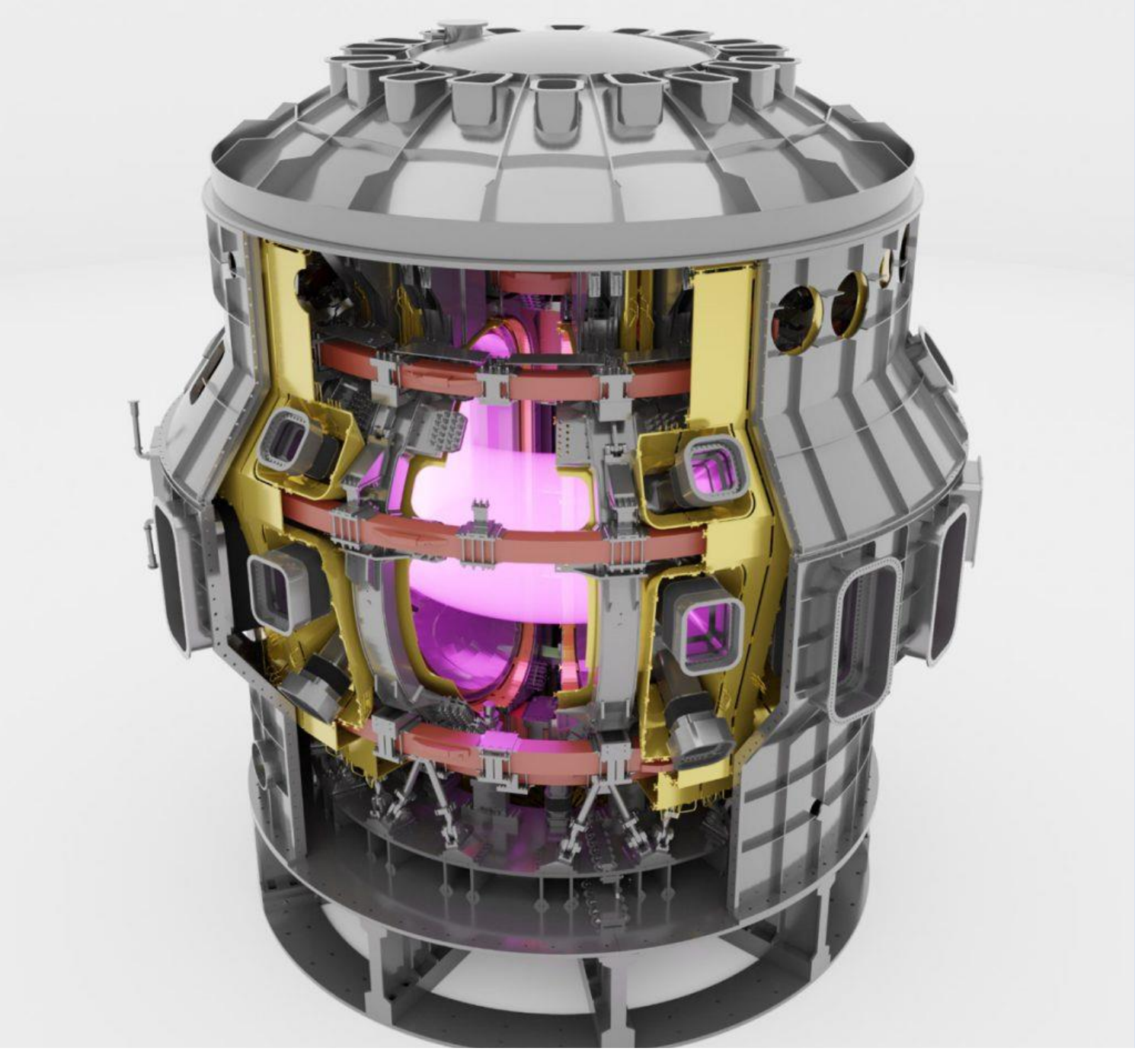
ABSTRACT

- JT-60SA tokamak Integrated commissioning started in April 2020, superconducting magnets tests from January to March 2021
- Toroidal Field (TF) magnet successfully achieved 25.7 kA nominal current
- TF current tests create AC losses in TF winding pack (WP) and casing



- Losses estimated from enthalpy balances using TF He inlet/outlet sensors
- Theoretical calculation of hysteresis and coupling losses in the WP and eddy currents losses in the casing
- Comparison between experimental and theoretical energy values

AC LOSSES MODELING

- **Hysteresis losses** computed as in [1] (Traps field map [2], B. Turck analytical formulae [3], deff=18 µm [4] and Jc(B,T) measured in [5].
- **Coupling losses** computed with $P = n\tau \dot{B_a}^2/\mu_0$ (TF discharge time constant > 10 s >> $n\tau$). We assume $n\tau(B) = cst/\rho_{Cu}(B) = 1/(aB+b)$; a and b deduced from $n\tau$(5.65 T)=279 ms (Sultan [5]) and $n\tau$(0.5 T)=604 ms (CEA [6]). To account for field orientaton, we use $P = n\tau(B_a)\big(\alpha\dot{B}_{a,x}^2 +$
- **Eddy currents losses in TF casing** are computed through solving of R,L circuits equations with data from [8]

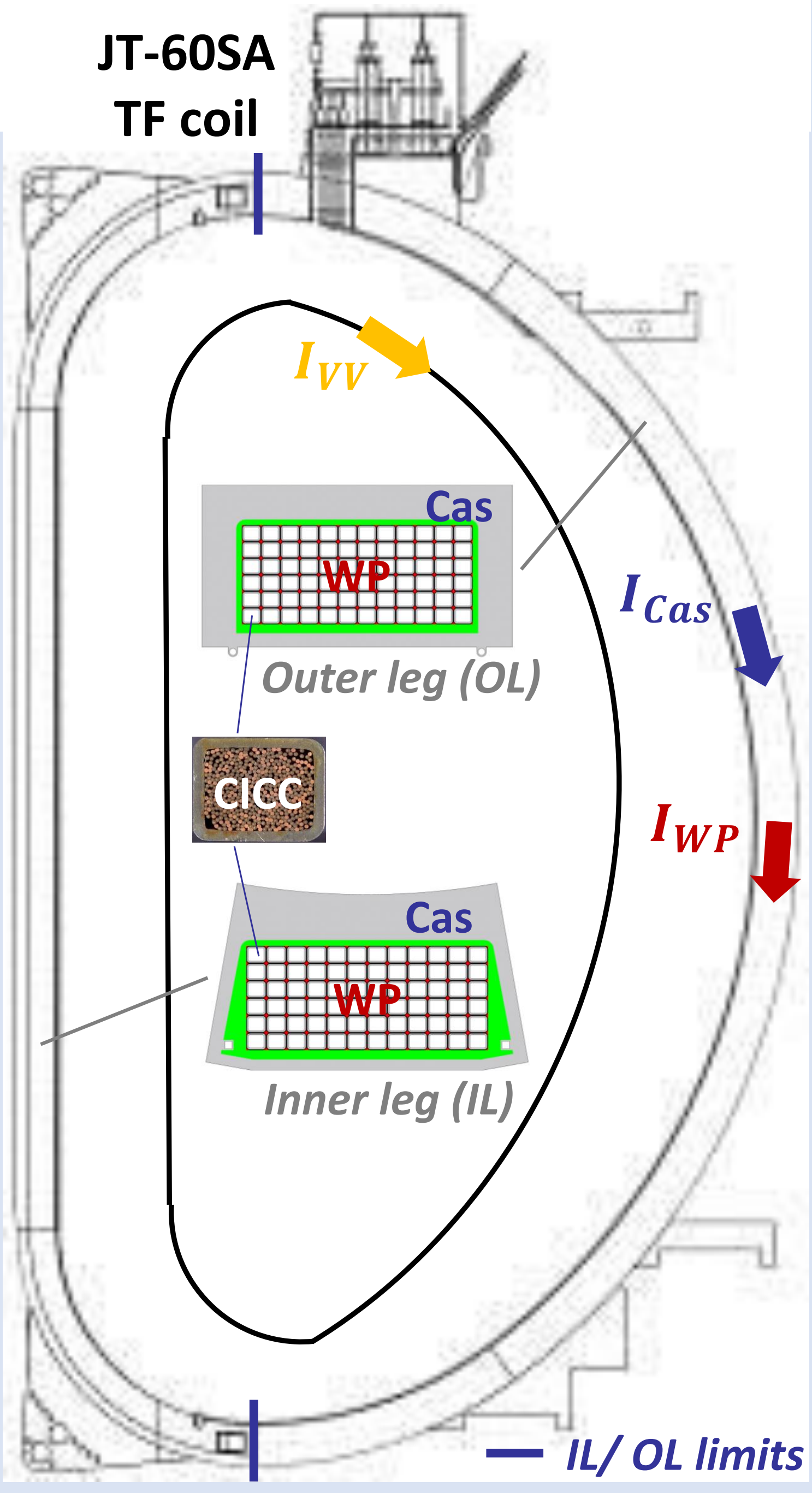
$$\begin{cases} R_{Cas}I_{Cas} + L_{Cas}\dfrac{dI_{Cas}}{dt} + M_{Cas/VV}\dfrac{dI_{VV}}{dt} = -M_{Cas/WP}\dfrac{dI_{WP}}{dt} \\ R_{VV}I_{VV} + L_{VV}\dfrac{dI_{VV}}{dt} + M_{Cas/VV}\dfrac{dI_{Cas}}{dt} = -M_{VV/WP}\dfrac{dI_{WP}}{dt} \end{cases}$$

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

Inner leg (IL) of casing is shorter and thinner than its outer leg (OL)

→ 43% of total power is generated in IL and 57% in OL

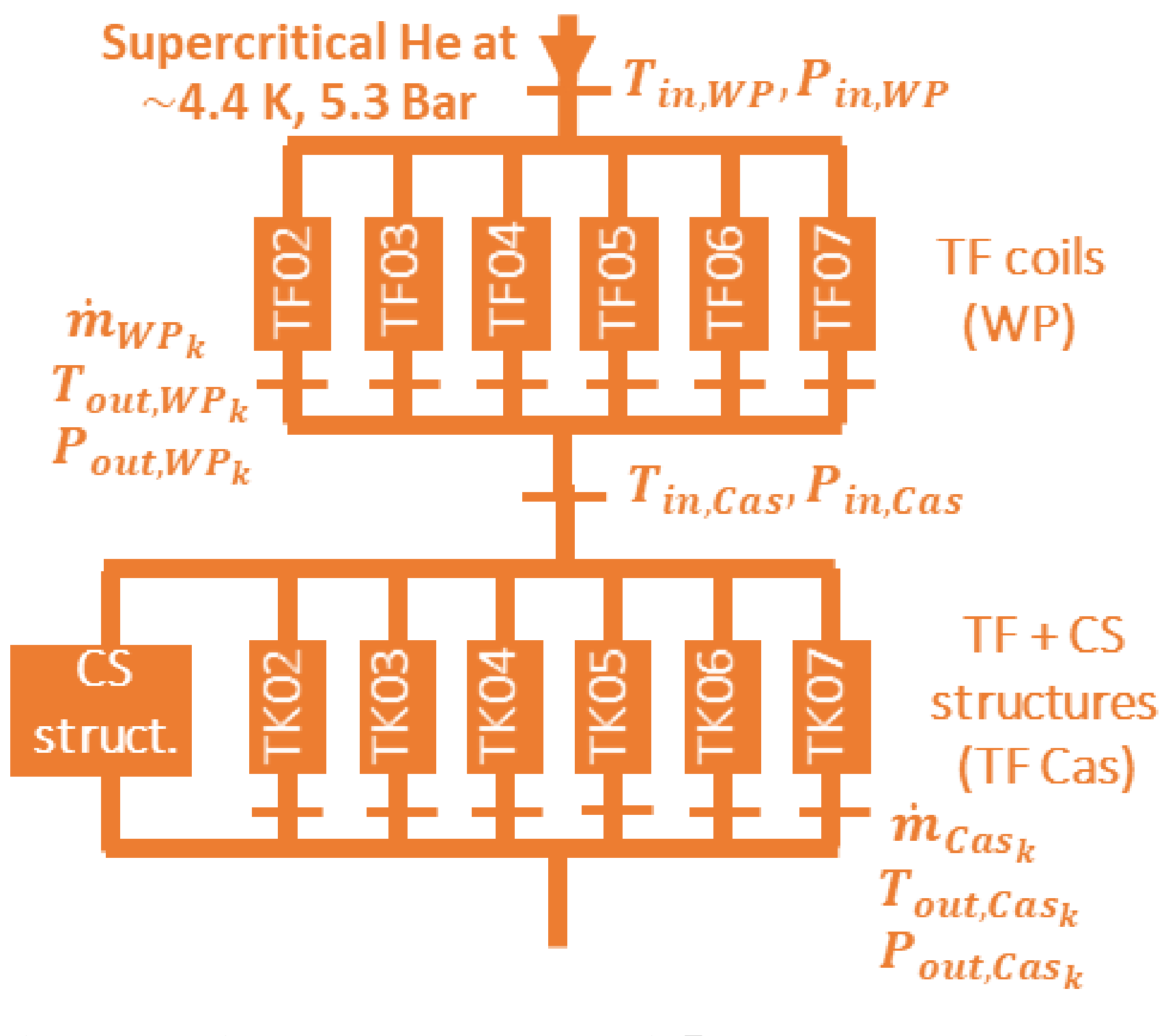
→ average power per unit volume is 1.55 times higher in IL than in OL.



EXPERIMENTAL DATA ANALYSIS

- **Enthalpy balances** of Helium flow in TF WP and casing during fast discharge tests allow AC losses determination (transient heat loads)

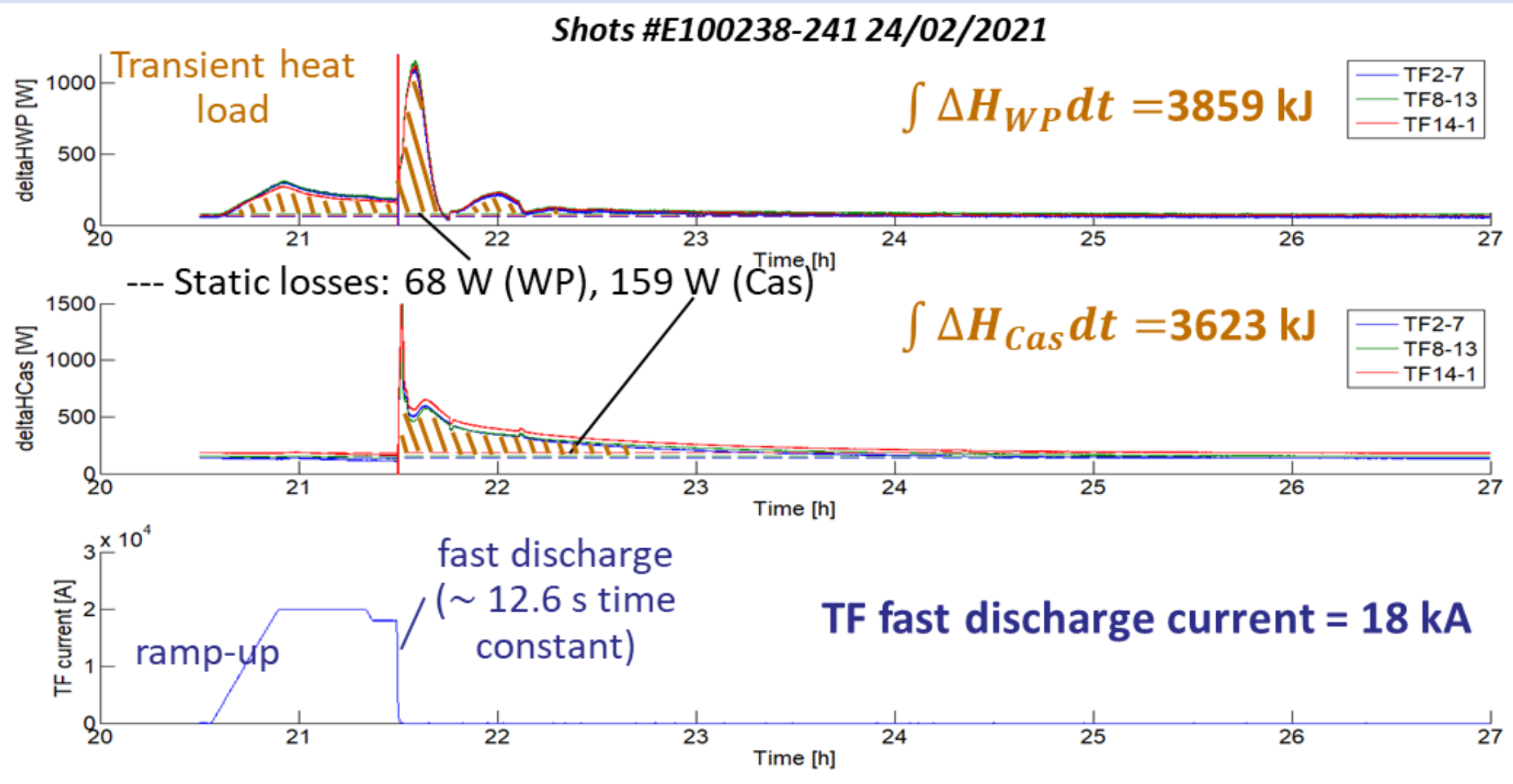
Simplified scheme of Helium mass-flow, temperature and pressure sensors is shown on the right.



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

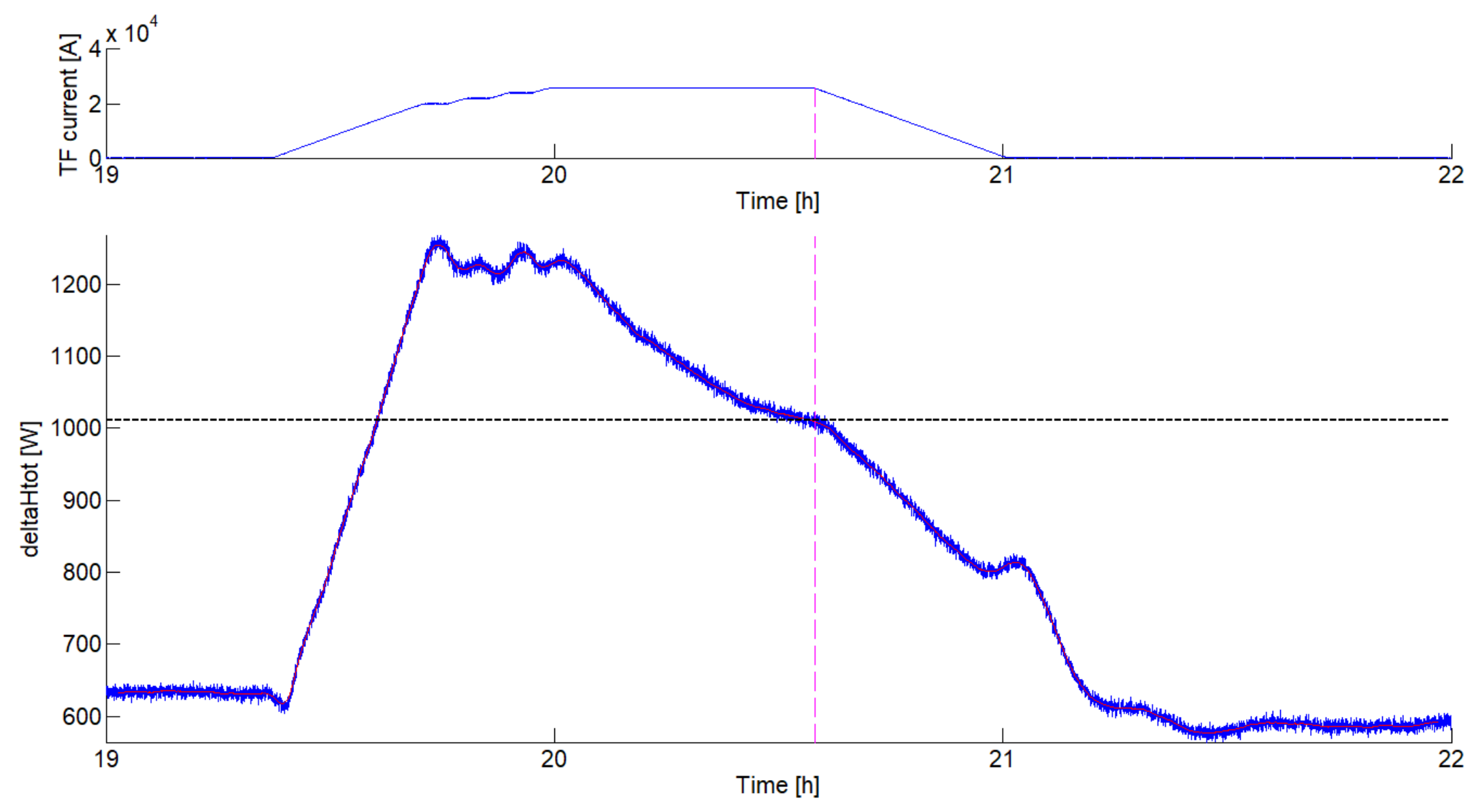
Results for different fast discharge (FD) currents I_{FD}:

I_{FD} [kA]	τ_{FD} [s]	Transient heat loads [kJ]	
		WP	Cas
10	14.9	1114	1191
15	13.0	2471	2451
18	12.6	3859	3623



TF fast discharge time constants τ_{FD} are decreasing with increasing I_{FD} because $\tau_{FD} = L_{TF}/R_d$ and the higher I_{FD} the higher the energy dissipated in the dump resistance R_d, so the higher its effective temperature and resistance.

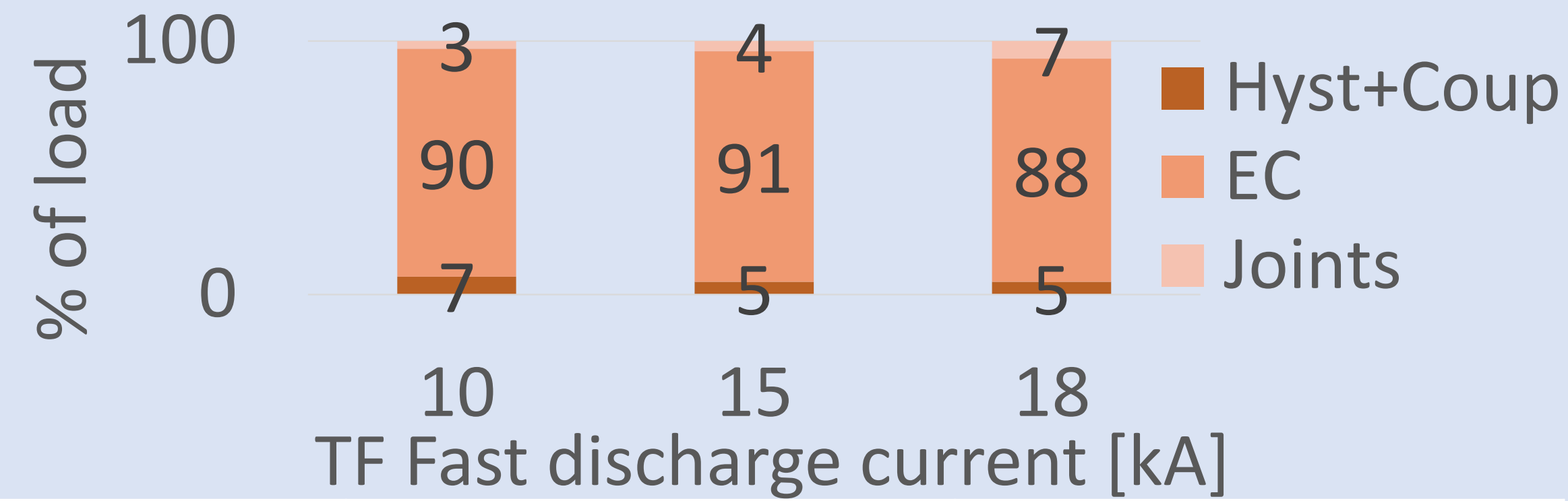
- **Joints Joule losses** participate in transient heat loads during TF currents tests so their total resistance $R_{TF\ joints}$ needs to be determined



At the end of the plateau at nominal current, from an enthalpy balance we determine $R_{TF\ joints}$ =573 nΩ. This value is conservative since the stationary regime is not completely reached (see plot above).

SYNTHESIS AND COMPARISON EXPERIMENT VS MODELING

- **Theoretical transient heat loads** computed with AC losses modeling and joints Joule losses estimate from $R_{TF\ joints}$. About 90% of the load is due to eddy currents losses in TF casings



I_{FD}[kA]	Total exp [kJ]	Total th [kJ]
10	2305	2703 (+17 %)
15	4922	5409 (+10 %)
18	7482	7975 (+7 %)

- **Comparison** between total **experimental** and **theoretical** transient heat load show a fair agreement in the 5-15% range even with a conservative estimate of the joints contribution
- WP absorbs about 50 % of the load while 90 % of it is generated in casing → **casing heats WP**
- **Lorentz forces increase this effect**

I_{FD}[kA]	Exp transient heat loads [kJ]	
	WP	Cas
10	1114 **(48.3 %)**	1191
15	2471 **(50.2 %)**	2451
18	3859 **(51.6 %)**	3623

CONCLUSION

- AC losses modeling in fair agreement with JT-60SA experimental results
- Major contribution of casing eddy currents and large redistribution to WP
- Consistency of observation with AC losses study in CTF [1]

ACKNOWLEDGEMENTS / REFERENCES

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