Test of the FeaTHeR-MO coils at high field and variable temperature in SULTAN

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SWISS PLASMA CENTER

August 11th, 2020

Outline

- SULTAN test facility
- FeaTHeR M0 coils
- Required upgrades
- Test results:
  - Coil instrumentation and cryostat
  - Joint resistances
  - I_c measurements
  - T_{cs} measurements
  - Heat generation in the coil
  - Quench data
- Conclusions

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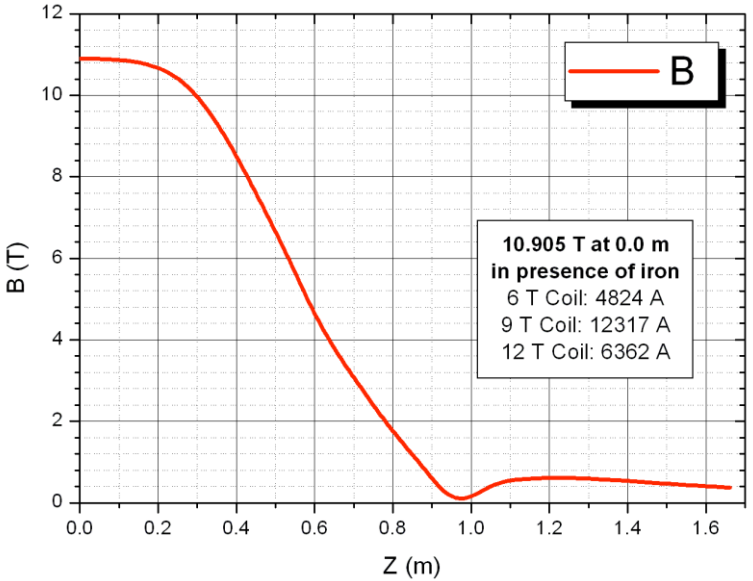
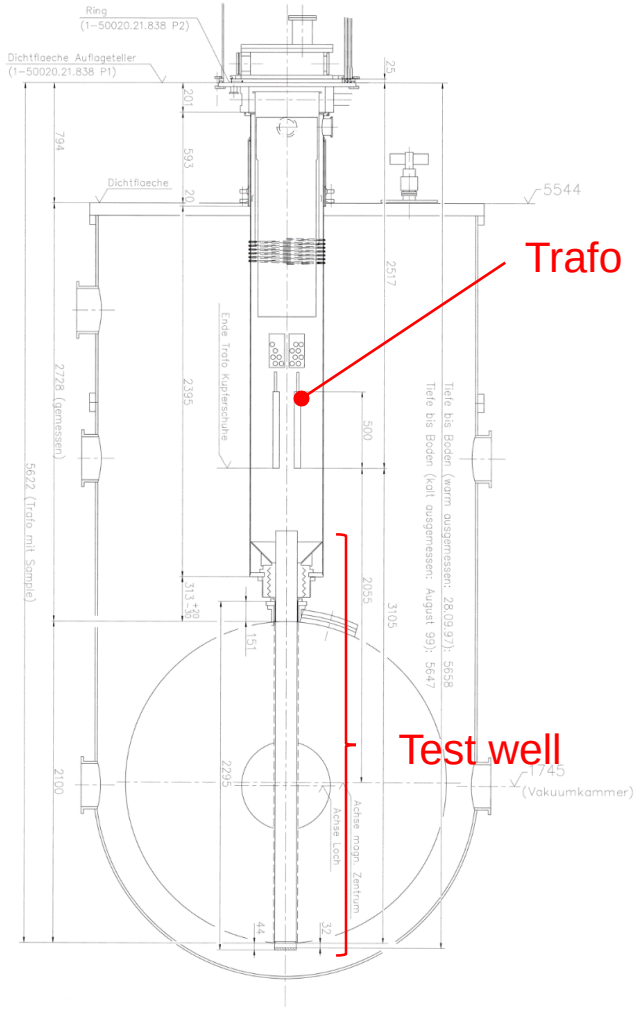
SULTAN test facility

- Field generated by 3 pairs of concentric **split solenoids:**
  - B_{max} = **10.905 T** in test well
  - Homogeneity (2%) along ~400 mm



SULTAN test facility

- **Samples**:
  - Typically **cable-in-conduit conductors**
  - Inserted through a vertical test well (144 mm × 94 mm rectangular pipe)
  - Nb-Ti trafo supplies $I_{sample} \leq 100$ kA



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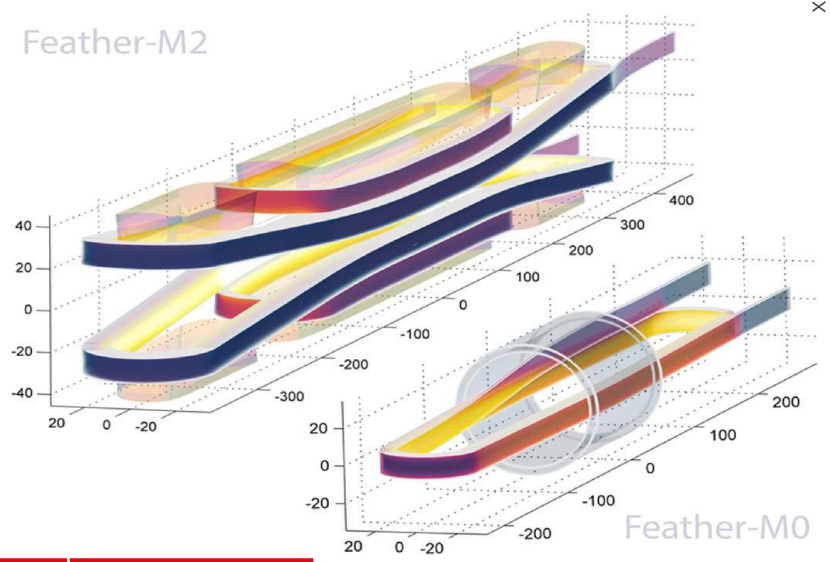
FeaTHeR coils

- **FeaTHeR-M0** and **FeaTHeR-M2** are two sets of HTS insert-magnets produced at CERN and wound with **REBCO-Roebel cable**
- FeaTHeR-M0s are **sub-scale planar racetrack coils** (one single pancake)
- Tests in SULTAN:
  - FM0.4: October 2017
  - FM0.5: March 2019



Coil	# turns	Tape supplier	# tapes	tape width (mm)	cable width (mm)
FM0.4	3	Bruker	15	5.5	12
FM0.5	4	SuNAM	15	5.5	12

J. van Nugteren Ph.D. thesis, University of Twente (2016)

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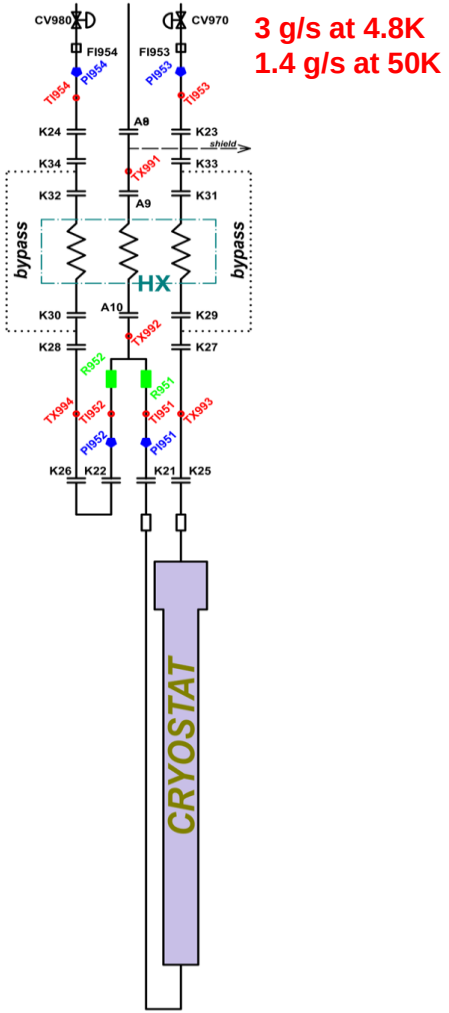
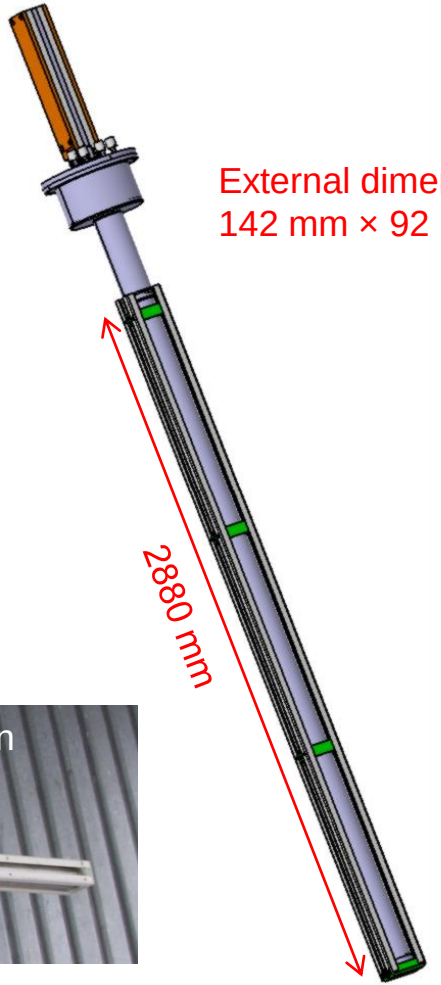
  - Typically **cable-in-conduit conductors**
  - Inserted through a vertical test well (144 mm × 94 mm rectangular pipe)
  - Nb-Ti trafo supplies $I_{sample} \leq 100$ kA

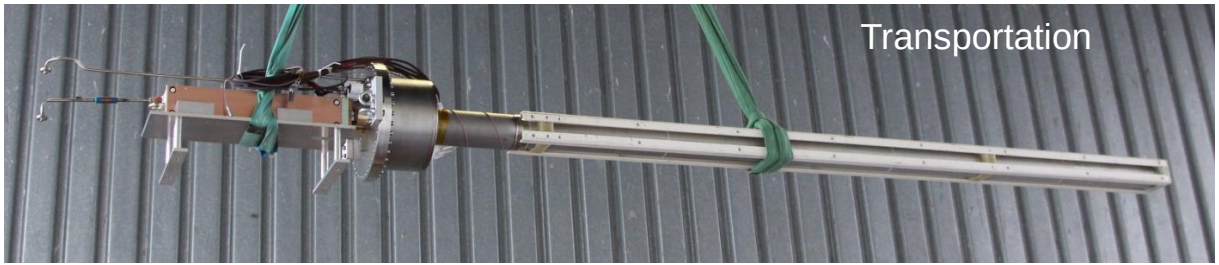
- The test of **FeaTHeR coils** requires:
  - **Cryostat:**
    - Confine flow of He in a volume where **temperature is regulated**: 4.8 to 50 K
    - **HTS current adapter** between HTS dipole and Nb-Ti trafo
  - **Heat exchanger:**
    - He must return to the cryo-plant as cold gas (T < 20 K)



Sample cryostat

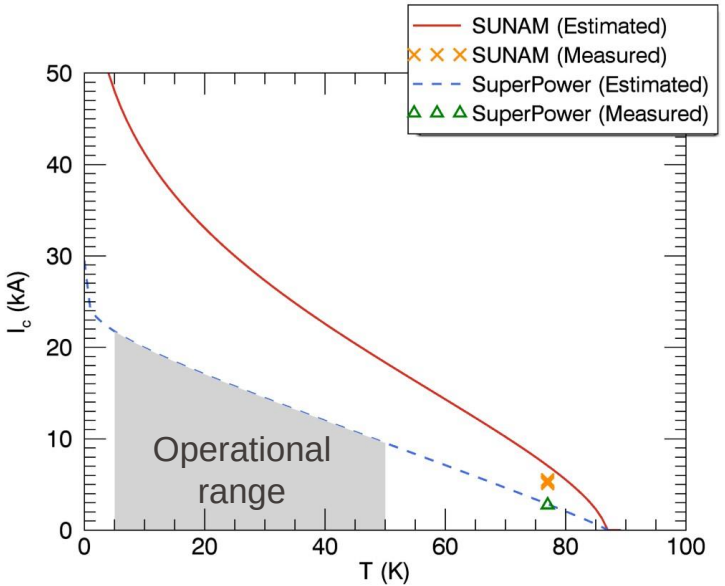
- 2880 mm-long cylindrical stainless steel chamber:
  - OD = 88.9 mm
  - ID = 83.7 mm
- It hangs from the SULTAN transformer

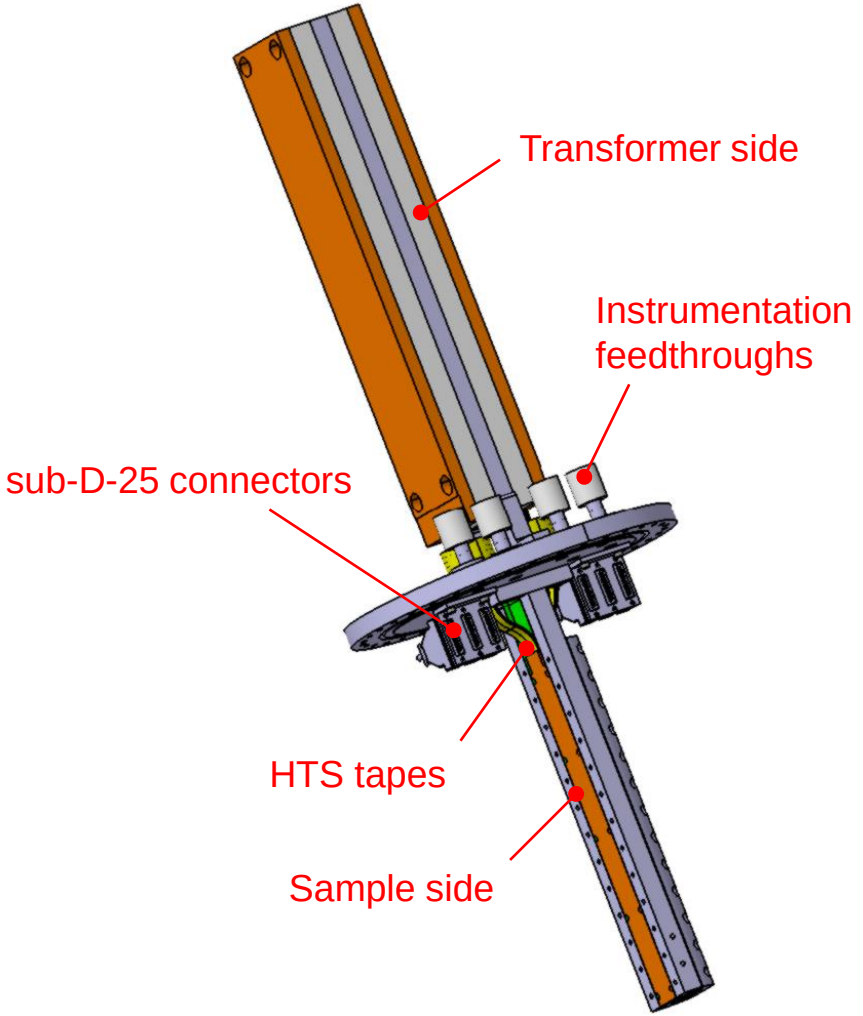




HTS current adapter

- Each leg made of:
  - 2 copper plates
  - Connected by 2 parallel stacks of:
    - 8× REBCO tapes +
    - 9× brass stripes





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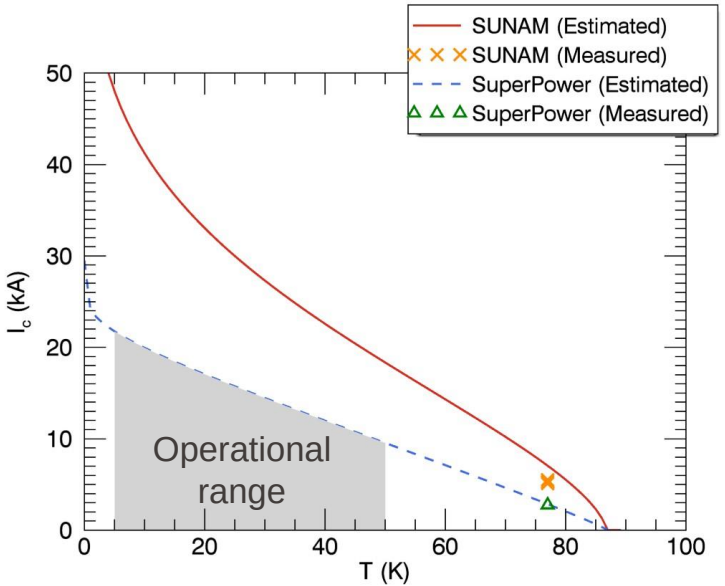
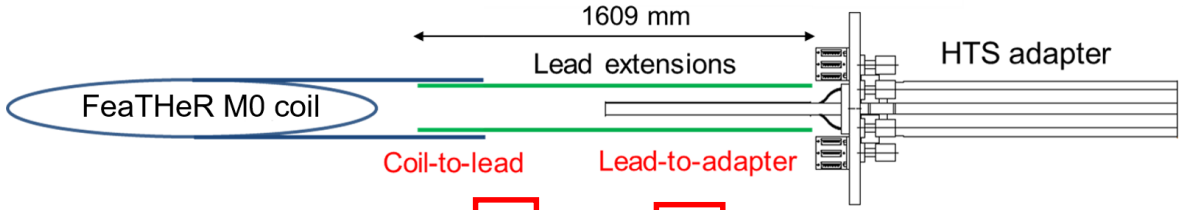
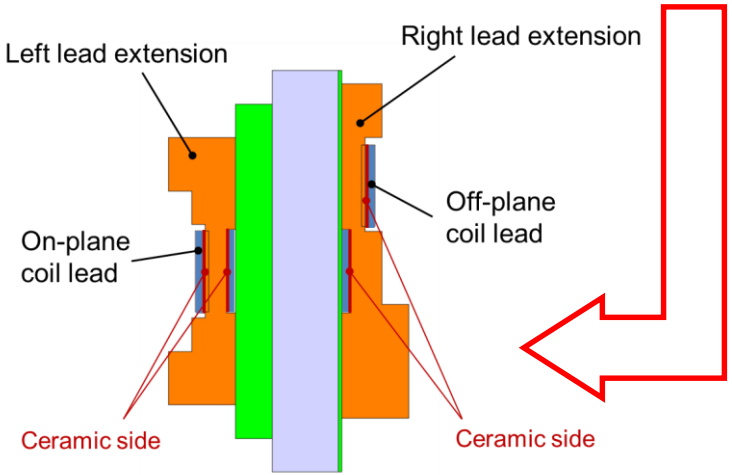


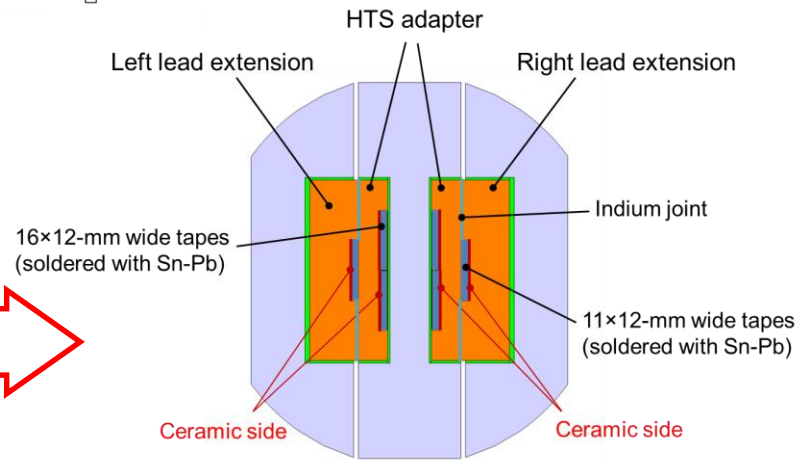
Lead extensions

- The lead extensions of the FeaTHeR M0 coils have to be **unsoldered** and **replaced** by ~1.6-m-long leads for the test in the high field region.
- Each lead extension is made of 11×12-mm-wide tapes in a Cu profile.





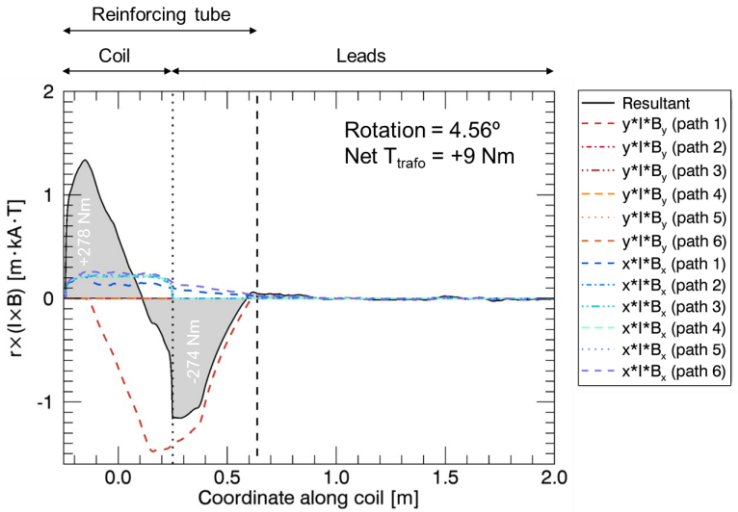
Ceramic sides facing each other

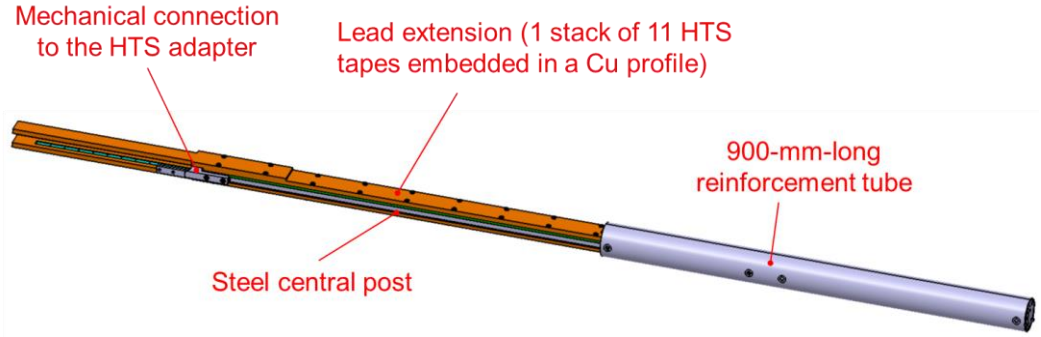


Non-facing ceramic sides

Mechanical considerations

- Cryostat (and coil) are hanging from the SULTAN transformer
- Efforts transmitted to the trafo:
  - F_z = **-2.5 kN (if centered) ✓**
  - Torque: **600 Nm ✗**
- The **net torque in the trafo cancels** if the coil is rotated **~4º**
- Still, the coil+lead assembly experiences an **internal torque**





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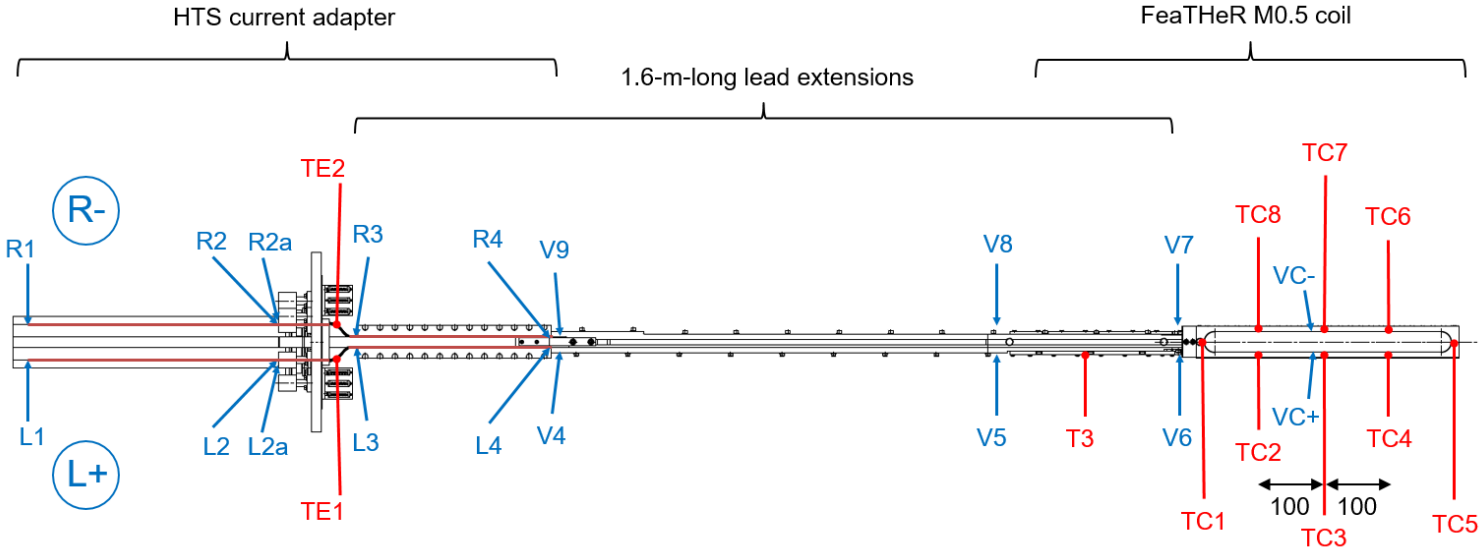
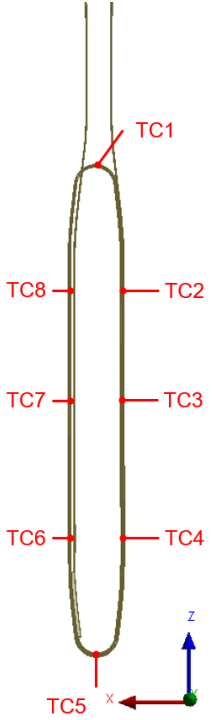
Instrumentation

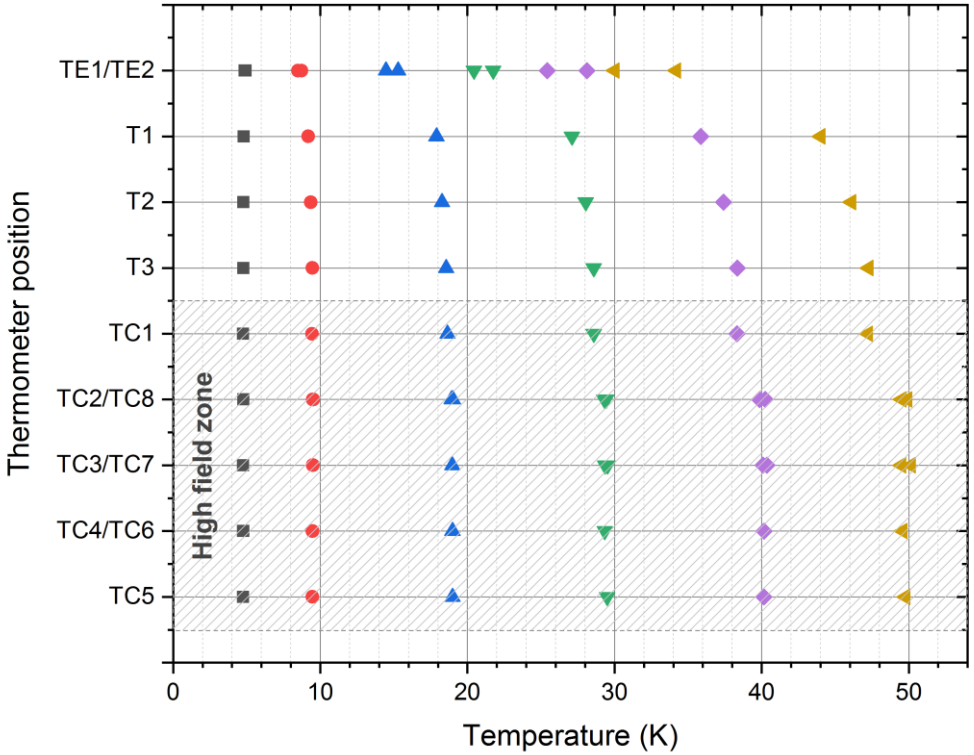


- **Voltage taps:**
  - All consecutive voltage taps are paired
  - Additionally, V6-V7(coil), V4-V9 (coil+extension) and L^{+}-R^{-} (overall V drop)
- **Cernox temperature sensors:**
  - 8 sensors in the coil (TC1-TC8) + 4 infrastructure sensors in cryostat
  - T_{in}/T_{out} in the cryostat, and T_{in}/T_{out} in the HEX are also monitored
- **FM0.5: All existing pickup coils** are connected to the Data Acquisition System (DAS)

Cryostat commissioning

- Operational temperature range: 4.8 - 50 K (uniform in the high field zone)
- Operational current: 20 kA @ 4.8 K – 9.5 kA @ 50 K





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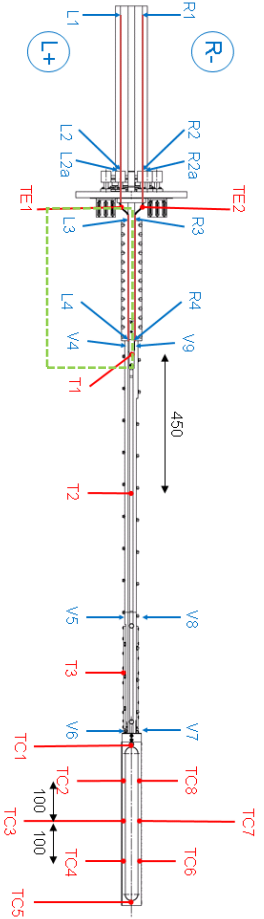
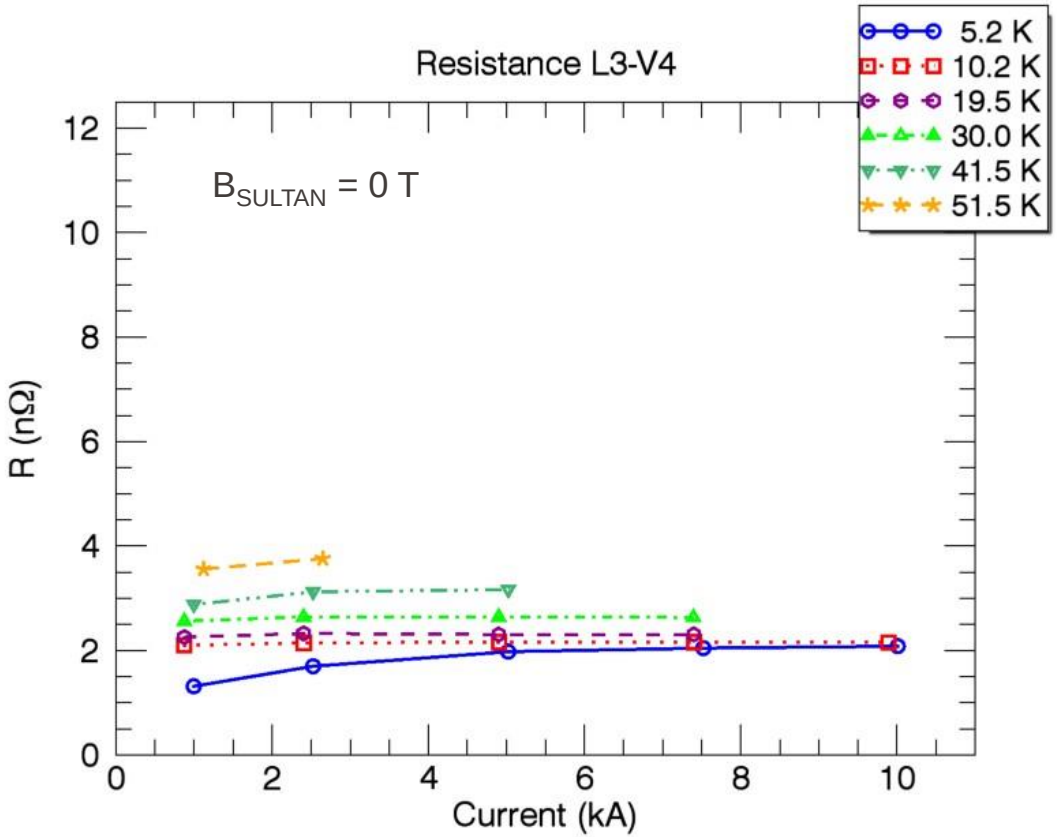
FM0.4: Joint resistances



HTS adapter to lead extension (left)



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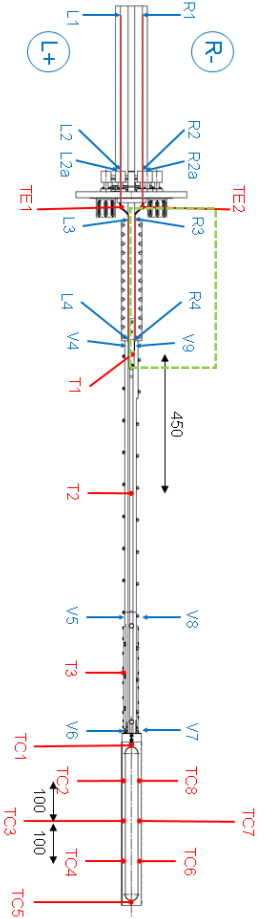
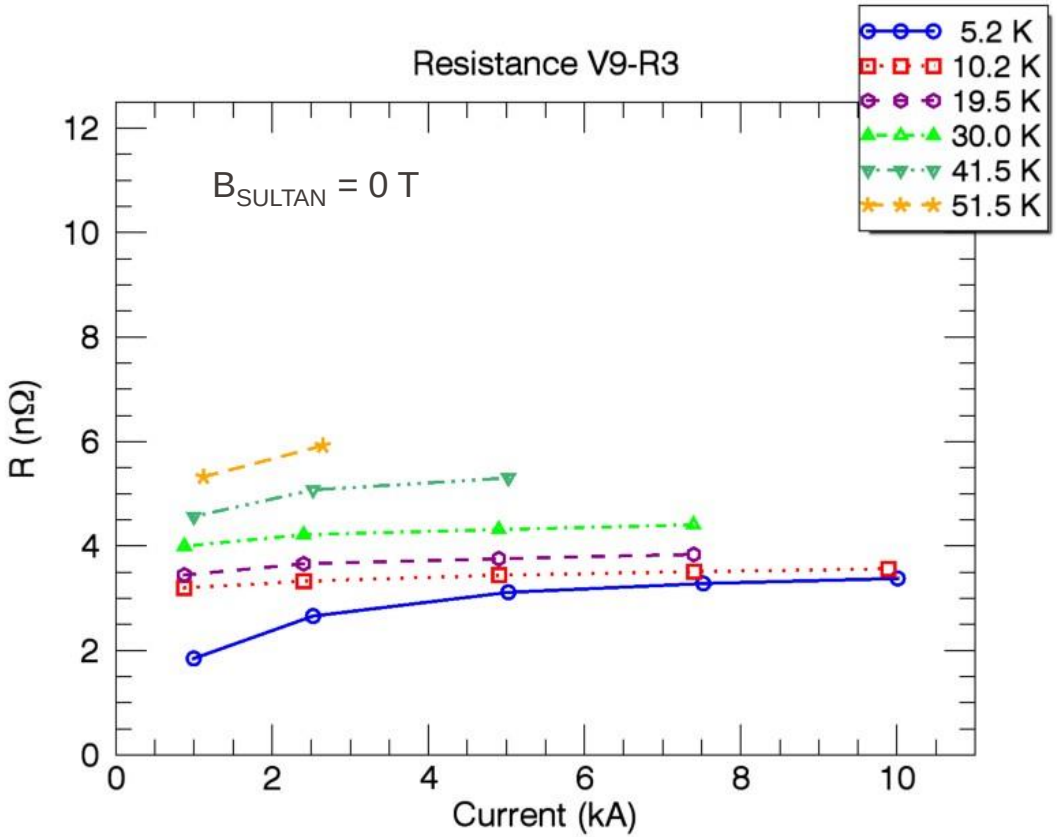


HTS adapter to lead extension (right)



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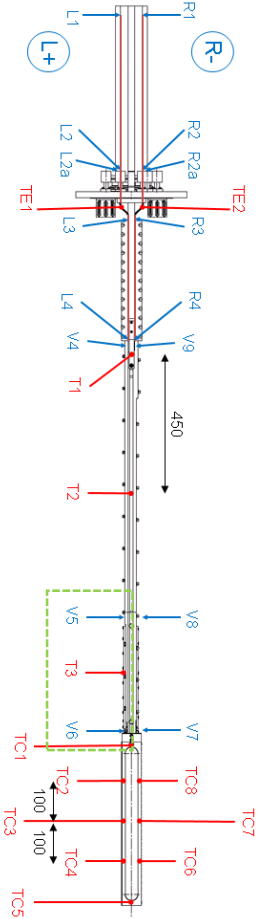
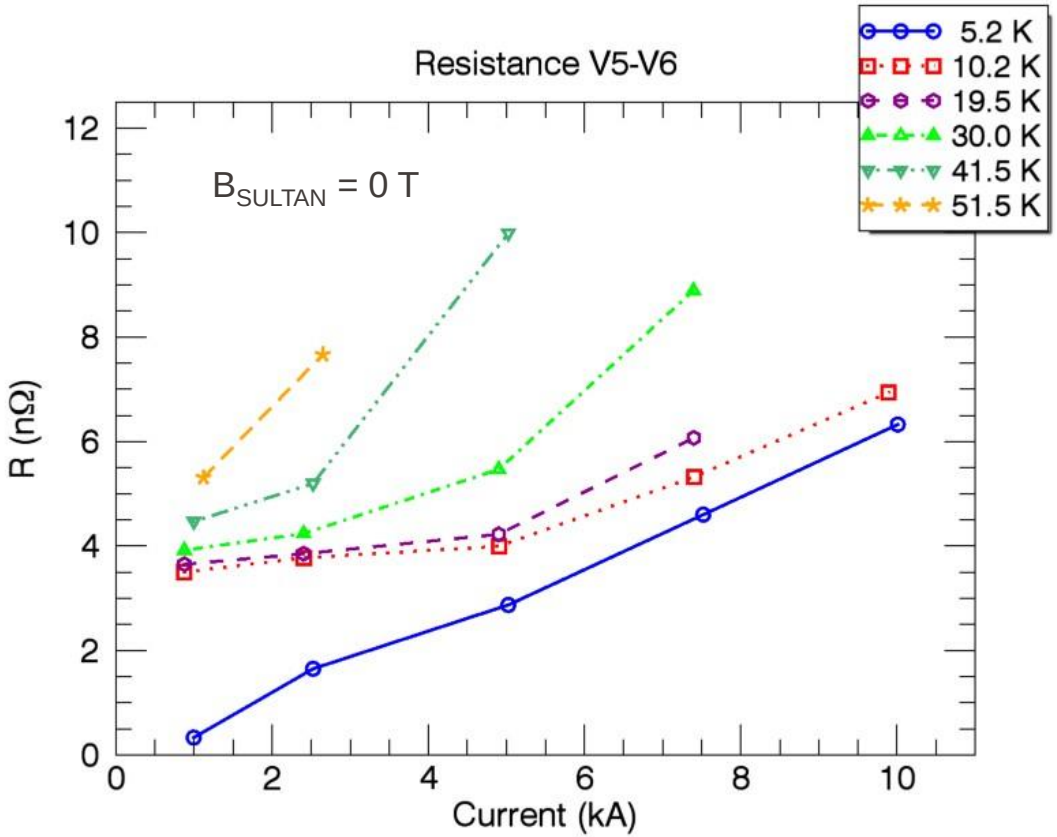


Lead extension to coil (left)



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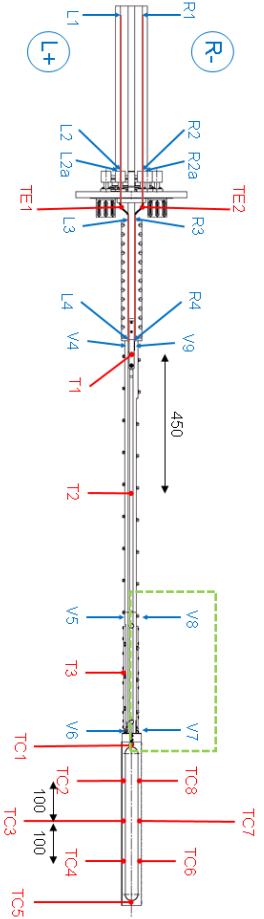
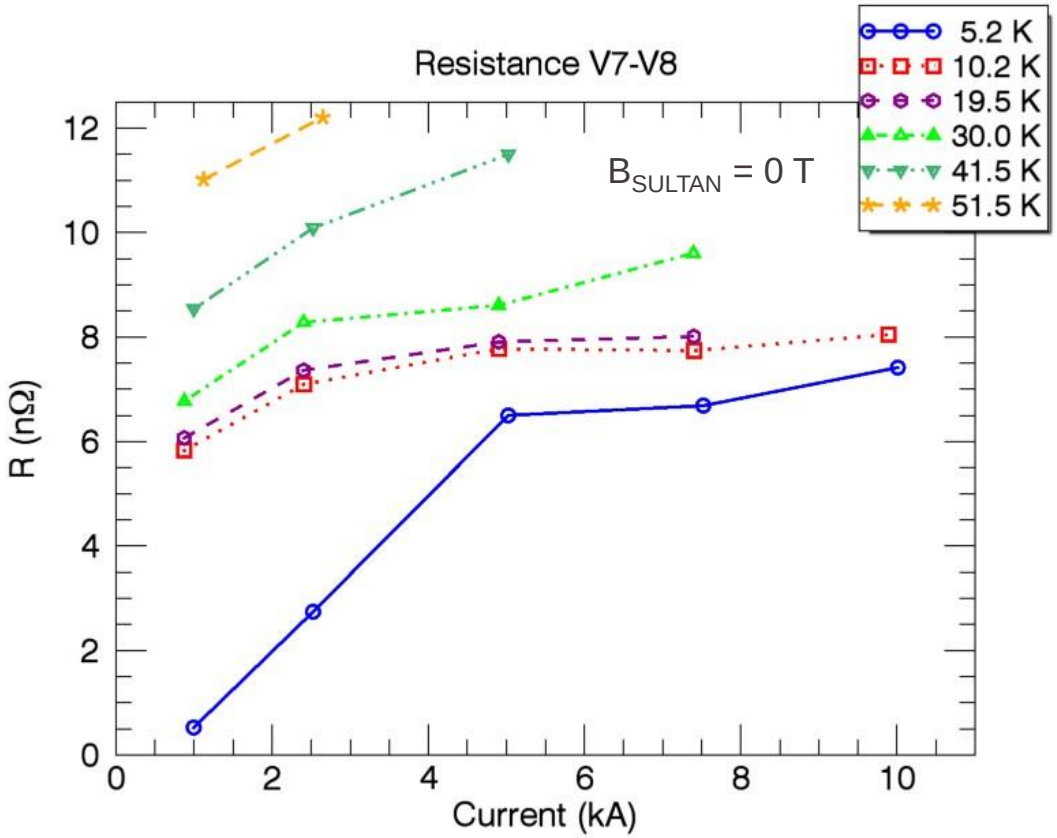
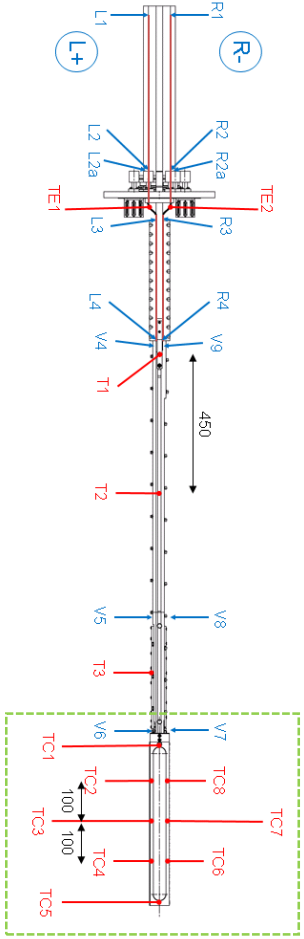


Lead extension to coil (right): off-plane lead

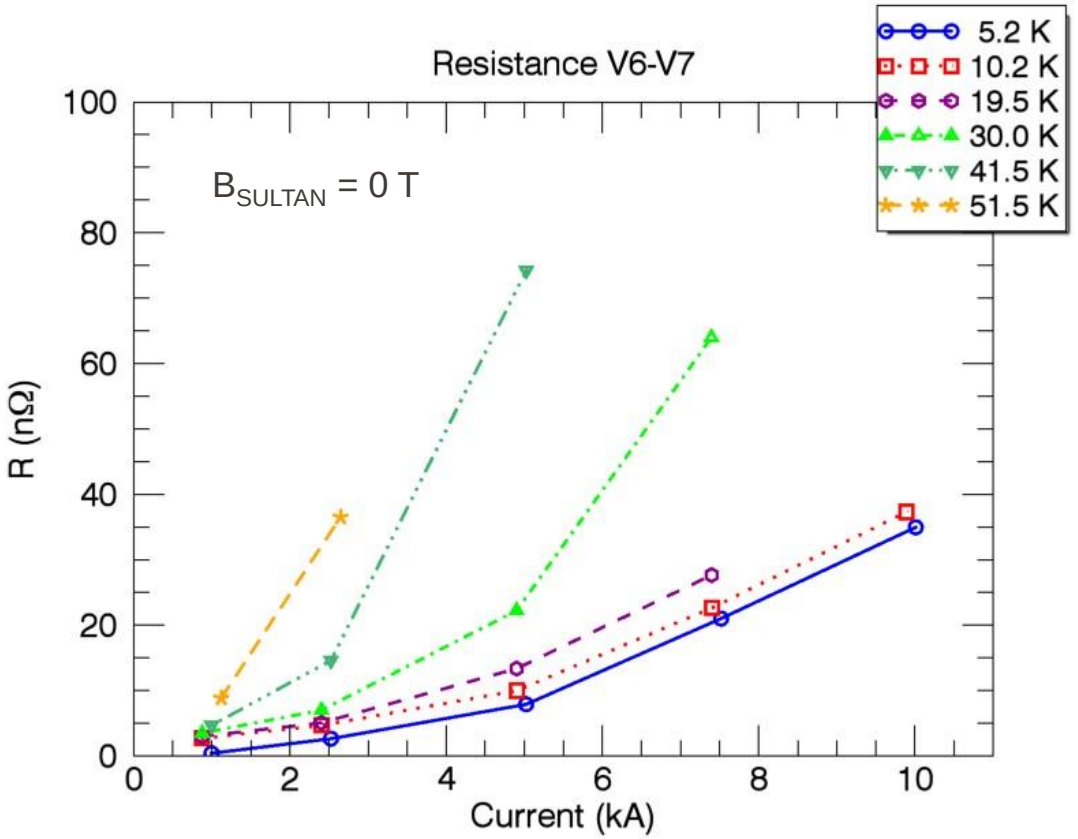


FM0.4: R across the coil

The largest contribution to R_{total} comes from the coil

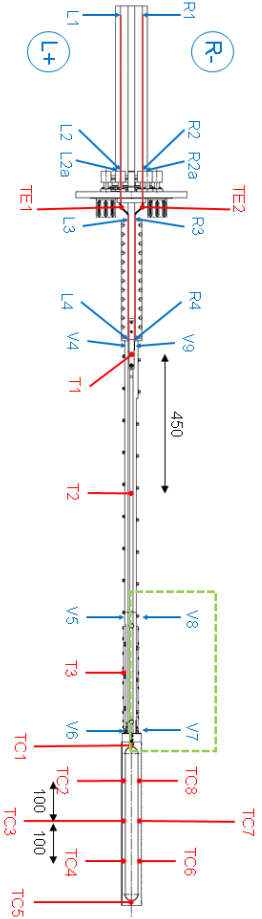


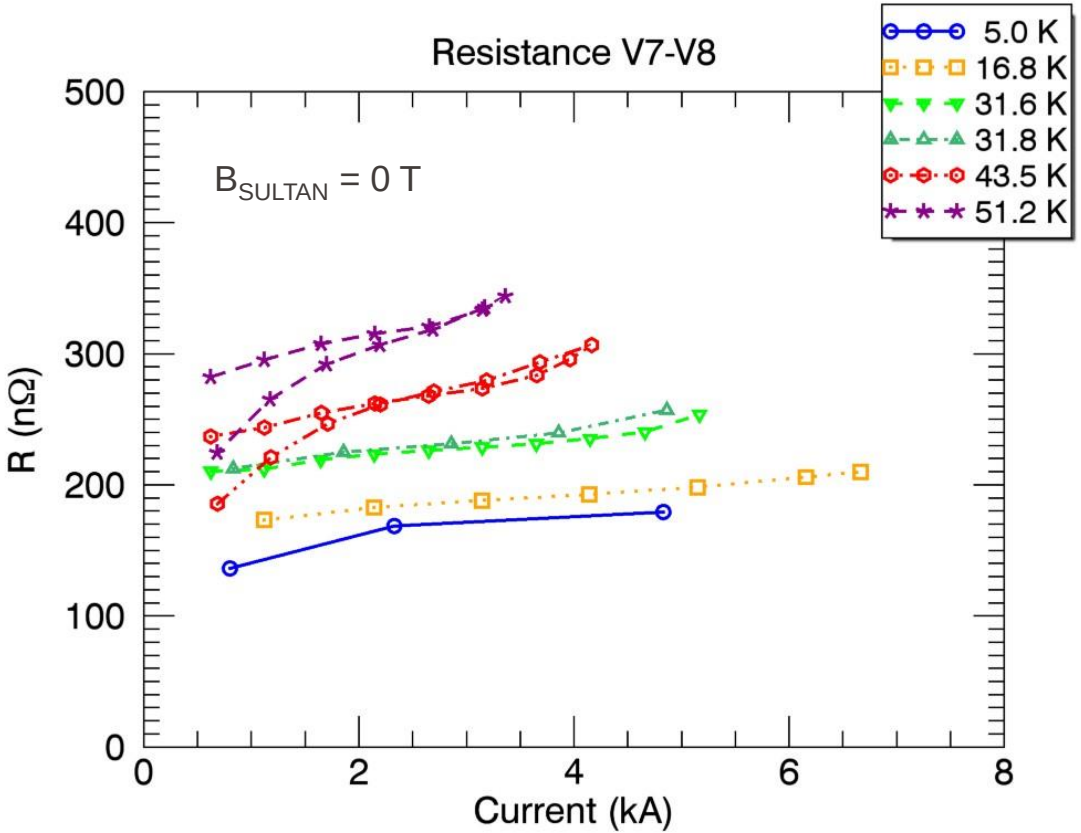
■ TEST OF THE FEATHER-M0 COILS IN SULTAN



FM0.5: Joint resistances

Similar results in **FM0.5**, but the lead-extension-to-coil resistances are more than one order of magnitude higher





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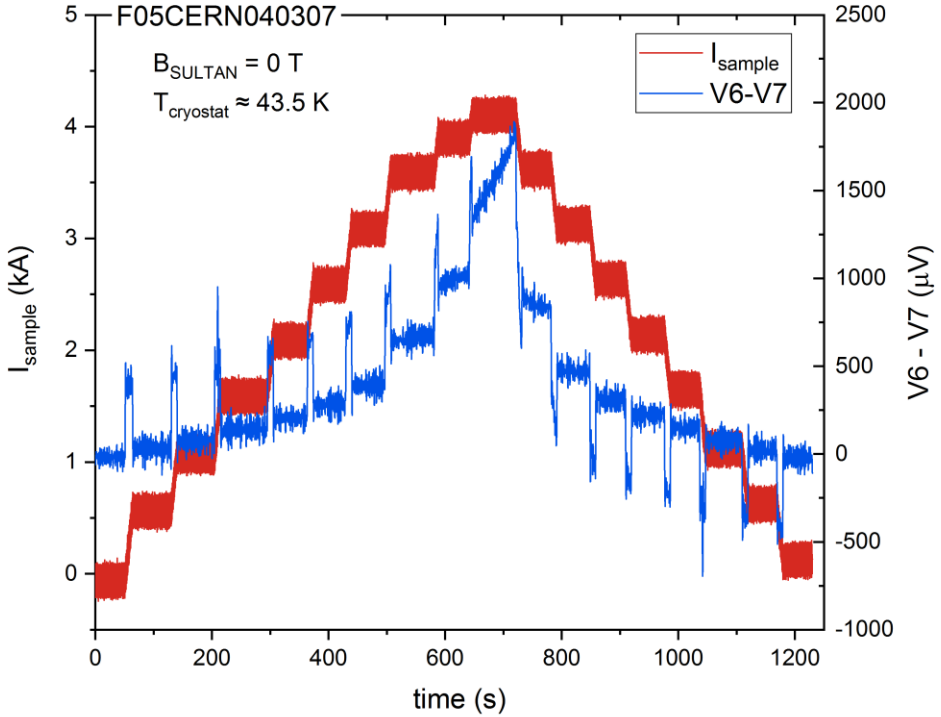
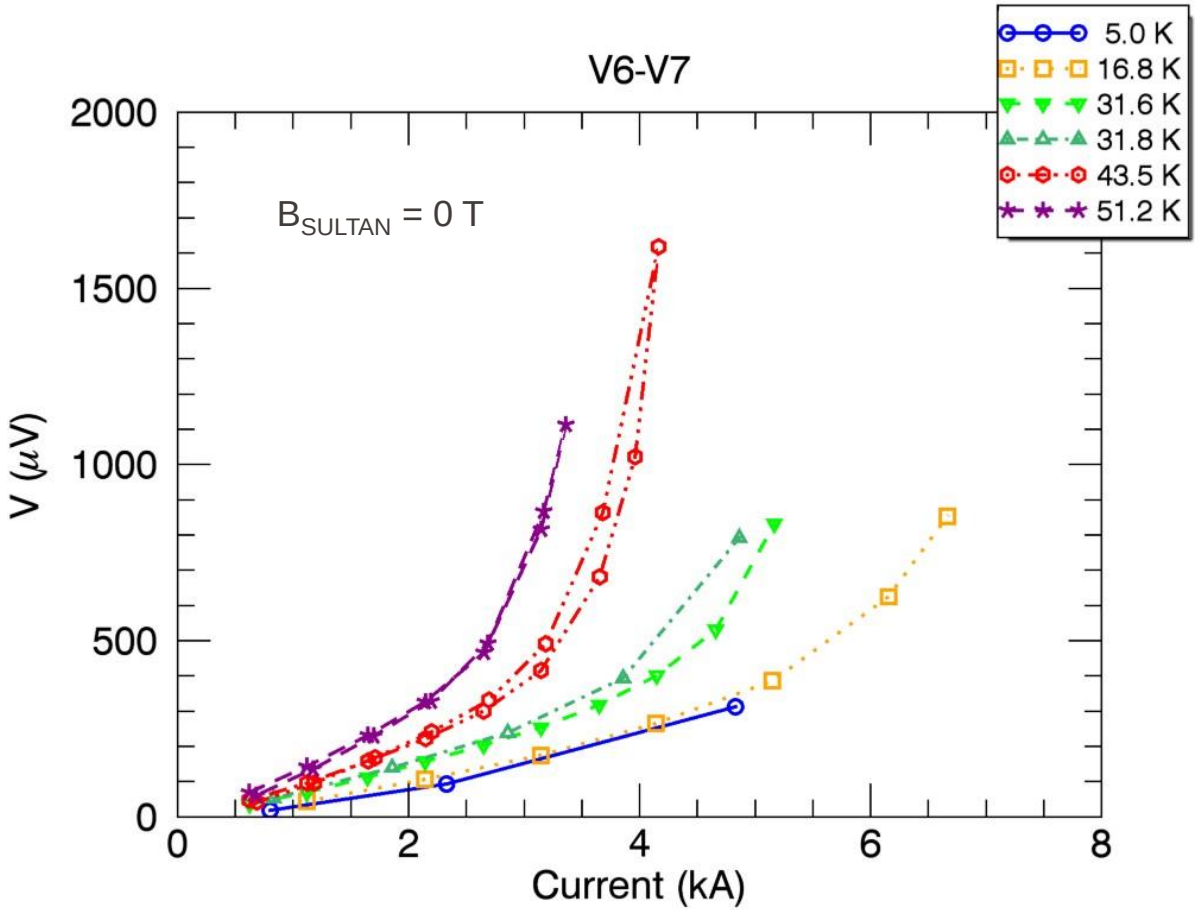
I_c measurements

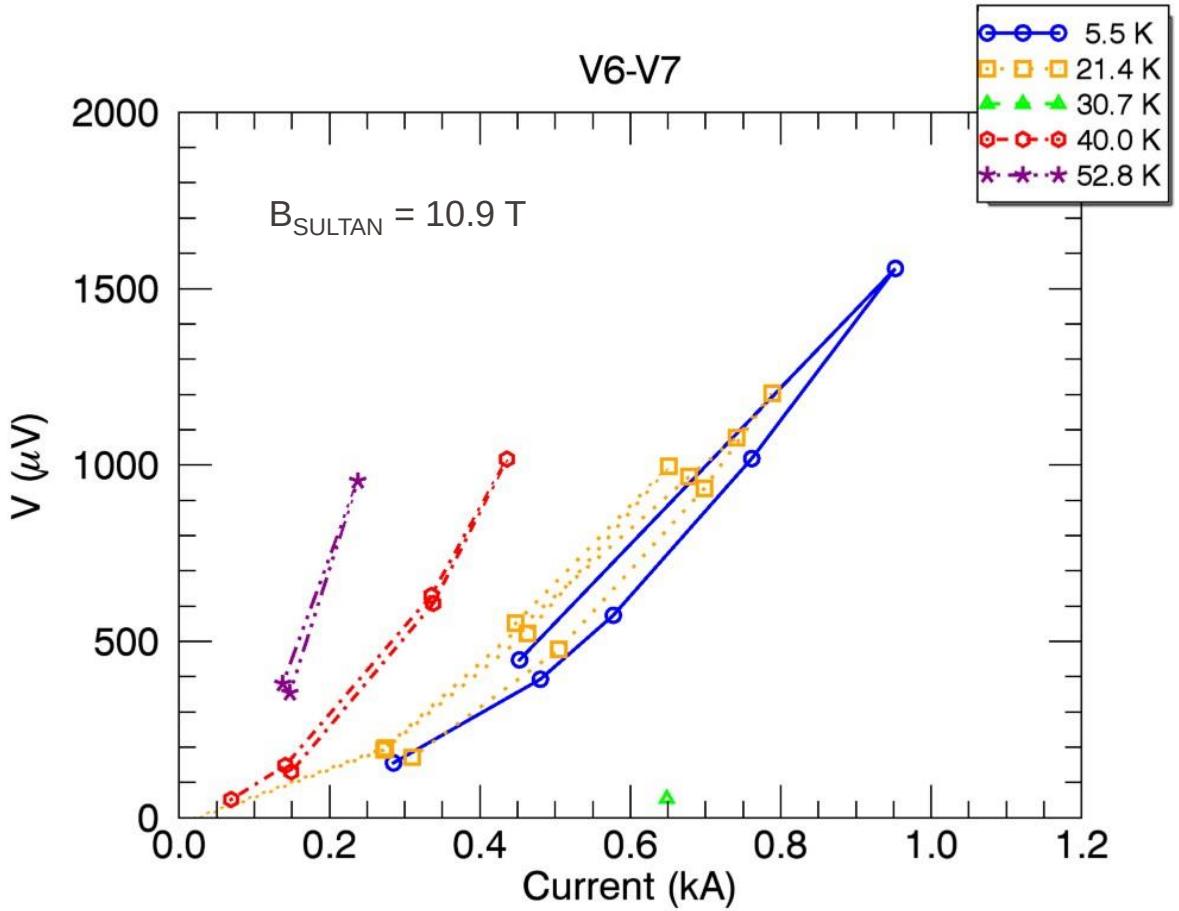
- Current is ramped up in steps until the signal across the coil starts to take off
- Then, ramped down
- Ramp rate: 50 A/s



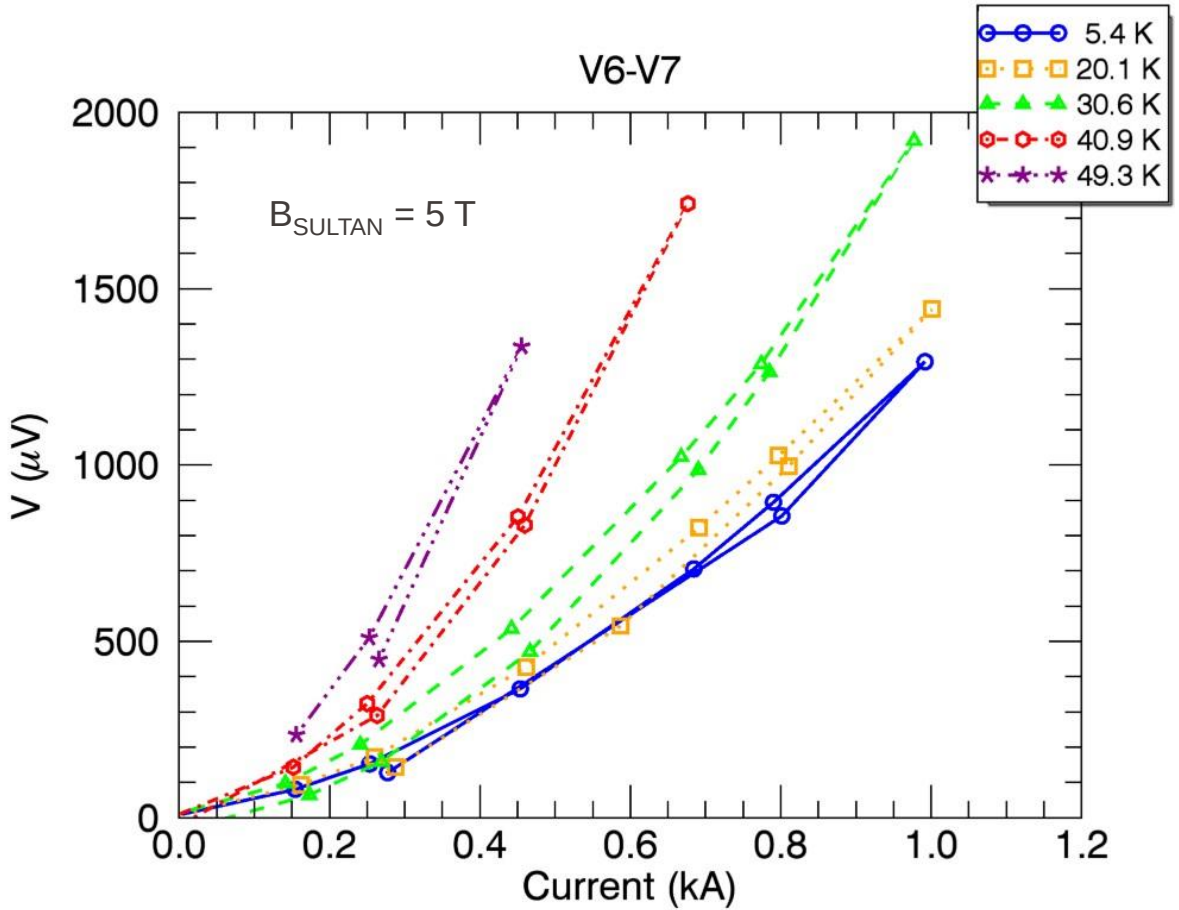
FM0.5: I_c measurements (B_{SULTAN} = 0 T)



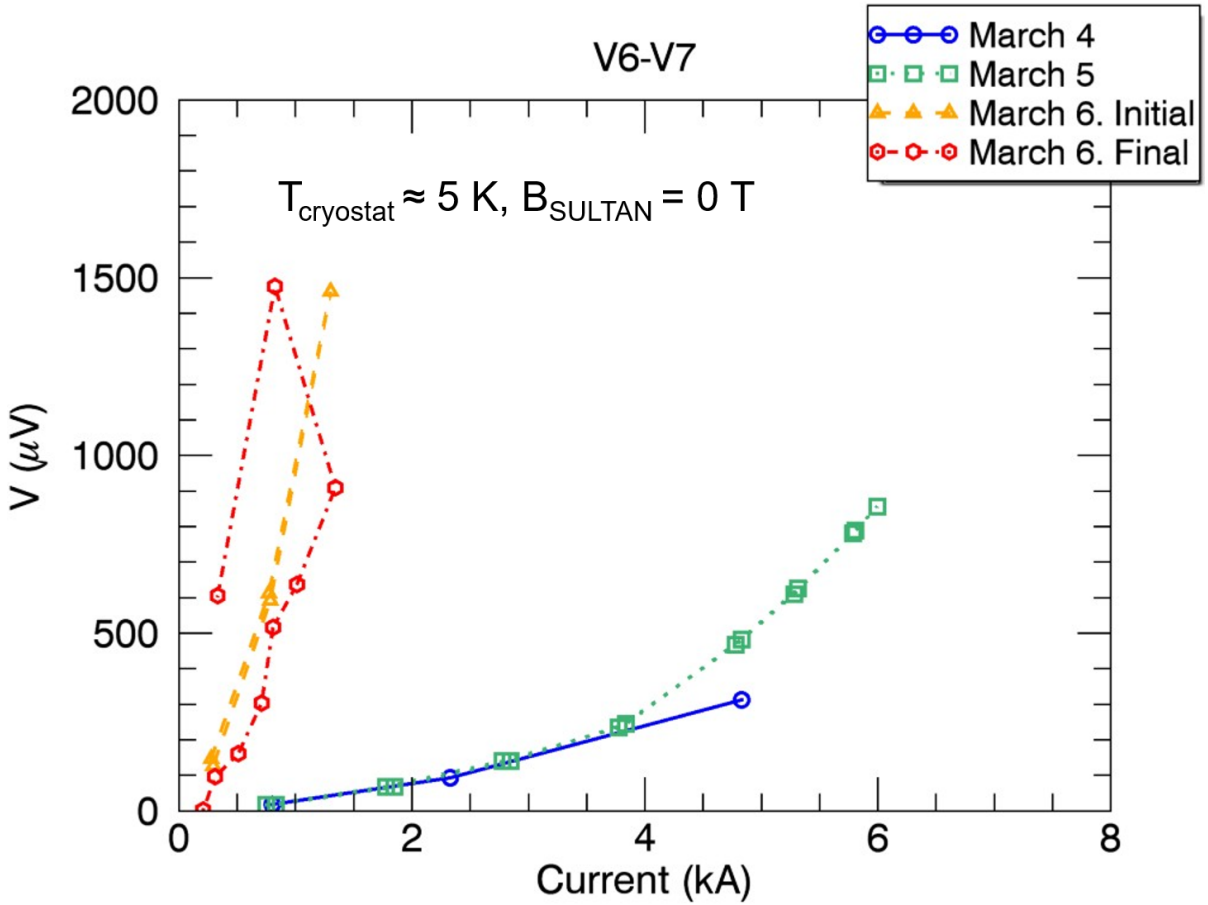
FM0.5: I_c measurements (B_{SULTAN} = 10.9 T)



FM0.5: I_c measurements (B_{SULTAN} = 5 T)

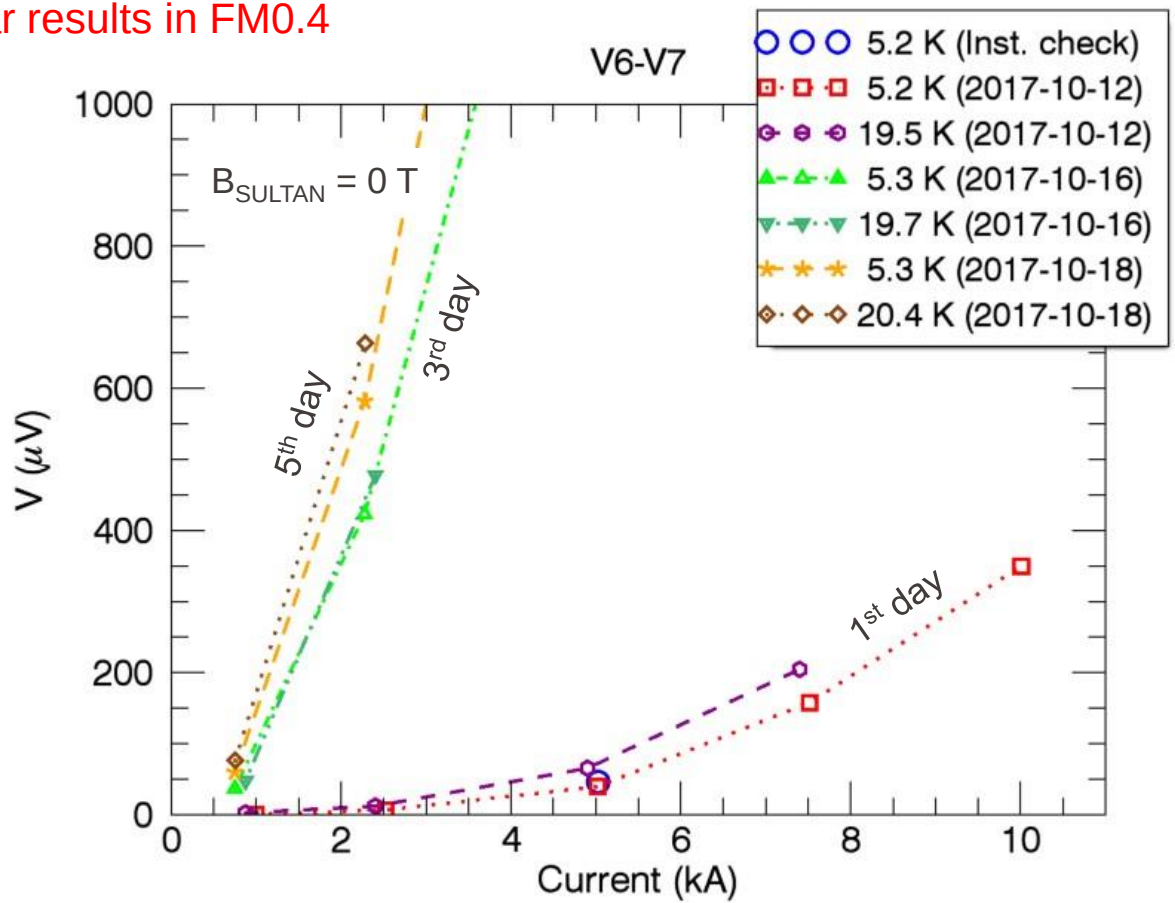


FM0.5: Degradation after tests at high field



FM0.4: Degradation after tests at high field

- Similar results in FM0.4



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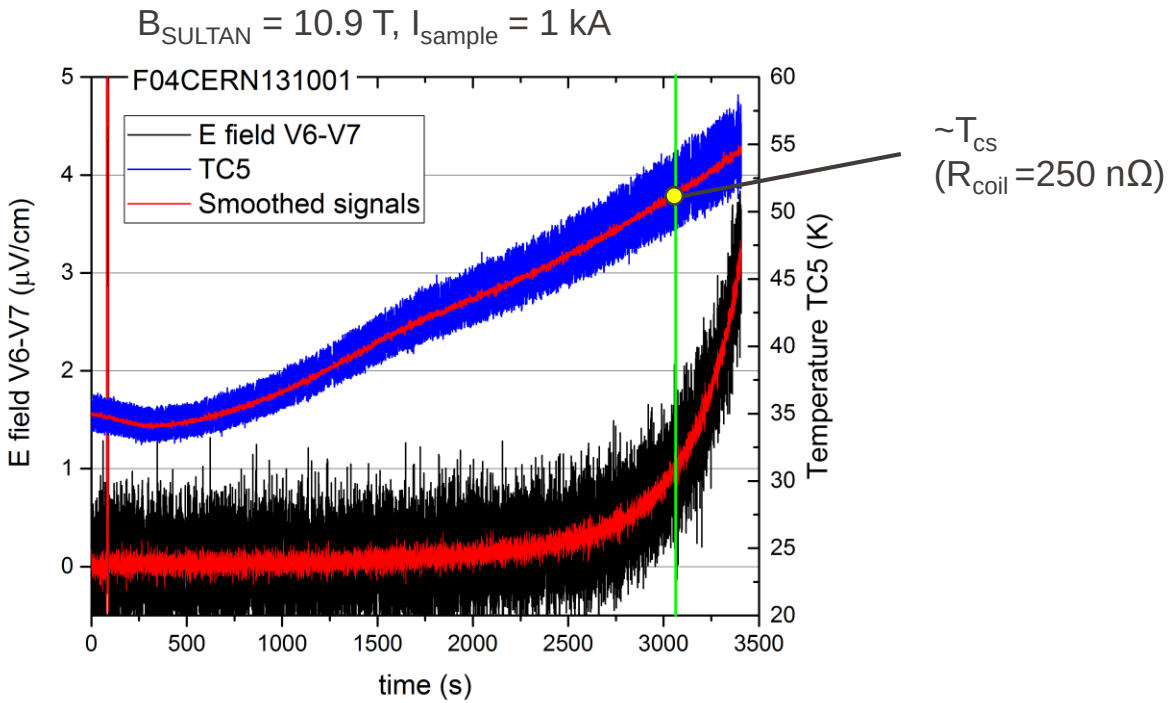
T_{cs} measurements: experimental procedure

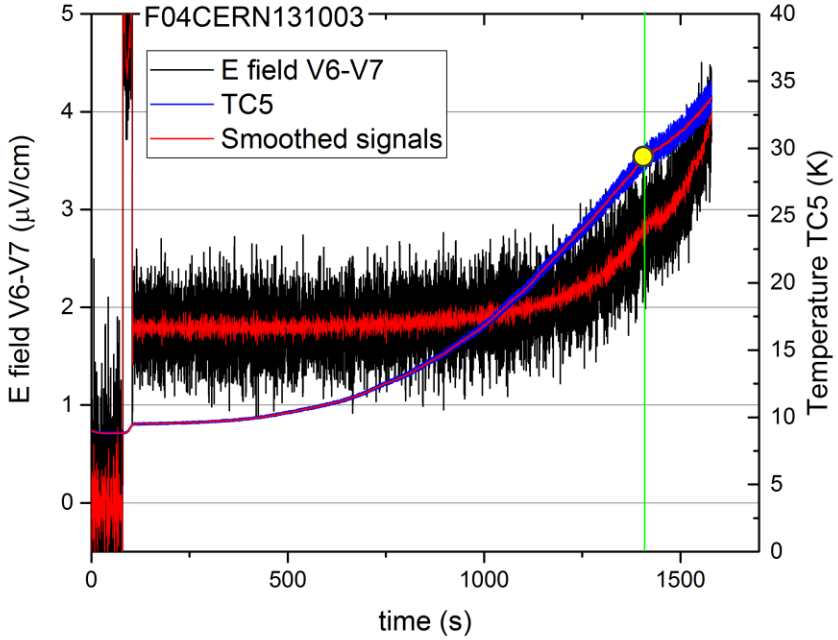
- Current is fixed and the temperature in the cryostat is slowly increased until the V signal across the coil starts to take off



T_{cs} measurements

- Unfortunately, T_{cs} measurements were not possible (neither in FM0.4 nor in FM0.5) due to the large R across the coil

B_{SULTAN} = 10.9 T, I_{sample} = 2.5 kA



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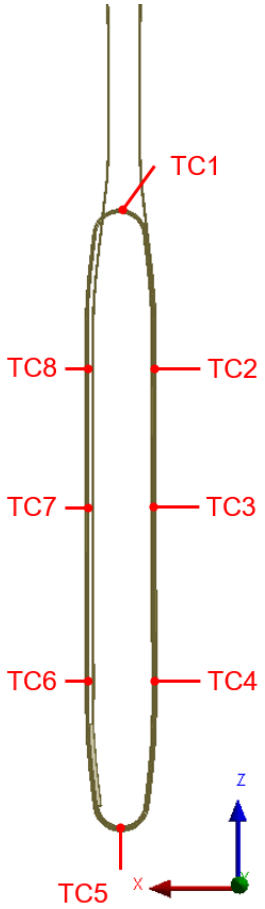
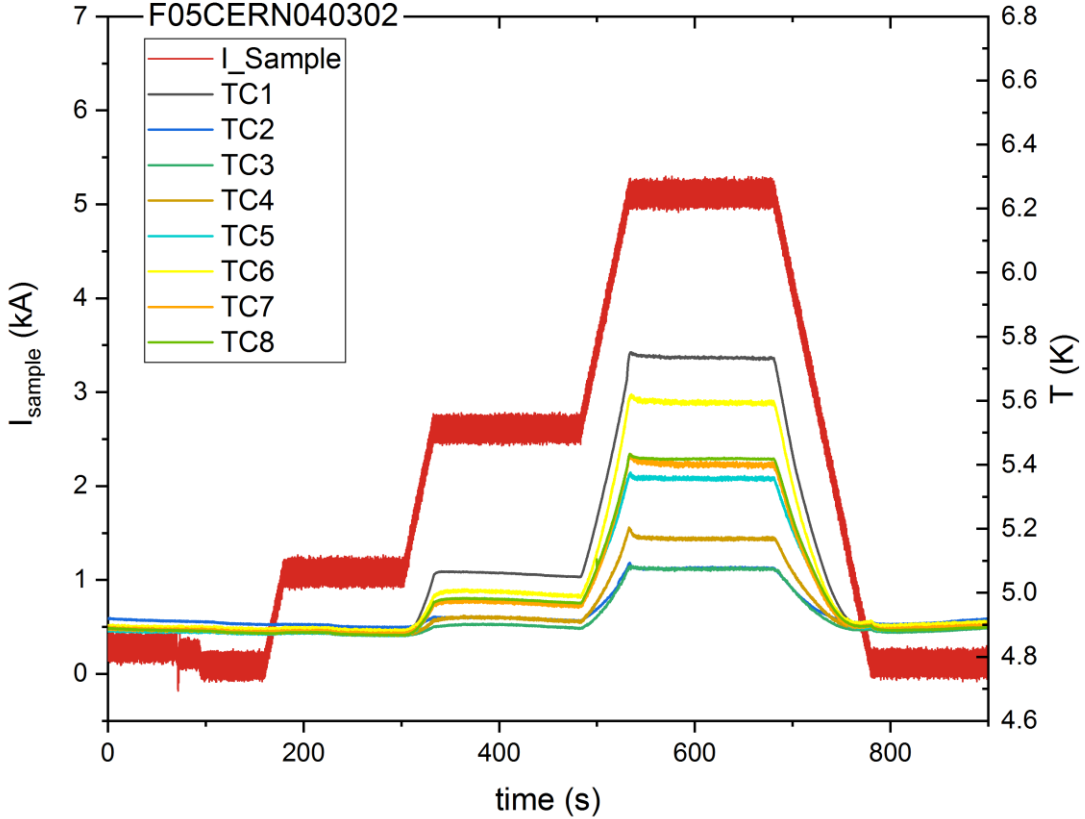
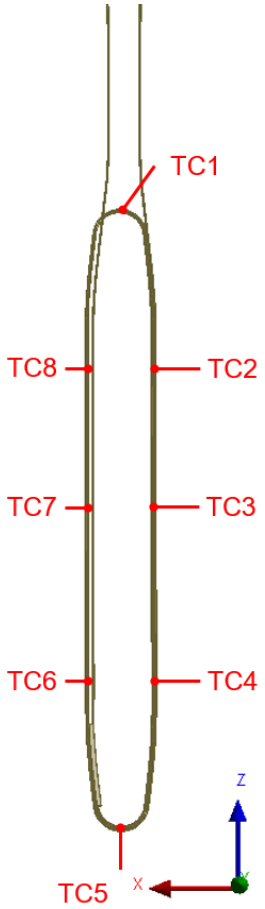
Heat generation in the coils



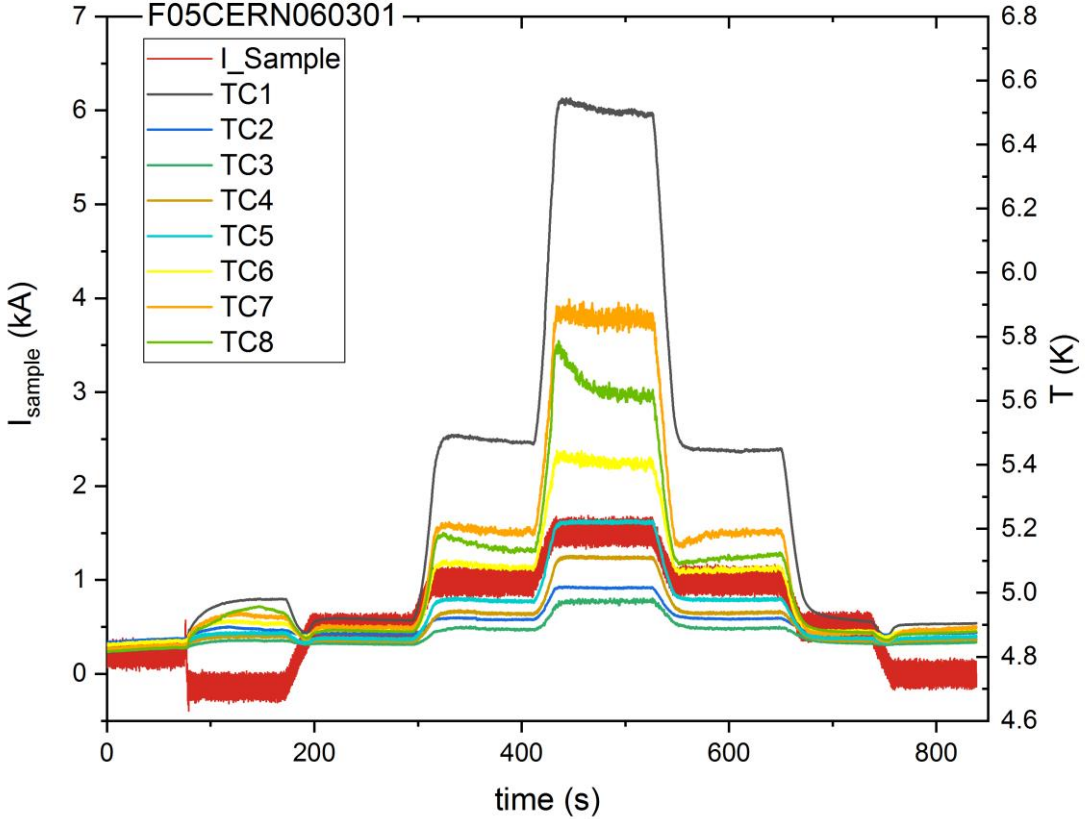
First run of FM0.5 in SULTAN (B_{SULTAN} = 0 T)



Heat generation in the coils

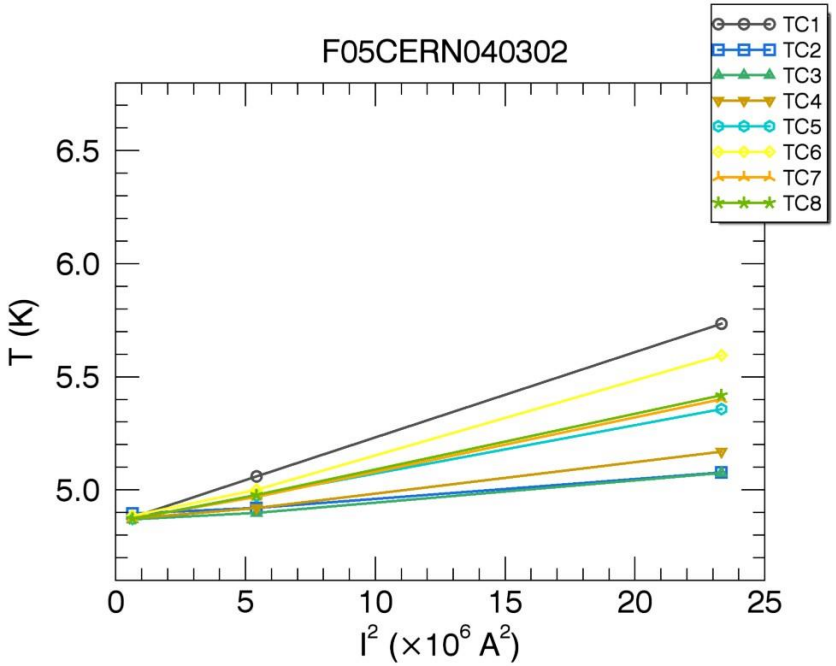


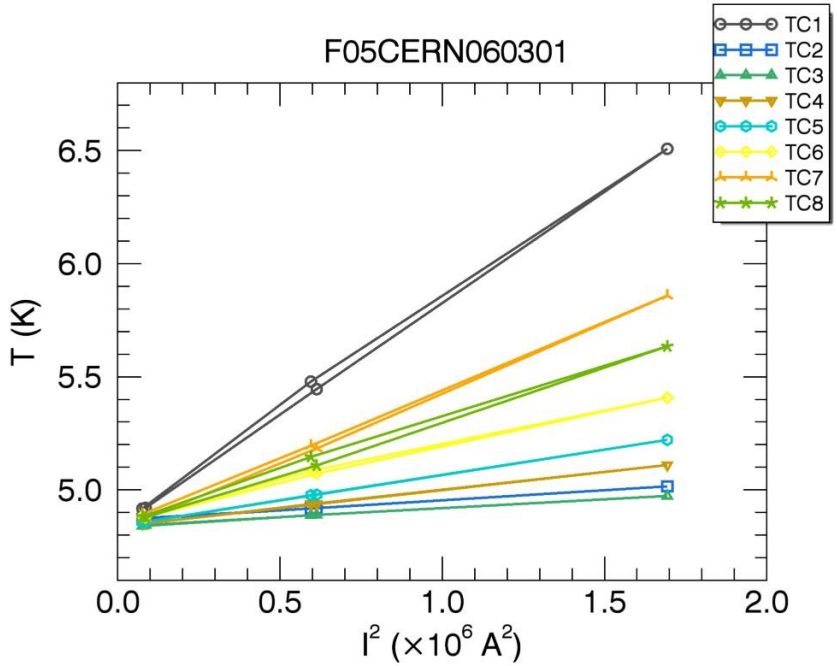
Temperature distribution after tests at high field



Heat generation in the coils

- The temperature in the coil sensors scales quite well with the square of the current





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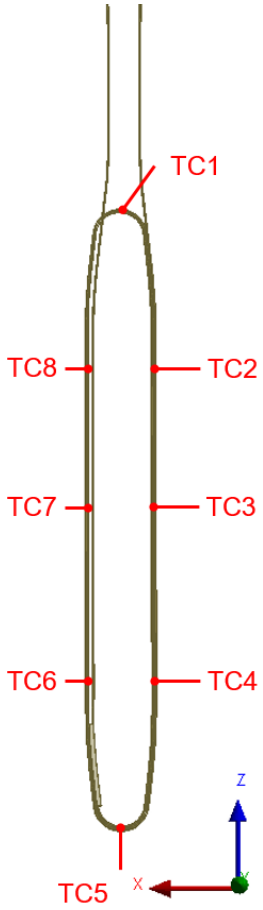
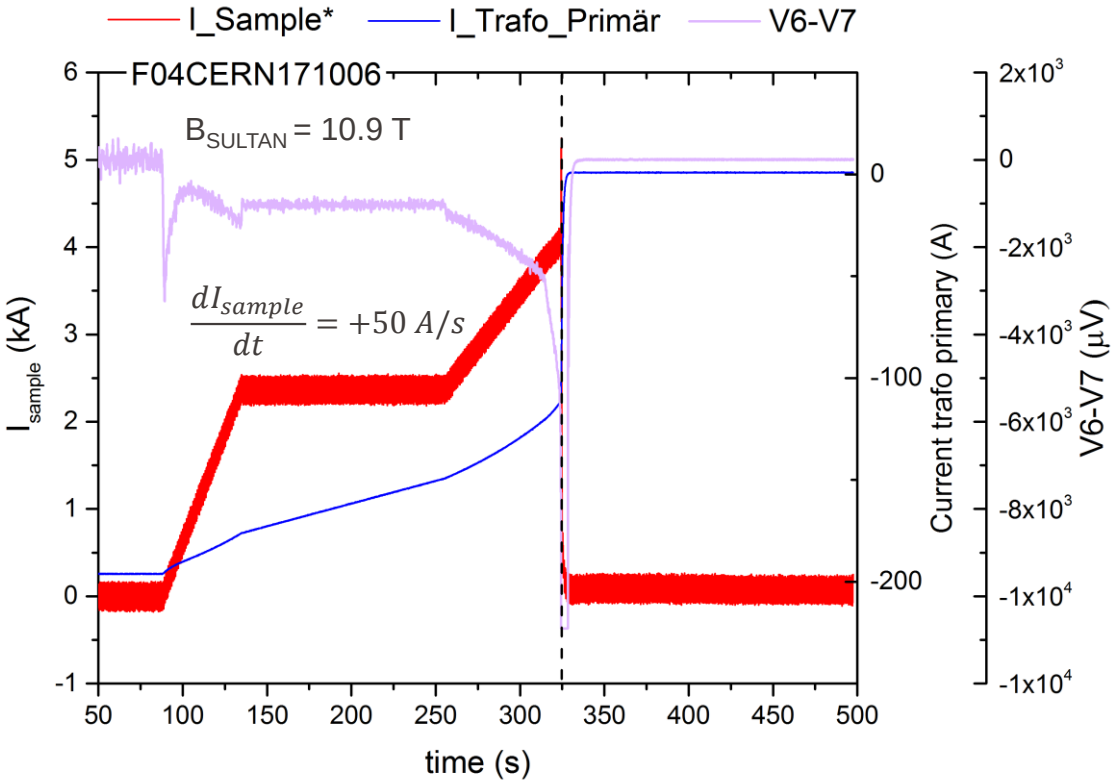
- Conclusions

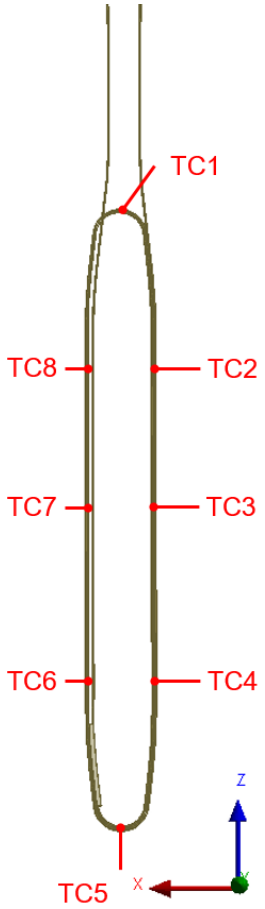
FM0.4: Quench during ramp-up

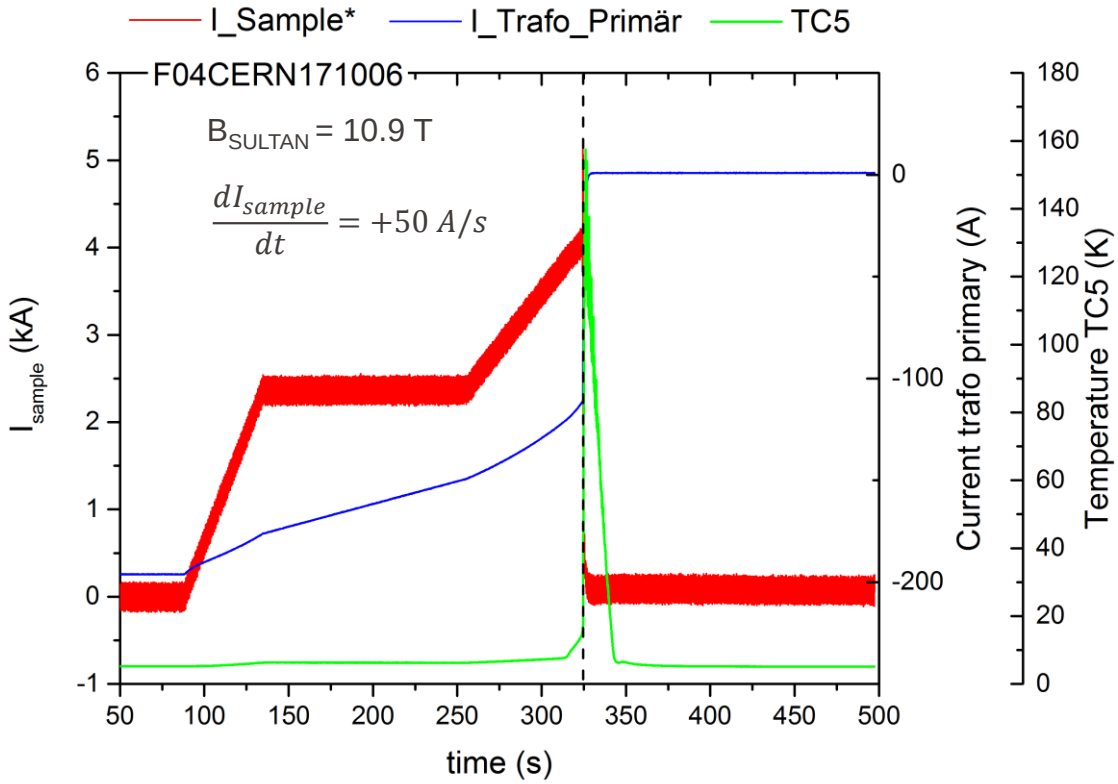




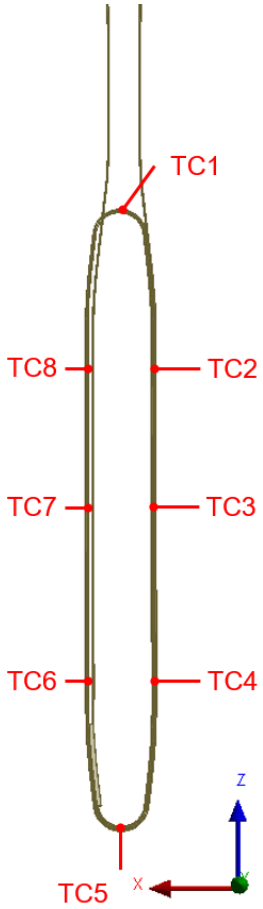
X. Sarasola

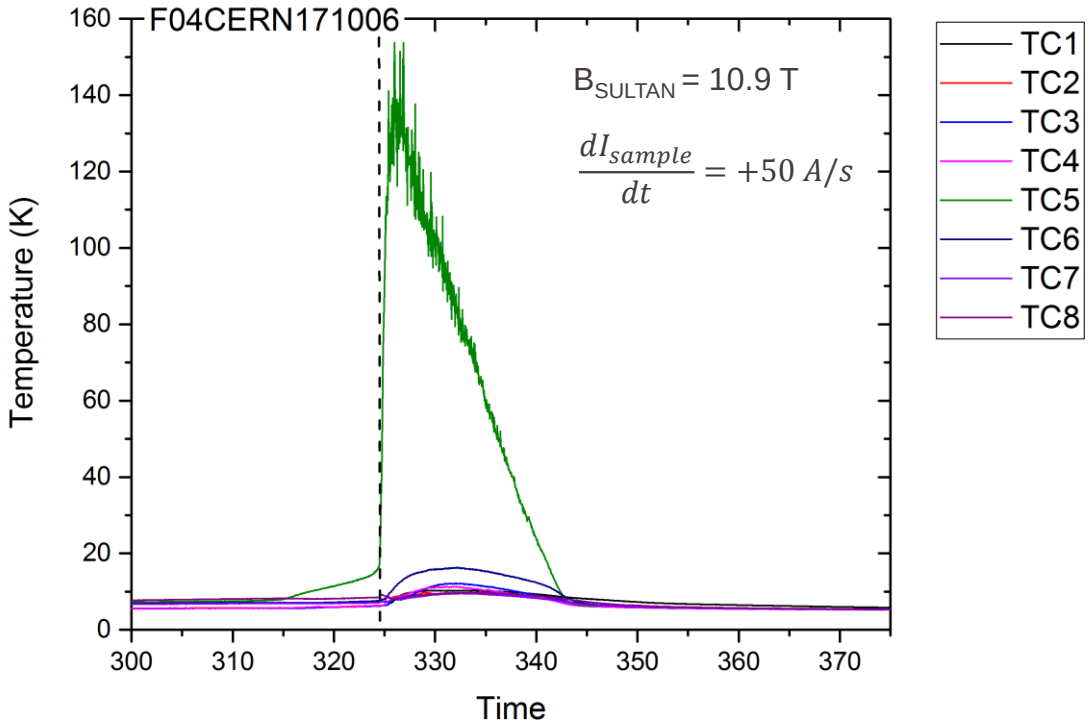
FM0.4: Quench during ramp-up



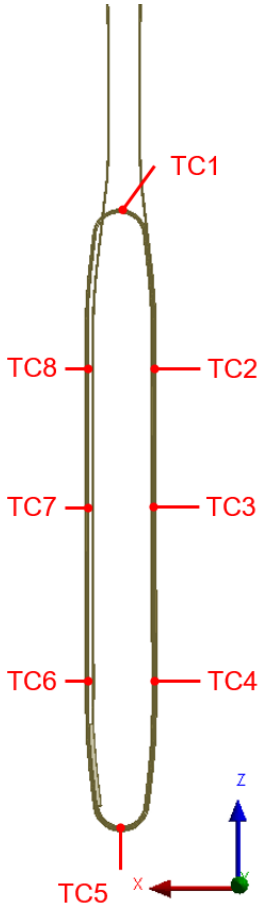


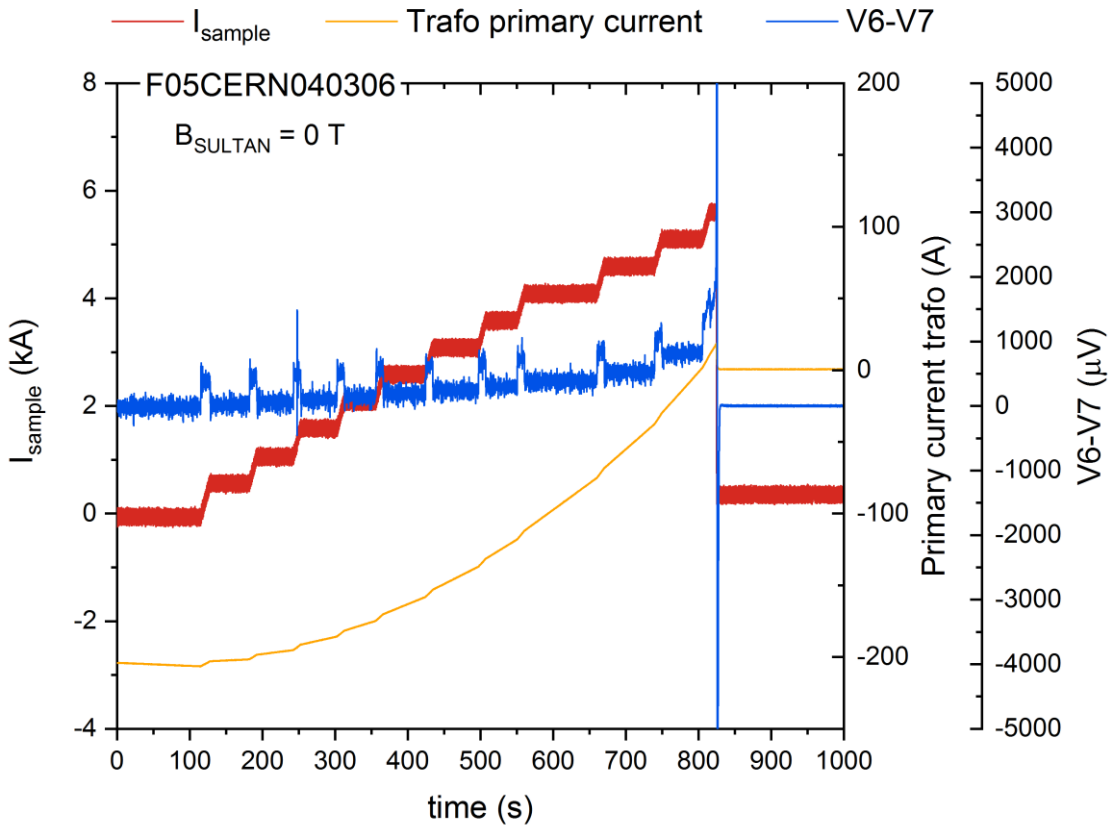
FM0.4: Quench during ramp-up



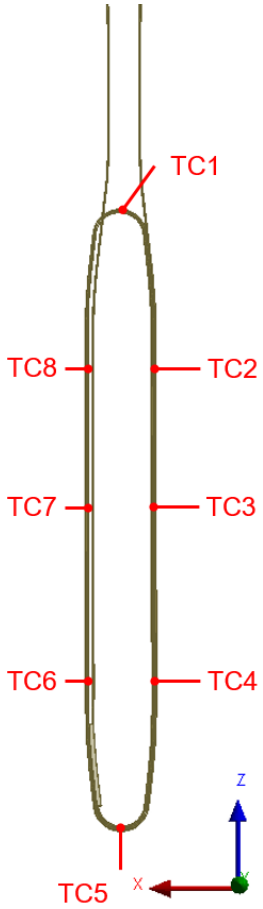


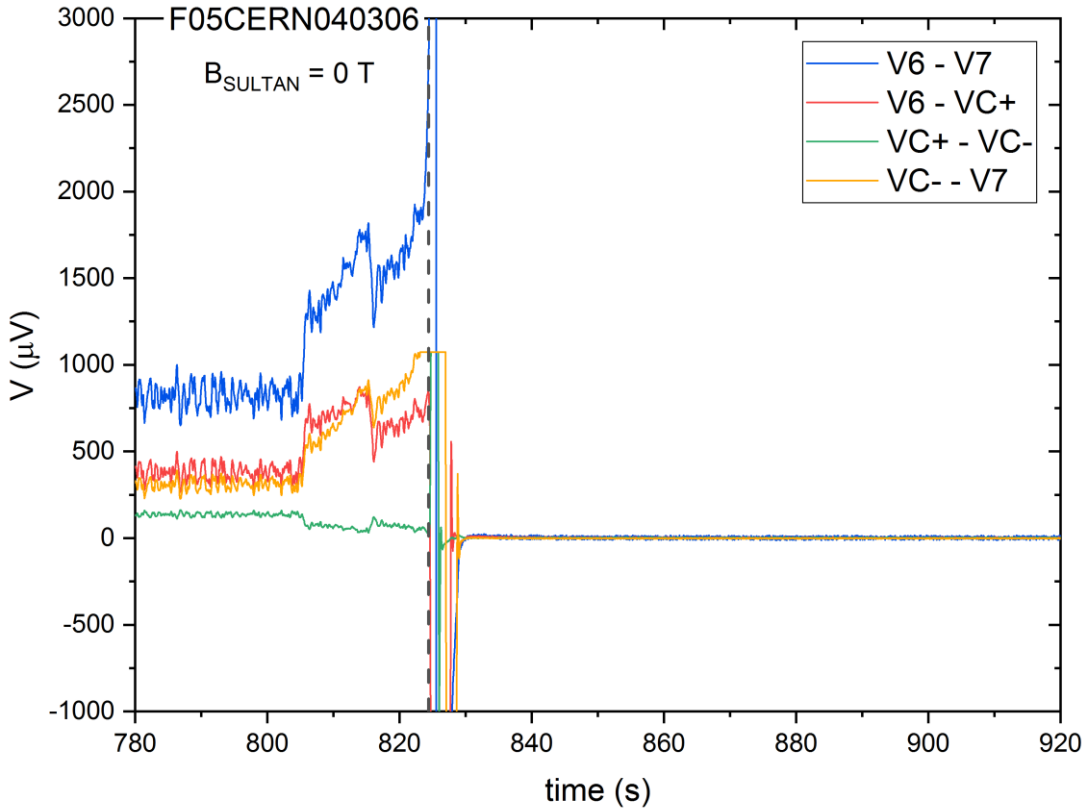
FM0.5: Quench during an I_c run



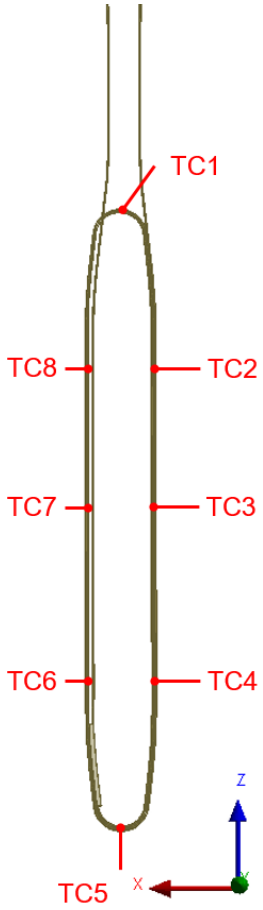


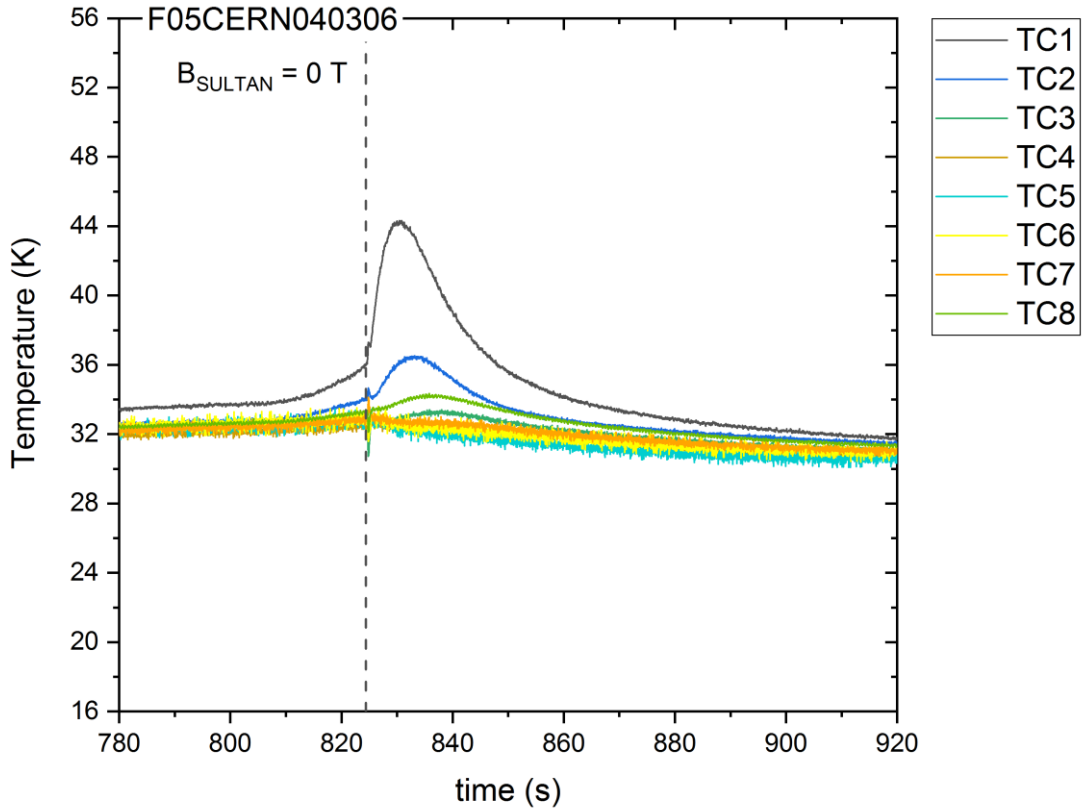
FM0.5: Quench during an I_c run



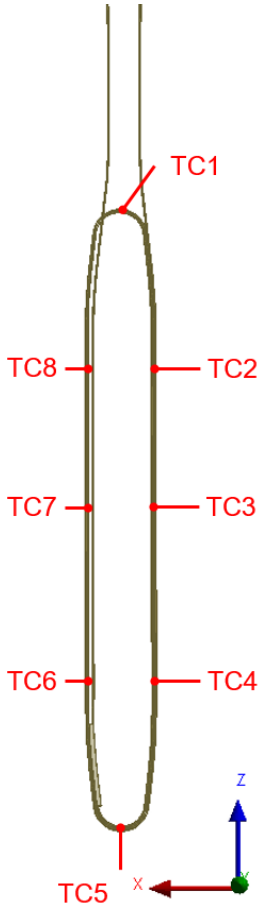


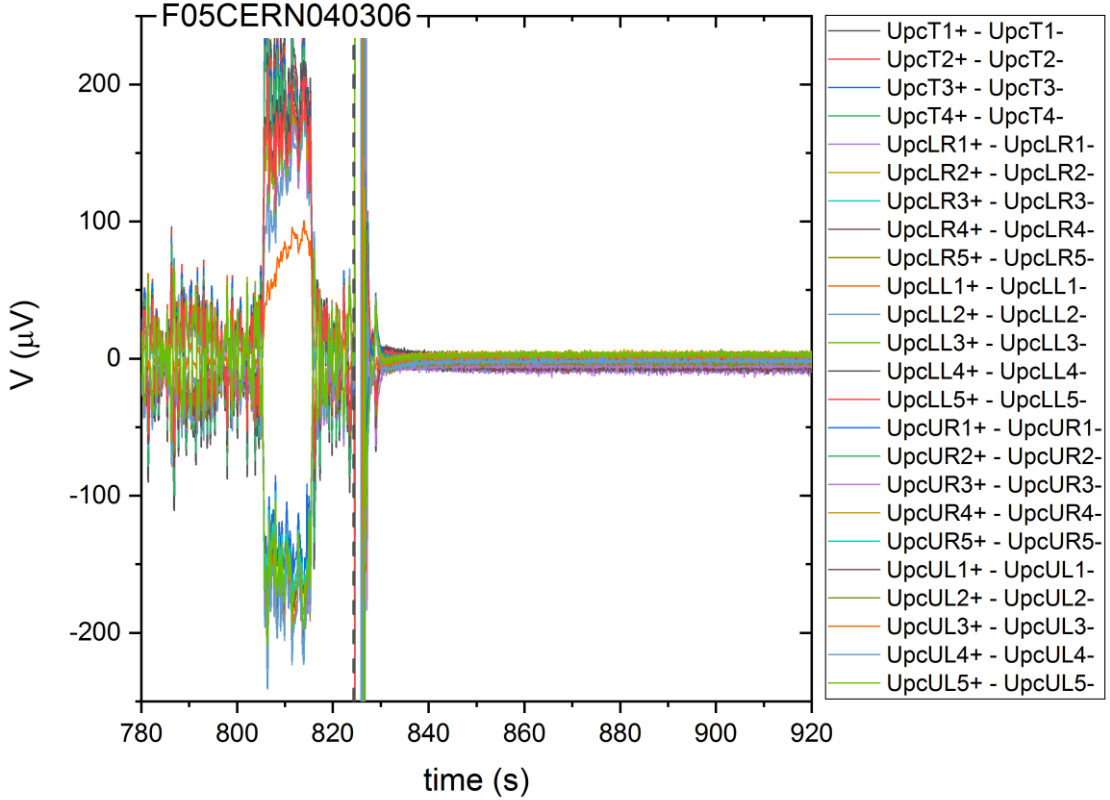
FM0.5: Quench during an I_c run



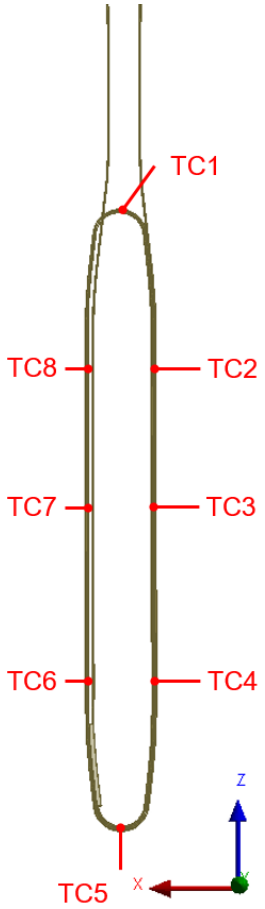


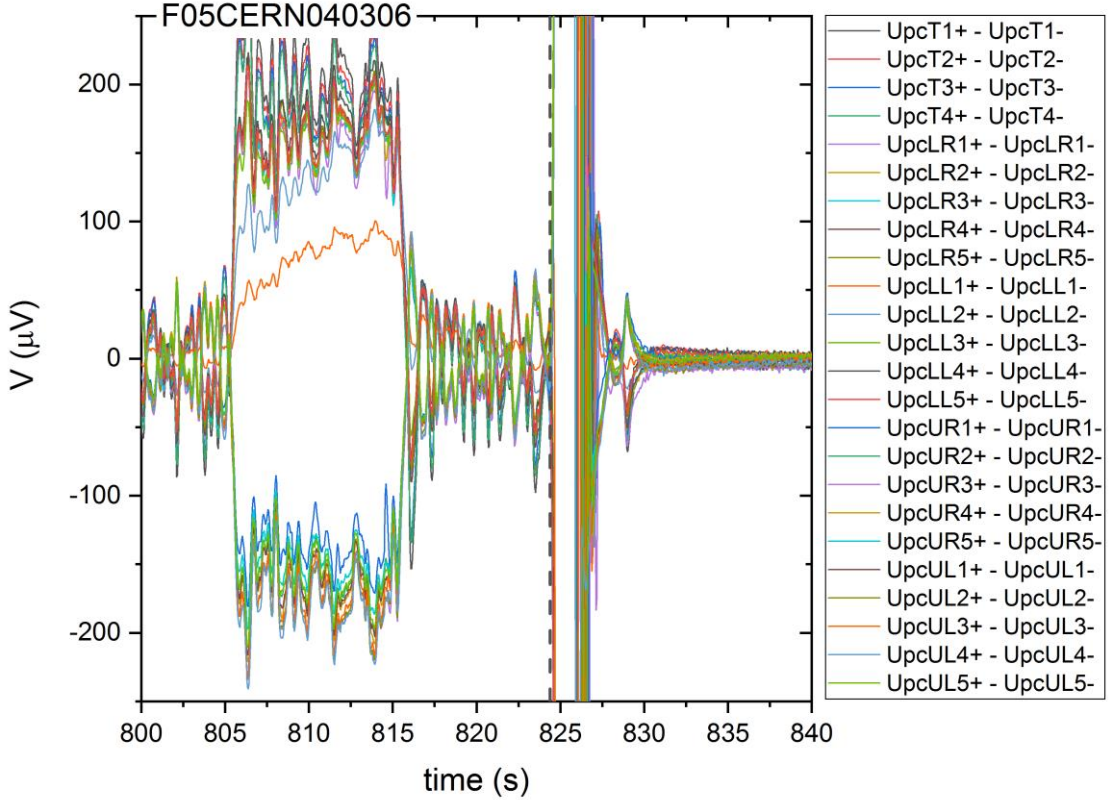
FM0.5: Quench during an I_c run





FM0.5: Quench during an I_c run





Outline

- SULTAN test facility
- FeaTHeR M0 coils
- Required upgrades
- Test results:
  - Coil instrumentation and cryostat
  - Joint resistances
  - I_c measurements
  - T_{cs} measurements
  - Heat generation in the coil
  - Quench data
- **Conclusions**

Conclusions

- **SULTAN** has been upgraded to test of **accelerator-relevant samples**:
  - Cryostat inner diameter: **83.7 mm**
  - Background field of **10.9 T**
  - Variable temperature: **4.8 - 50 K** (uniform in the high field zone)
  - Sample current: **20 kA @ 4.8 K – 9.5 kA @ 50 K**
- **Two HTS demonstrator coils** (FM0.4 and FM0.5) were among the first accelerator samples **tested** at **variable temperature** and **high magnetic field** in SULTAN.
- Both **tests** were **limited** by the **apparent resistance across the coil**, which **increased** dramatically after the tests at **high field**.
- **Coil-to-lead resistance** was also a **few hundred nΩ** in the coil **FM0.5**:
  - Preliminary inspection suggested that the orientation of the ceramic side of the tapes might not be always on the same side of the Roebel.
- **Heat generation** is observed inside both coils since the very first runs.