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# Mise en service cryogénique tokamak JT-60SA



F. MICHEL, C. Hoa, L. Zani, A. Louzguiti  
+ QST and F4E-Garching Teams

FROM RESEARCH TO INDUSTRY



Creation of Harmonious Diversity

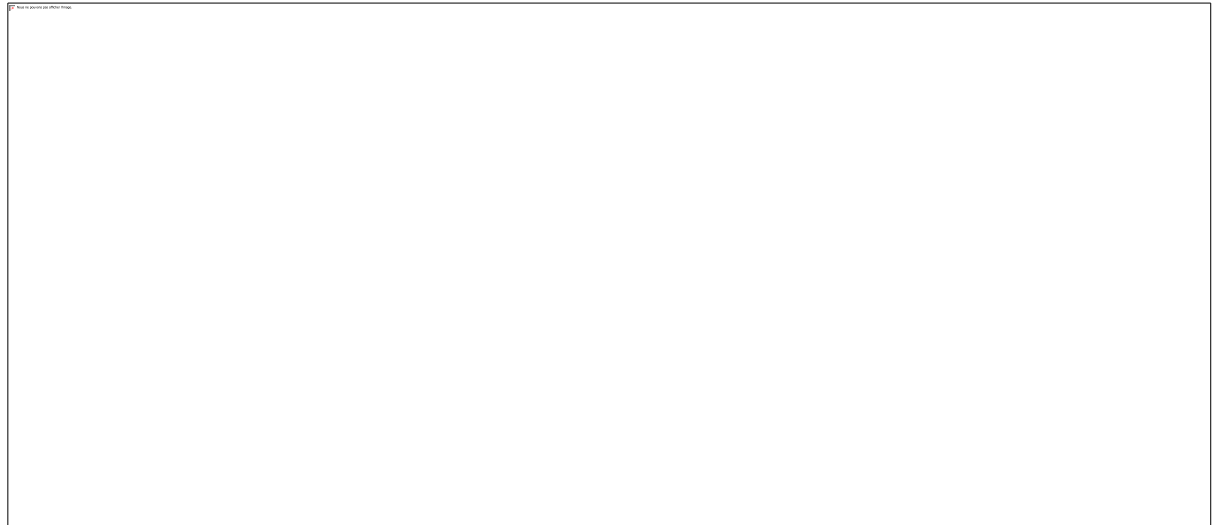
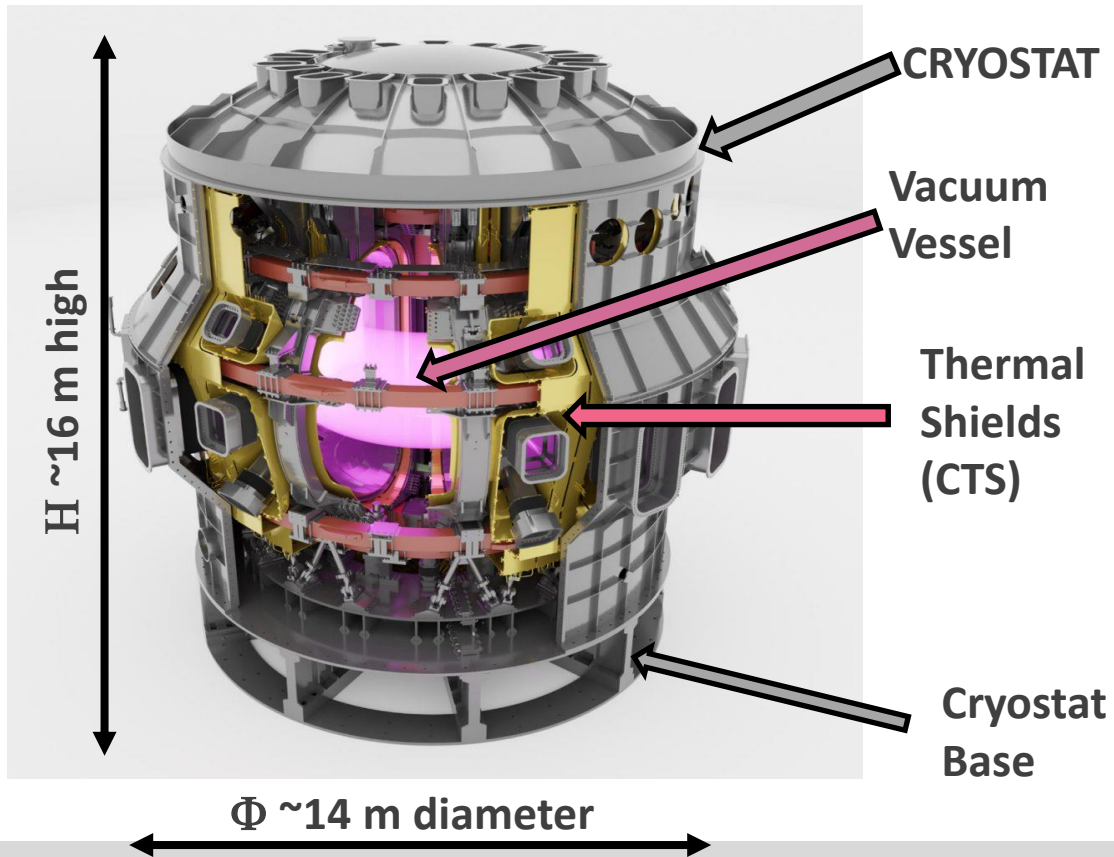


Département des Systèmes Basses Températures (D-SBT)

- Introduction
  
- 1ere mise en froid du Tokamak JT-60SA
  
- Bilan des charges thermiques
  
- Incident sur le joint terminal EF1
  
- Conclusions et perspectives

- **Introduction**
  
- 1ere mise en froid du Tokamak JT-60SA
  
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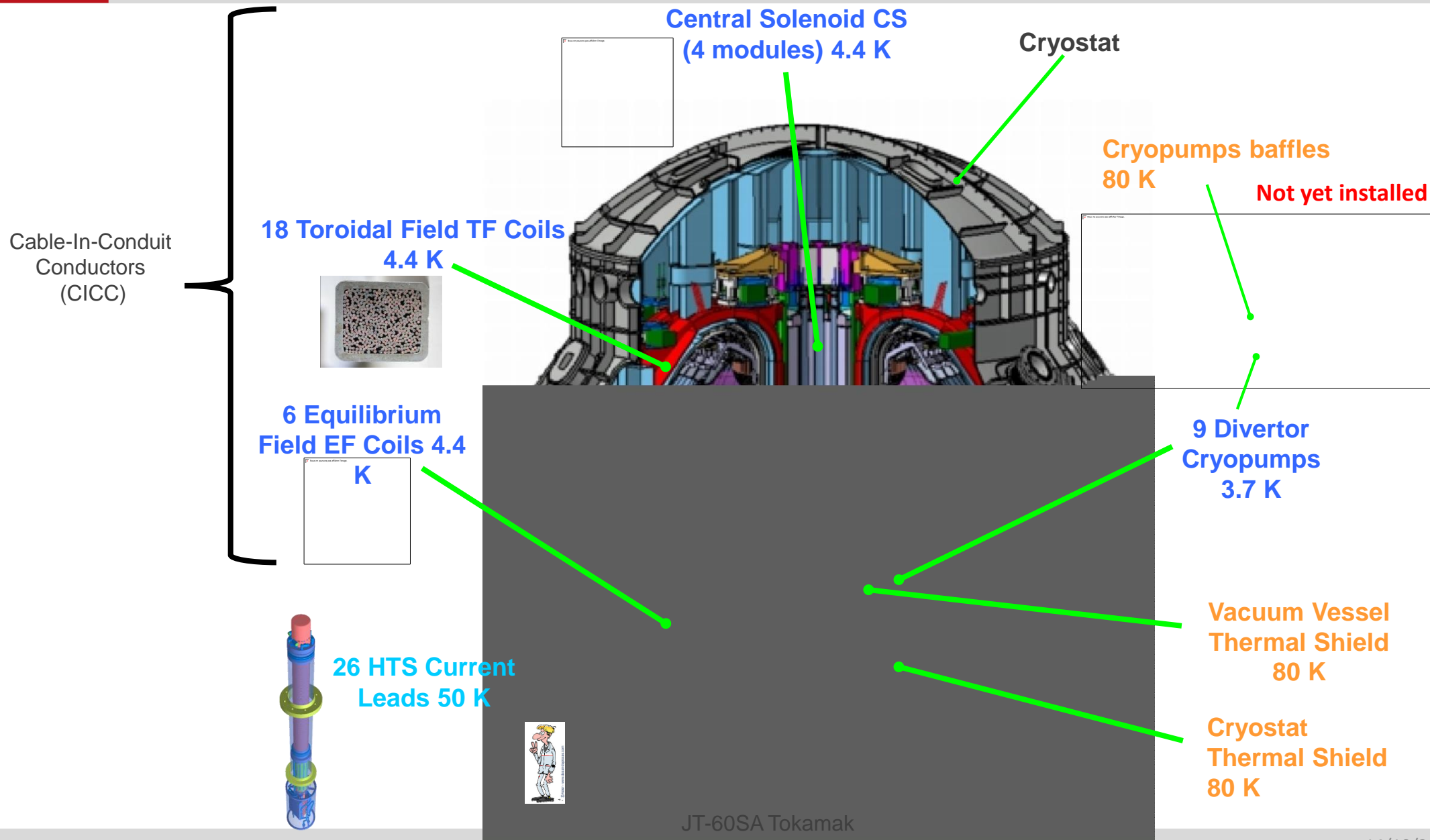
- The JT-60SA supraconducting tokamak was built on the QST Naka site (Japan, Ibaraki prefecture) in the framework of the Broader Approach Agreement between Japan and Europe signed in February 2007.
- The JT-60SA tokamak integrated commissioning started mid 2020 with a Japanese and European integrated team, following the assembly completion (March 2020).
- The JT-60SA tokamak fusion project aims to support the exploitation of ITER in resolving essential physics and engineering issues for DEMO reactors. DEMO is the advanced phase towards the industrial-scale fusion reactor.



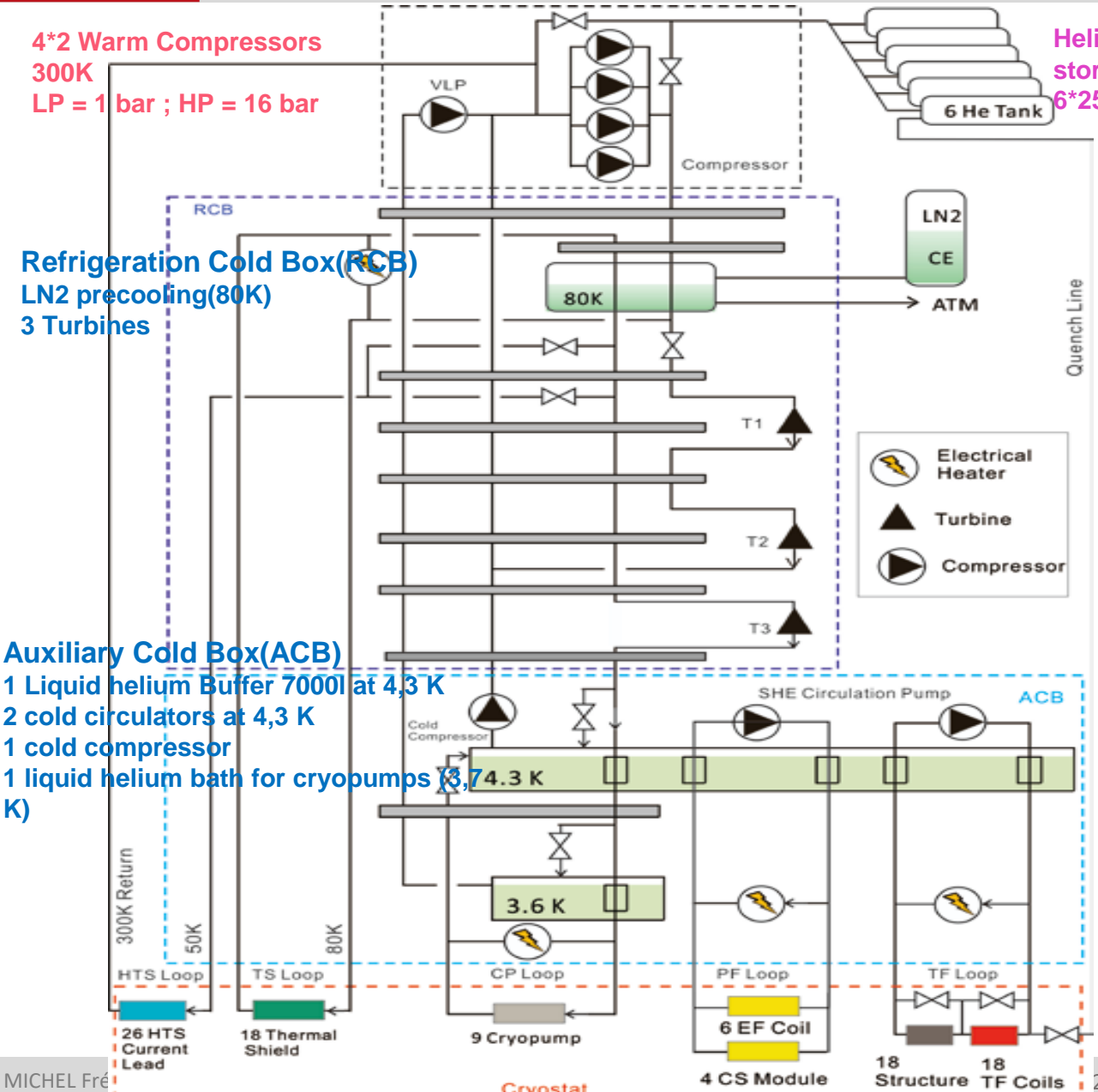
*Comparison of the plasma volumes : Courtesy from F4E*

- 18 TF coils (NbTi)
  - ❖ Magnet energy of the 18 TF coils 1.06 GJ
  - ❖ Max field at conductor 5.65 T
  - ❖ Total Weight ~ 420 Tons (~ 100 Tons for WP /320 Tons for structures)
  - ❖ Nominal current 25.7kA
  
- 4 CS modules (Nb<sub>3</sub>Sn)
  - ❖ Peak field 8.9 T
  - ❖ Total Weight ~ 100 Tons
  - ❖ Operating current 20kA
  
- 6 EF coils (NbTi)
  - ❖ Peak field 4.8T (6.2T for EF3/EF4)
  - ❖ Total Weight ~ 178 Tons
  - ❖ Operating current 20kA
  
- Current Leads 26 HTS-CL
  - ❖ 6 HTS-CL for TF coils
  - ❖ 8 HTS-CL for CS coils
  - ❖ 12 HTS-CL for EF coils

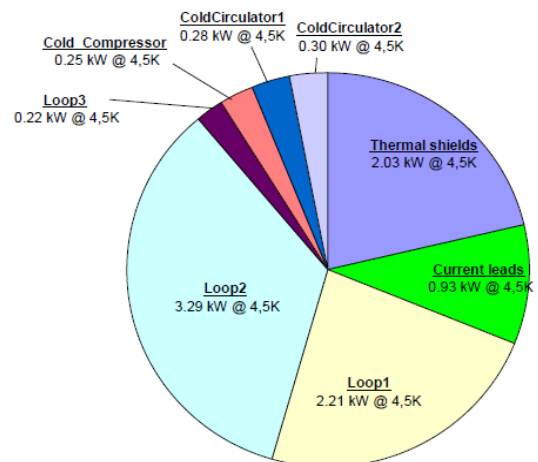
**TOTAL cold mass to cool-down until 4.5 K  
(~700 Tons)**







- Cryoplant equivalent power at 4.5 K ~ 9 kW
- Magnet System cooling (2 Loops SHe 4.4 K and 0,5 MPa)
  - ❖ Loop 1 for TF coils and Structures: 860 g/s with DP ~ 0.13 MPa
  - ❖ Loop 2 for EF et CS coils: 960 g/s with DP ~ 0.10 Mpa
- Cryopannels in the Vacuum vessel cooled by SHe 3.7 K ; 0.5 MPa ; 270 g/s
- HTS-CL current leads cooling: Helium 50 K-300K; 0.4 MPa; 25 g/s
- Thermal shields cooled at 80 K/100 K by ; 400 g/s Helium flow between 1.8/1.6 MPa



Based on design values



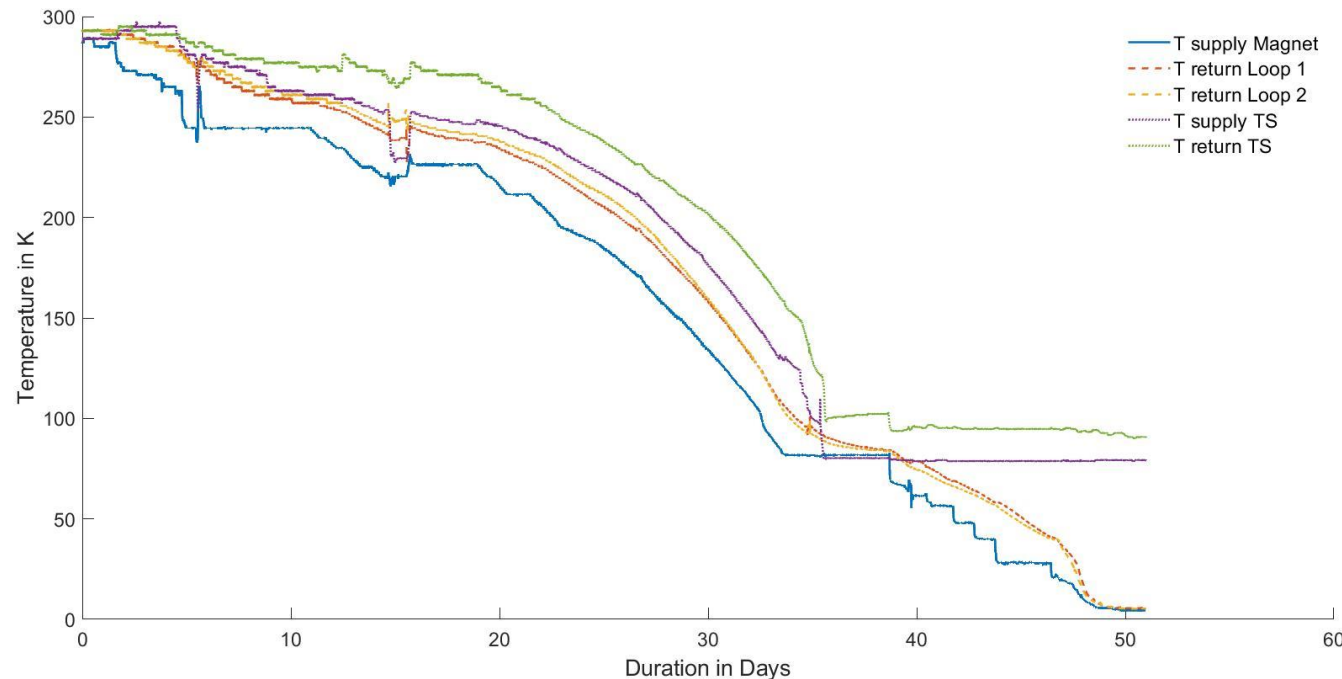
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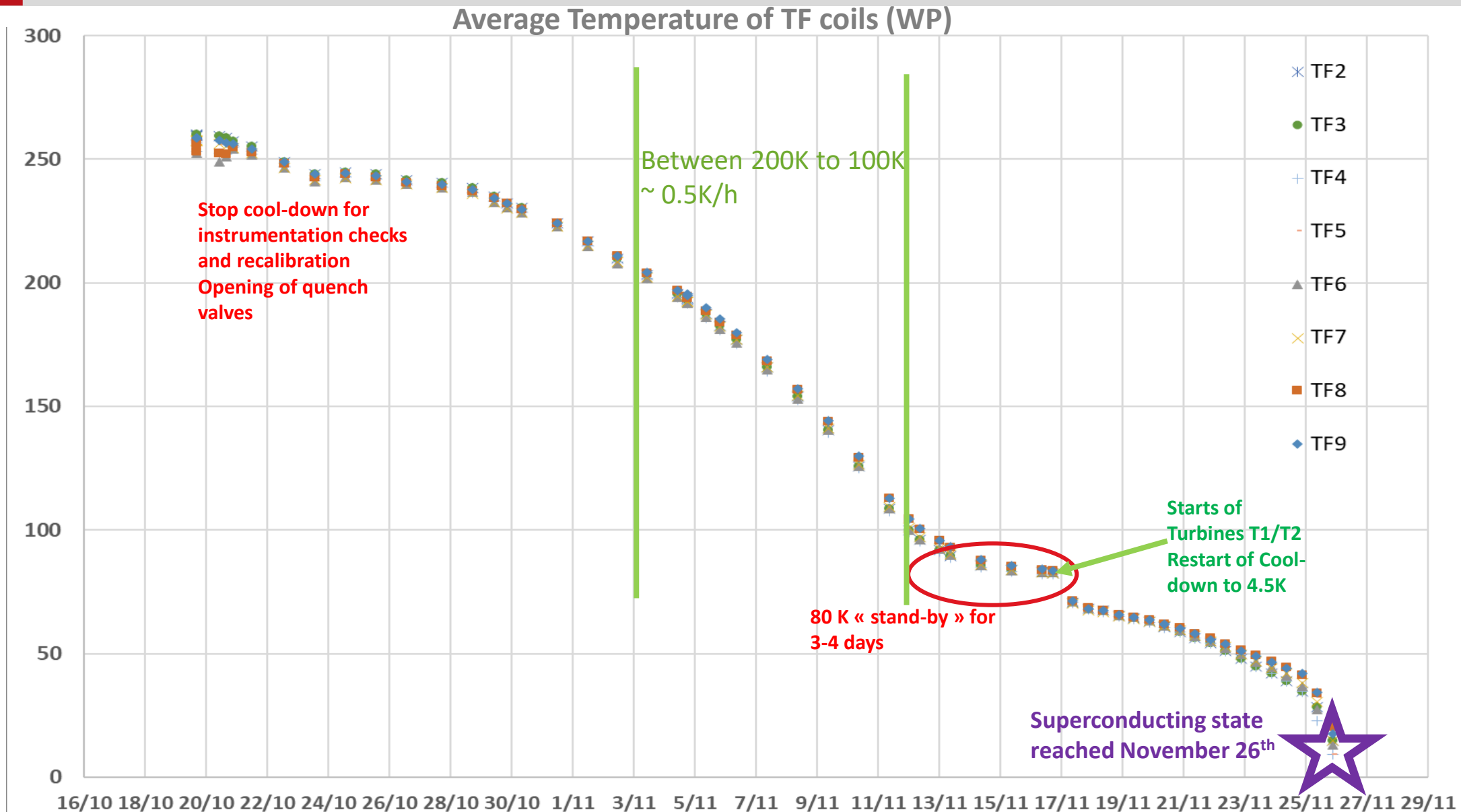
### ➤ Main cool-down requirements

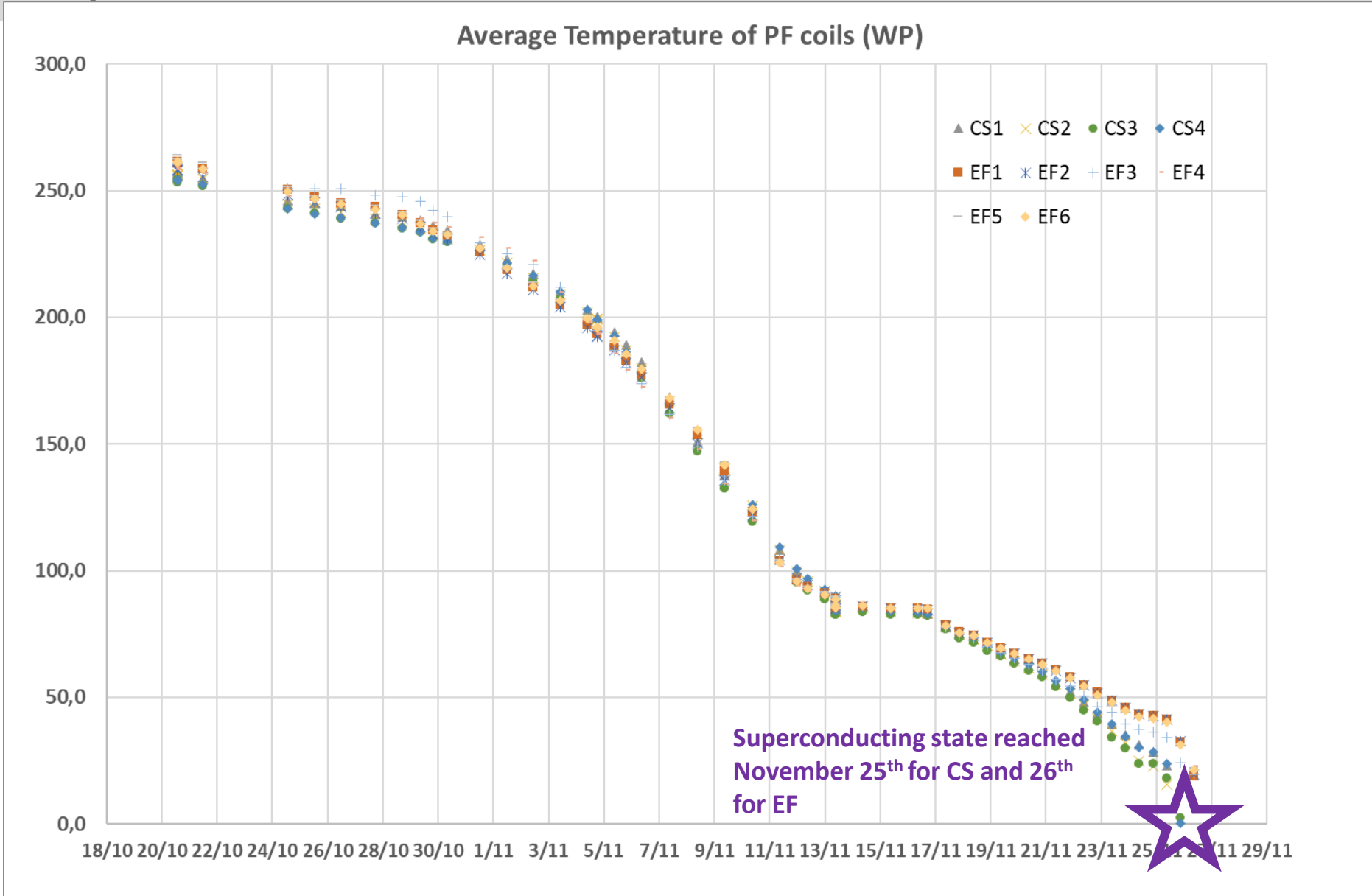
- ❖ Cool-down speed shall not exceed 1 K/h (**nominal cool-down speed is 0.6 K/h**) cool-down expected duration 20 days
- ❖ The temperature difference between inlet and outlet of thermal shields and coils should be less than 40 K
- ❖ The temperature difference between thermal shields and coils shall be kept within 50 K with the **thermal shield always warmer than the coils** in order to protect the shield surfaces from frozen impurities

### ➤ Main cool-down performances reached

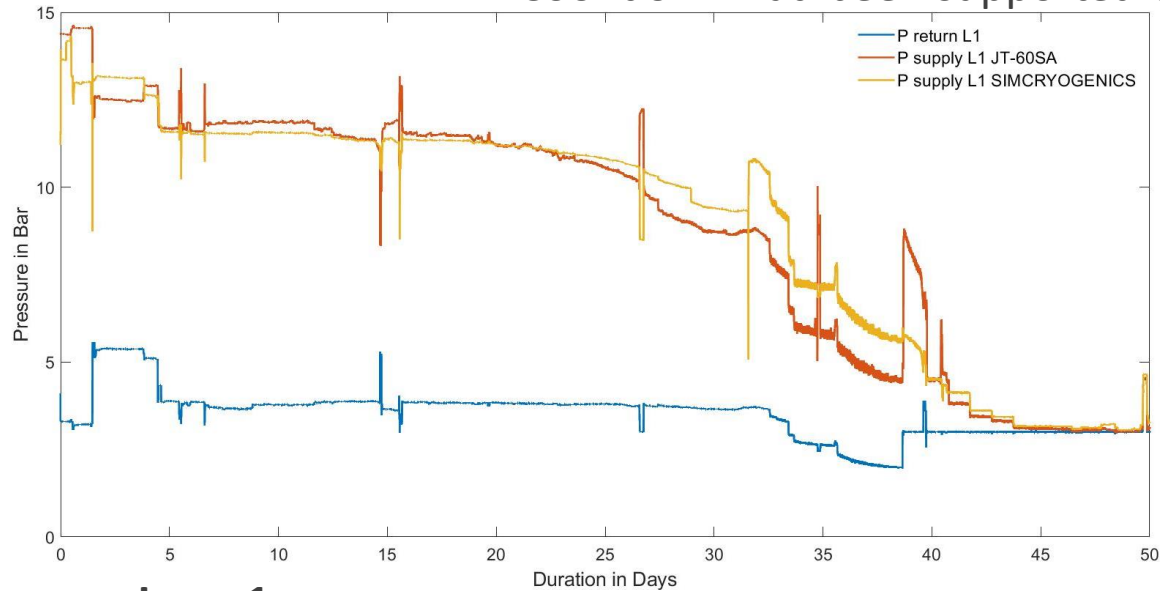
- ❖ This first cool-down of the JT-60SA was also used to check and assess the procedures, the instrumentation and the associated controls: we spent about 14 days for checking instrumentation and various systems
- ❖ The tokamak cool-down took place in 47 days with 33 active cooling days. Therefore, the average cool-down speed was about **0.37 K/h**.
- ❖ This cool-down was fully compliant with protection requirements concerning magnets and thermal shields (even more conservative requirements had been applied, which also impacted the cool-down speed).



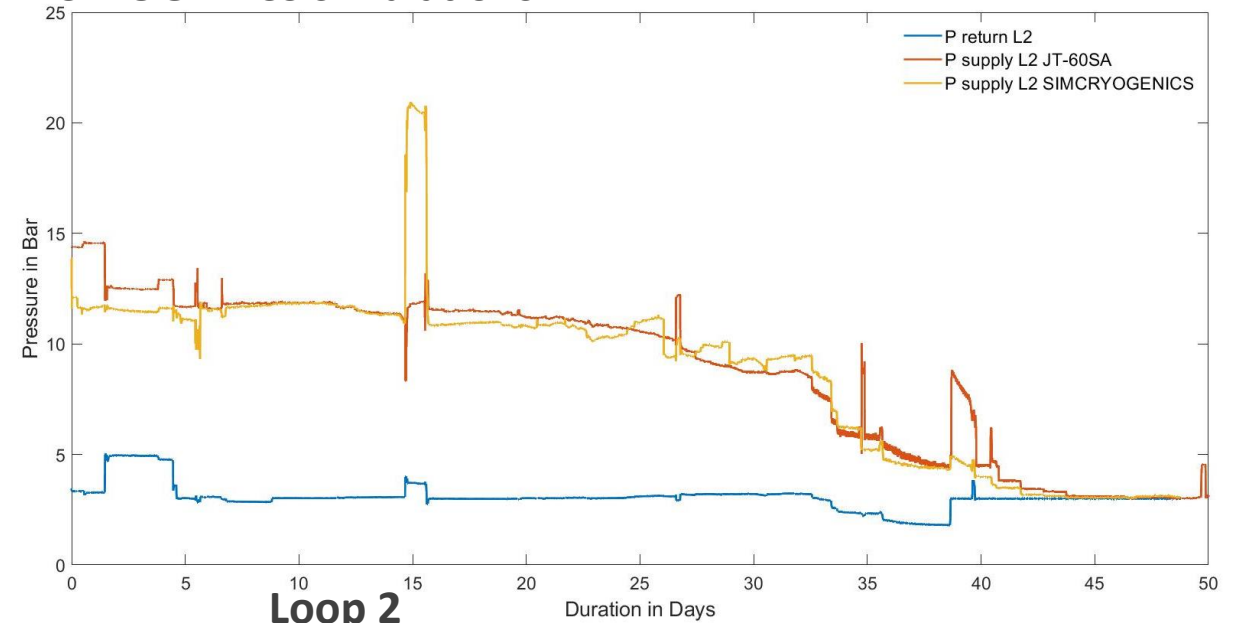




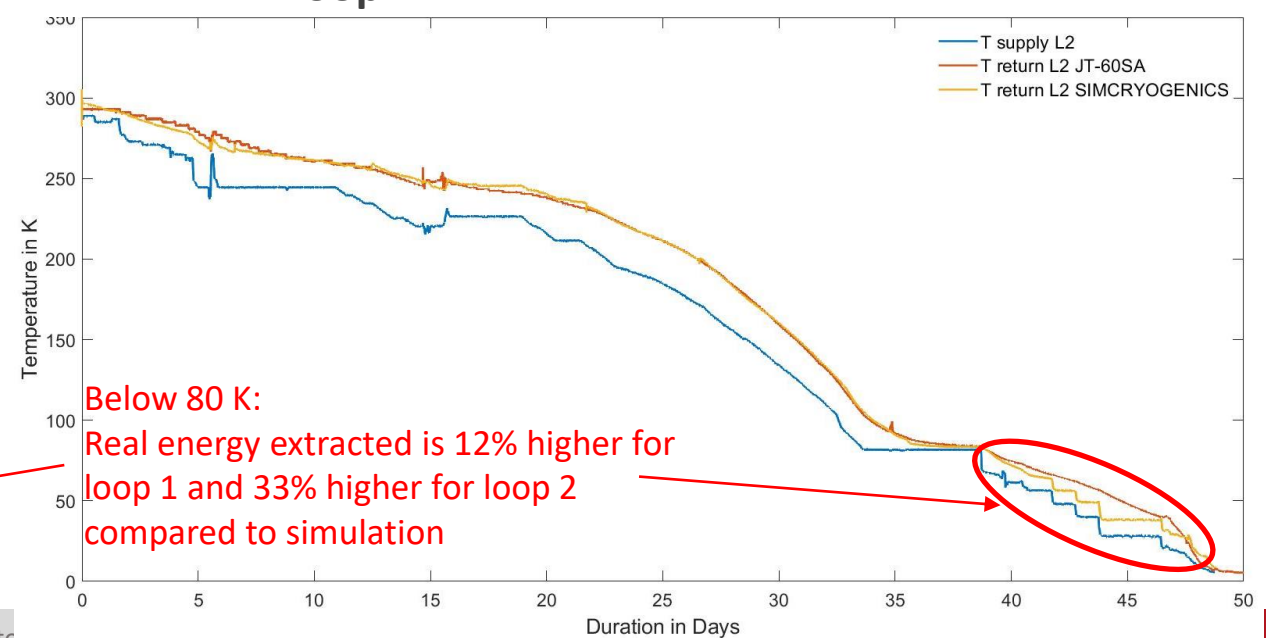
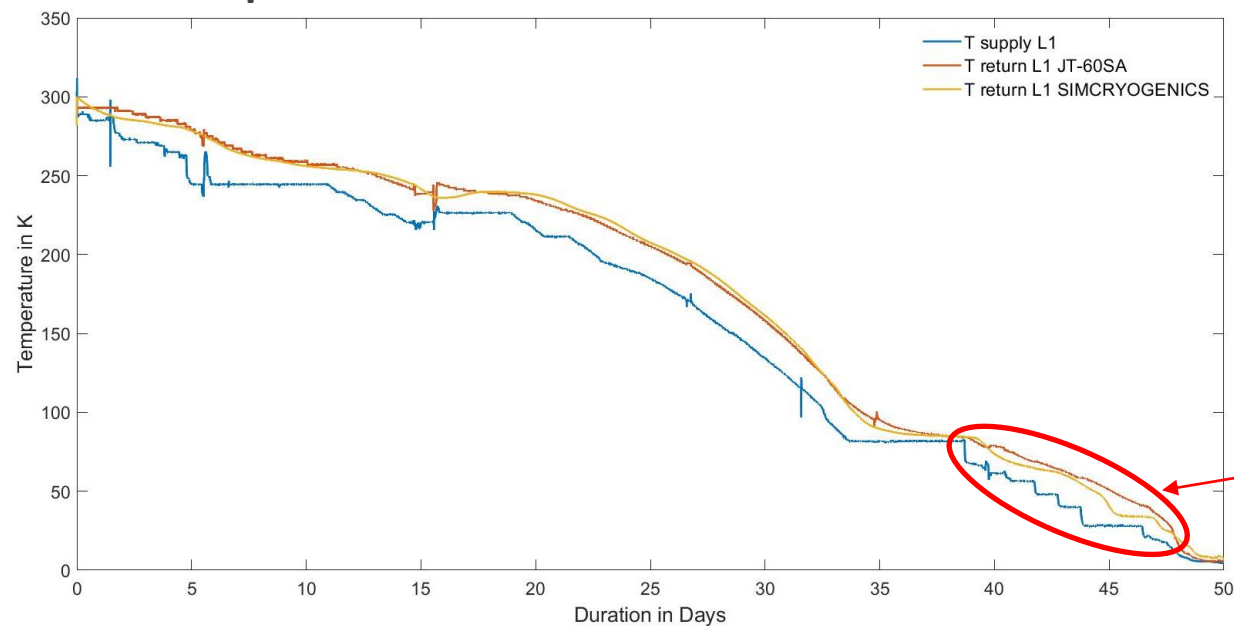
## Cool-down had been supported by SIMCRYOGENICS simulations



Loop 1



Loop 2



Below 80 K:  
Real energy extracted is 12% higher for  
loop 1 and 33% higher for loop 2  
compared to simulation

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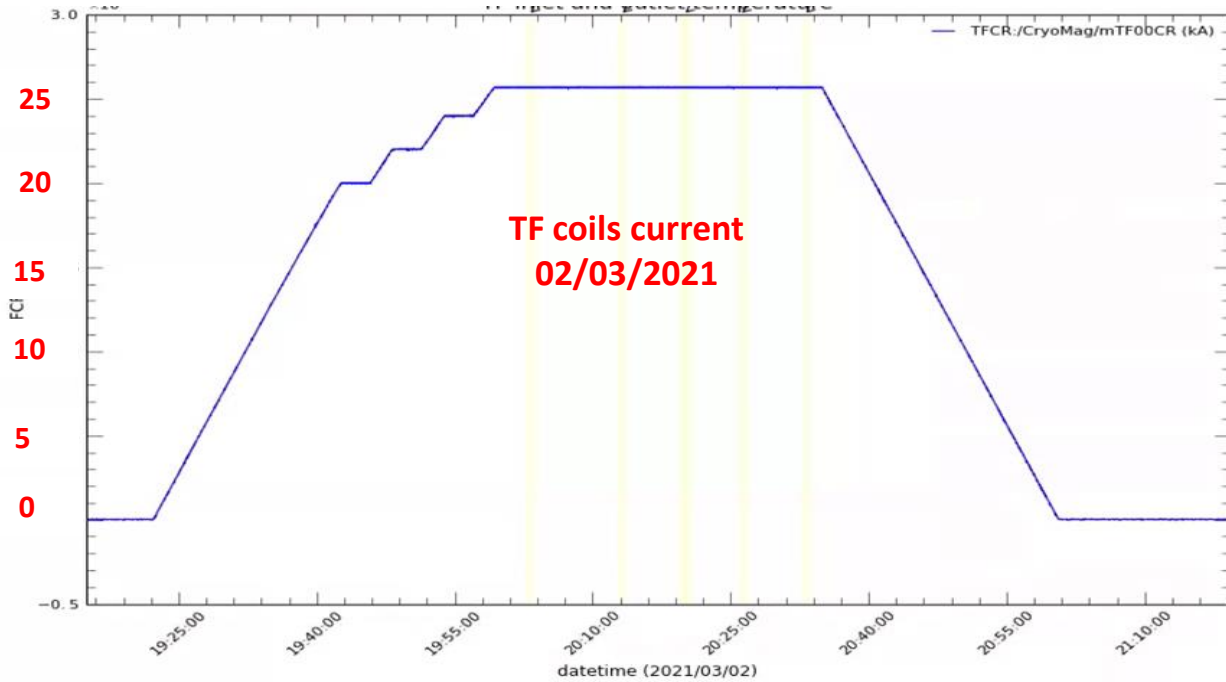
- After the 1<sup>st</sup> cool-down and temperature equilibrium, first thermal balances had been conducted and compared to the design values

VV Temperature	Vacuum Vessel in operating condition 50°C (323 K)		Vacuum Vessel in Baking condition 200°C (473K)	
Source of heat loads	Average measured heat loads Cryodistribution+Magnets	Estimated heat loads (design values)*	Average measured heat loads VV~460K	Estimated heat loads(design values) VV at 473K *
Loop 1 at 4.5K TF coils (WP+Structures)	~830 W	~ 1500 W for loop 1 and loop 2	~2475 W	2260 W
Loop 2 at 4.5K EF and CS coils	~620 W		~1185 W	1130 W
Thermal Shields at 80K	~30.2 kW	33.1 kW (without cryopumps)	~95 kW	134.8 kW

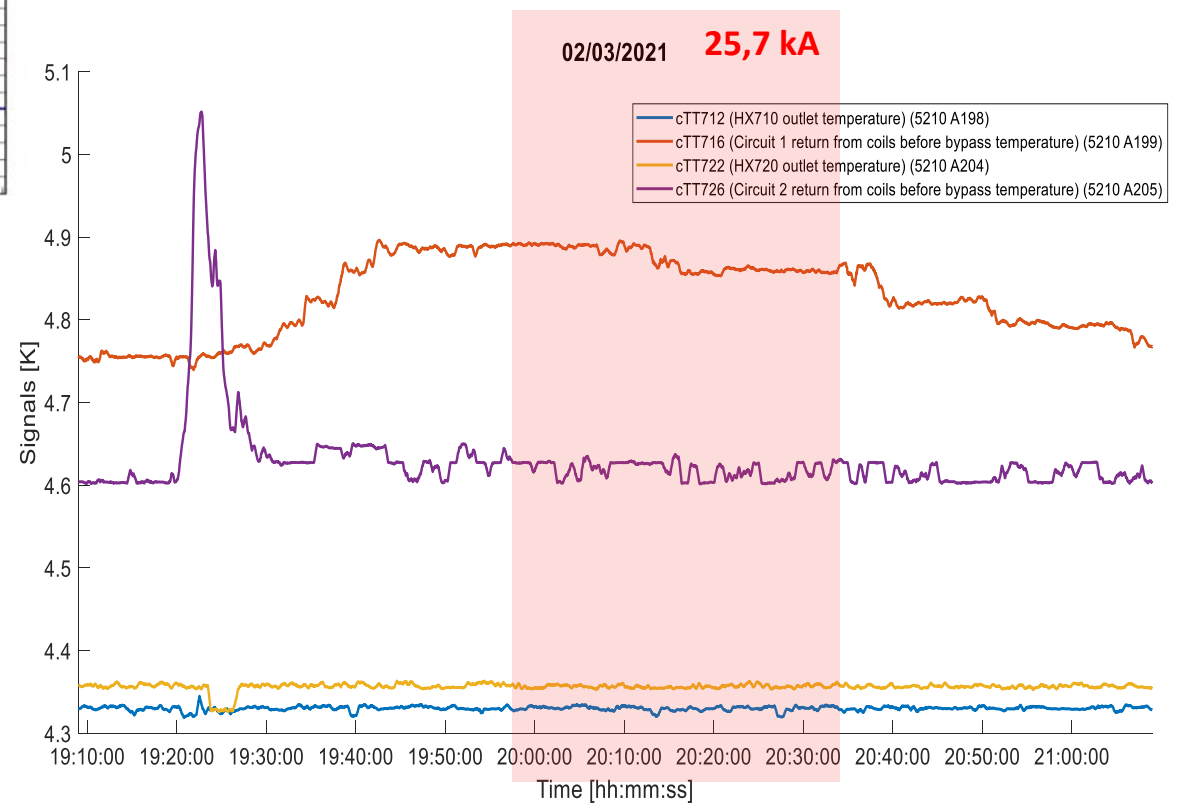
\* Design margins  
~14% at 4.5K and  
18% at 80K

- **Excellent agreement on the static heat loads in nominal operation at 4.5 K and 80 K**
- **For baking, heat loads are a bit lower on 80 K TS than estimates and a bit higher on 4.5 K coils**
  - ❖ The Vacuum Vessel did not reach 200°C and maximum average temperature was around 190 °C which could explain lower value on TS
  - ❖ On coils 4.5 K surface, heat loads were larger in a favourable conditions with TS at 100 K instead of 110 °C.





- TF coils current 25.7 kA (02 March 2021) ~ 40 Minutes
- Impact of the TF current ramp-up on the cryogenic (Loop 2: EF+CS et Loop 1 TF+Structures)



### ➤ Heat loads with 25.7 kA in TF coils

Source of heat loads	Average measured heat loads	Estimated heat loads (design values)
Loop 1 at 4.5K TF coils (WP+Structures)	1385 W	1773 W for loop 1 and loop 2
Loop 2 at 4.5K EF and CS coils	725 W	
Thermal Shields at 80K	31.5 kW	33.1 kW (without cryopumps installed)

+ 550 W/static heat loads with 25.7 kA  
Design estimates ~ + 280 W






### ➤ Cold circulator heat dissipation (remind on Design values in purple)

- ❖ Real operation of Loop 1 : Mass flow ~ 950 g/s (860);  $\Delta P$  ~ 1.94 bar (1.3) ;  $Q$  ~ 1.86kW (~1.3) ; isentropic efficiency ~ 0,72
- ❖ Real operation of Loop 2 : Mass flow ~ 950 g/s (960) ;  $\Delta P$  ~ 1,17 bar (1.0) ;  $Q$  ~ 1.24kW (~1) ; isentropic efficiency ~ 0,64
- ❖ Total dissipation for cold circulators ~ 3.1 kW (2.3 kW : +25% due to higher mass flow and higher  $\Delta P$  in loop 1 )

➤ Need to assess heat loads and pressure drops in order to optimize operating conditions (dedicated campaign during the next Integrated Commissioning phase)

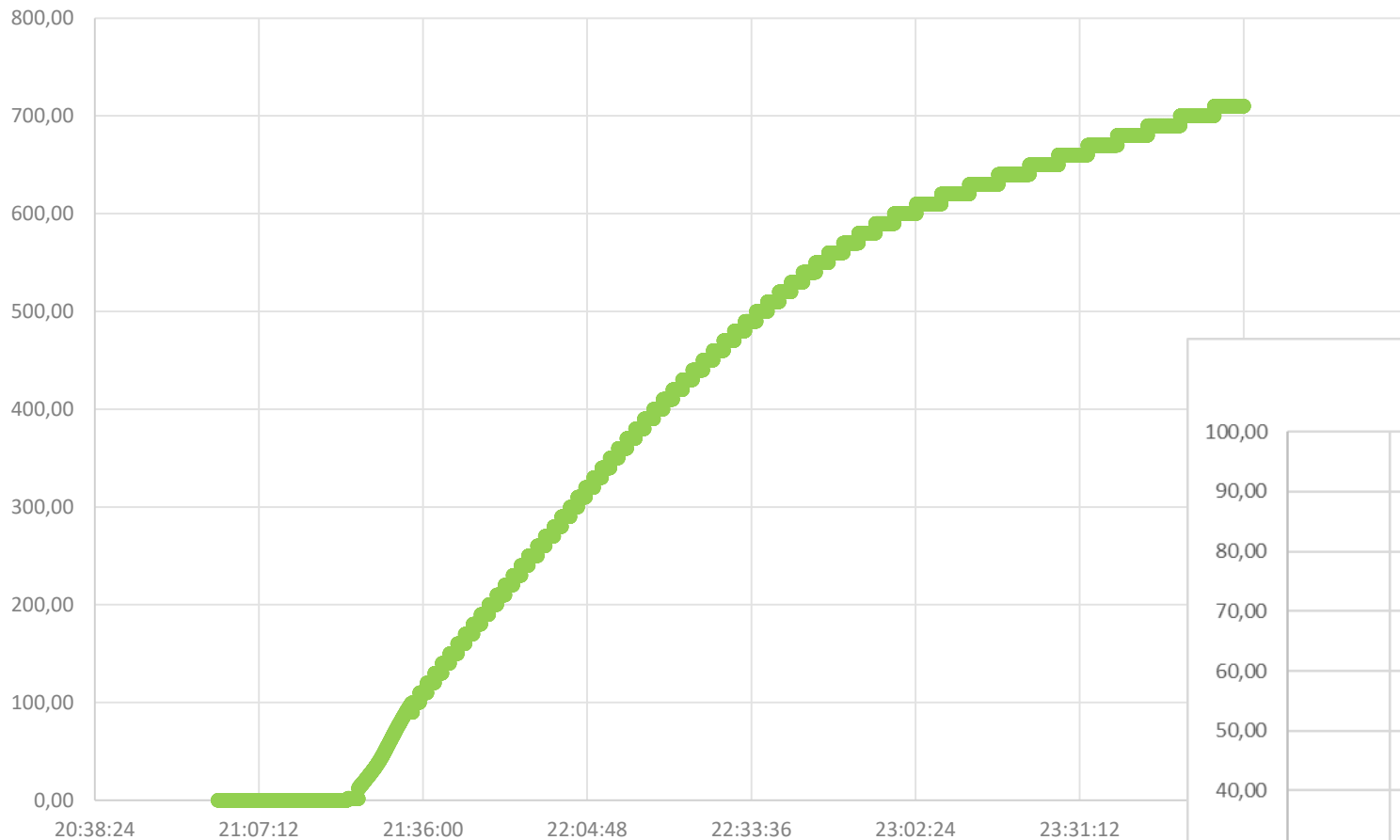
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**Even list from QST (mag/cryo team):**

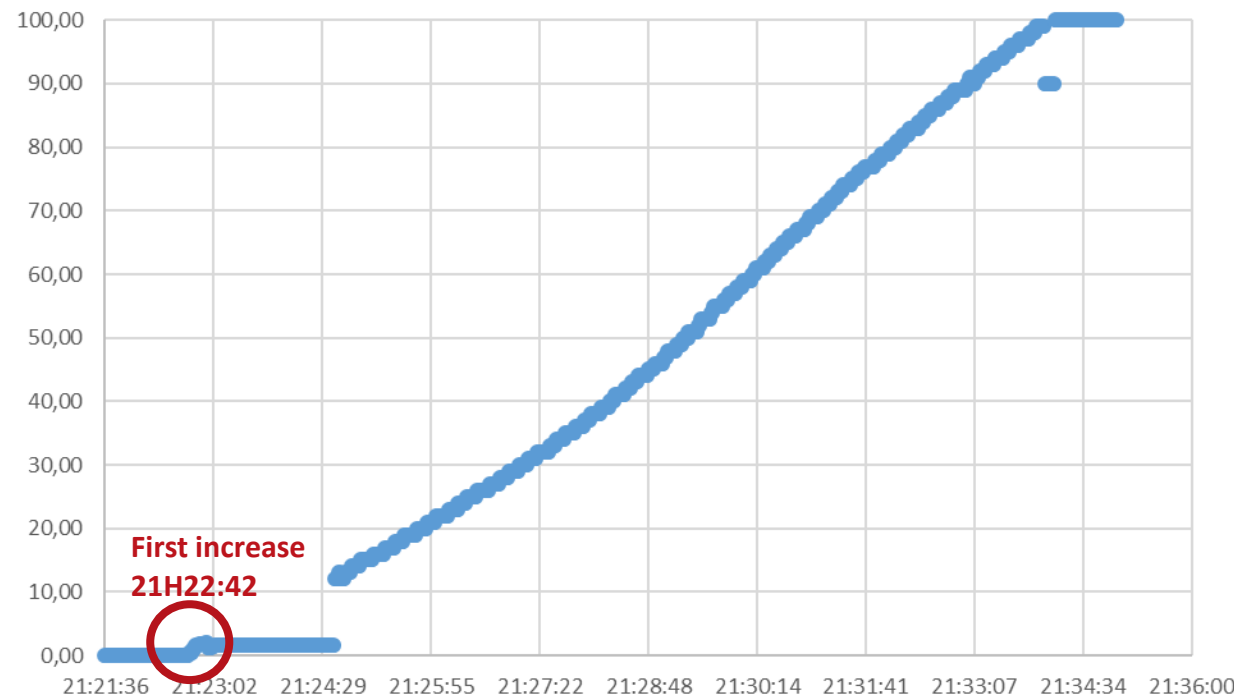
- 21:22:33 Leak occurred due to electrical arc on EF1 terminal joint (during Shot E100353)  
The Pressures in loop 1 and 2 were increasing quickly.
- 21:22:42 First increase of cryostat vacuum 
- 21:26:08 Stop of Turbines T1/T2 (on High outlet pressure T2 PT329 > 1.6 bar) 
- 21:26:30 Disconnection of Loop1/Loop2 by valves closing in ACB (on high pressure in loop 1 **PT712 > 15 bar**) 
- 21:27:24 One rupture disc attached on the outlet of TF8-13 (1SVB53) burst.
- 21:28 Operators realized that all pressure relief valves are manual mode. 
- 21:30 Operators finished to change valve operation mode to automatic mode.
- 21:30:30 One rupture disc attached on the outlet of EF5 (1SVD65) burst.
- 21:31:18 Pressure relief valve attached on the outlet of EF4 (1EVD64) opened.  
Quench tank pressure was increasing. 

Events completed by CEA

### Cryostat Vacuum (Pa)



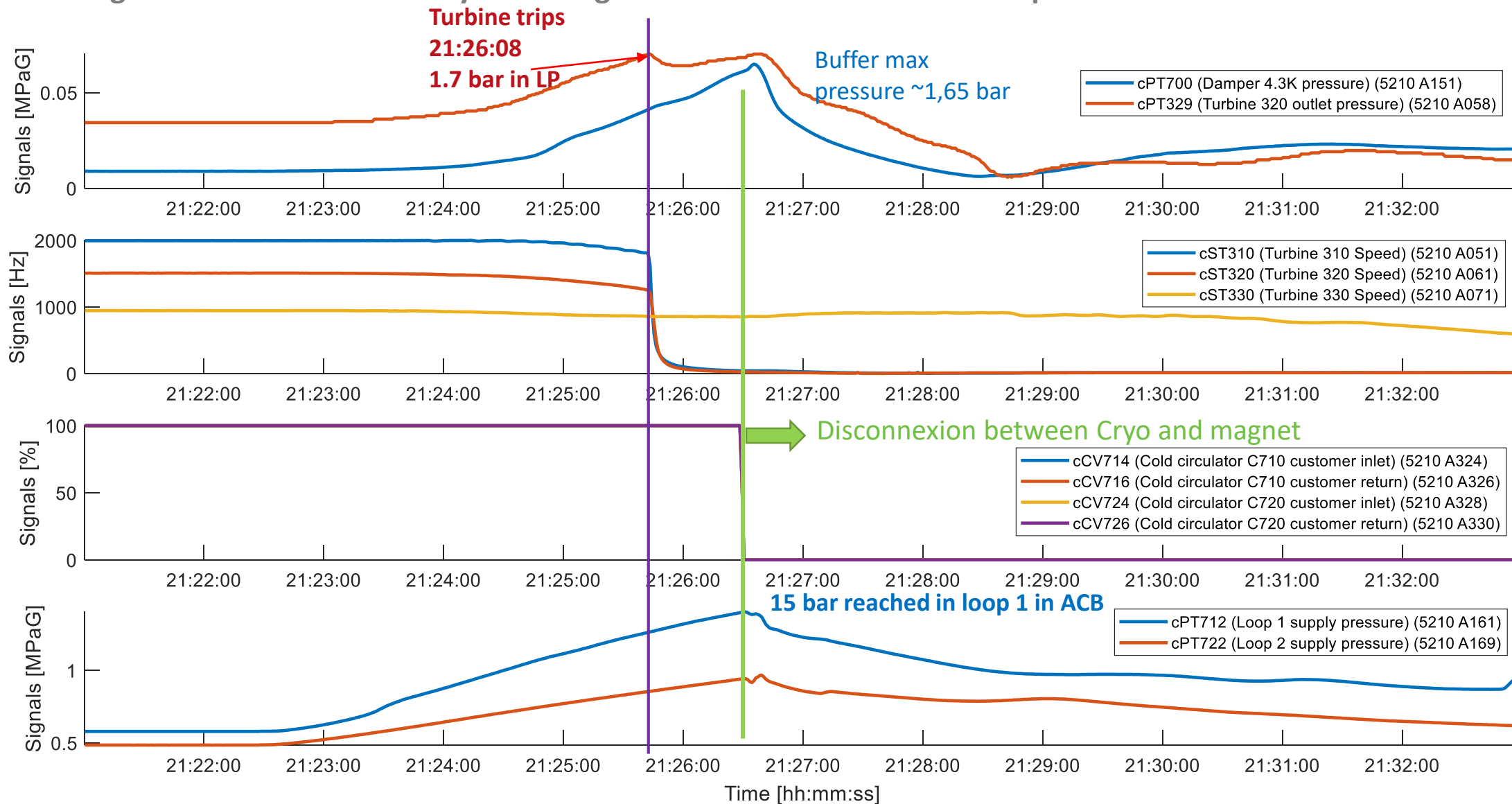
### Cryostat vacuum (Pa)

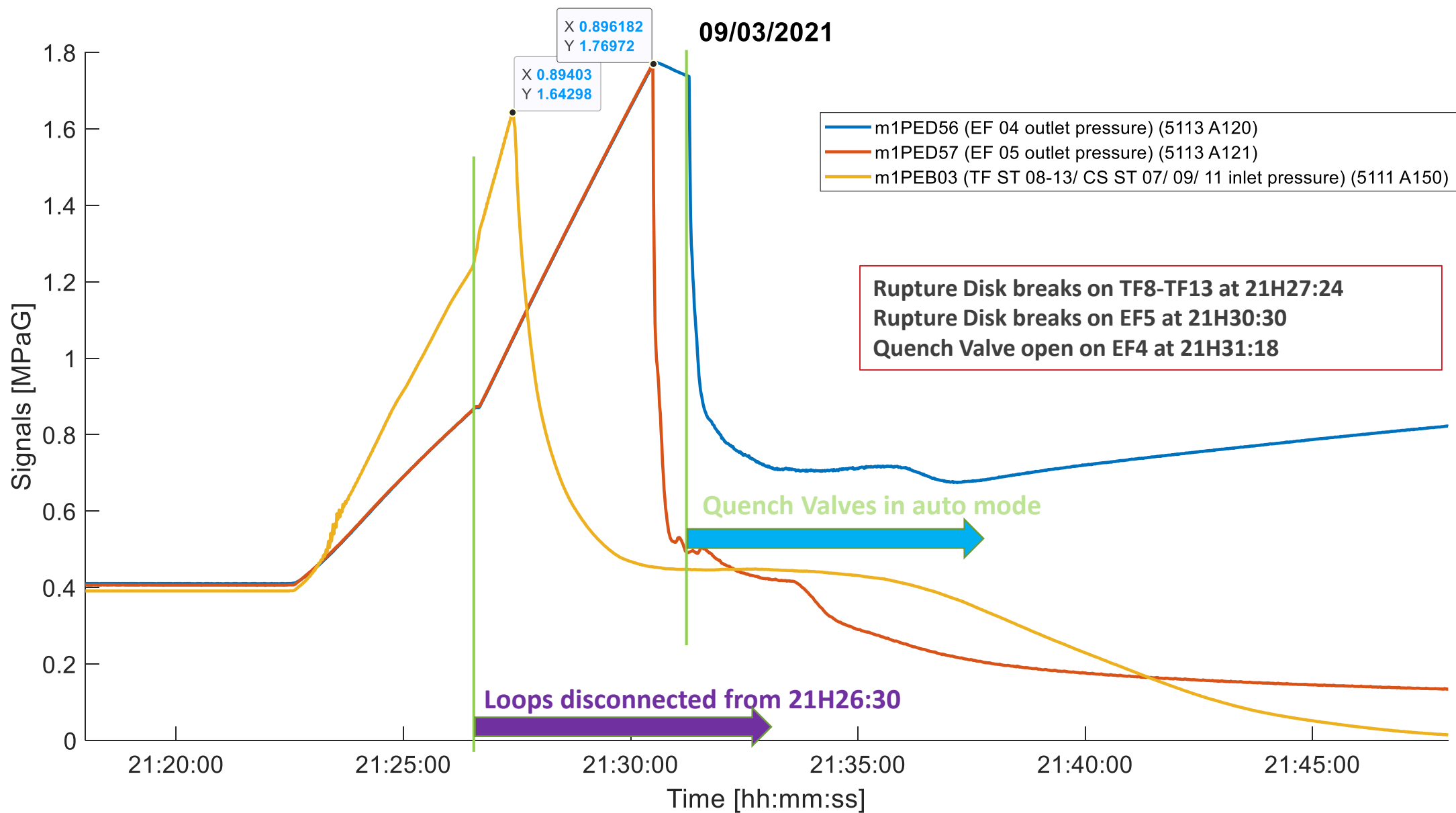


**First increase**  
**21H22:42**

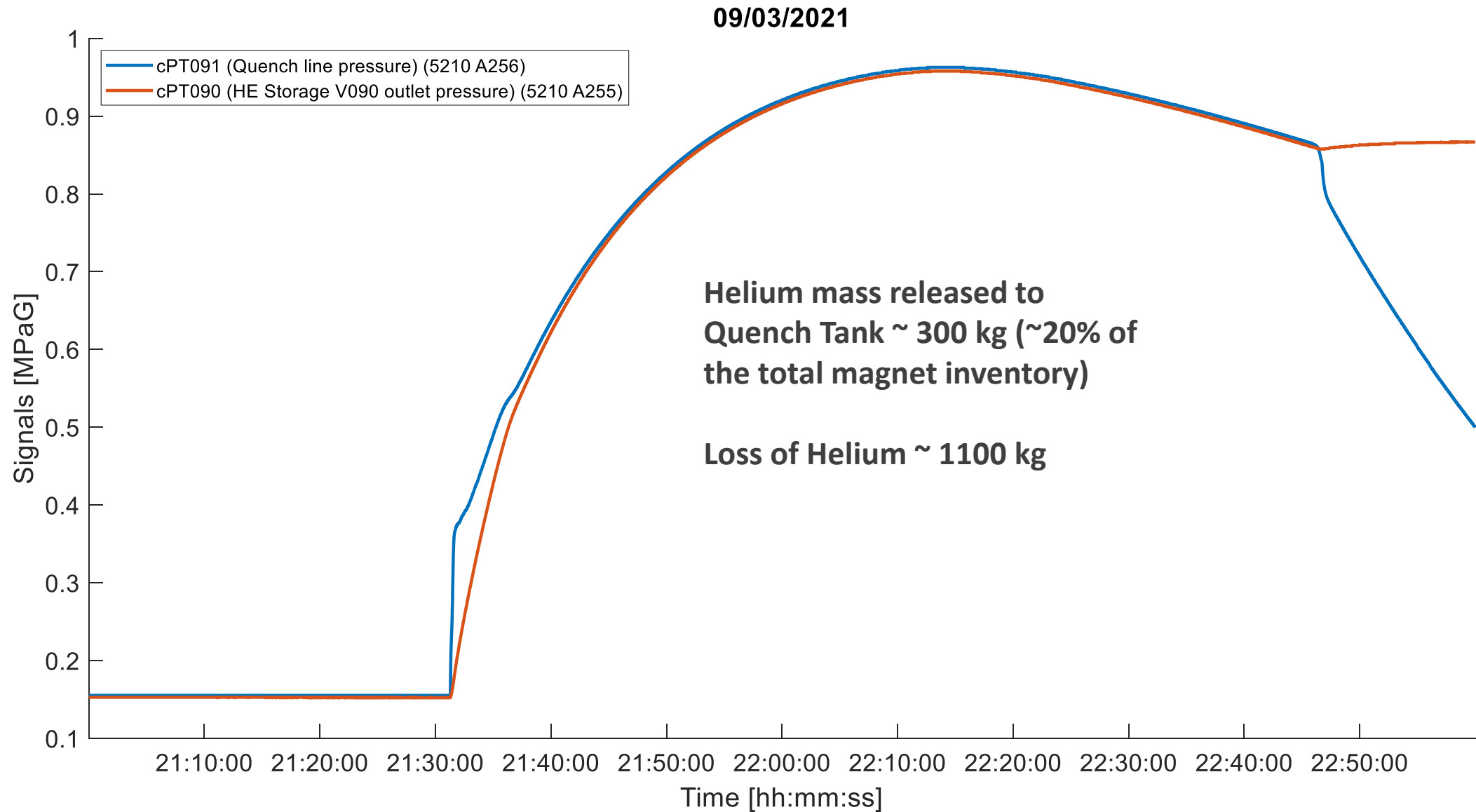


- Following the loss of vacuum in cryostat: large increase of the heat loads deposited in the helium buffer located in ACB



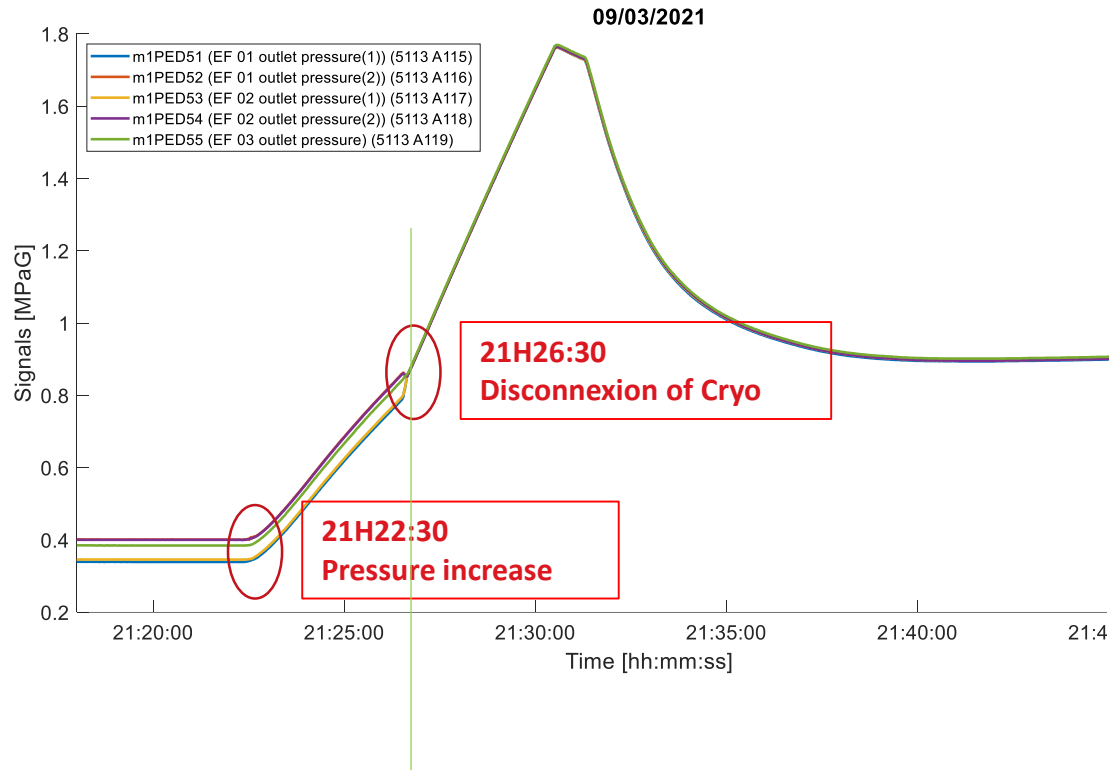




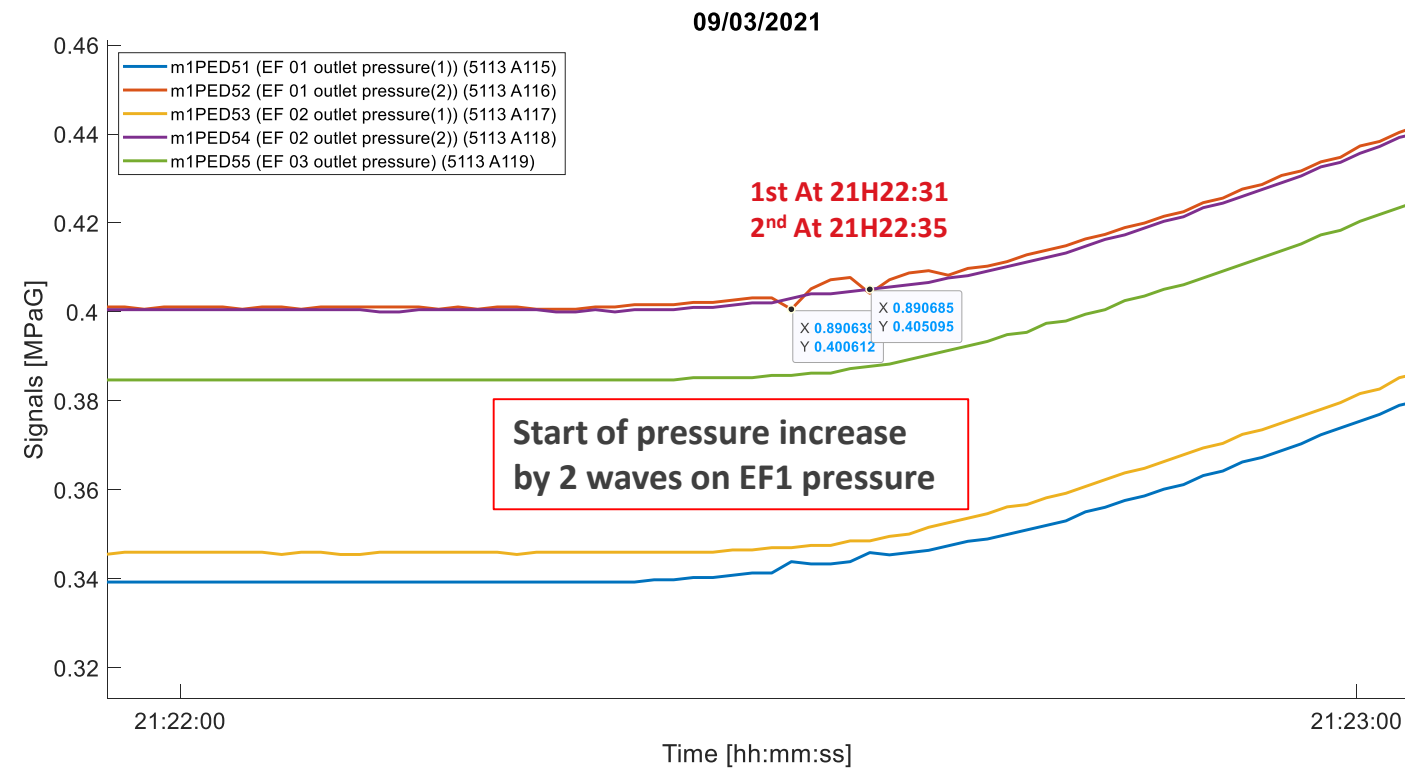


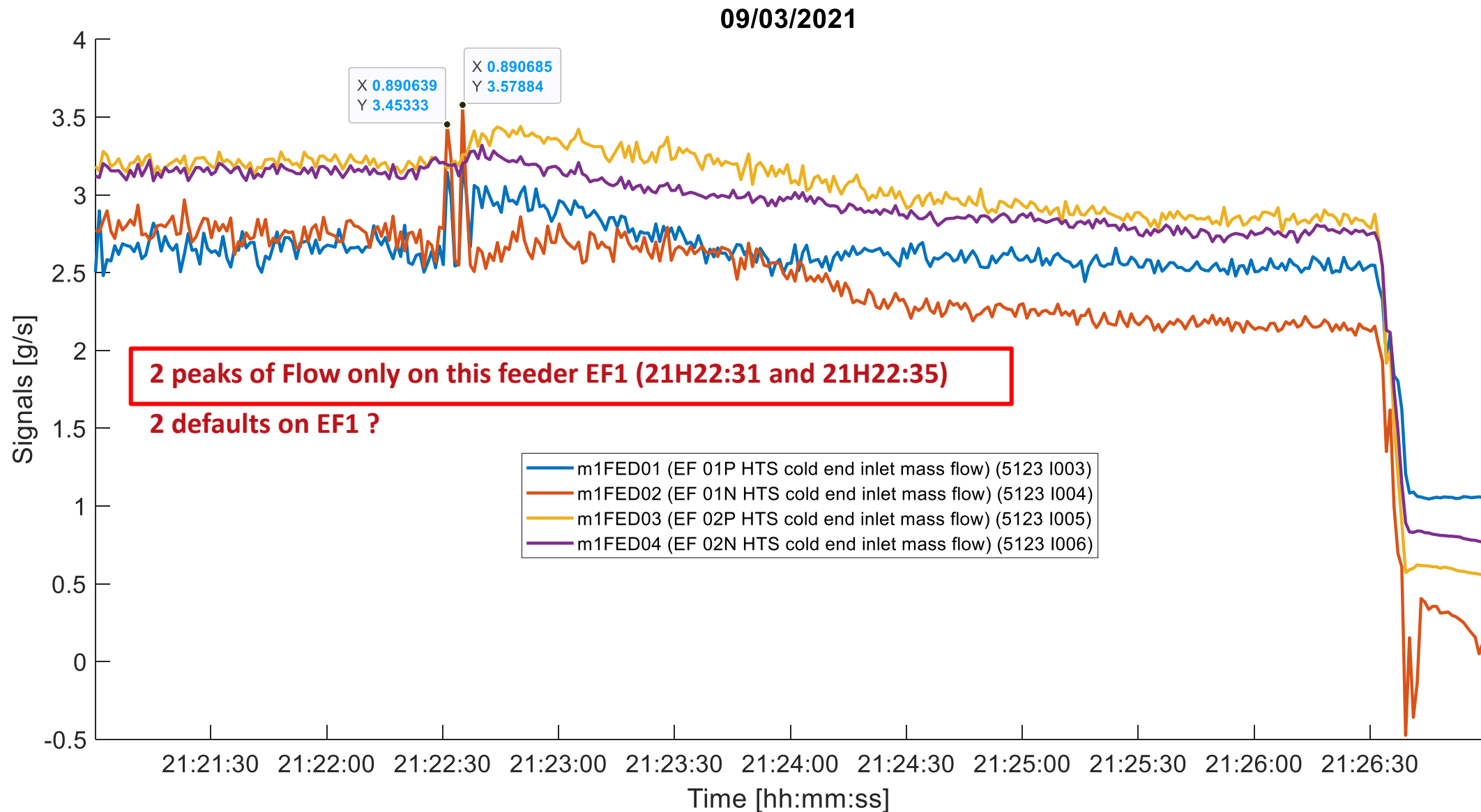
- **Participation à l'équipe cryomagnétique JA/EU pour le commissioning intégré JT-60SA (2020-2021)**
- **Mise en froid du système cryomagnétique en respectant les exigences pour les aimants/TS en 47 jours**
  - 1ere mise en froid avec des exigences supérieures sur les  $\Delta T$ .
  - Nombreuses vérifications et calibrations des capteurs (température, pression, débit) en début de mise en froid
  - Charges thermiques par rayonnement prise en compte uniquement sur boucle 1 (non négligeable sur les aimants EF: Boucle 2)
  - Comparaison avec simulations SIMCRYOGENICS : Résultat de simulation en accord jusqu'à 80 K. En dessous de 80 K l'énergie à extraire supérieure aux estimations (Simulations et résultats présentés aux CHATS 2021 F. Michel et al.)
  - Intérêt d'un modèle numérique pour l'ajustements des débits, ouvertures de vannes... Inclure le réfrigérateur serait utile pour améliorer les prochaines mises en froid
  - Quelques difficultés de refroidissement en dessous de 80 K : Gestion des retours froids (et compromis débit/température), énergie supérieure aux prévisions (Support du système magnétique: Gravity Support ? ...)
- **Charges thermiques statiques en accord avec les estimations faites en phase de design**
- **Charges thermiques supérieures lors de l'énergization des aimants TF ~ 270 W (à affiner)**
- **Incident joints terminaux EF1**
  - Bonne réaction de l'usine cryogénique (pas de dommage): isolation des circuits et arrêt des turbines
  - Problème sur l'opération des soupapes (quench valves) et de rupture des disques de rupture en dessous du tarage
  - Perte de 1100 kg d'hélium (uniquement 300kg récupéré)
- **Redémarrage du Commissioning Intégré prévu au printemps 2022 après réparation et changement de nombreuses jonctions électriques**

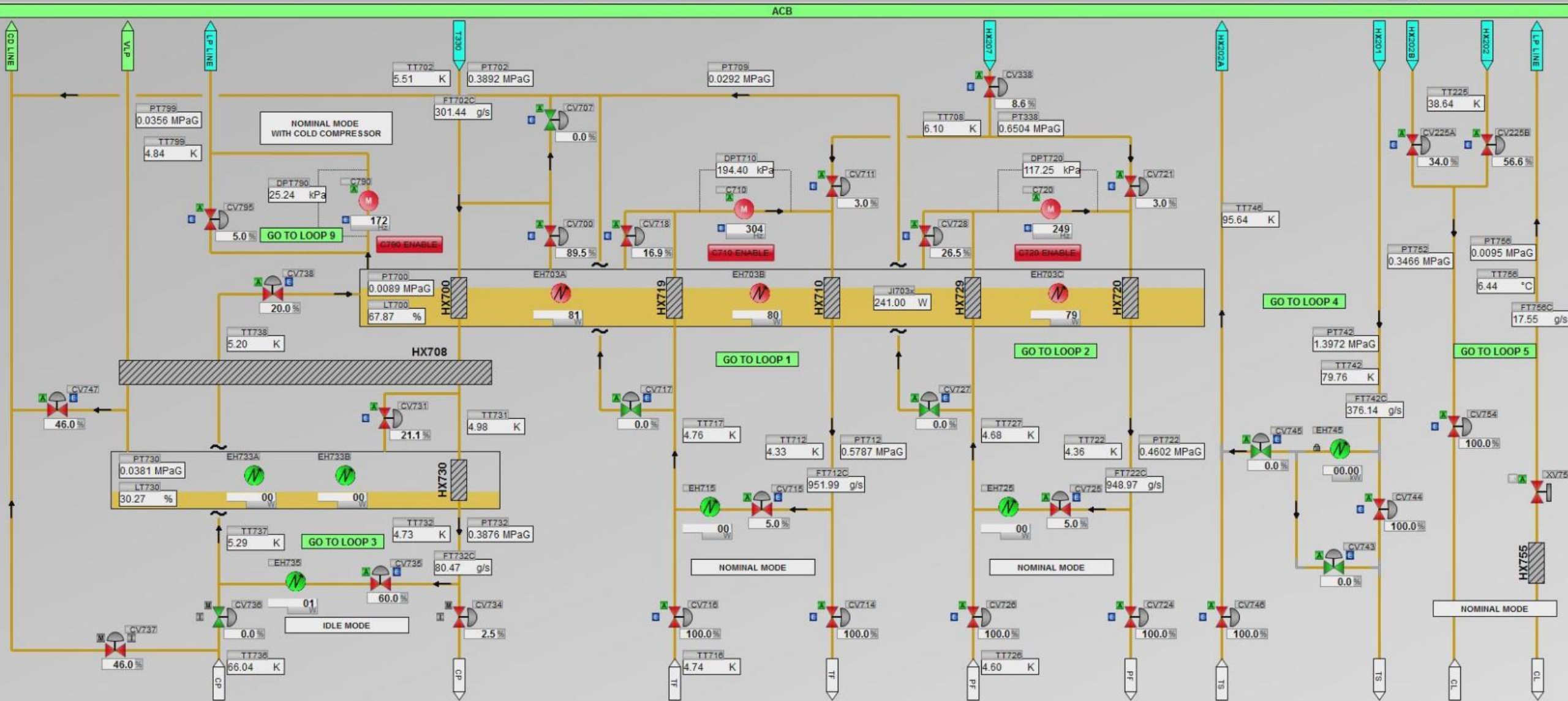
## Additional slides



## Zoom in between 21:22 and 21:23



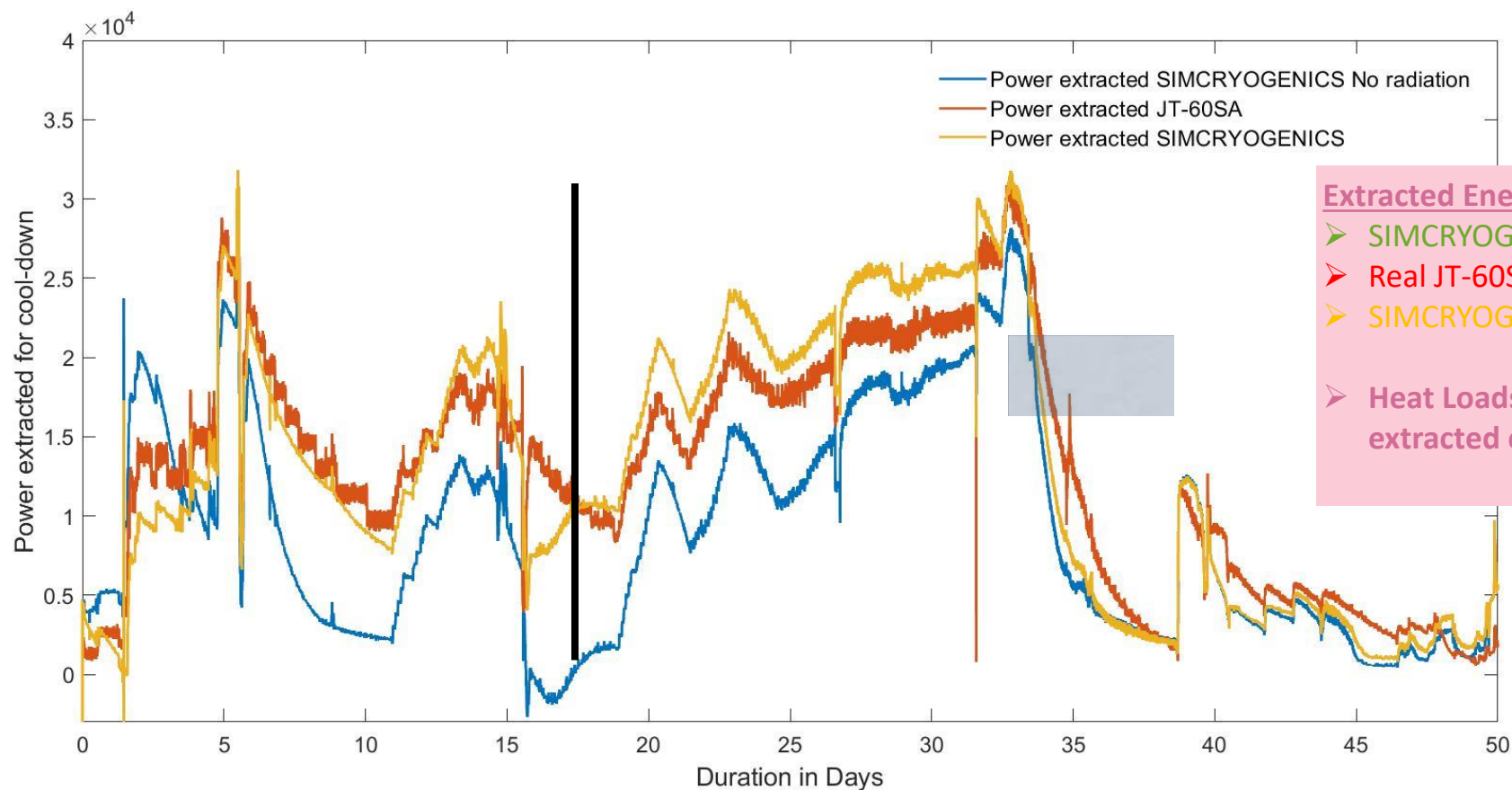






## Extracted power comparison on Loop 1 for TF-WP and structures

- Additional simulation added without any external heat loads by radiation (Blue plot)
- It is **necessary to consider the heat loads during cool-down phase** (coming mainly from radiation)
- Only small discrepancies on extracted power between SIMCRYOGENICS simulation (Yellow) and JT-60SA (Red)
- Total extracted energy is well aligned.



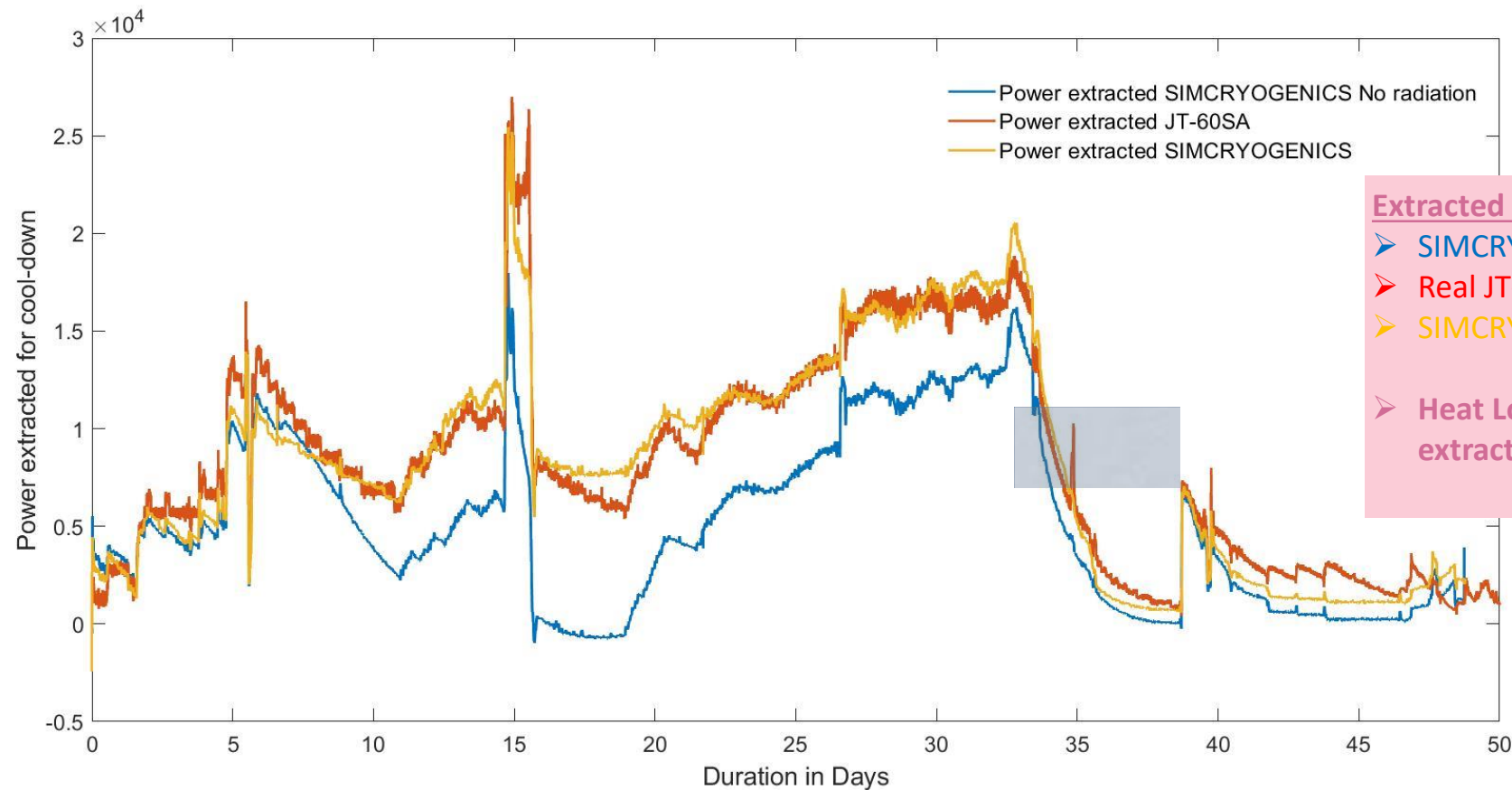
## Extracted Energy L1 during Cool-down :

- SIMCRYOGENICS no radiation  $\sim 38.30$  GJ
- Real JT-60SA data  $\sim 55.57$  GJ
- SIMCRYOGENICS  $\sim 55.76$  GJ
- Heat Loads  $\sim 17.46$  GJ about 31 % of the total extracted energy



## Extracted power comparison on Loop 2 for EF and CS coils

- **Additional simulation** added without any external heat loads by radiation (Blue plot)
- It is **necessary to consider the heat loads during cool-down phase** on loop 2 ~ 39% of the total extracted energy
- **Excellent agreement** between SIMCRYOGENICS simulation (Yellow) and JT-60SA (Red) concerning extracted power

**Extracted Energy L2 during Cool-down :**

- SIMCRYOGENICS no radiation ~ 21.60 GJ
- Real JT-60SA data ~ 35.39 GJ
- SIMCRYOGENICS ~ 34.48 GJ
- Heat Loads ~ 13.79 GJ about 39 % of the total extracted energy