JT-60SA Cryogenic System integrated commissioning 2020-2021

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+ QST and F4E-Garching (Magnet/Cryo integrated Team)

FROM RESEARCH TO INDUSTRY

Creation of Harmonious Diversity

Département des Systèmes Basses Températures (D-SBT)

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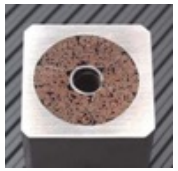
- Introduction
- 1st Cool-Down of the JT-60SA tokamak
- Heat loads summary and comparison with design data
- EF1 terminal joint incident
- Conclusions and perspectives 2022

Introduction: The main cryogenic users

Cable-In-Conduit Conductors (CICC)

TOTAL cold mass at 4.5 K (~700 Tons)

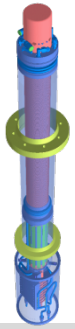


Central Solenoid CS (4 modules) 4.4 K

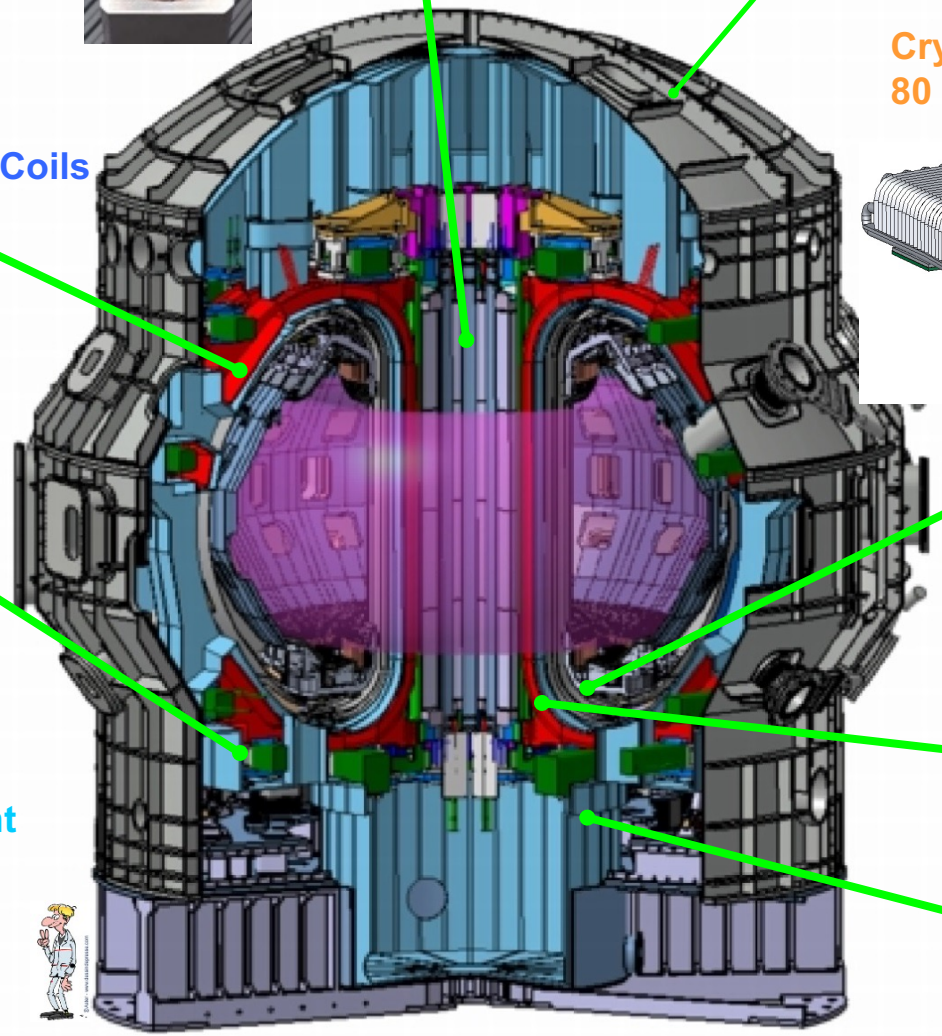
Cryostat

18 Toroidal Field TF Coils 4.4 K

6 Equilibrium Field EF Coils 4.4



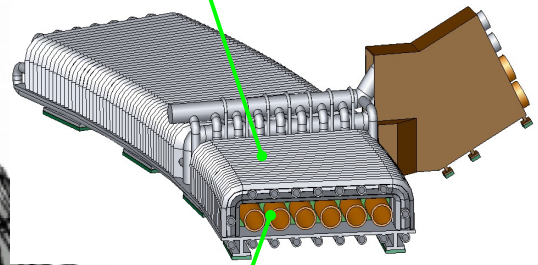
26 HTS Current Leads 50 K



JT-60SA Tokamak

Cryopumps baffles 80 K

Not yet installed

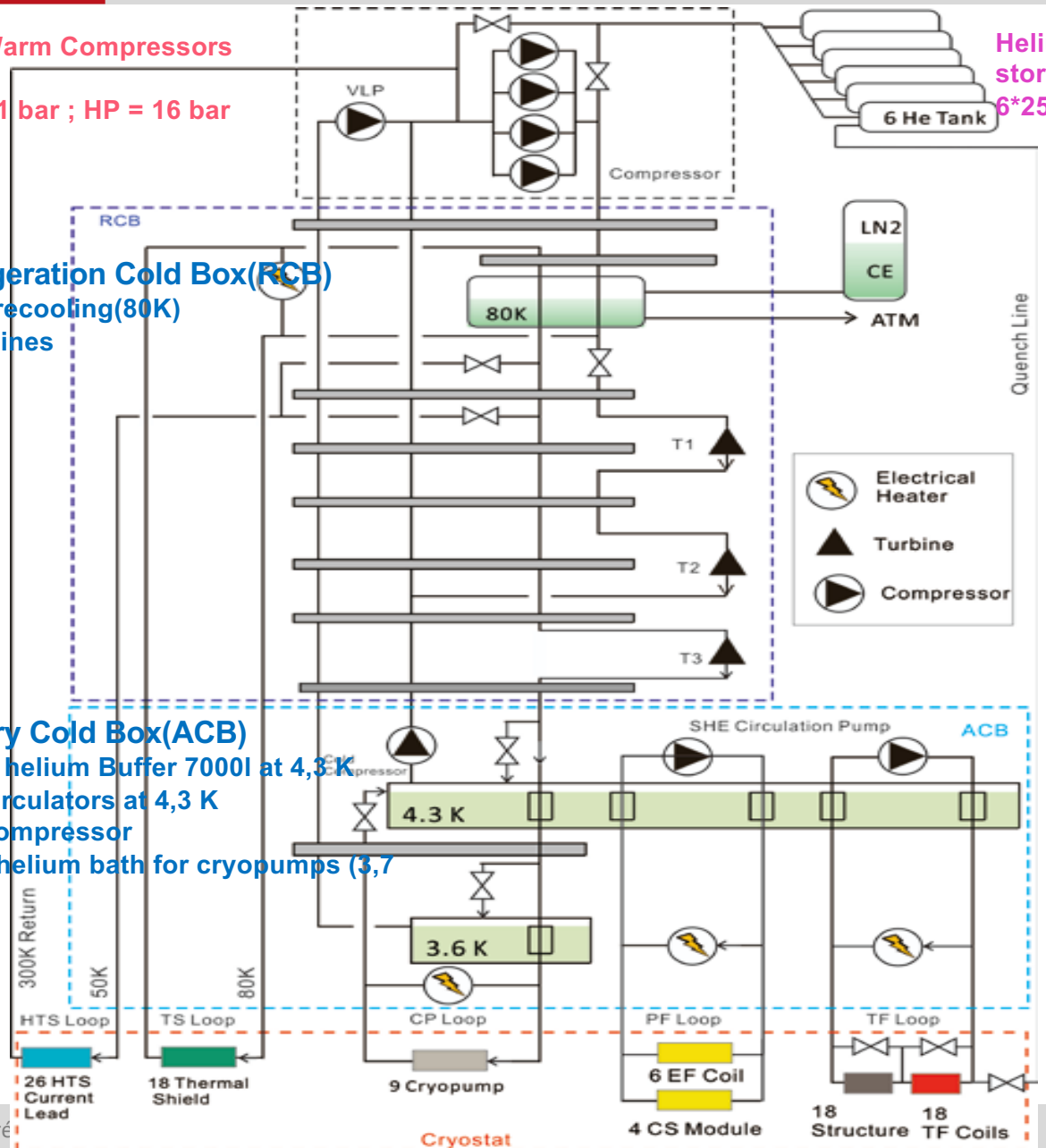


9 Divertor Cryopumps 3.7 K

Vacuum Vessel Thermal Shield 80 K

Cryostat Thermal Shield 80 K

Introducton: The JT-60SA cryogenic system



- 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

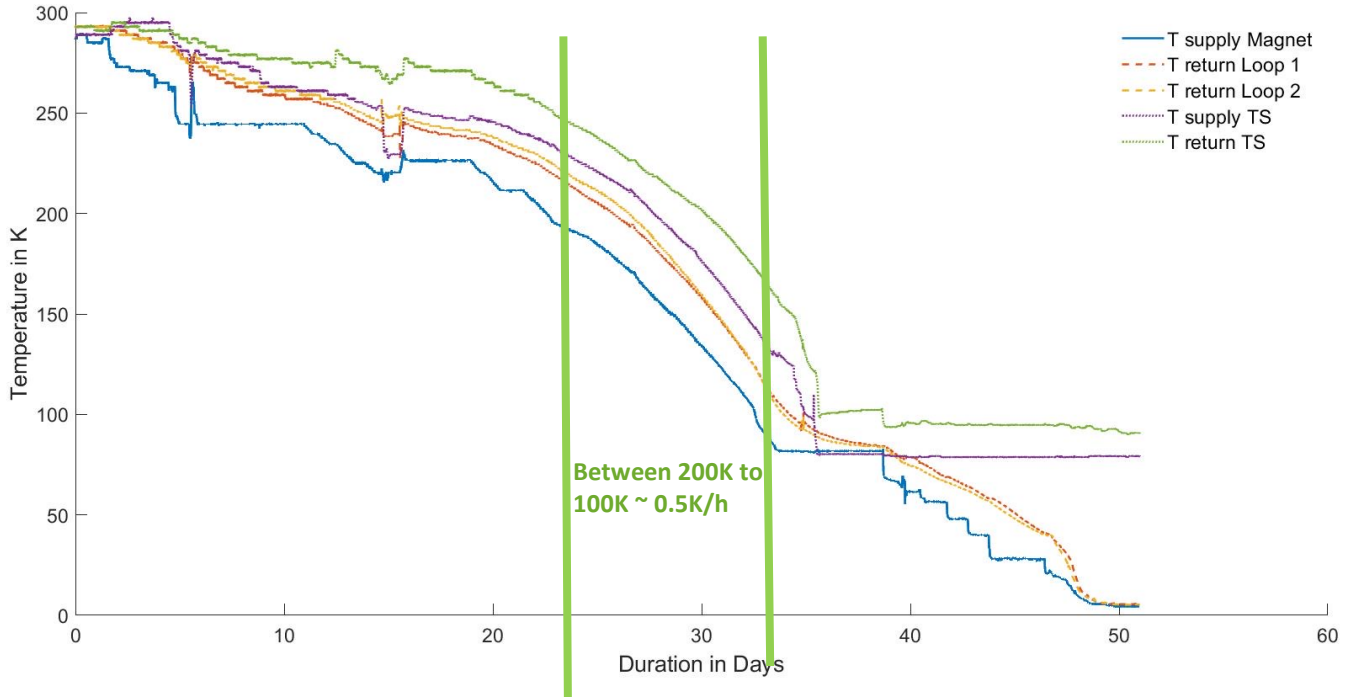
The JT-60SA tokamak first cool-down

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).



Heat loads summary and comparison with design data

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

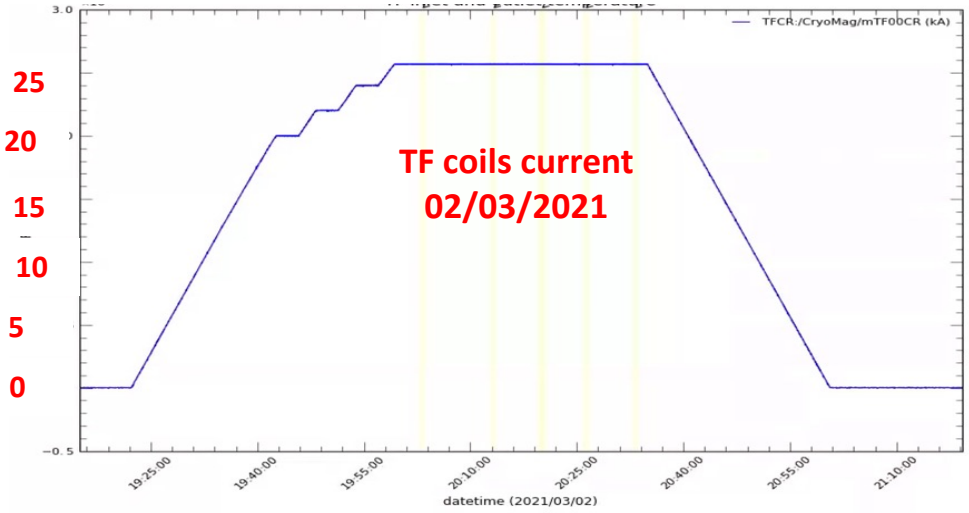
VV Temperature	Vacuum Vessel in operating condition 50°C (323 K)		Vacuum Vessel in Baking condition 200°C (473K)	
Source of heat loads	Average measured heat loads Cryodistribution+Magnets	Estimated heat loads (design values)*	Average measured heat loads VV~460K	Estimated heat loads(design values) VV 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.

Heat loads during the TF nominal energization at 25.7 kA

➢ TF coils current 25.7 kA (02 March 2021) ~ 40 Minutes



➢ 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 (~1500 W without current)
Loop 2 at 4.5K EF and CS coils	725 W	
Thermal Shields at 80K	31.5 kW	33.1 kW (without cryopumps installed)

* + 280 W due to a decrease of the TF casing temperatures during energization… + other reasons ? to be explored during next IC

➢ Cold circulator heat dissipation (remind on **Design values in purple)**

- Real operation of Loop 1 : Mass flow ~ 950 g/s (860); ΔP ~ 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) ; ΔP ~ 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 ΔP 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)

EF1 terminal joint incident: Cryogenic system impact

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 Cryoplant Turbines (triggered by Cryoplant return pressure > 1.6 bar) : **Too large heat loads from magnets**
21:26:30	Disconnection of cooling Loop1/Loop2 by valves closing in ACB to magnets (on high pressure in loop 1 **> 15 bar**)
21:27:24	One rupture disc attached on the outlet of TF8-13 (1SVB53) burst.
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.

Helium mass released to Quench Tank ~ 300 kg (~20% of the total magnet inventory)
Loss of Helium ~ 1100 kg (Total helium inventory > 3 Tons:)

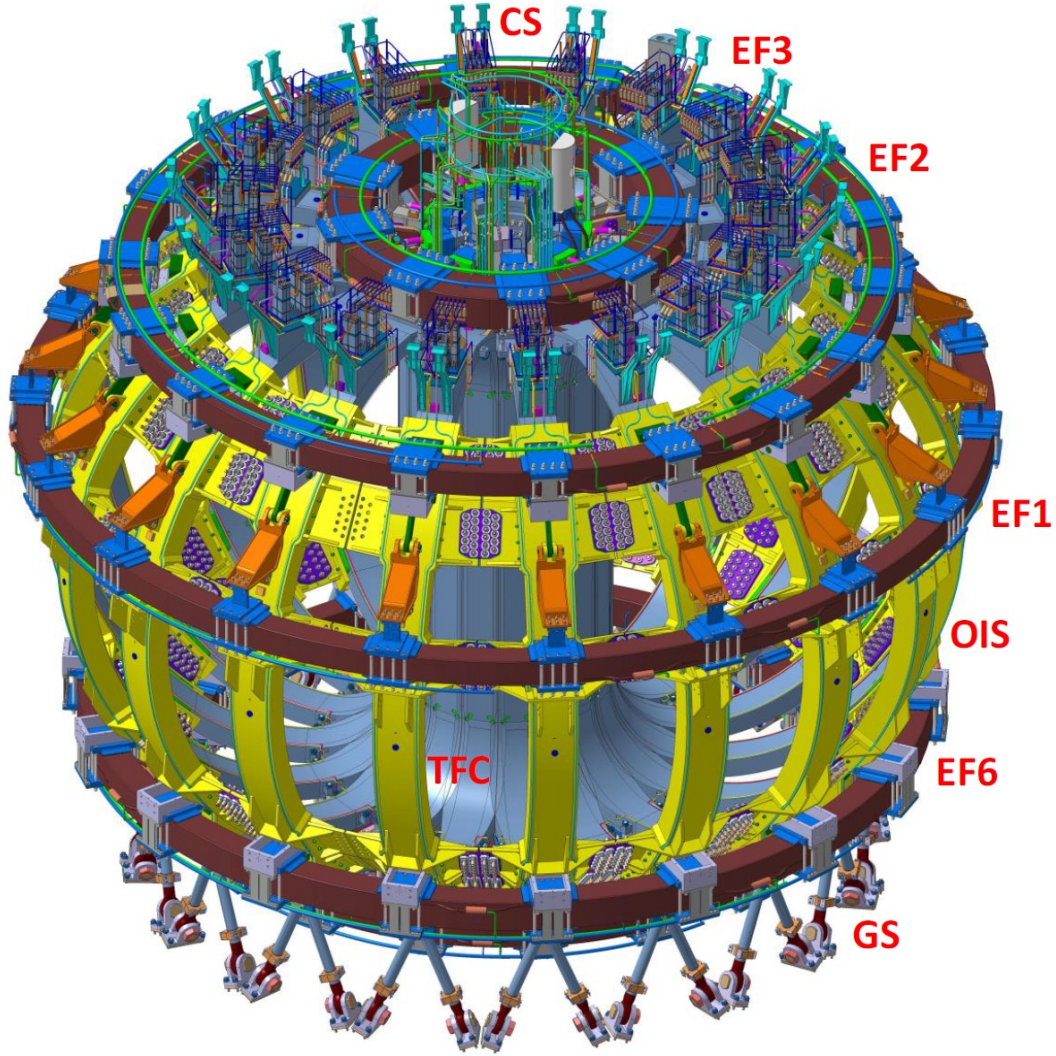
Conclusions and perspectives 2022

- **Participation from Mid 2020 and 2021 to the JA/EU Integrated Commissioning team for JT-60SA**
  - Preparation of the cool-down and remote participation to the cryogenic system operation from october 2020 to March 2021
  - 1st Cool-down of the tokamak following the design requirements (a bit longer than expected).
  - Verification and calibration of sensors for Temperatures, pressures, mass flow rates ….
  - Heat load summaries and cryogenic system operation assessments.
  - Heat loads aligned with estimations from design phase
  - Some validations and investigations are still needed during the next phase of the Integrated Commissioning (heat loads, pressure drops, cooling of the terminal joints, …)
  - During the 2nd part of 2021, simulation of the cool-down with SIMCRYOGENICS were performed to investigate and improve this phase: CHATS conference 2021 F. Michel et al.)
- **EF1 terminal joint incident which stops the JT-60SA IC.**
  - Good reaction of the cryoplant (stop of turbines and closing the isolation valves between cryoplant and magnets)
  - Issue on the operation of the quench valves (QST) and burst disk broke below their setting pressure.
  - Loss of 1100 kg of Helium (only 300 kg recover)
- **Perspectives 2022**
  - Improvement of the cryogenic control system (on going) + interlocks added on Quench valves and change of some safety devices
  - Preparation of the next cool-down phase (improvement of the procedures, Integrated Commissioning Plan …)
  - Restart of the cryogenic system installation (2nd semester 2022 ?)

Additional slides

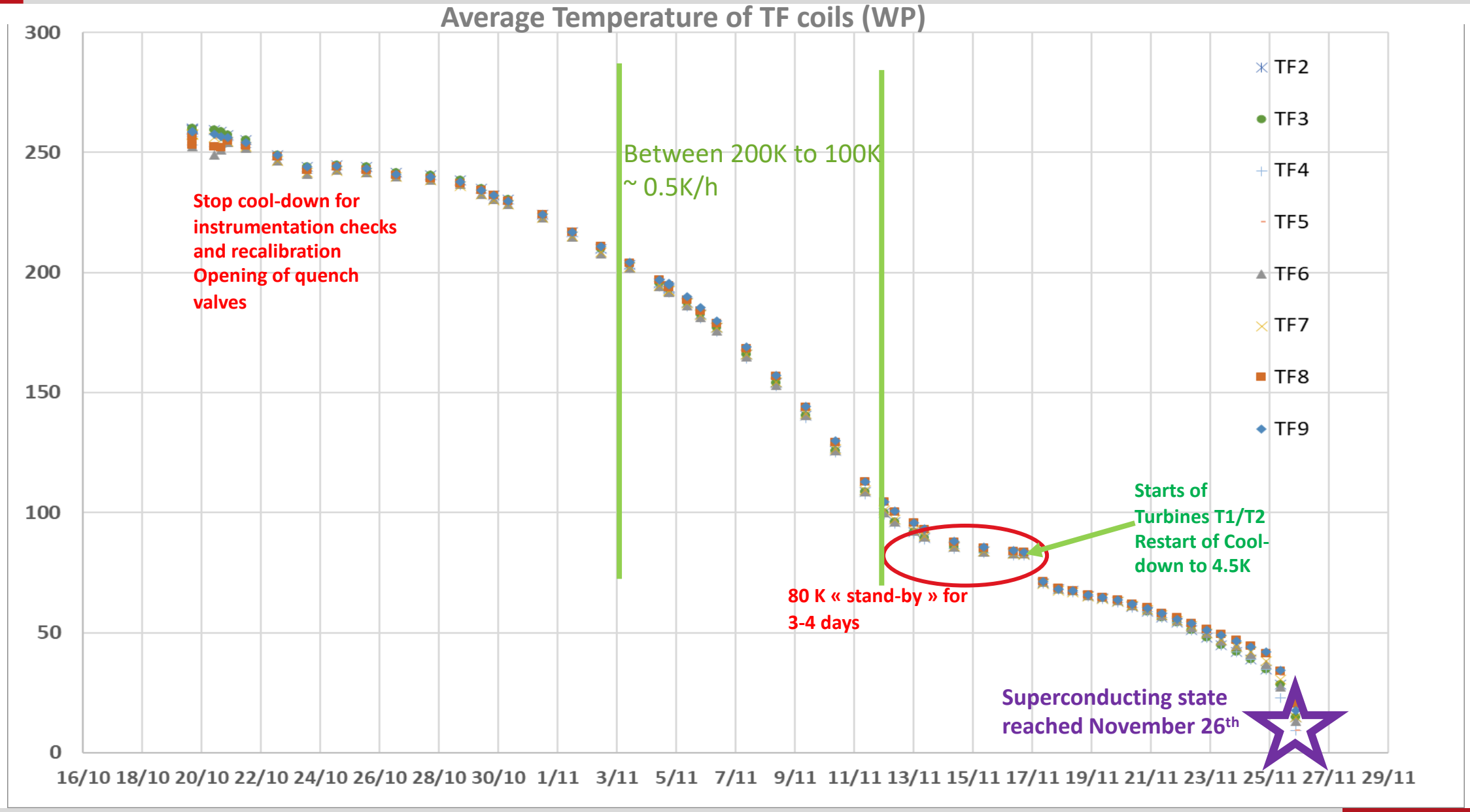
The JT-60SA magnet system

- 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_3Sn)
  - 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

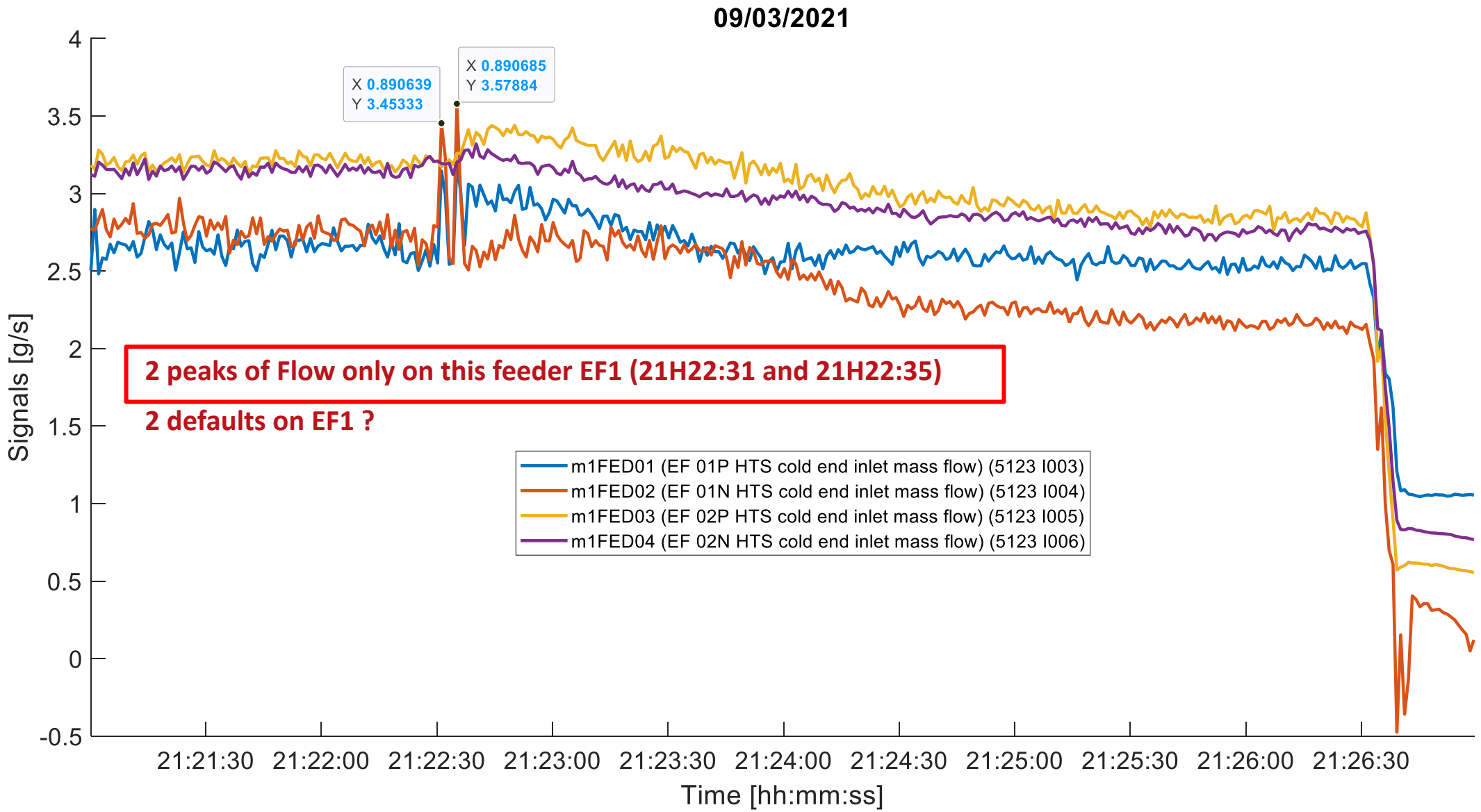


TOTAL cold mass to cool-down until 4.5 K (~700 Tons)

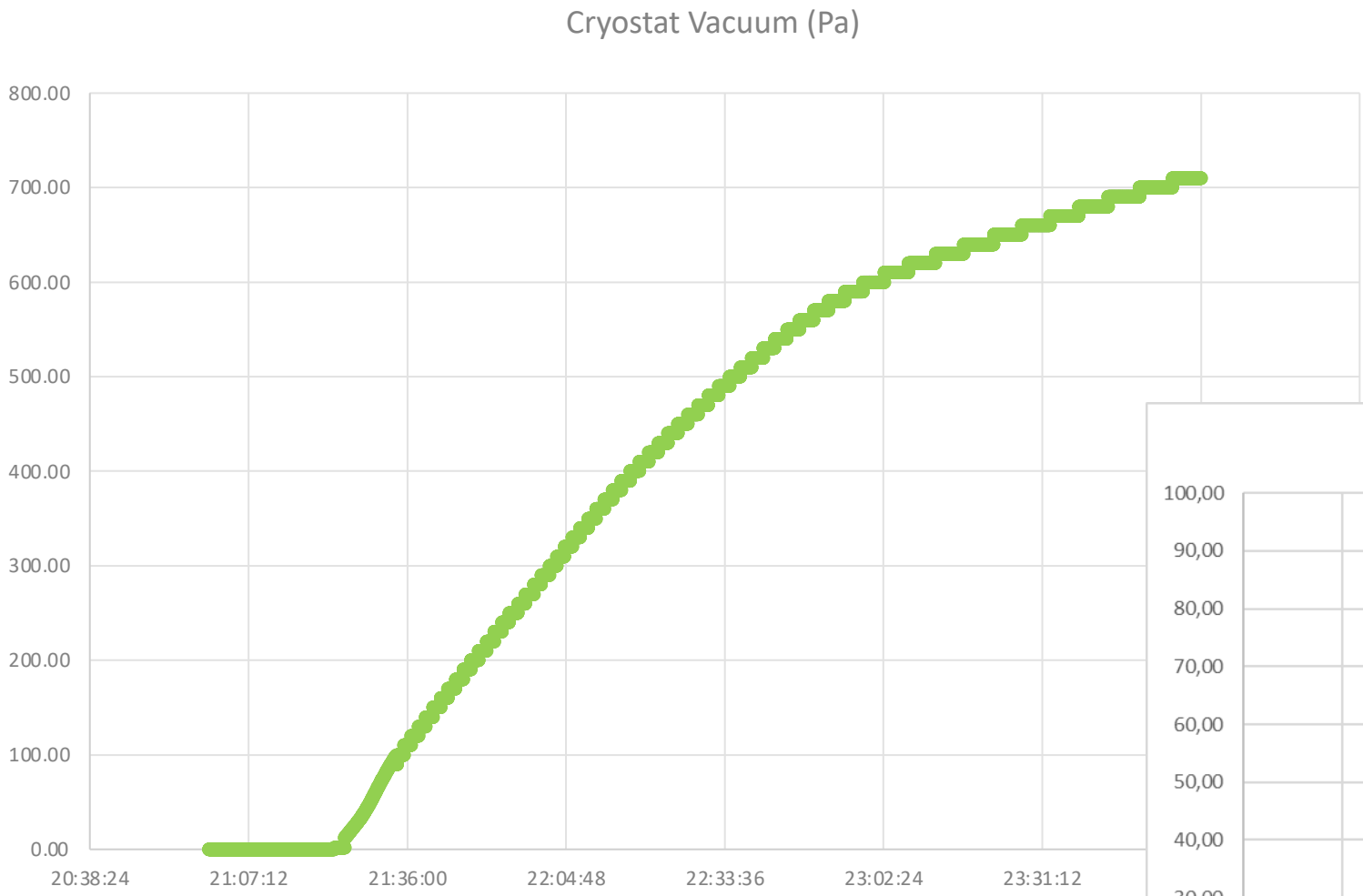
First Tokamak Cool-Down: TF WP Temperatures

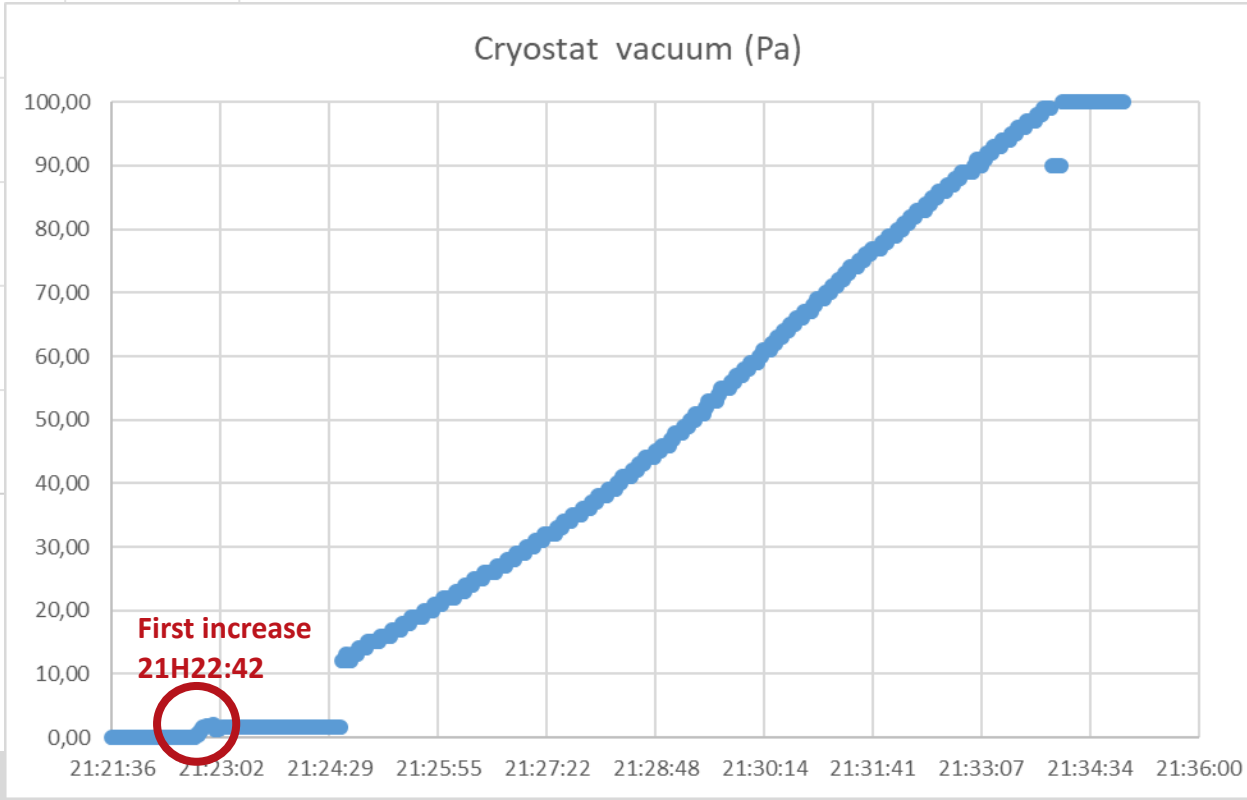


Mass Flow in EF Feeders (EF01 and EF02)



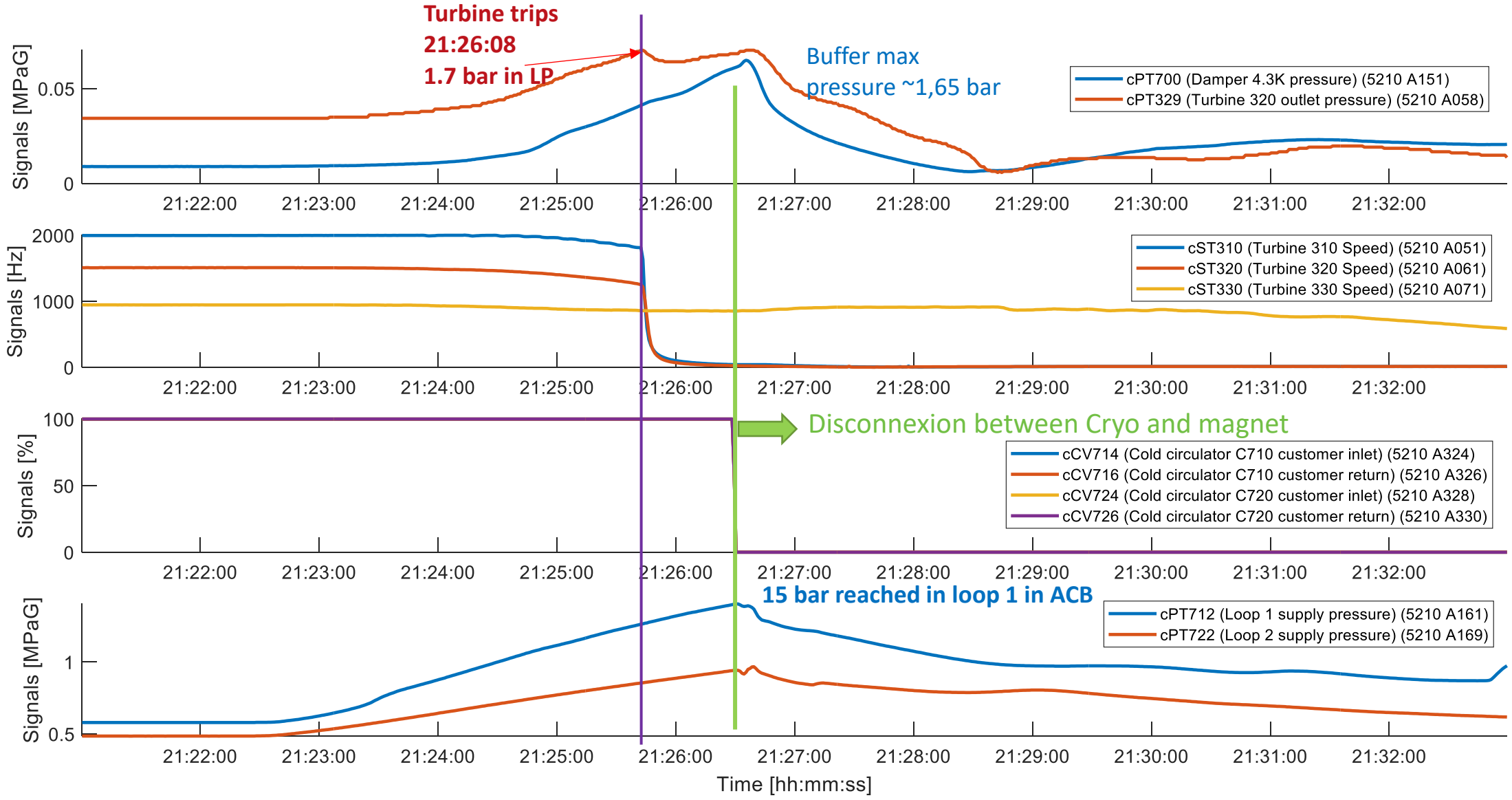
Cryostat Vacuum



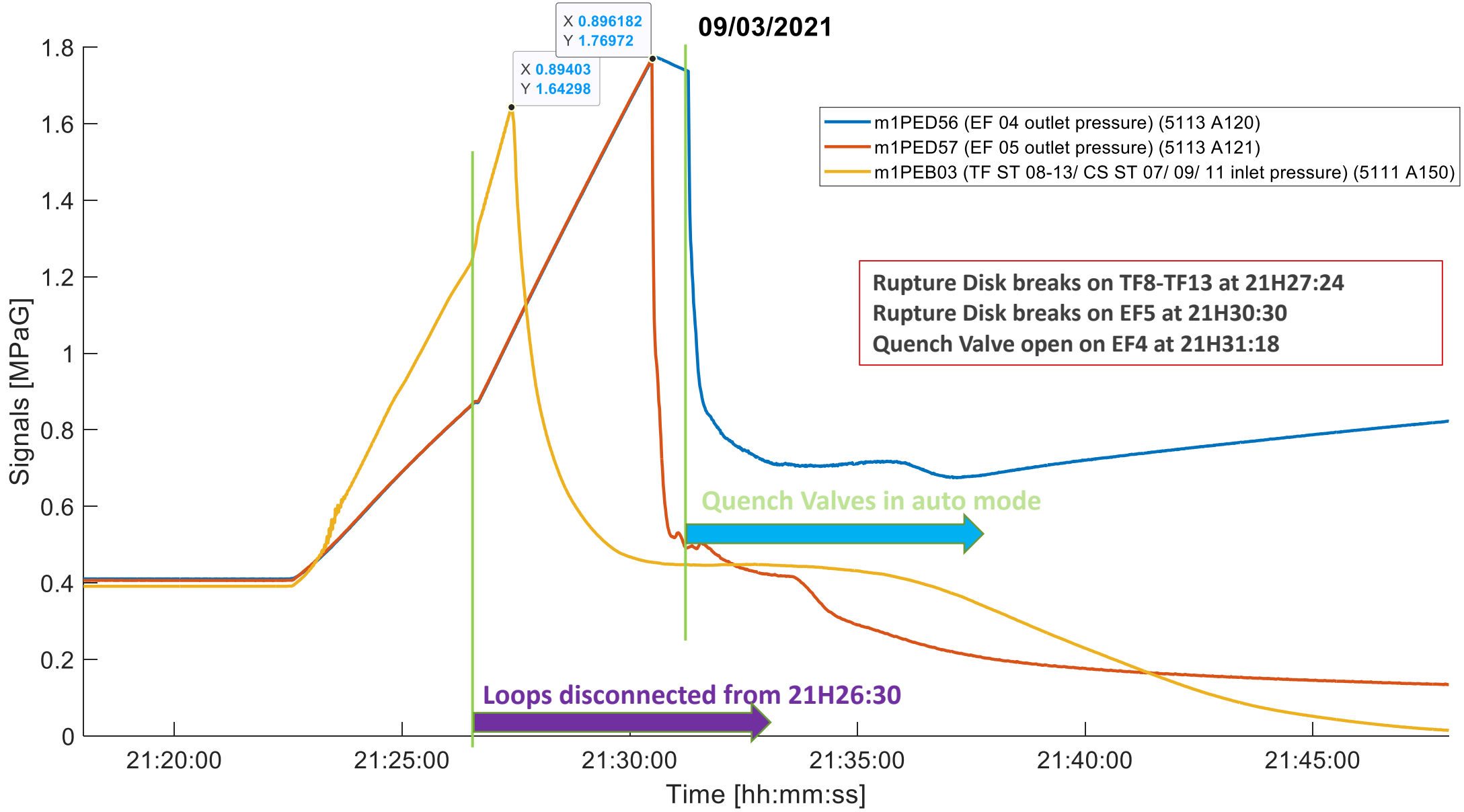


RCB and ACB responses

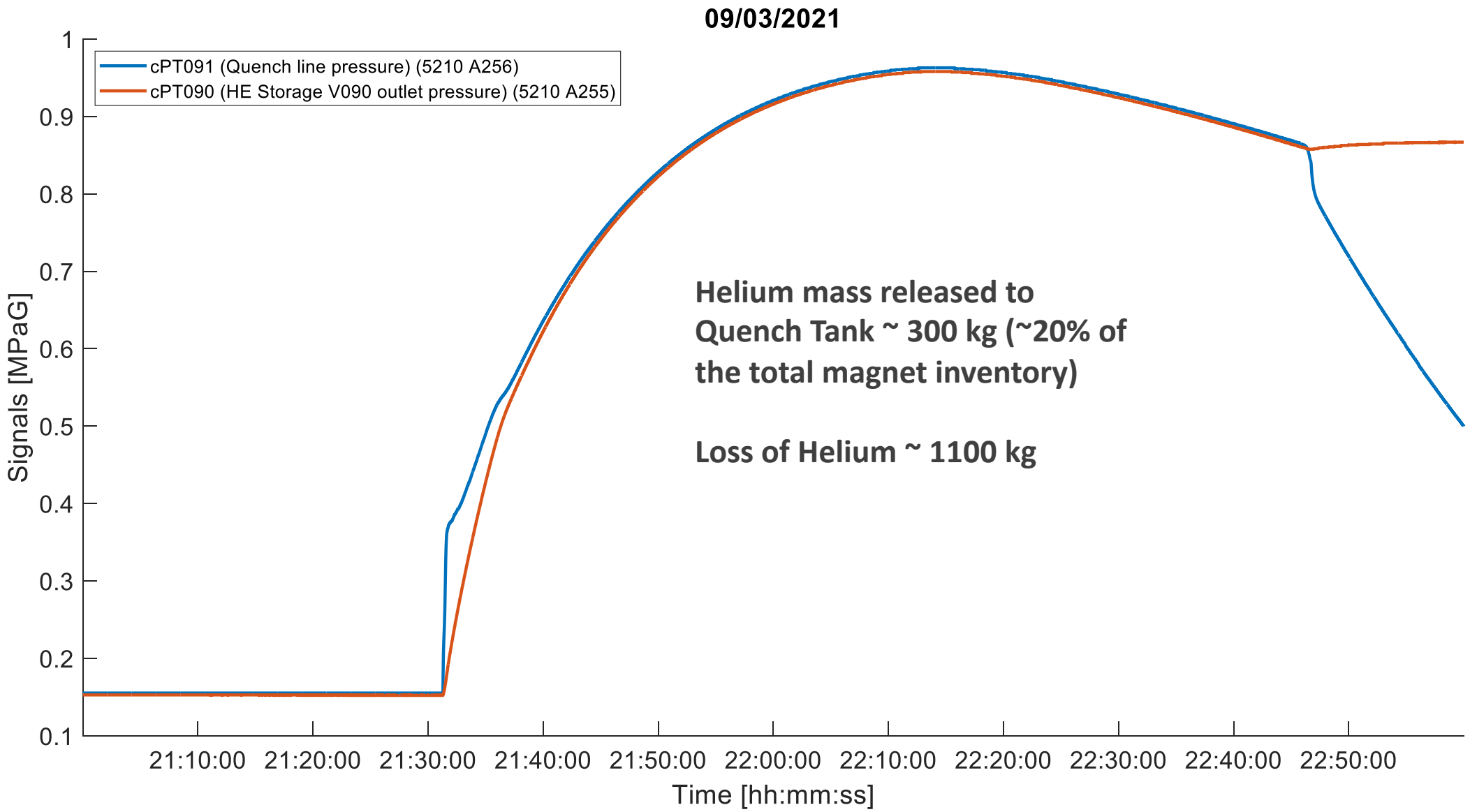
- Following the loss of vacuum in cryostat: large increase of the heat loads deposisted in the helium buffer located in ACB



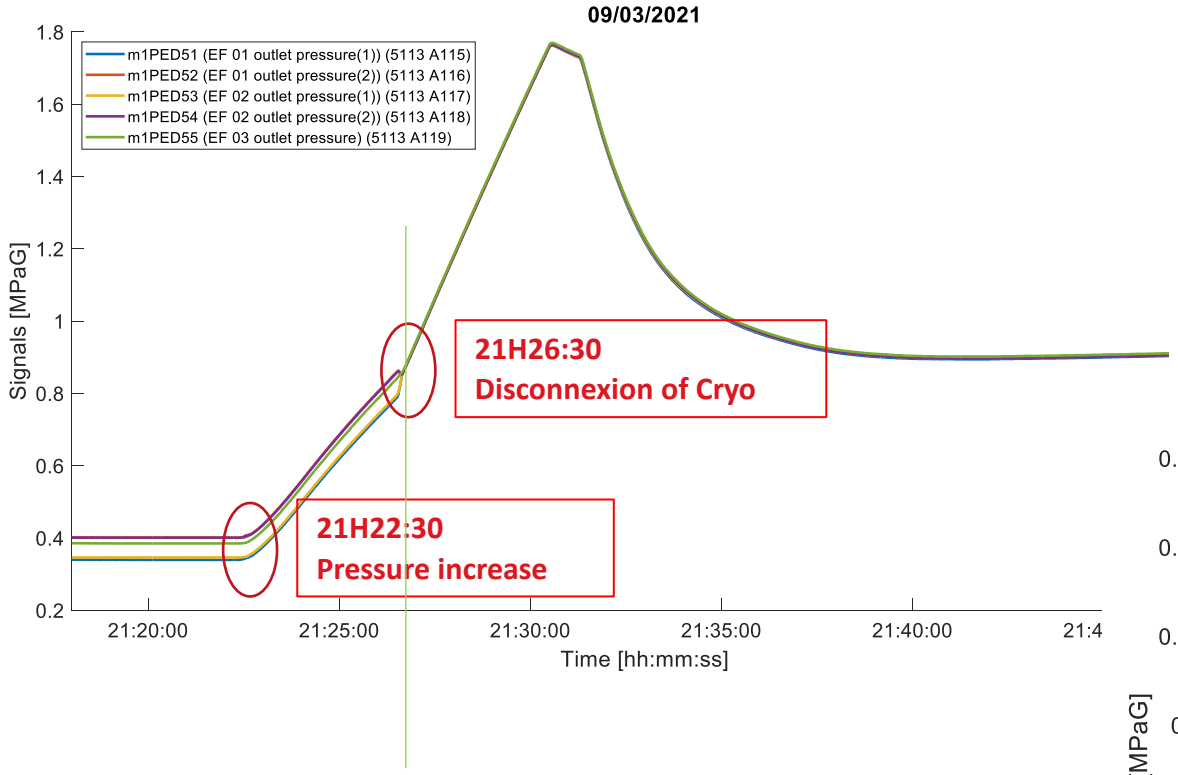
Magnet Pressure EF vs TF coils



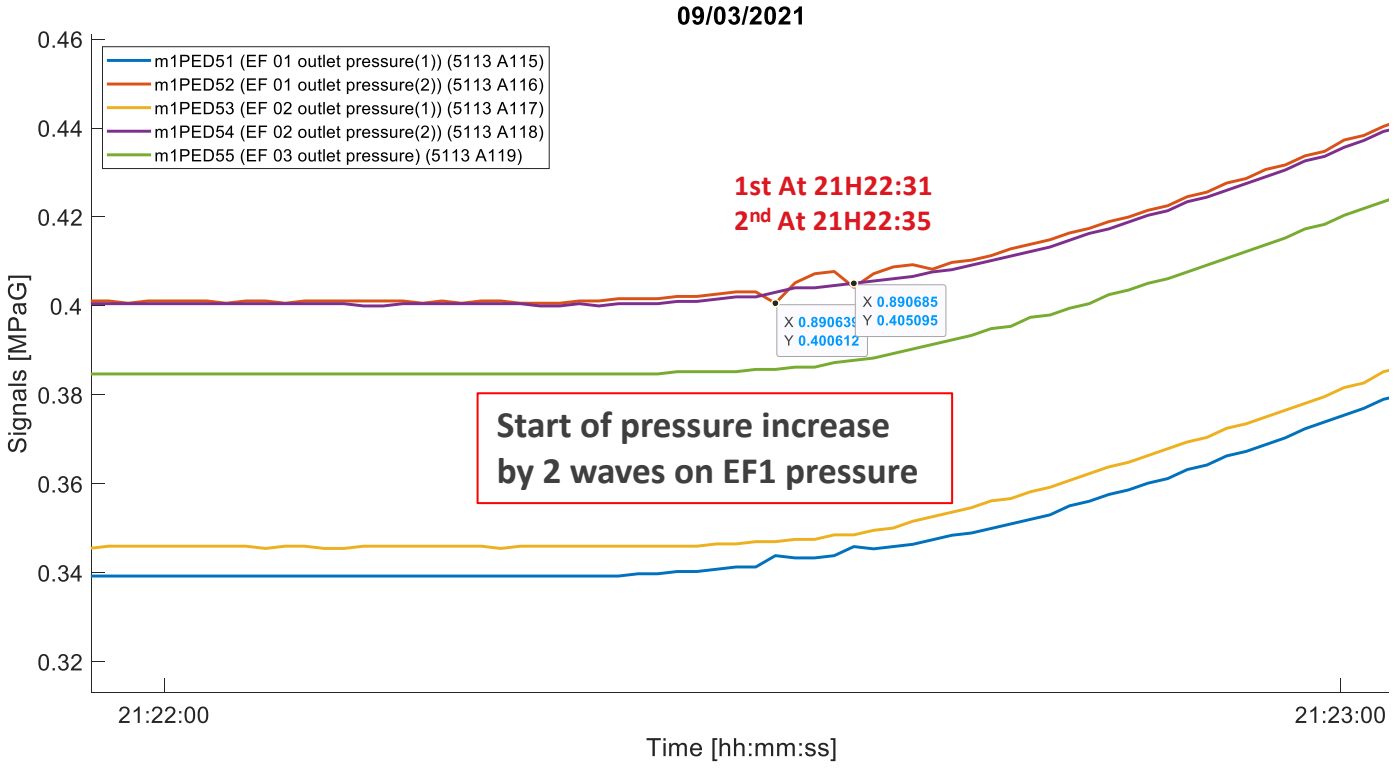
Quench Tank/Quench Line pressure

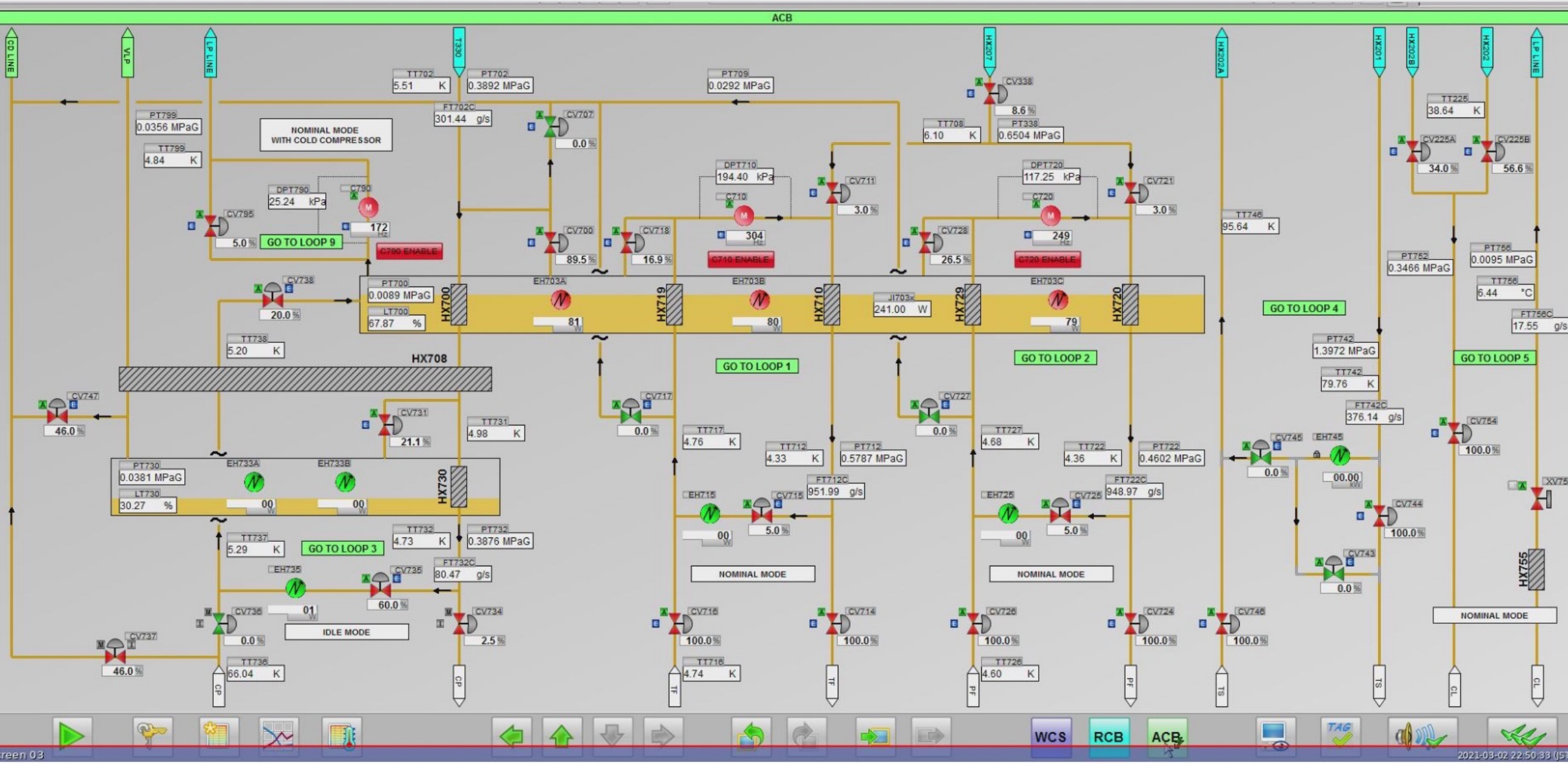


Comparison Pressure in EF coils (top) EF1/EF2/EF3 between 21H18 and 21H30



Zoom in between 21:22 and 21:23




ACB
NOMINAL MODE
WITH COLD COMPRESSOR
GO TO LOOP 9
GO TO LOOP 1
GO TO LOOP 2
GO TO LOOP 3
GO TO LOOP 4
GO TO LOOP 5
IDLE MODE
NOMINAL MODE
HX708
WCS
RCB
ACB