Cool down and warm up of Nb_3Sn magnets at CERN and experienced impact on magnet performance

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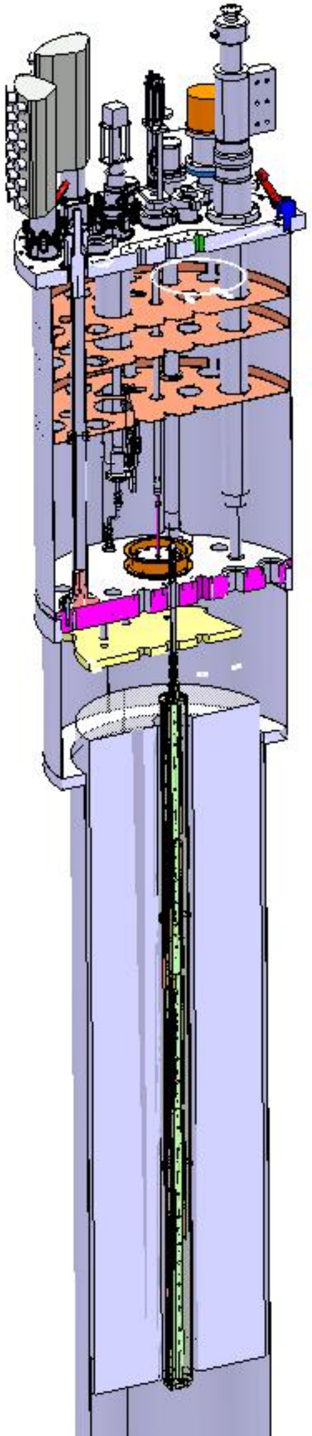
Three different cryogenic processes

- Long station
  - Cool down by dumping liquid helium
  - Warm up by electrical heaters
- HFM and Cluster D
  - Cool down with He gas (300 → 80 K), dumping liquid helium
  - Evaporate with electrical heaters, He gas (80 and 300 K)
- Horizontal stations
  - Cool down with He gas (300 → 80 K), dumping liquid helium
  - Warm up by drifting to 80 K *, He gas (80 and 300 K)

*: Drifting only used for MBHB-002

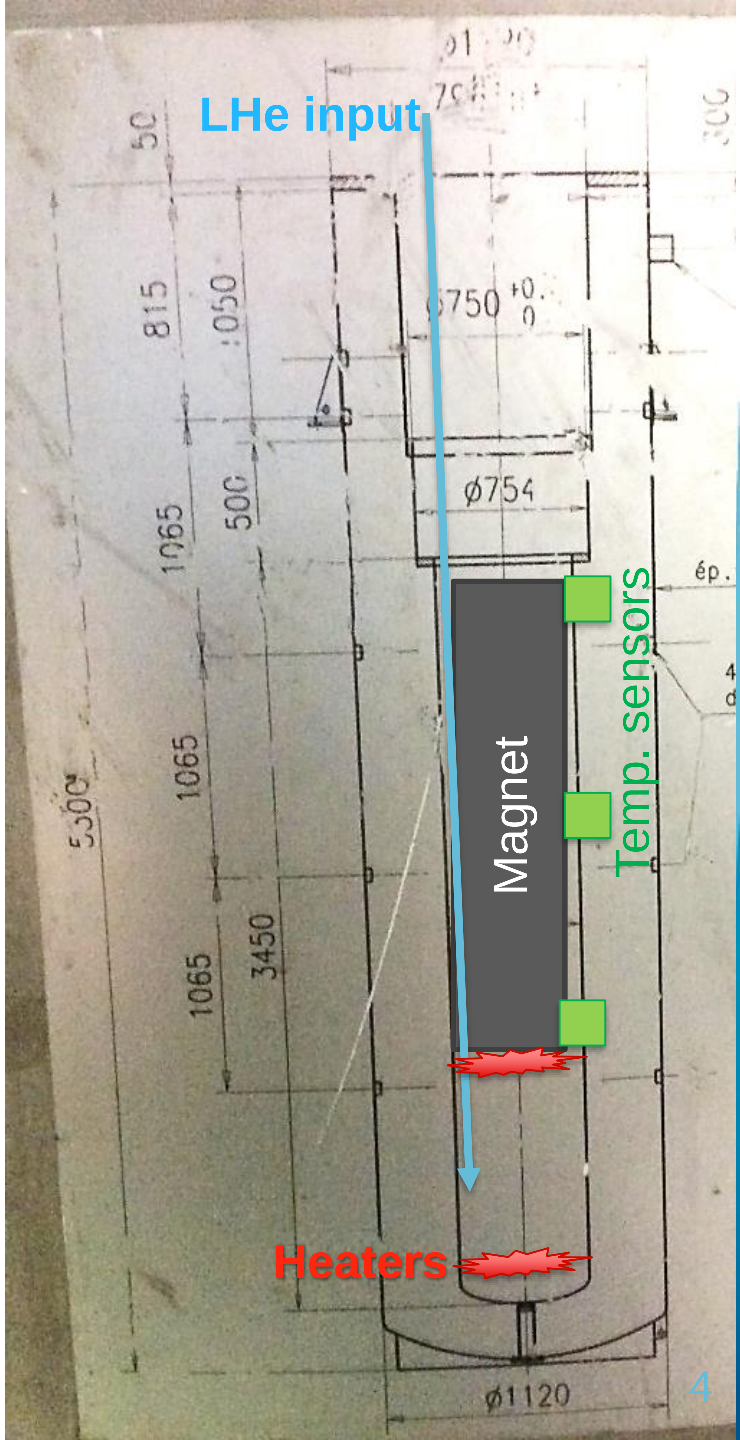


Test station 1 Long

Cool down and warm up process

- Cool down
  - Liquid helium input directly to the bottom
  - Flow ~ 6 g/s
- Warm up
  - Heaters at the bottom of cryostat, bottom of magnet
- Control
  - Temperature sensors in the magnet
  - Maximum temperature difference specified by us in test plan

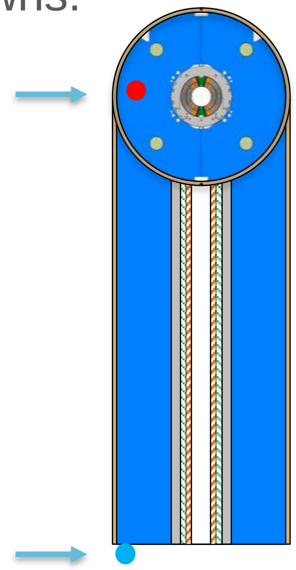
- Flow area: ~2cm ring between magnet and cryostat walls

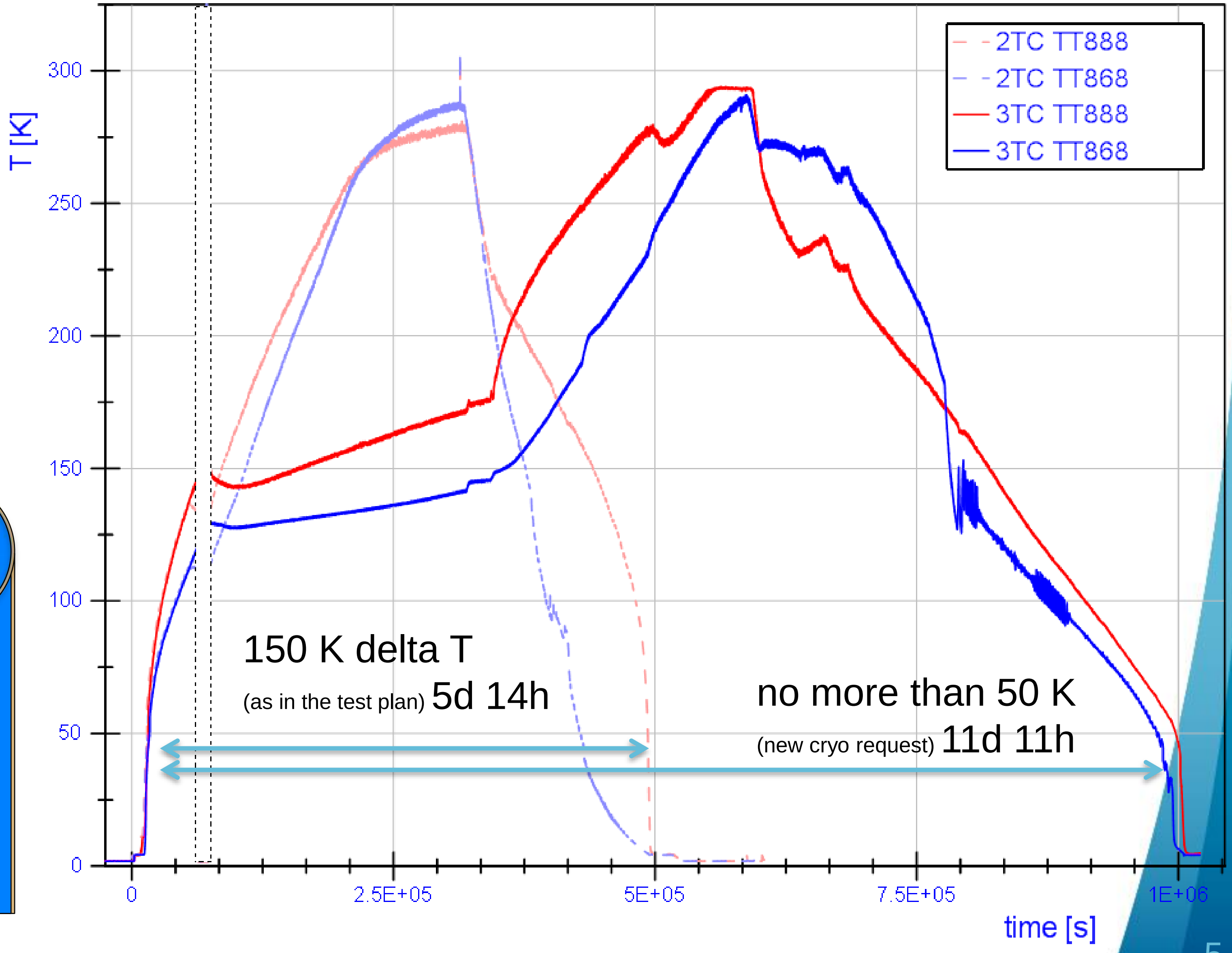


SP109: 3rd and 4th cooldowns temperature

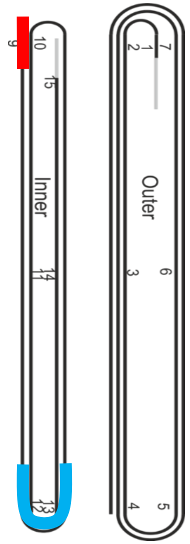
- The TC (cooldown 3) revealed a degradation of the conductor (VI curves). As a consequence we looked into the CDWU process (specified for 150 K deltaT) and decided to go for limited deltaT (ex. 50 K for cooldown 4)

- Temperature change of the **magnet shell** over the last cooldowns:
  - dT 150K
  - dT <50K





SP109: 3rd and 4th cooldowns delta-T

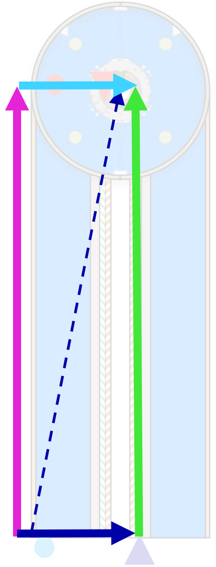


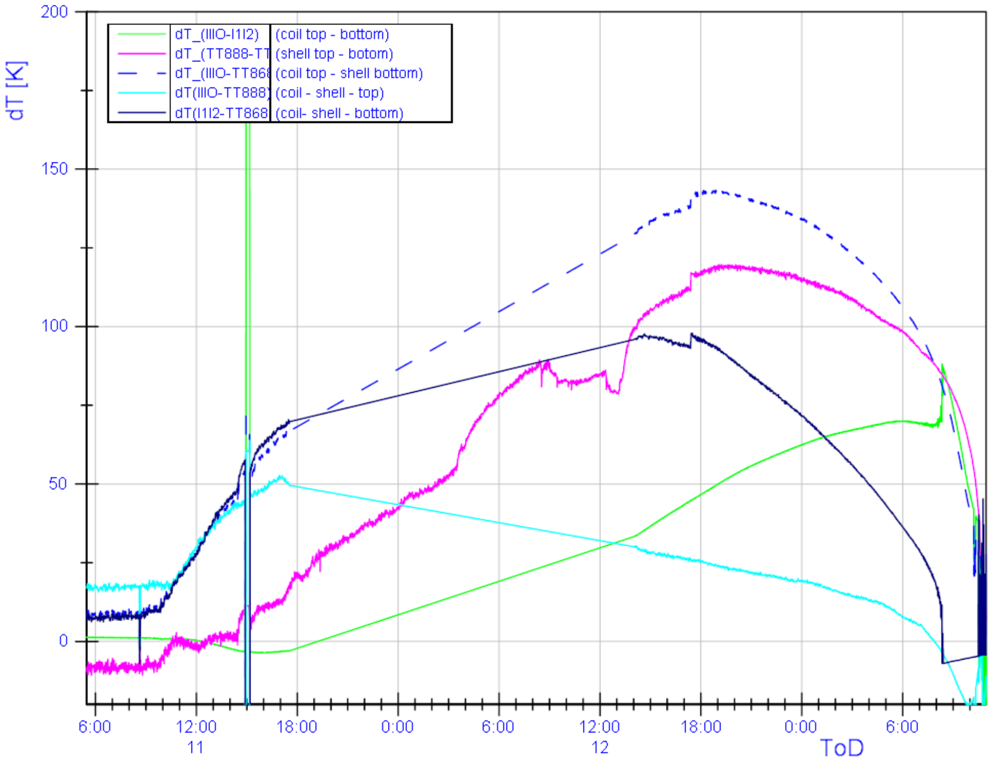
Longitudinal and **radial** temperature difference over the **magnet**

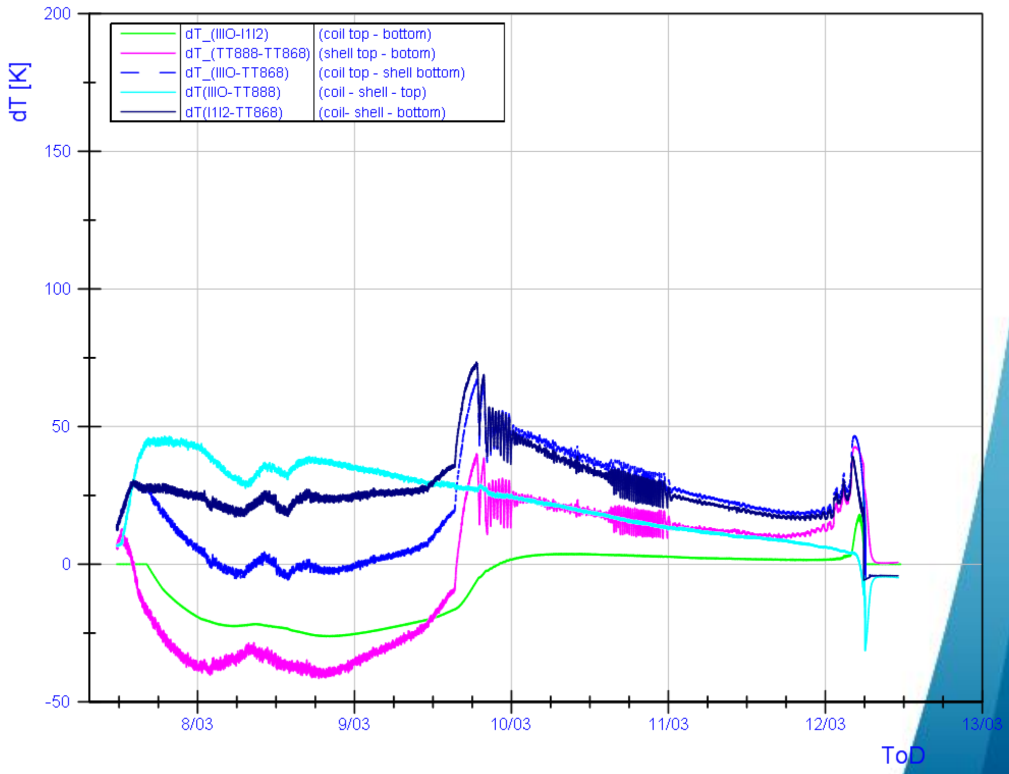
Longitudinal: coil bottom to top
Longitudinal: shell bottom to top
Radial top: shell to coil
Radial bottom: shell to coil

Shell bottom to coil top
(from V and T sensor)

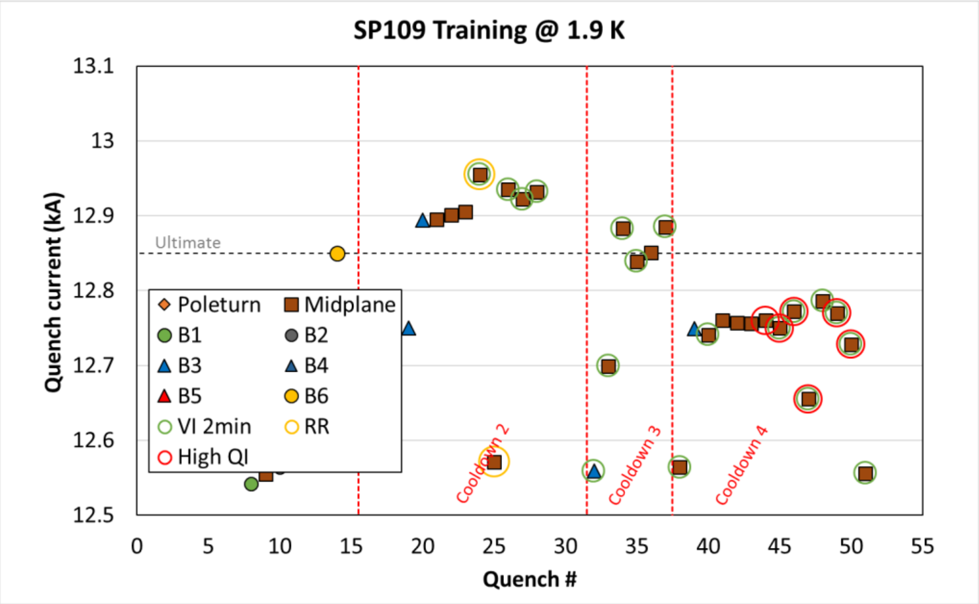
Here we are using short segments of the coil as temperature sensors

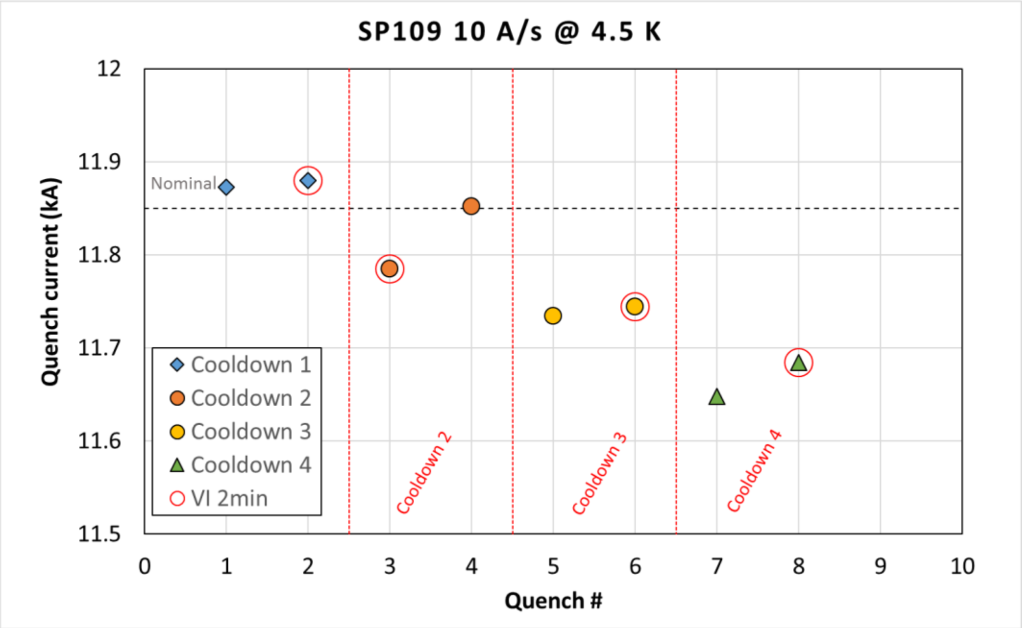


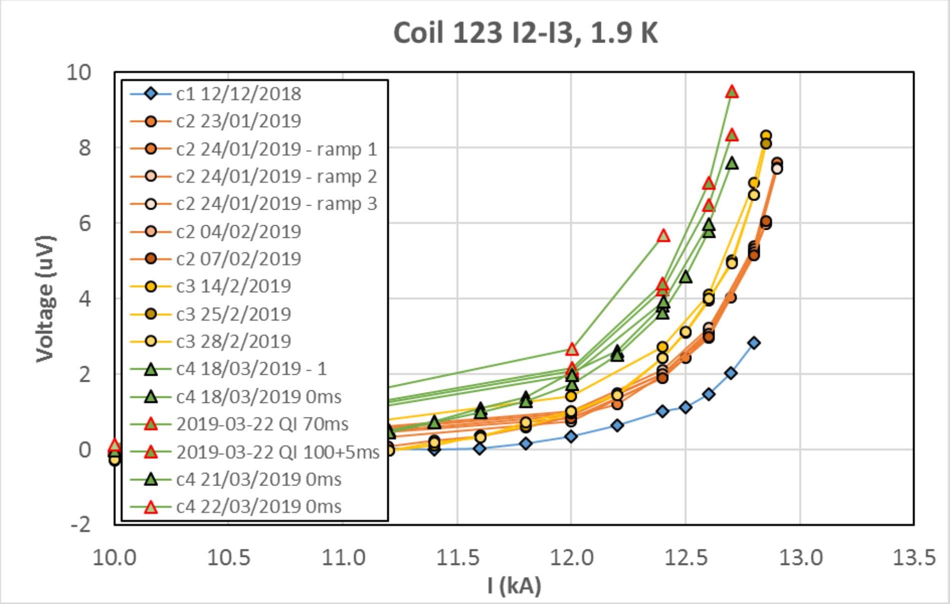


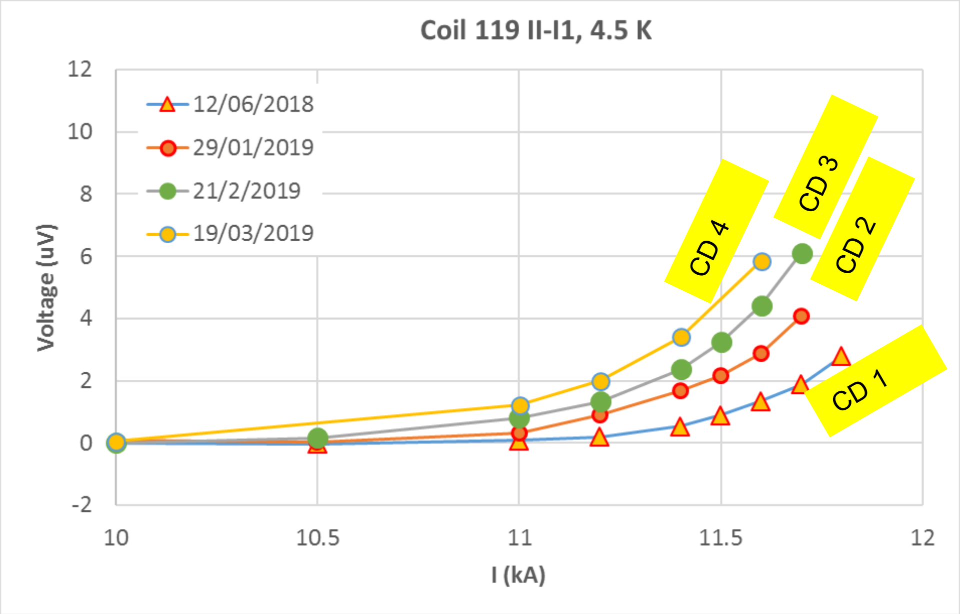


SP109: consequence of thermal cycling









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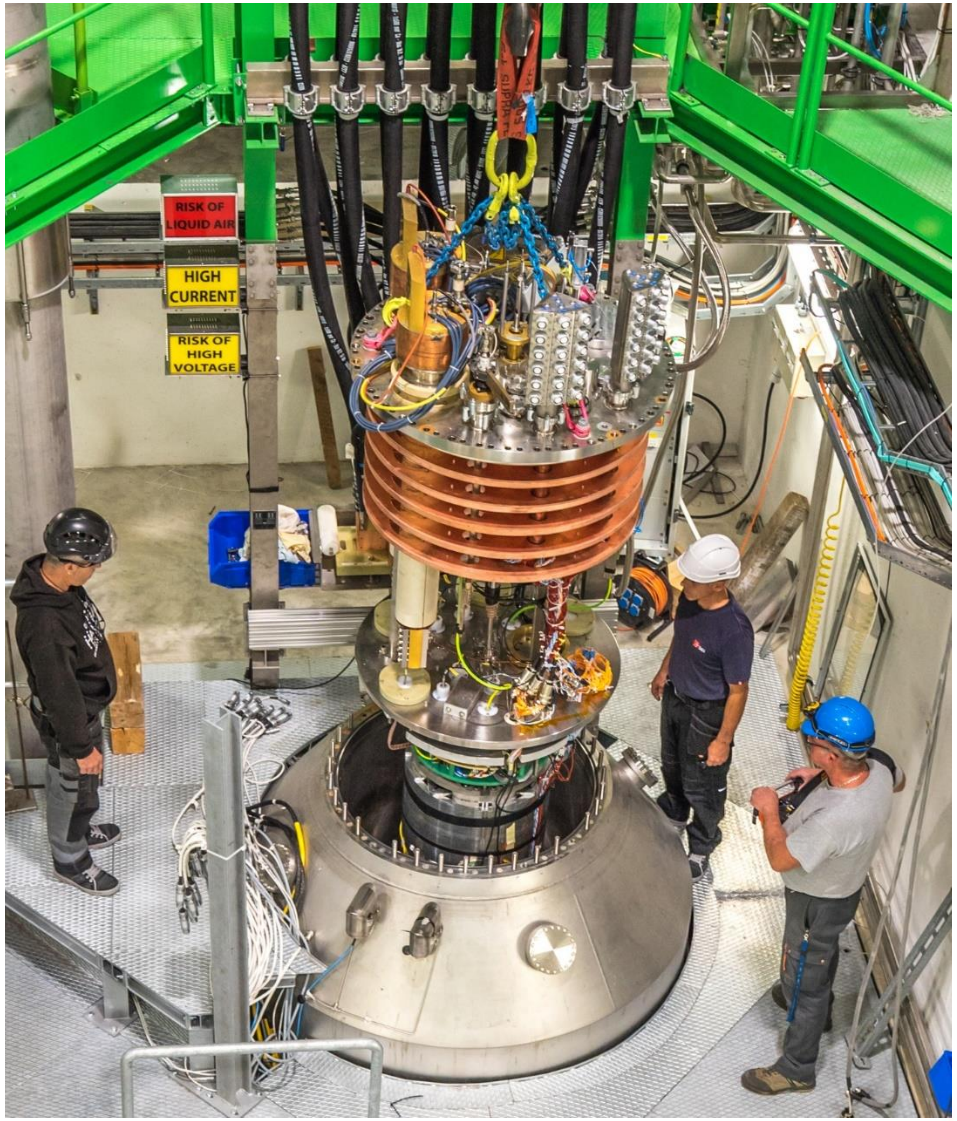
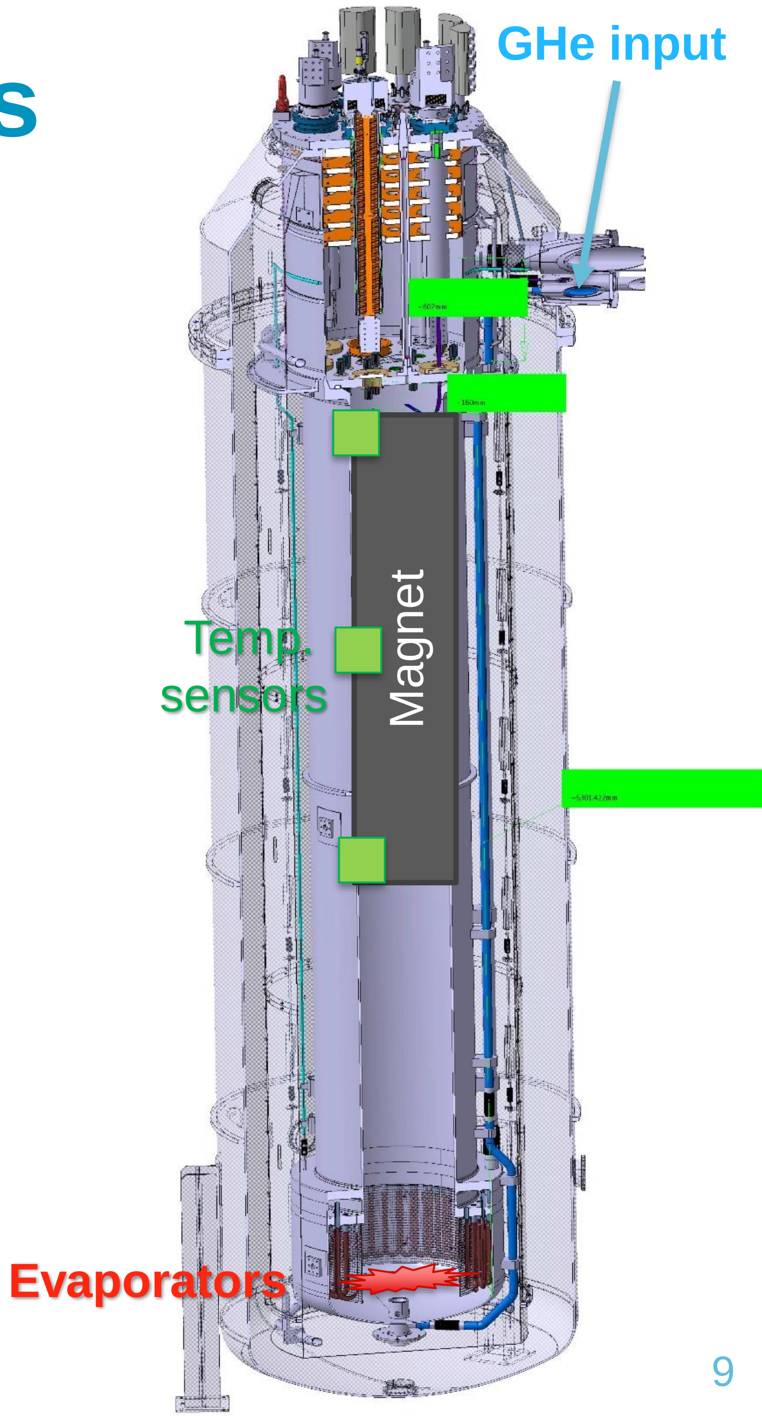


Test station 2
HFM, Cluster D

Cool down and warm up process

- Cool down
  - Controlled temperature helium gas input 300-80 K
  - Dump liquid helium below 80 K
  - Flow ~ 60 g/s
- Warm up
  - Evaporators at the bottom of cryostat (to 10-20 K)
  - 80 K helium gas up to 80 K, controlled temperature helium gas up to 300 K
  - Flow ~ 60 g/s
- Control
  - Temperature sensors in the magnet
  - Maximum temperature difference specified by us in test plan

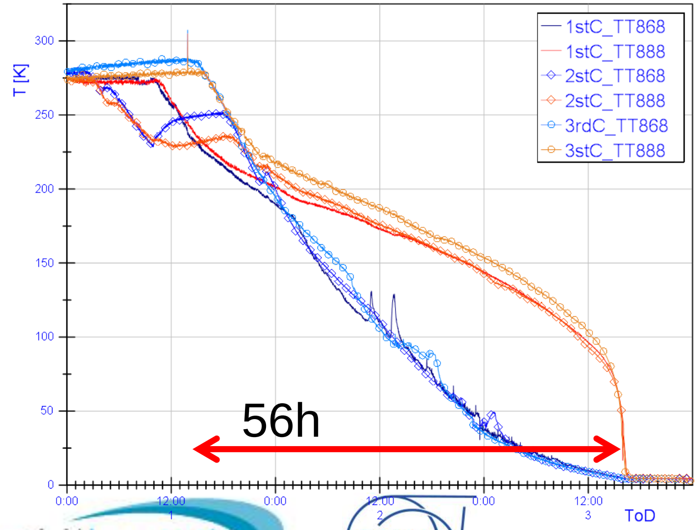
- Flow area: ~10 cm (Cluster D) ring between magnet and cryostat walls

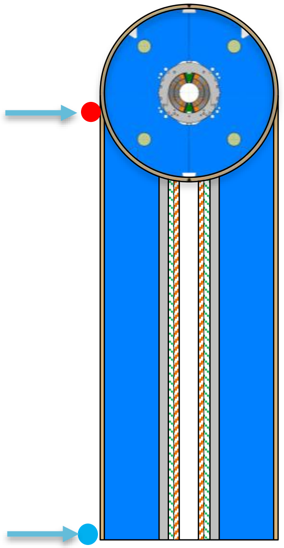


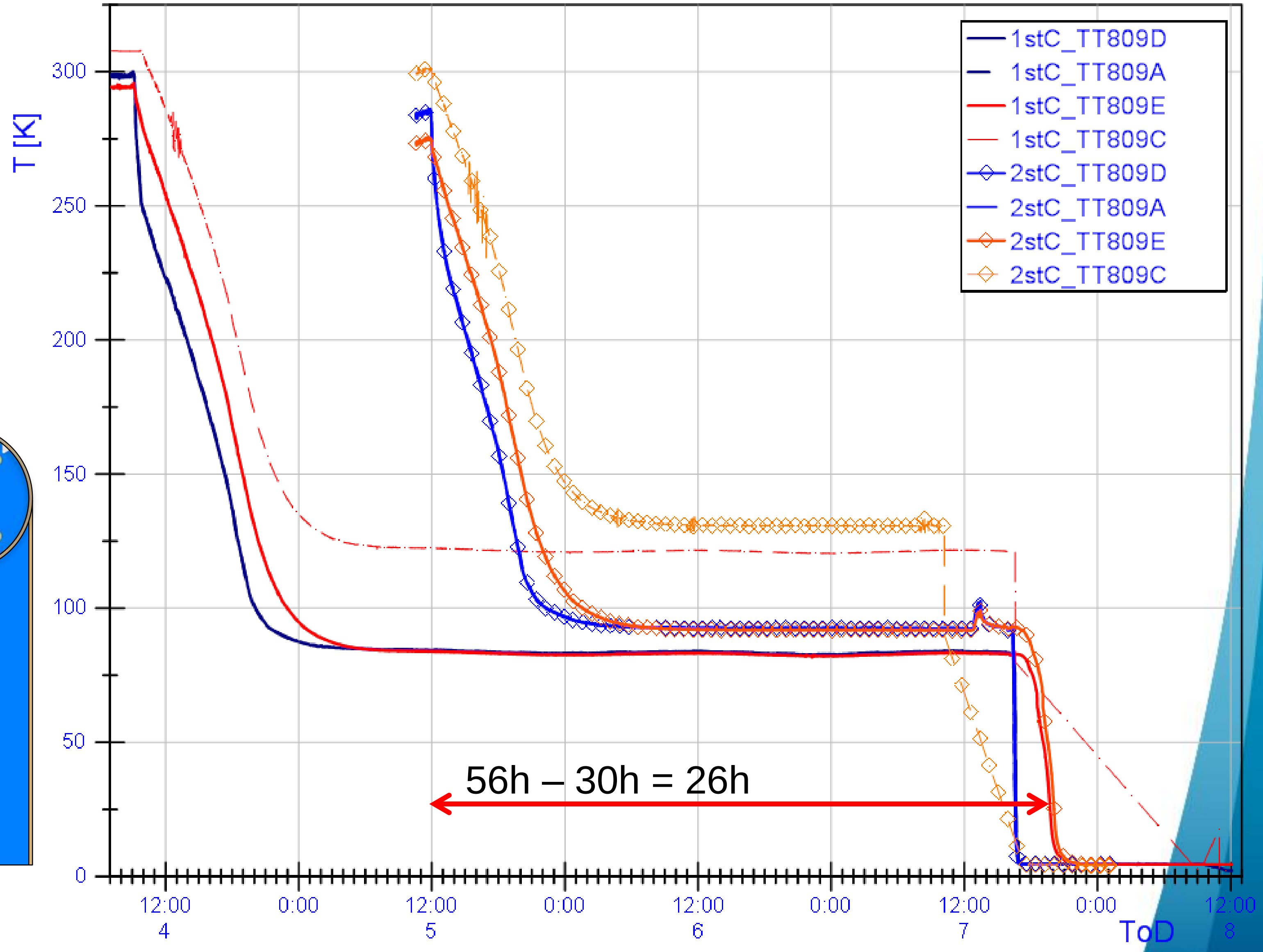
SP107: 1st and 2nd cooldowns temperature

- Cool down rate of SP107 (in HFM) and SP109 (in Long) different:
  - HFM – bottom and top: 15 K/h
  - Long – bottom: 6 K/h; top: 2.5 K/h

SP109 in long

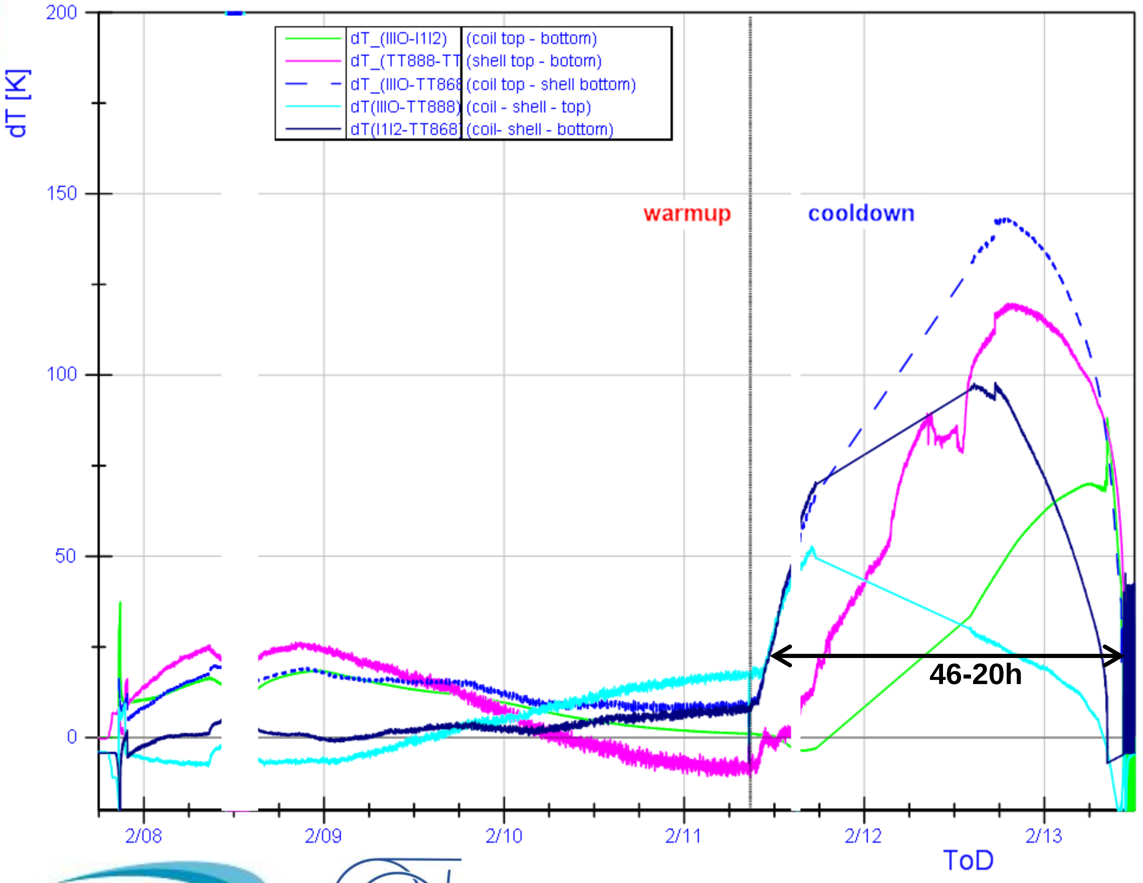




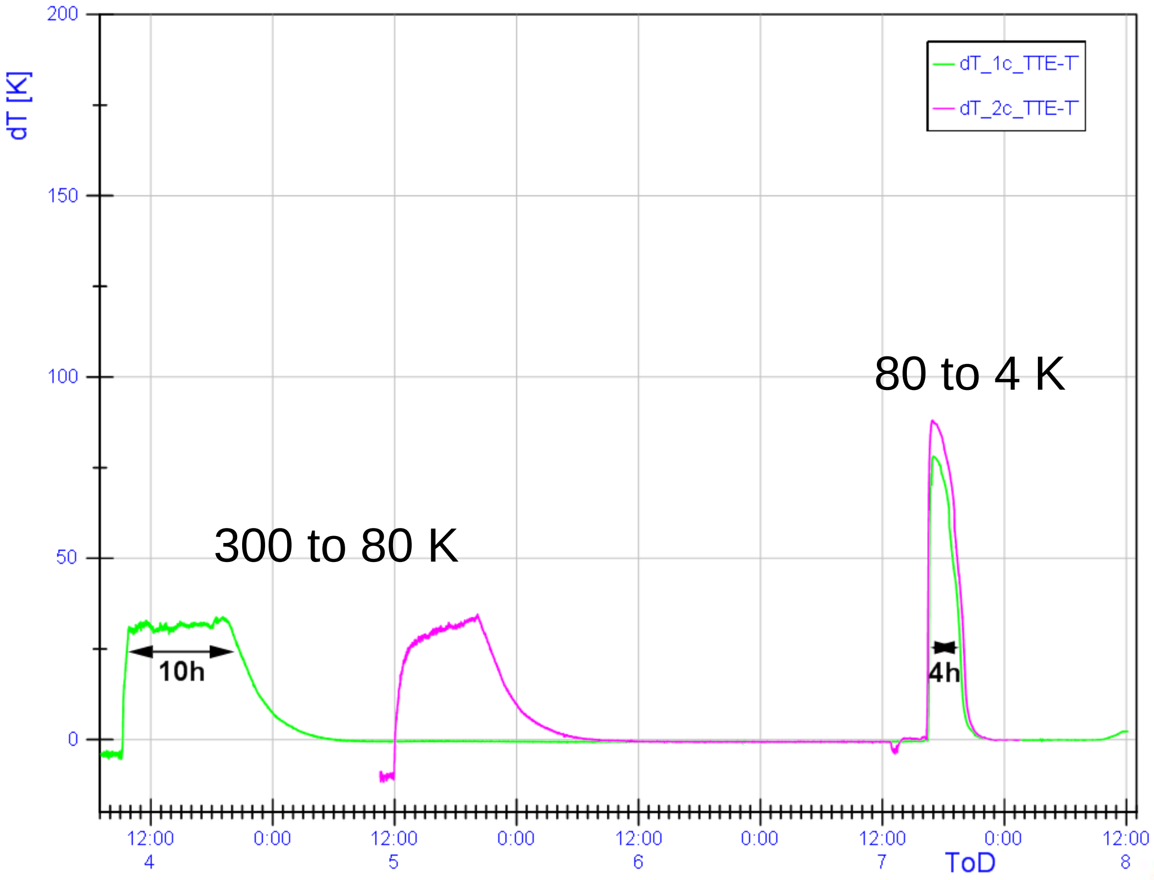


Delta-T in SP109 (Long) vs SP107 (HFM)

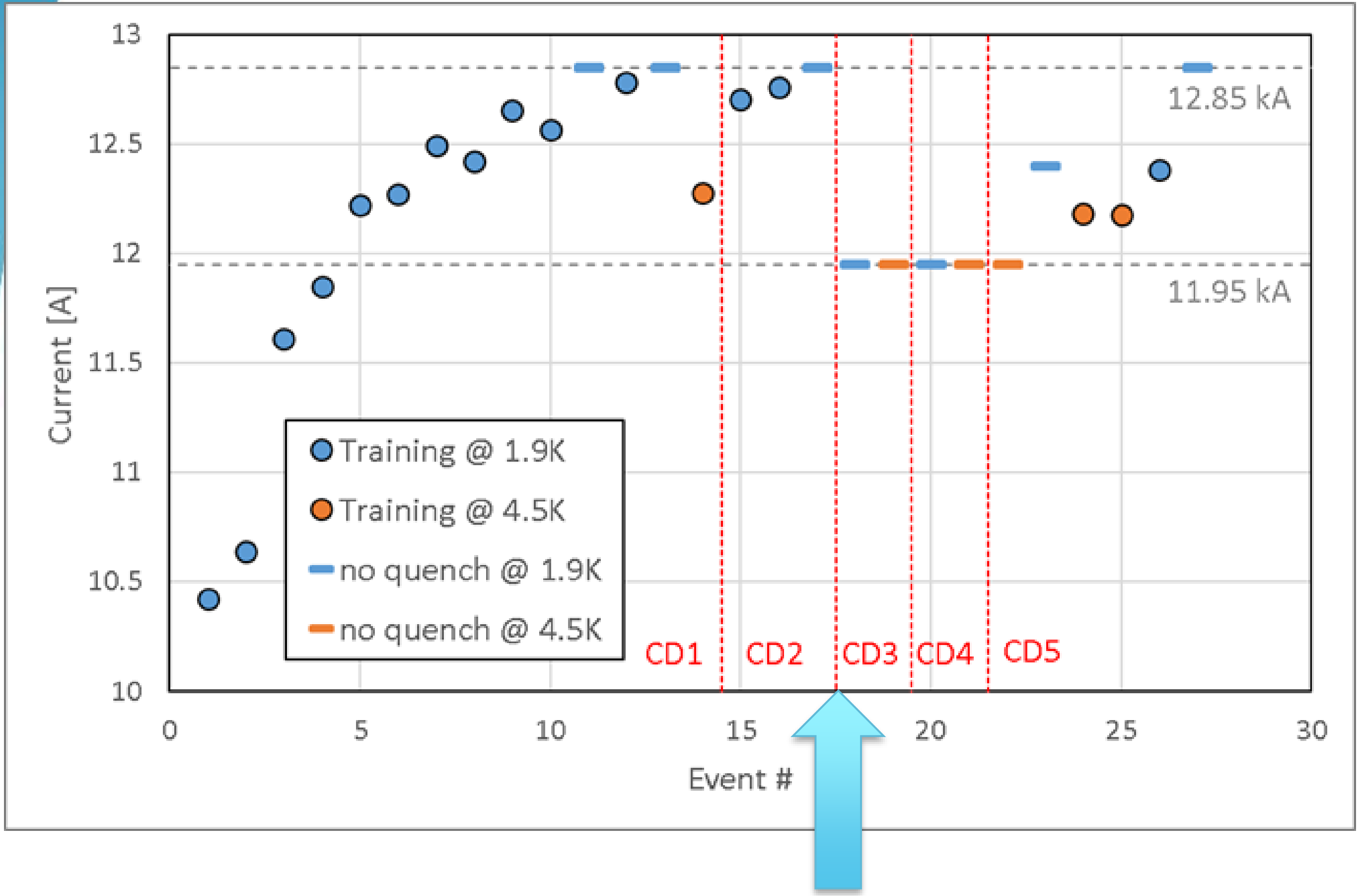
SP109 in long

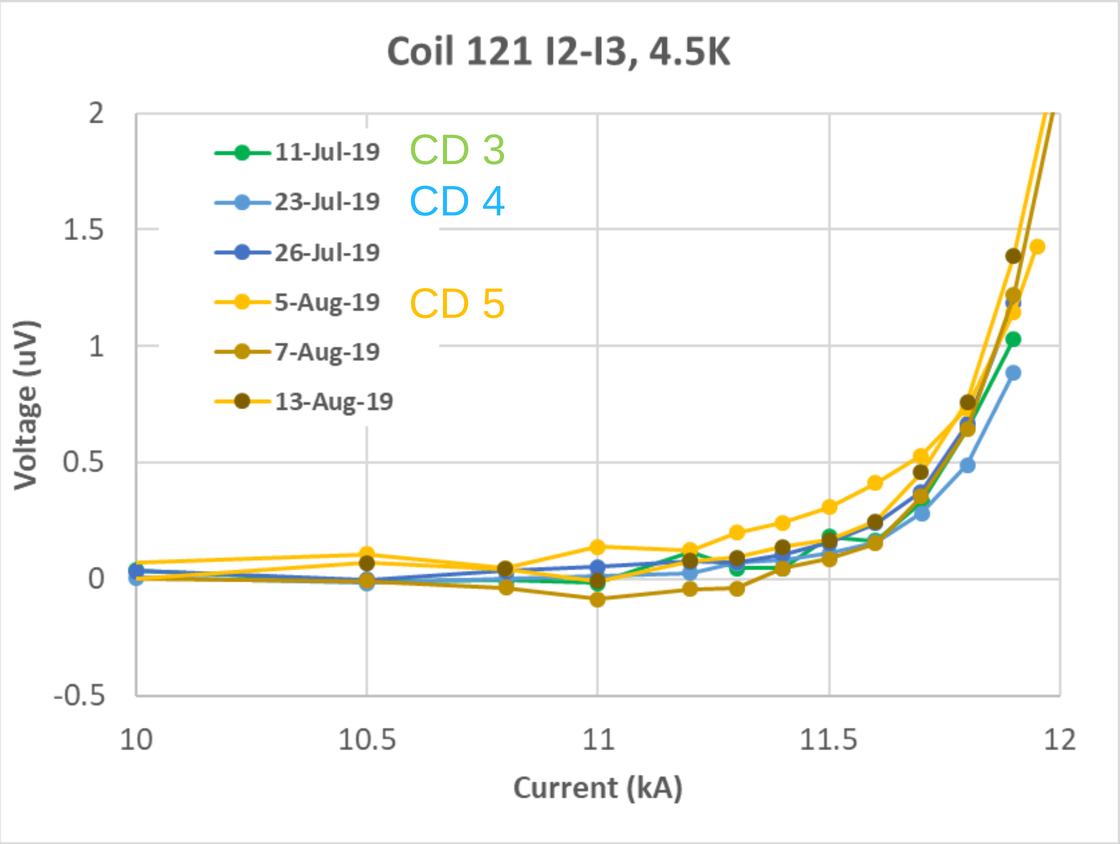


SP107 in HFM



SP107 performance after thermal cycles

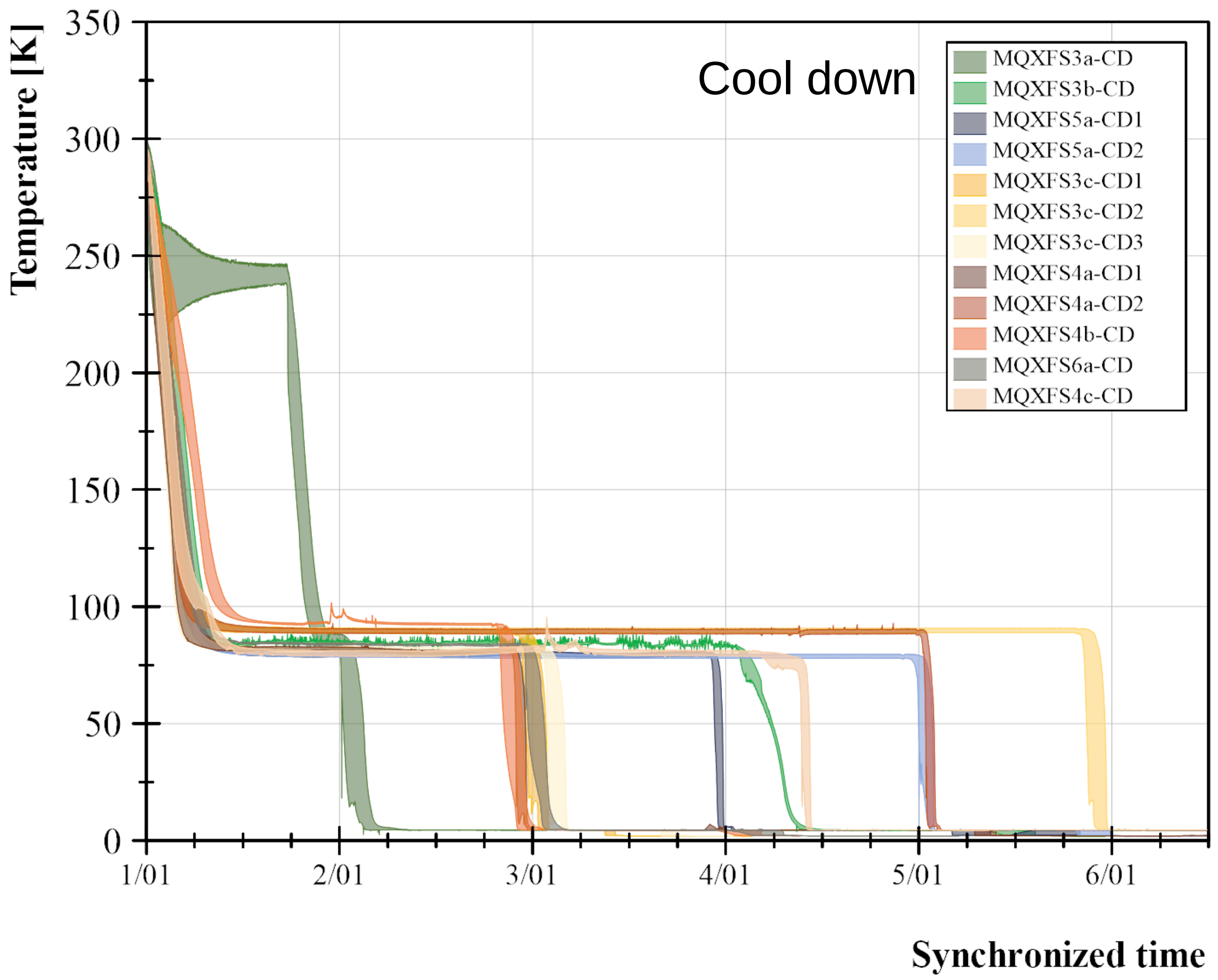


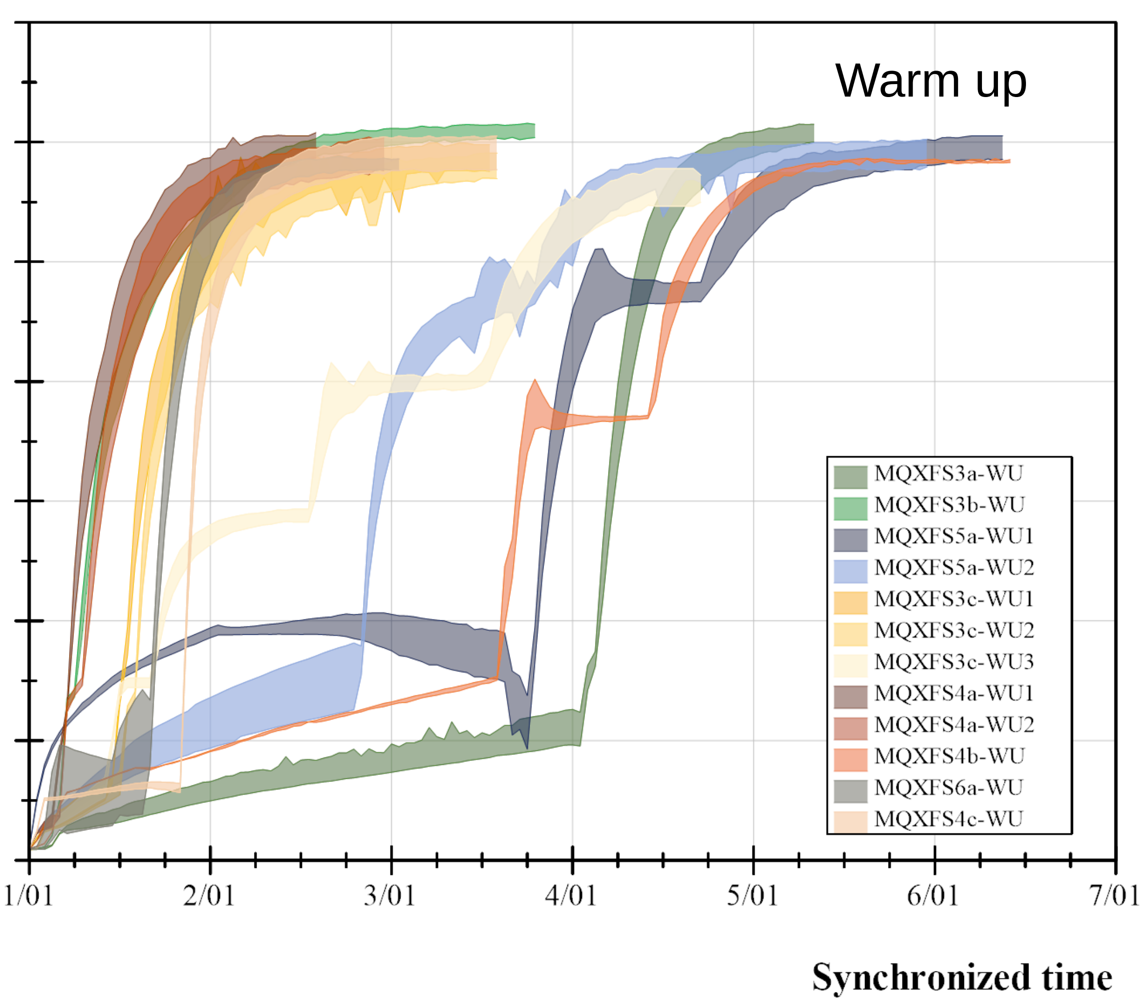


10 additional thermal cycles to 80 K

No observable difference after repeated thermal cycles in HFM

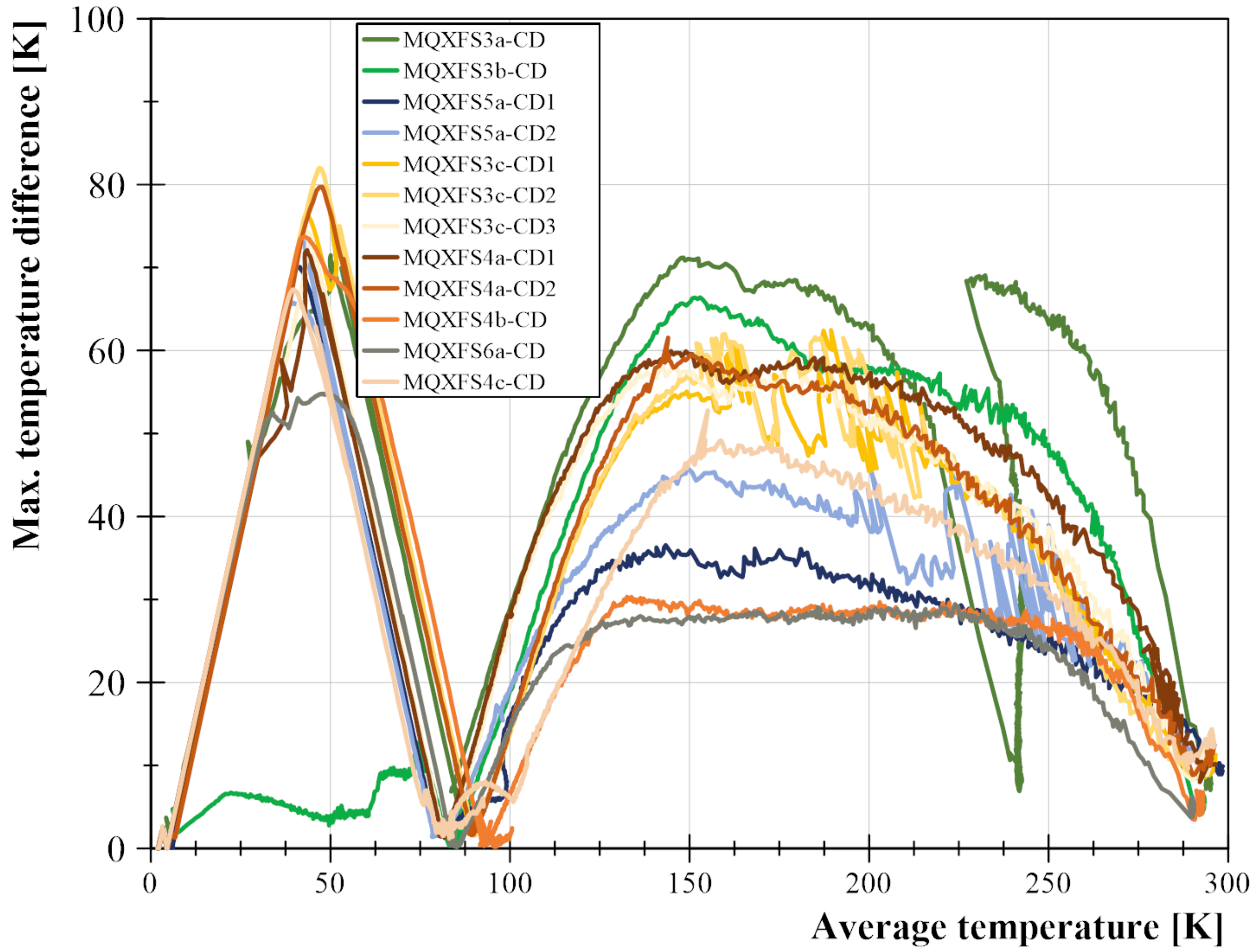
MQXFS tested at CERN: temperature

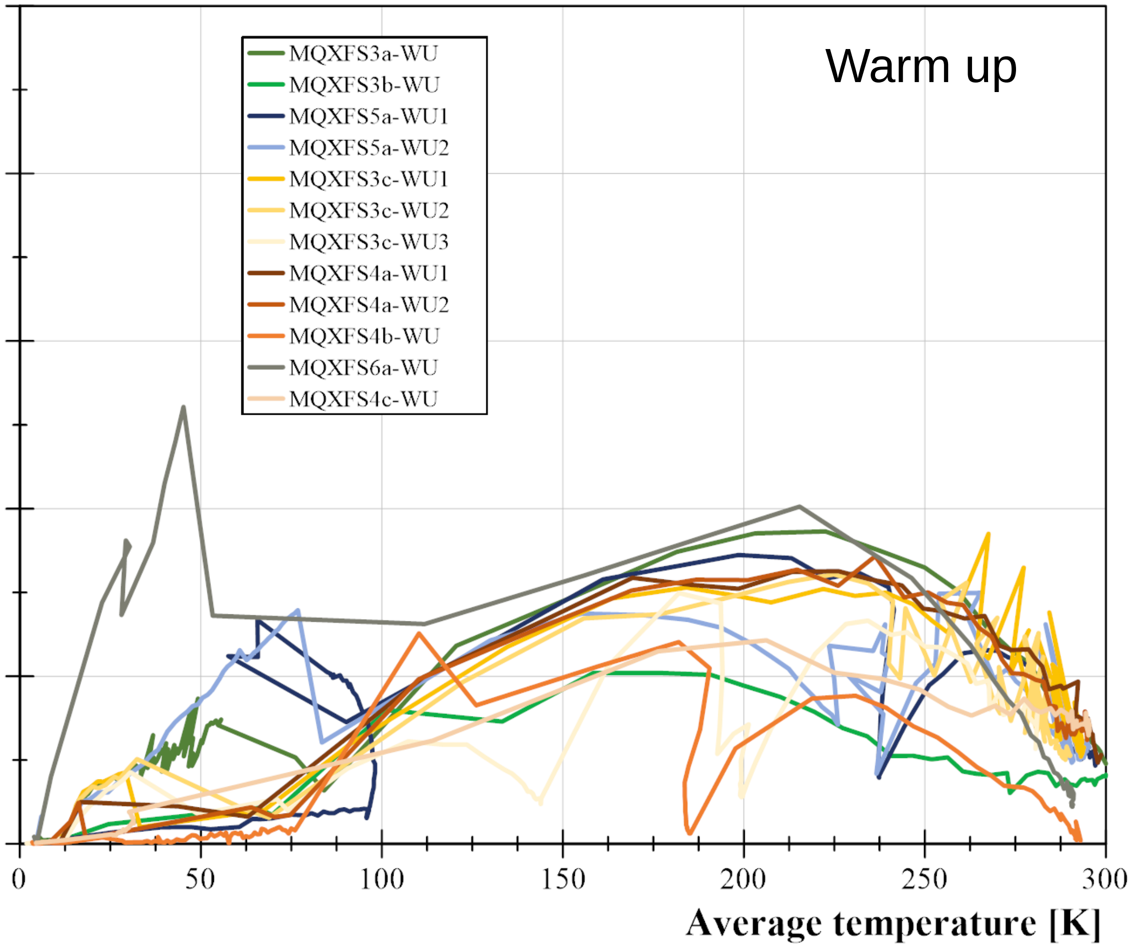




Synchronized to start of cool down (300 K) or warm up (4.5 K)

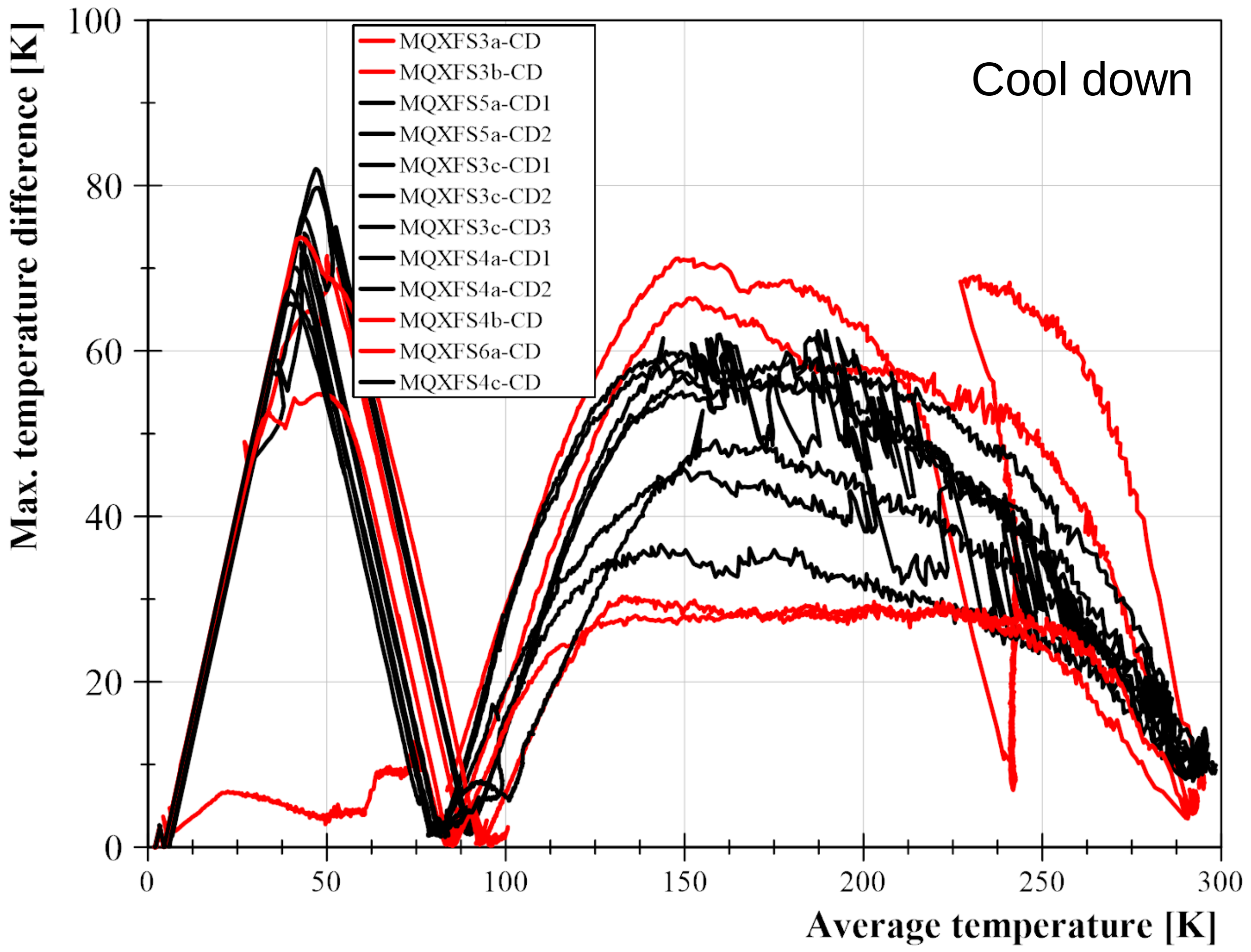
MQXFS tested at CERN: delta-T vs T

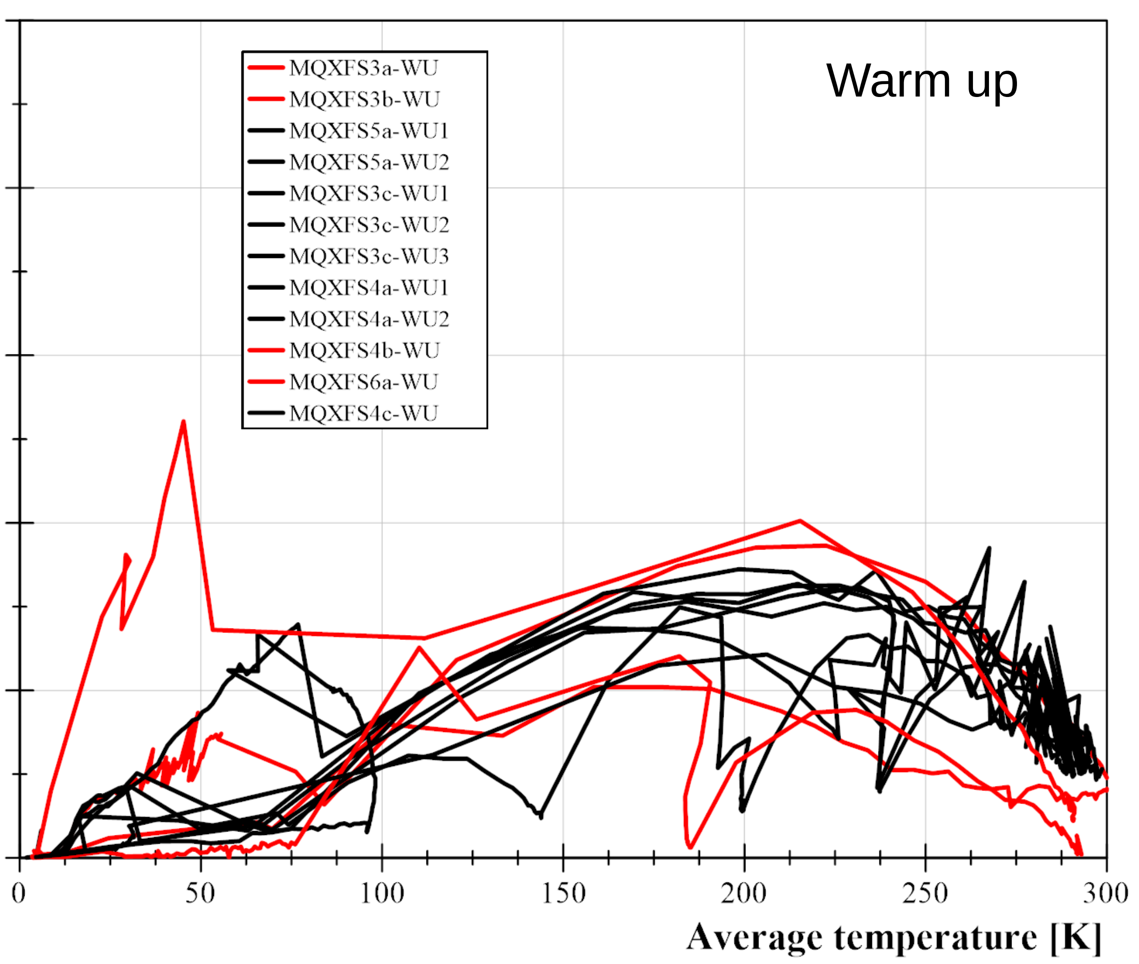




Specification: maximum 100 K

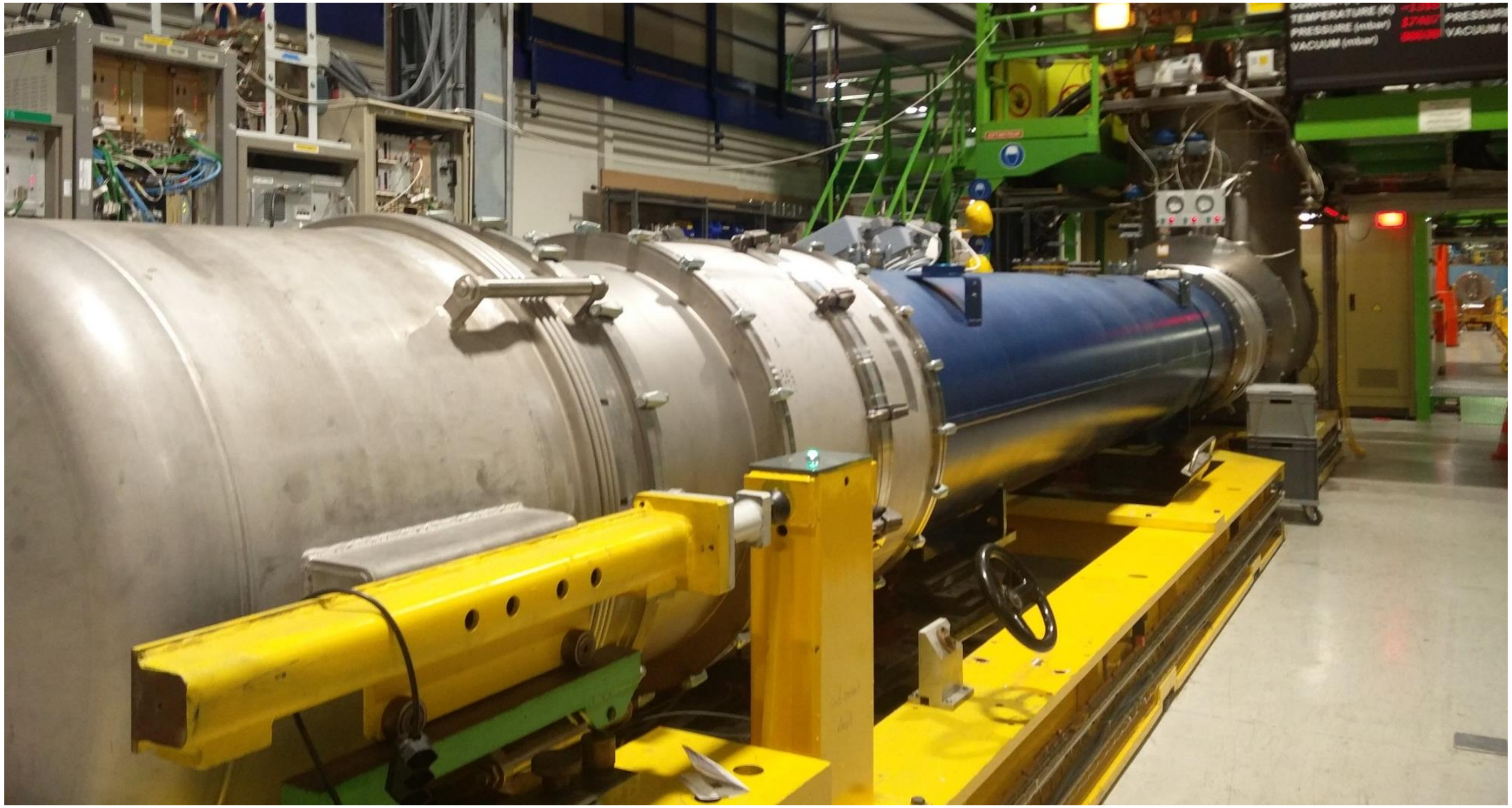
MQXFS tested at CERN: delta-T vs T



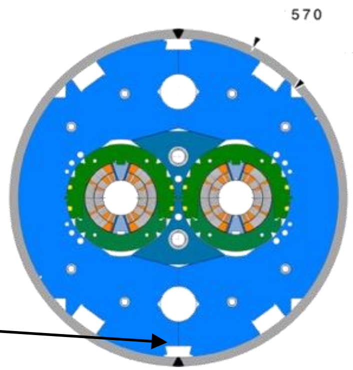


HFM (red) and Cluster D (black) comparison

Test station 3
Horizontal



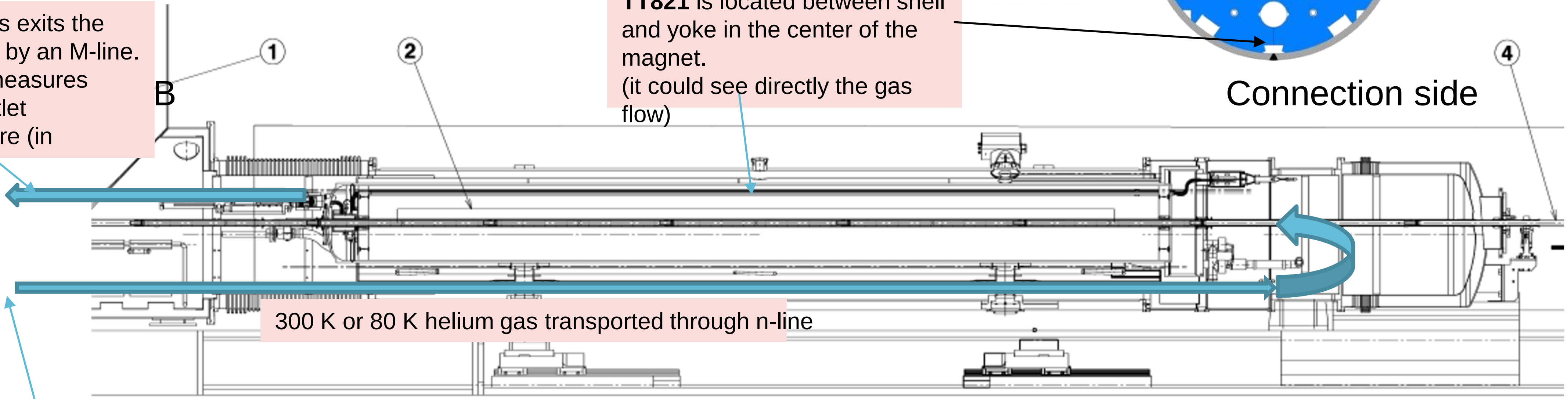
Cool down and warm up process



The helium gas flows through holes in the cold mass (but not in the beam tube or heat exchanger tube).

TT821 is located between shell and yoke in the center of the magnet.
(it could see directly the gas flow)

Helium gas exits the cold mass by an M-line. **TT150A** measures helium outlet temperature (in feedbox)

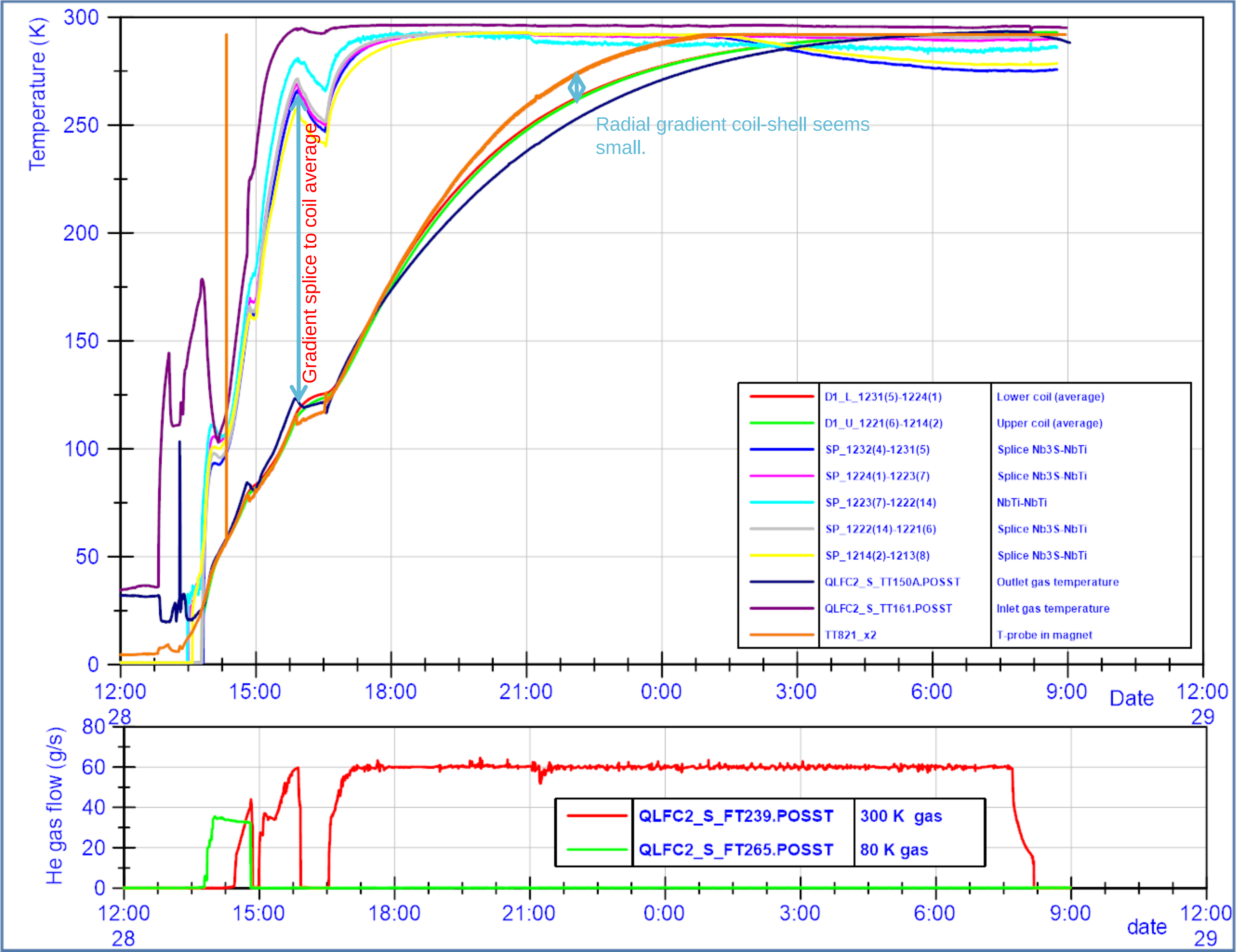


300 K or 80 K helium gas transported through n-line

Injected in cold mass on connection side

TT160 temperature probe measures helium inlet temperature (in feedbox)

- Old process (LHC):
  - Cool down by 80 K helium gas and then liquid helium
  - Warm up by 80 K and then 300 K helium gas
- New process:
  - Controlled temperature helium gas to 80 K, then LHe
  - Warm up by drifting to 80 K, then controlled temperature helium gas to 300 K



MBH-hybrid 2nd warm up

Standard/fast warm up
60 g/s gas flow of 300 K.

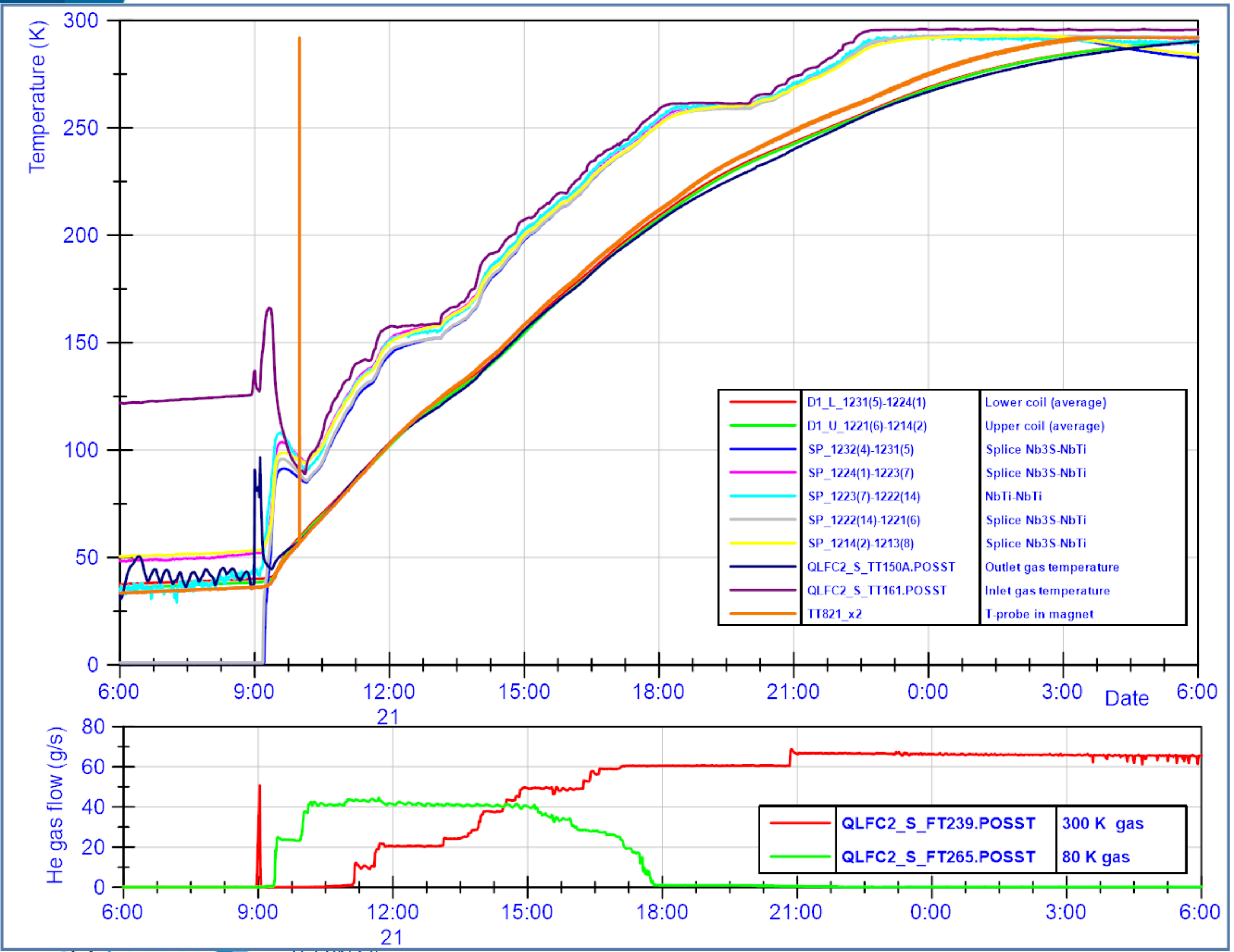
Maximum delta T of **150 K** between exit and entrance gas temperature in the magnet.

Maximum delta T of 150 K between middle of het magnet (TT821) and entrance gas temperature in the magnet.

Gradient at the non-connection half of the magnet seems to be very small.

The NbTi-NbTi splice is fully exposed to the He gas.

MBH-hybrid 3rd warm up



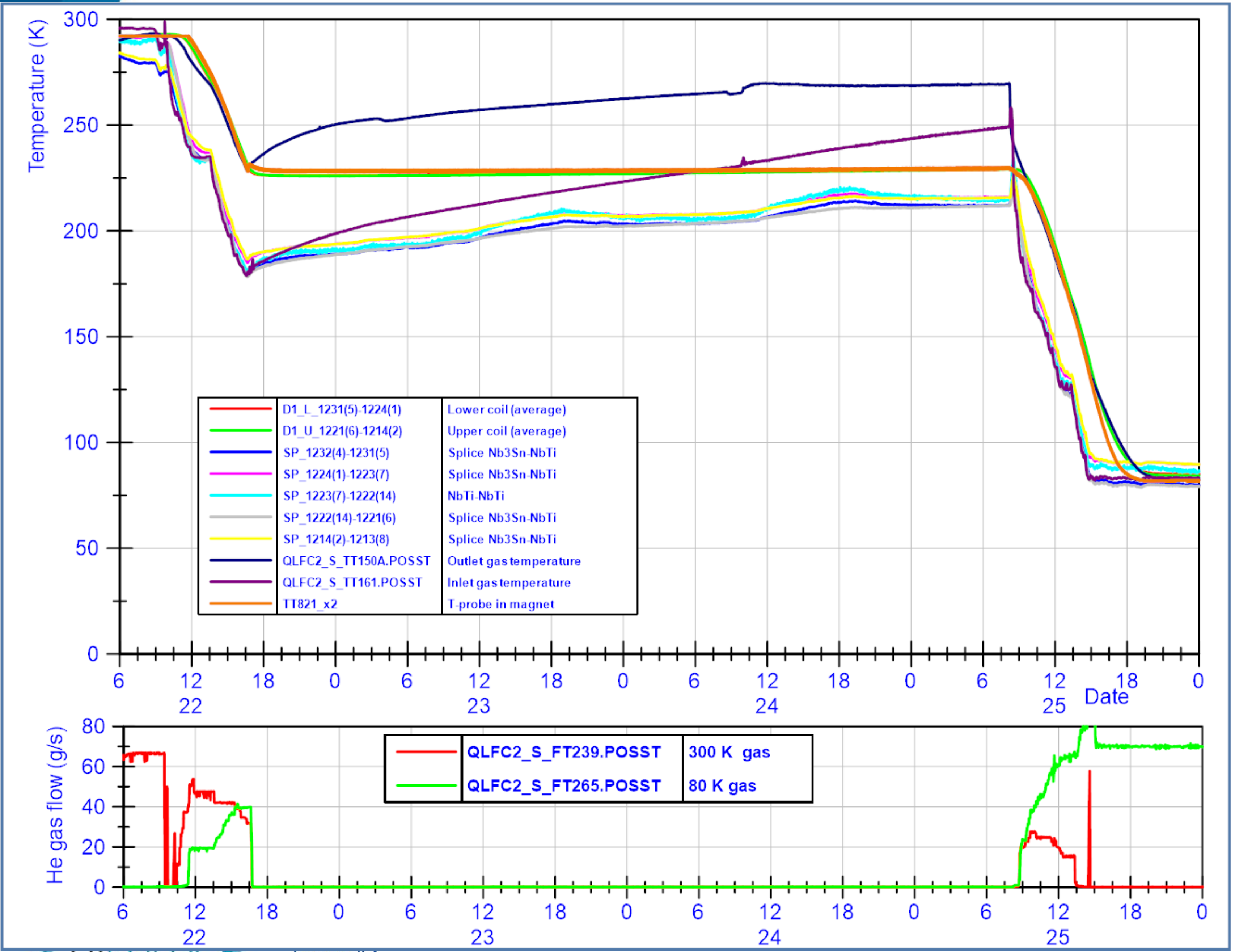
Slow warmup

- Good control of temperature by mixing helium gas (manual contol, to be automized).
- TT821 and coil average temperatures are similar. No radial gradient??
- Splices do respond quickly to the temperature changes in the He gas of the inlet. For example at the start it may be difficult to avoid warm gas from the CFB, which is directly visible in the splices (just after 9:00 in the plot).

Mixing of the helium gas:

- Only 80 K at the start (green curve)
- Adding step by step 300 K gas.
- At the end only 300 K gas

MBH-hybrid 3rd cool down



Slow cool down

- Good control of temperature by mixing helium gas (manual contol, to be automized). Since the process is manual, it could not be continued over the weekend.
- TT821 and coil average temperatures are similar. No radial gradient??
- Splices do respond quickly to the temperature changes in the He gas of the inlet.
- When there is no gas flow, the inlet and outlet temperatures drift away from the magnet temperature, but this has no significant meaning for the gradients.

Mixing of the helium gas:

- Only 300 K at the start (red curve)
- Adding step by step 80 K gas.
- At the end only 80 K gas (green curve)

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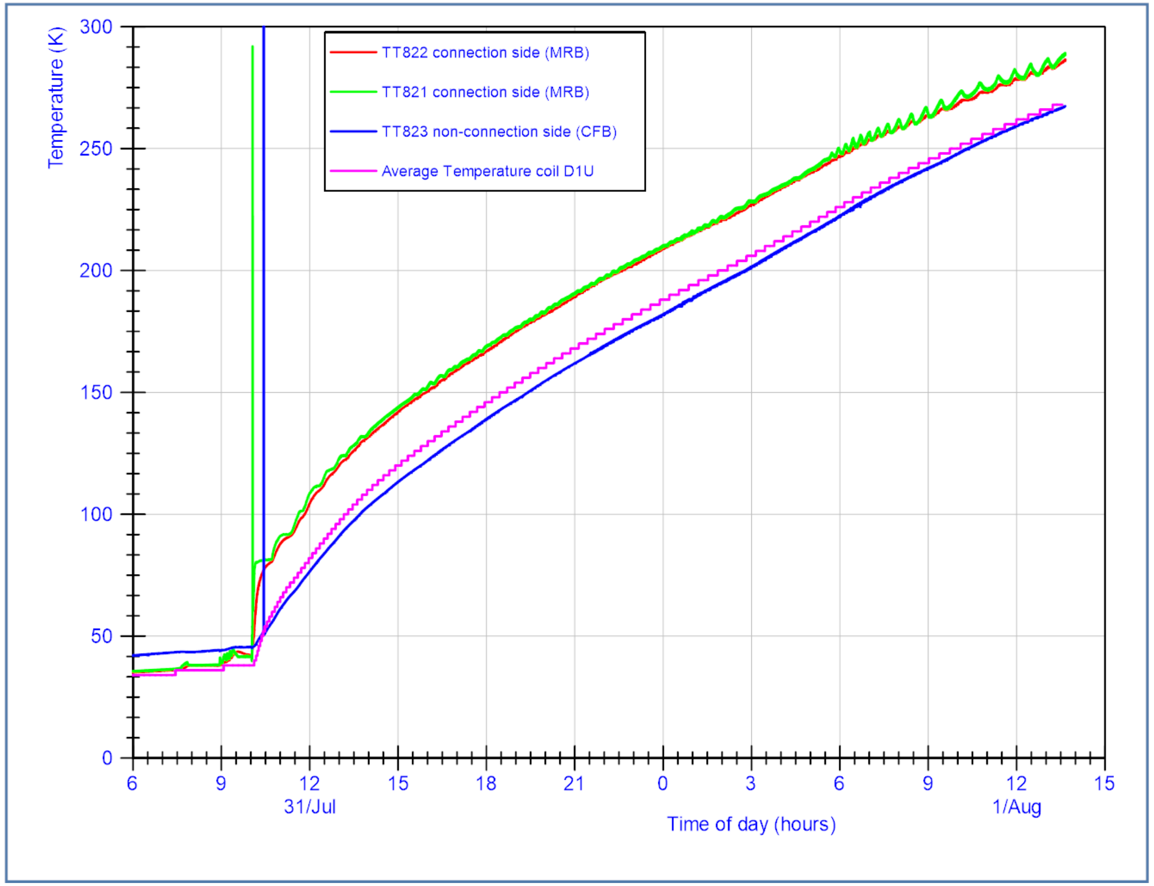
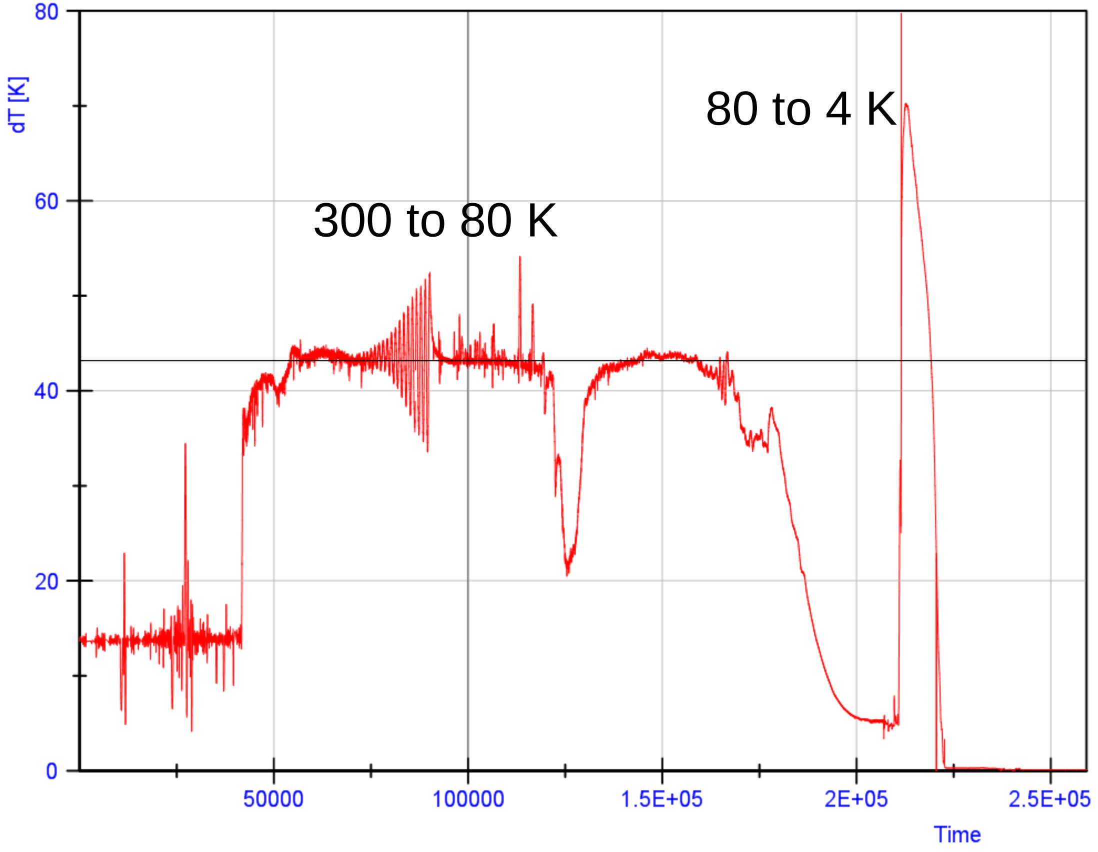
MBHB-002 1st warm up and 2nd cool down

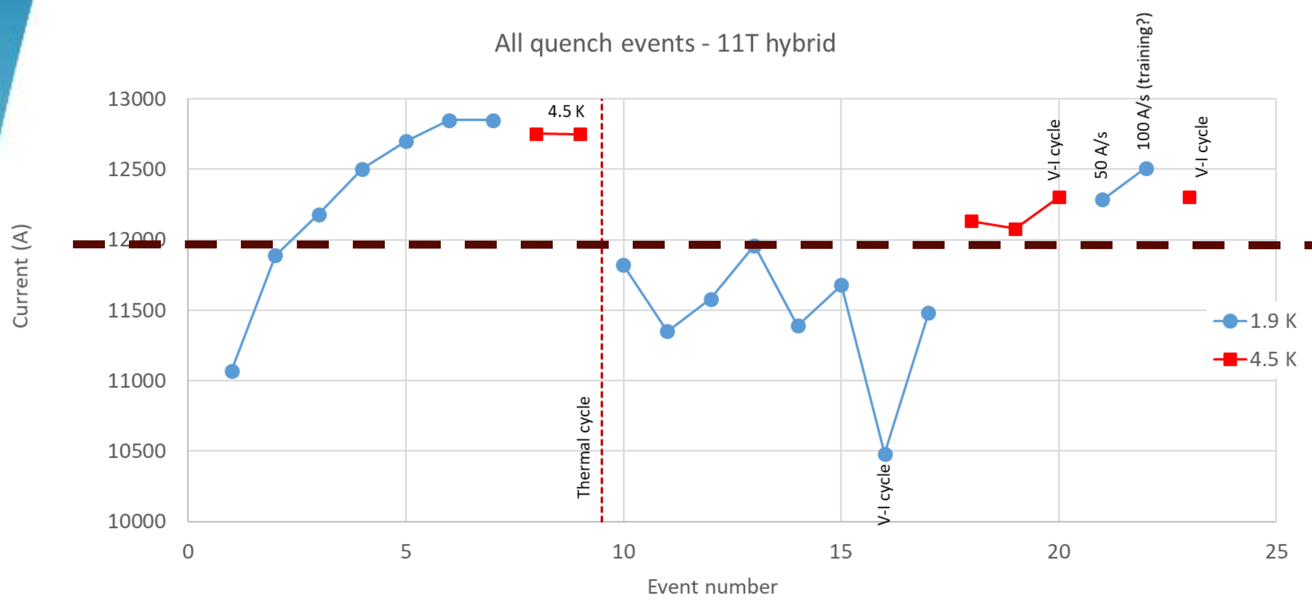
Temperature during warm up

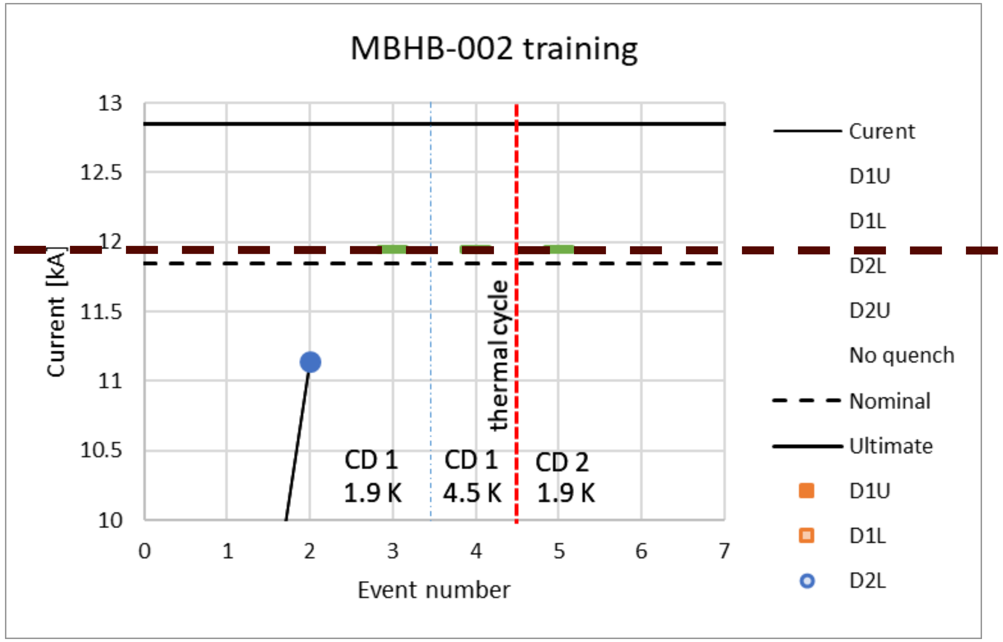


Delta-T during cool down



Comparison MBH-Hybrid and MBHB-002





Brown dashed line: MBHB-002 target of 11.95 kA

Hybrid has problems after thermal cycle, but still reached 12.3 to 12.5 kA at 4.5 K and 1.9 K with various ramp rates.

Note that the prototype did not reach more than 10 kA.

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Conclusions

- Cool down and warm up process is critical to control
  - SP109 and MBH-hybrid damaged during them
- Actions done in SM18:
  - Long station: new process (to be tested), same magnet comparison between HFM and Long
  - HFM and Cluster D: tests ongoing, seems OK
  - Horizontal: process changed and tested, seems OK