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CHART
Swiss Accelerator Research and Technology

Michael Daly presenting on behalf of PSI Team & CERN SM18
(inputs from Franco Mangiarotti)

Summary of Test Campaign of PSI's Nb3Sn CCT 'CD1' Accelerator Magnet

This work was performed under the auspices and with support from the Swiss Accelerator Research and Technology (CHART) program

01/03/2023

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  - PSI's CCT Goals
  - CD1 Overview

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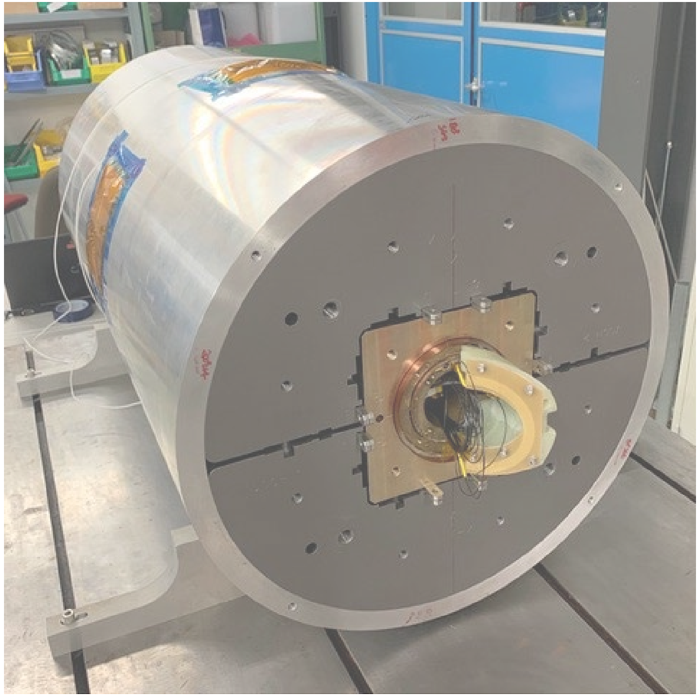
    - Spot heaters
    - Resistance and RRR
    - Concluding remarks

- Looking ahead at PSI/CHART



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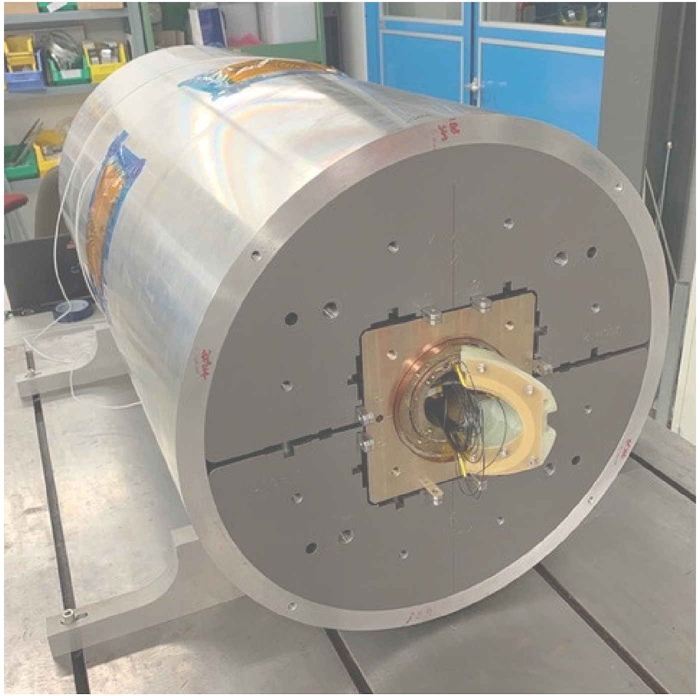
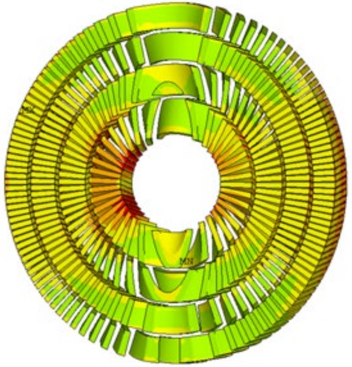
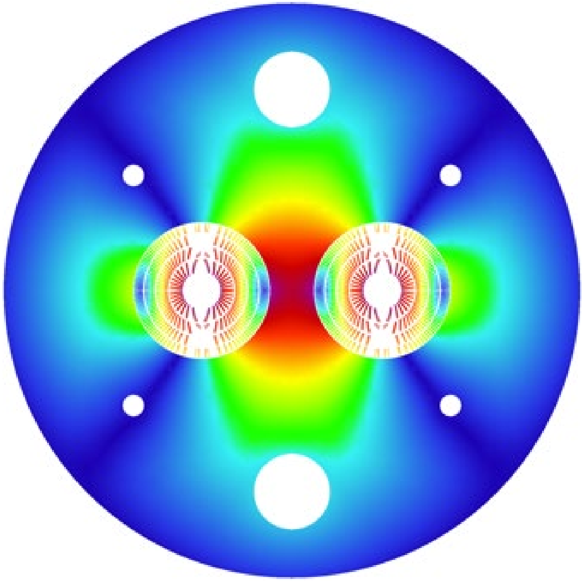
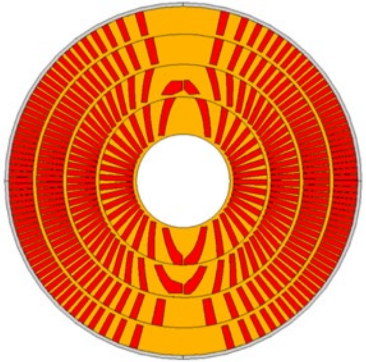


PSI CD1 Background

- CHART1 goals (mid-2016 to mid-2019) :
  1. The design of an optimised 16 T Canted Cosine Theta (CCT) dipole magnet, as an option for the FCC hadron collider main magnet;
  2. The development (design and prototype) of a high-field dipole magnet with CCT technology and a 90 m^2 lab.



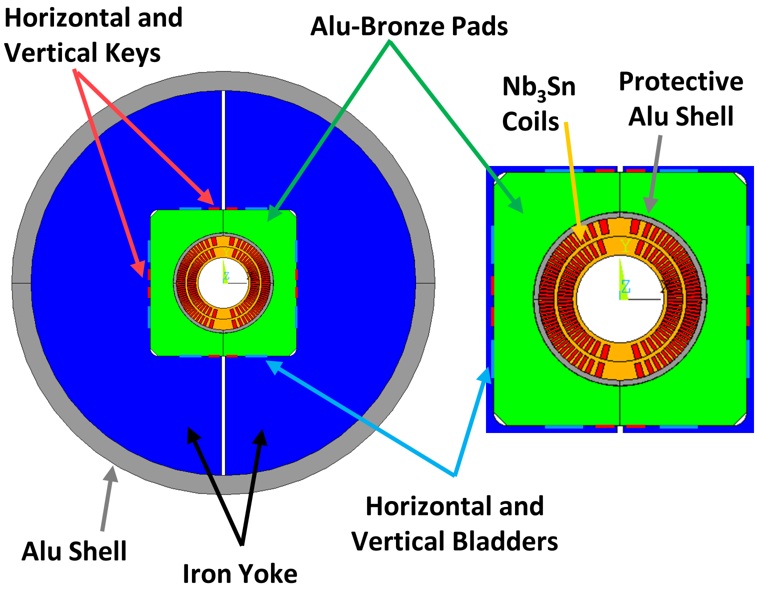




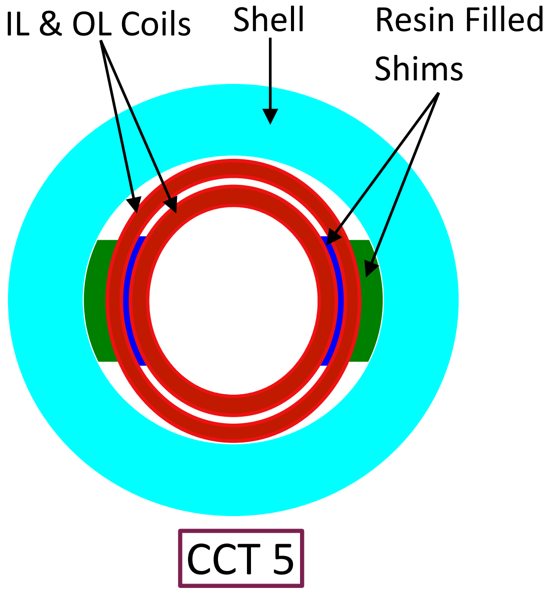
B. Auchmann et al., *Electromechanical Design of a 16-T CCT Twin-Aperture Dipole for FCC*, IEEE Trans. on Appl. SC 28 (April, 2018) no. 3.

CD1 Overview

- Design of CD1 done in collaboration and support from LBNL.
- Can be compared to some extent with LBNL's CCT 5 (Conductor supplied by LBNL, Resin…)
- Instrumentation: Strain gauges, vtaps, x4 acoustics sensors (Maxim's design)



	CD 1	CCT 5
Cable	21 QXF strand, 0.85 mm, RRP 108/127	
Resin	FSU's Mix 61	
Former	Aluminium Bronze	
Pre-stress	Bladder & keys	Bend & Shim
Layer interface	Sliding plane	Spars and Alu Shell
Potting	Coil Assembly	Individual layers
Inner Bore [mm]	63.6	90



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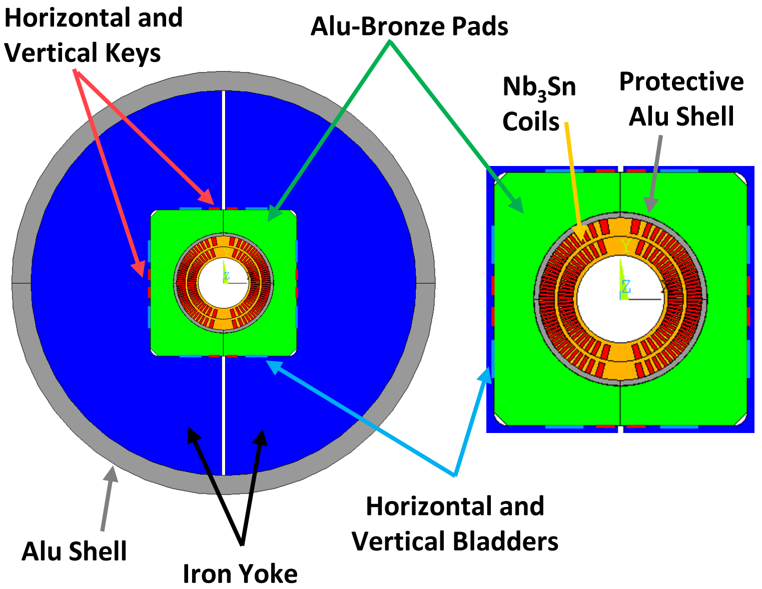

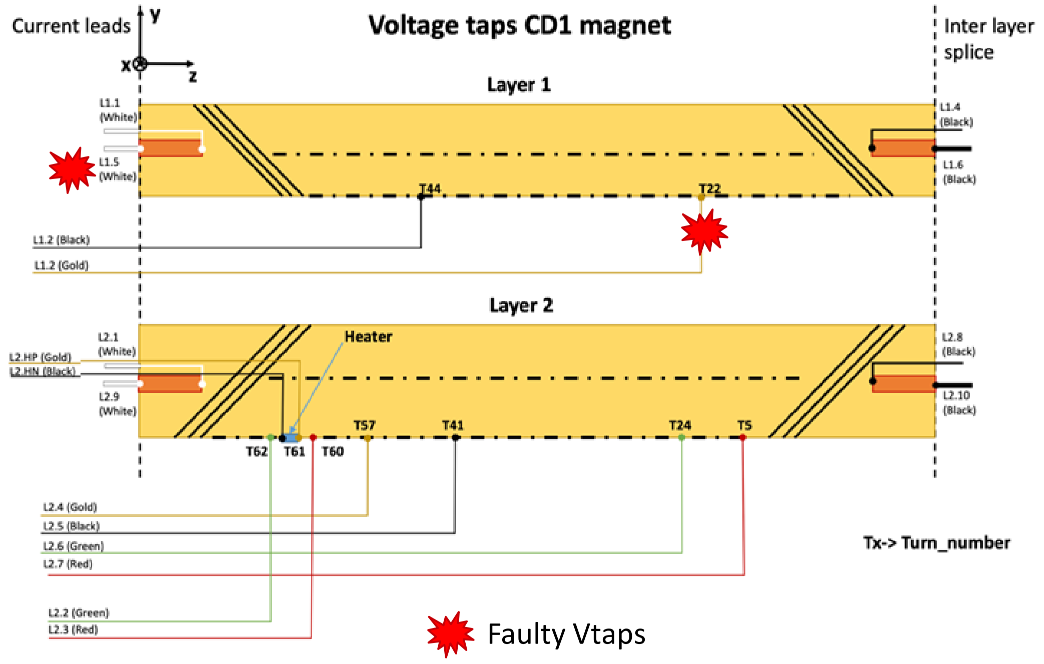

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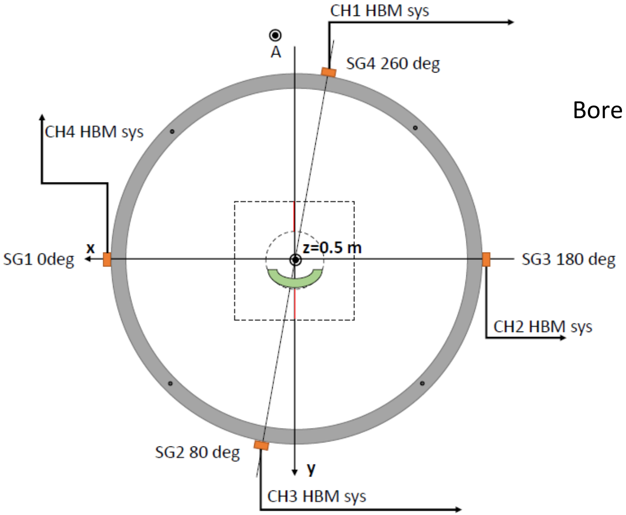
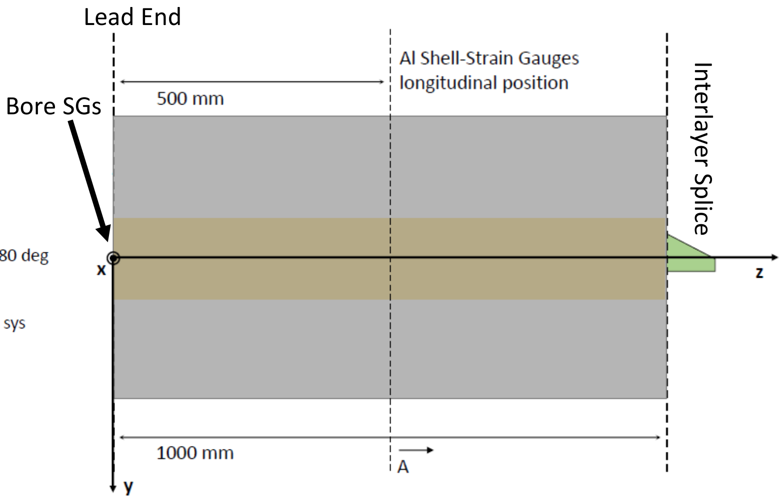
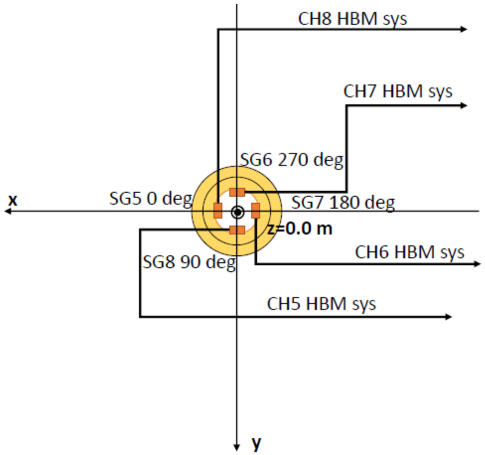
Alu Shell Strain Gauges





Bore Strain Gauges



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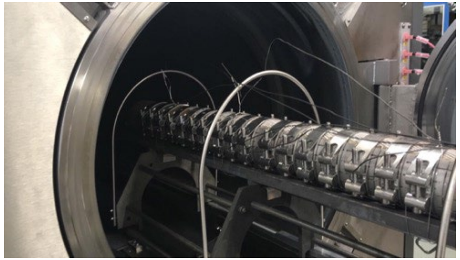
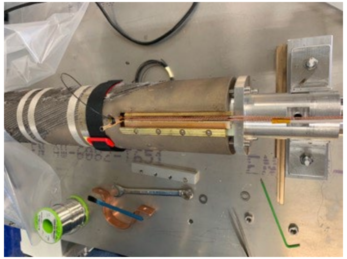
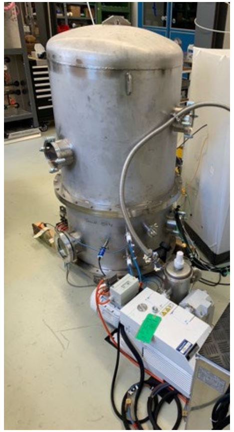
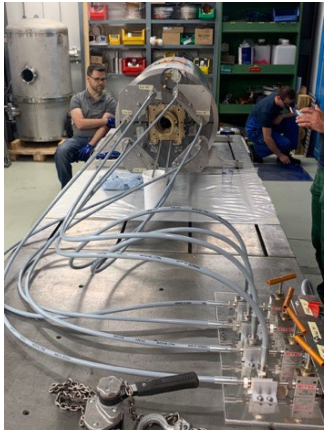
CD1 Fabrication & Assembly

- Completed in October 2019 (Project started in 2016)


G. Montenero et al., *Coil Manufacturing Process of the First 1-m-Long Canted-Cosine-Theta (CCT) Model Magnet at PSI*, IEEE Trans. on App. SC., Vol 29(5), 2019.
G. Montenero et al., *Mechanical Structure for the PSI Canted-Cosine-Theta (CCT) Magnet Program*, IEEE Trans. on Appl. SC., Vol 28(3), 2018.

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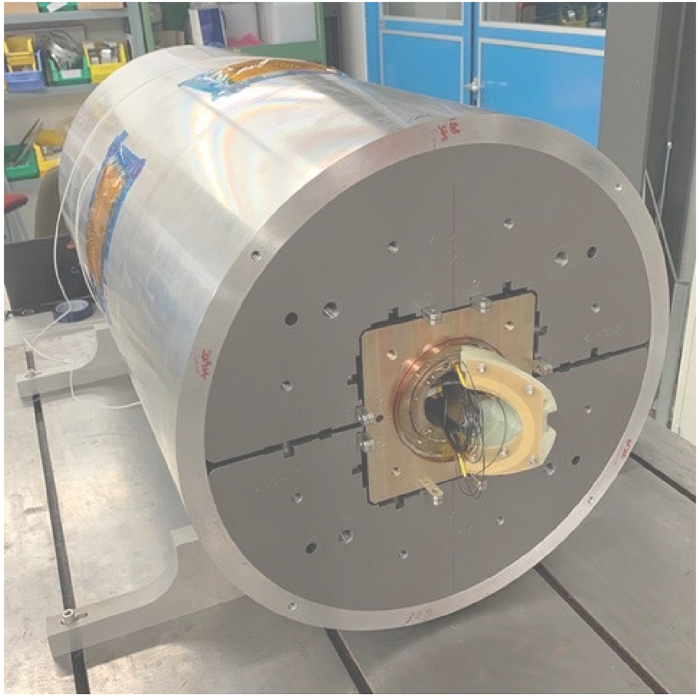
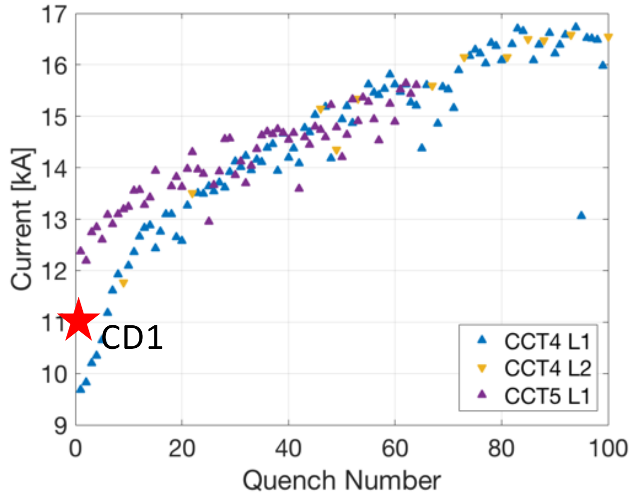
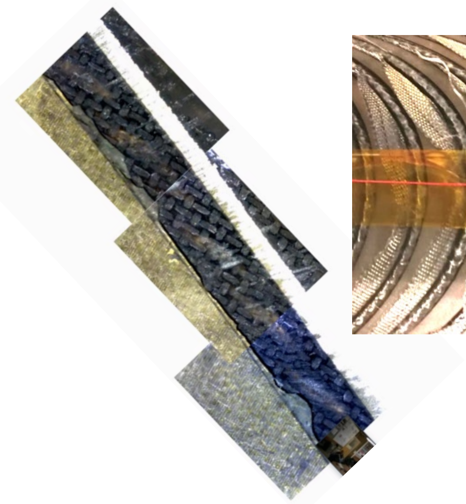


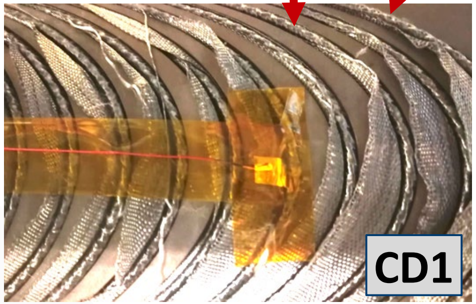
CD1 Testing Odyssey

- Magnet was shipped to LBNL in Nov. 2019.
- The test preparation was interrupted by COVID 19 and resumed in Aug. 2020.
- Magnet test started in Sept. 2020 but interrupted by cryo problem.
- Max. current after 2 quenches: 11.1 kA or 62.5% of short sample, 6 T in the bore.
- **Test continued at CERN in Nov-Dec 2022 & Jan 2023**.
- LBNL experience points to debonding and cracking causing excessive training.





Protruding cable



Courtesy D. Arbelaez, LBNL.

CD1 testing at CERN

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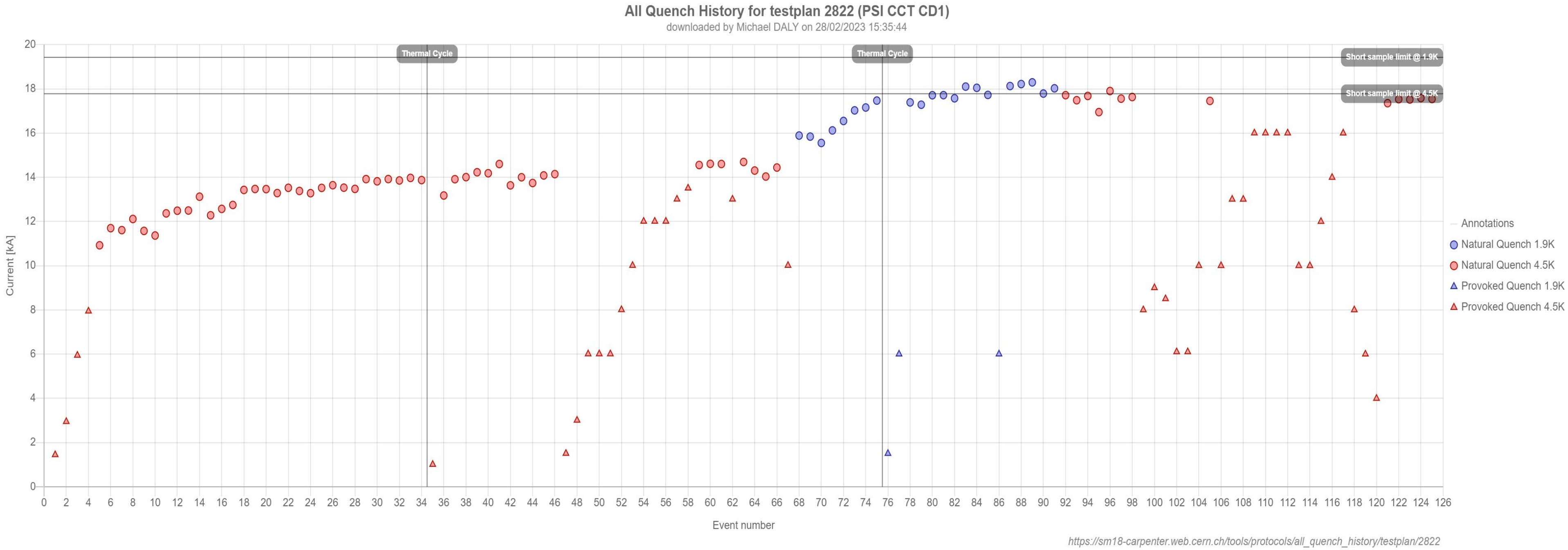
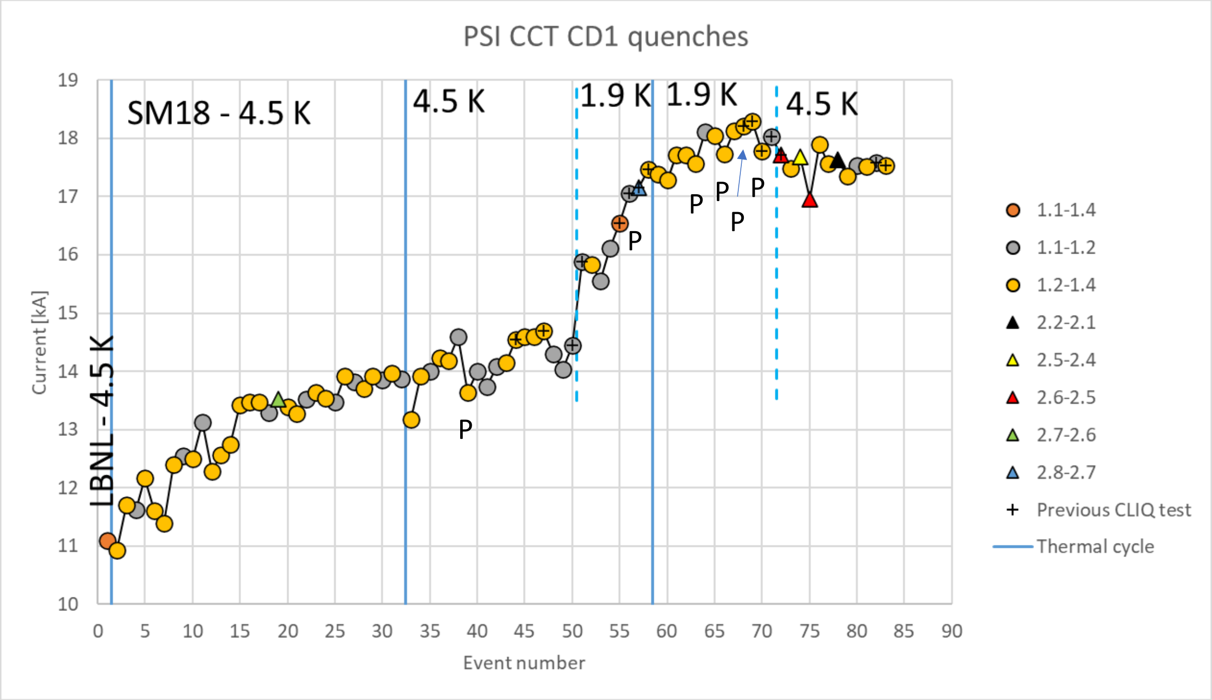
- Test campaign Nov 2022 – Jan 2023
- Ic @ 4.5 K = 17.783 kA; Ic @ 1.9 K = 19.429 kA



CD1 Training

- Ic @ 4.5 K = 17.783 kA
- Ic @ 1.9 K = 19.429 kA
- Most quenches occur in inner layer.
- Overall, good memory after thermal cycle.
- CD1 retains training memory from 1.9 K training.
- Training at 1.9 K with CLIQ seems to have accelerated training.



Courtesy of Franco Mangiarotti

CD1 Training: Summary

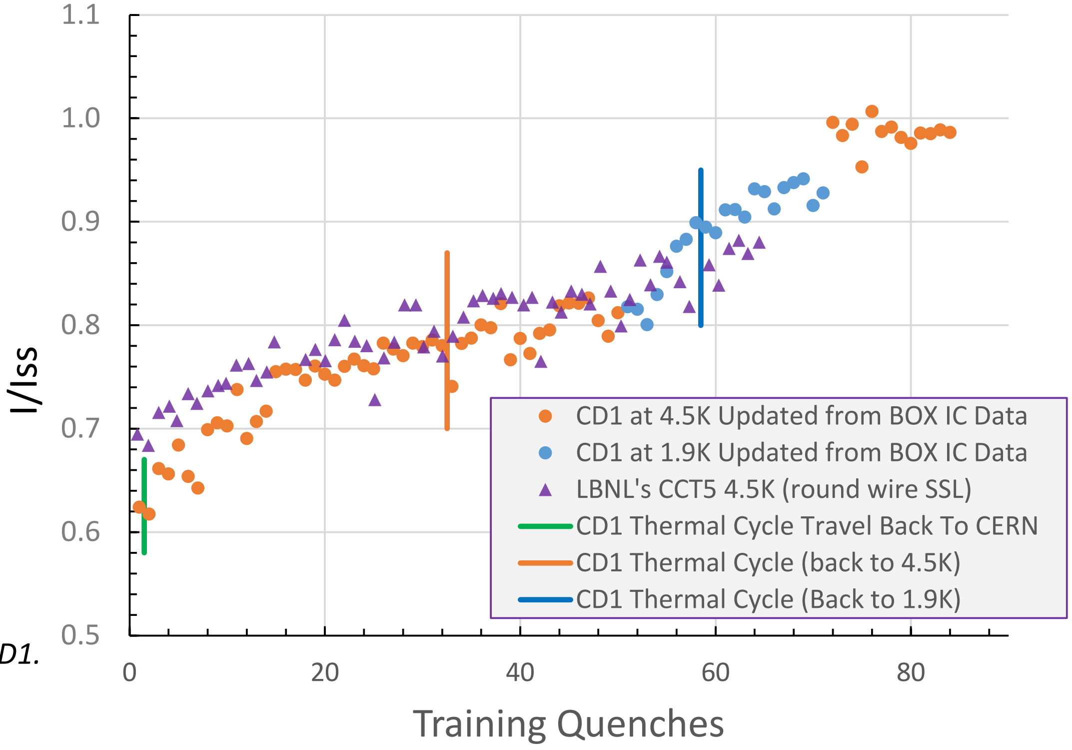
- CD1 training tracks nicely with LBNL's CCT 5.
- Not-so-perfect magnet fabrication did not drastically limit performance.

	4.5 K	1.9 K
Max Current [kA]	17.903	18.295
Max Fraction of Iss [kA]	101%	94%
Max Dipole Bore Field [T]	9.86	10.08
Max Conductor Peak Field [T]	10.81	11.05

Field values calculated, no field measurements performed on CD1.

Ic measurements adjusted by taking into account Ic (Ic B) measurements done at Uni Twente on BOX samples.

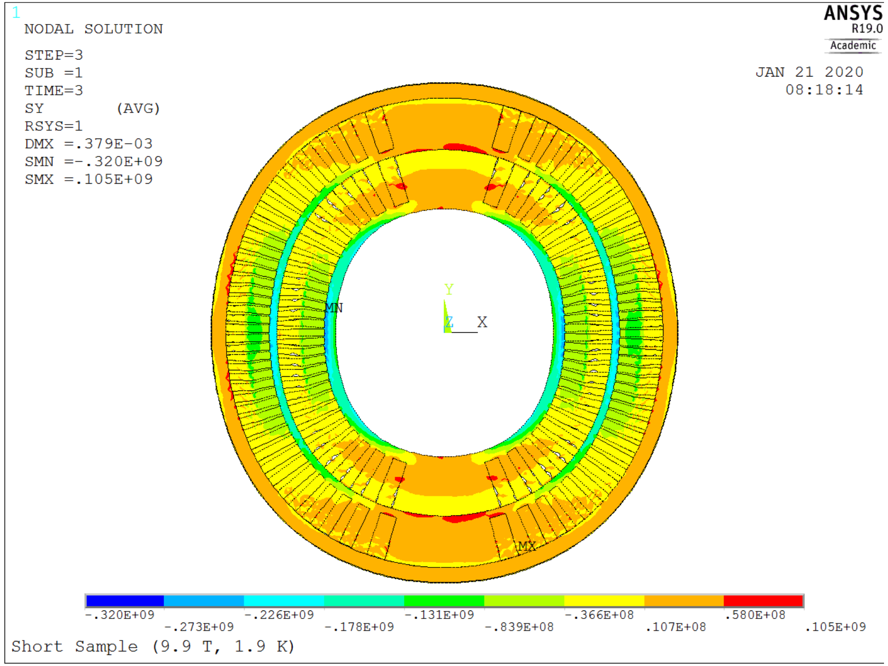
Training Curves Comparisons

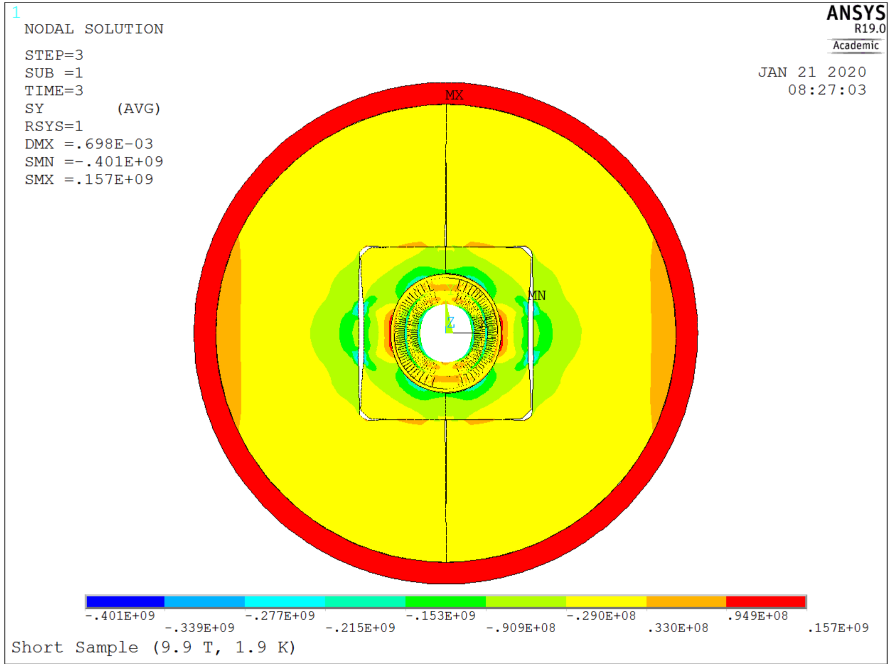


Note: For the last thermal cycle **("back to 1.9K")**, the magnet was entirely removed from Cryostat and reinserted.

FEA: Reminder

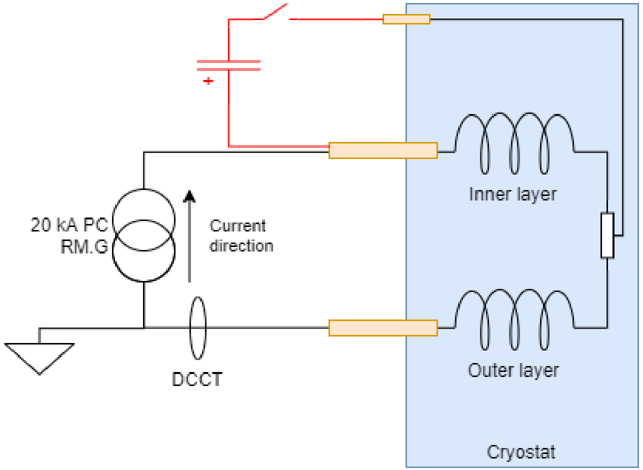
- Previous simulation considered 9.9 T at 1.9K.
- Validation against Strain gauge data on-going.
- Overall trends for cool down and powering seem reasonable ($\varepsilon_{cool\ down} > \varepsilon_{powering}$).





CD1 Protection: Energy Extraction & CLIQ

- Assess protection of CD1 with EE only and, CLIQ with a EE delay.
- Based on Jiani's PhD Thesis.
- First, EE triggered at lower currents and extraction quench integral (MIITs) calculated.
- CLIQ assessed by triggering at lower currents to gauge max current in inner coil.
- Significantly lower quench integral than expected (2X to 3X)
- CLIQ tests have larger quench integral because we added some energy extraction delay.



Coupling-Loss Induced Quench (CLIQ) Parameters:

Capacitance: 10 mF and 40 mF

Voltage: 100, 200 and 300 mV

EE R_{dump} = typically 40 mOhms

EE delay: between 200 and 20 ms

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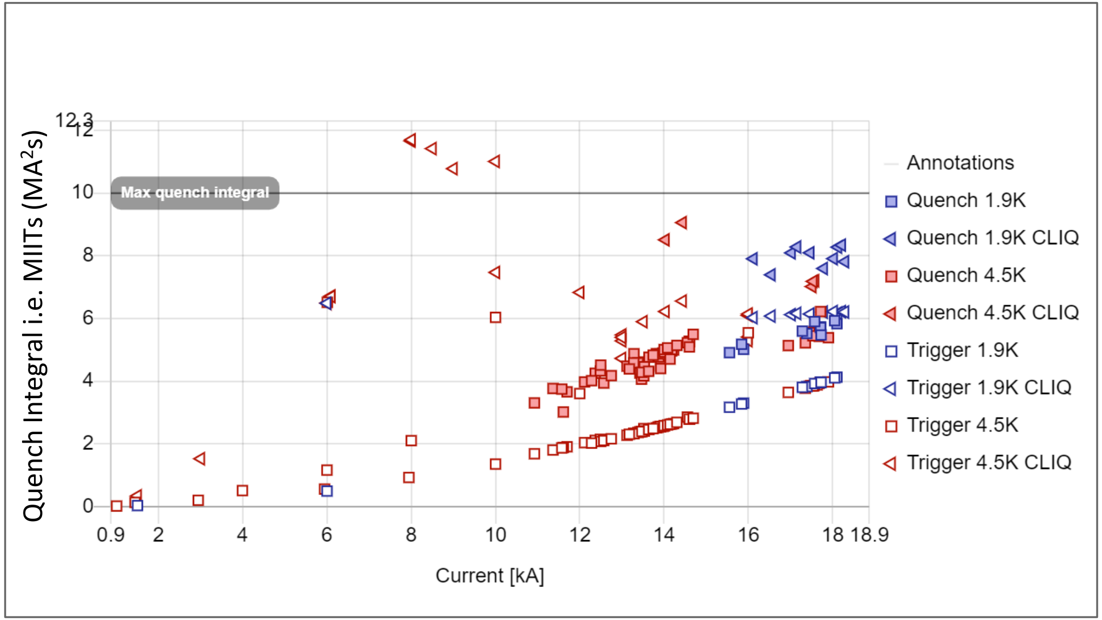

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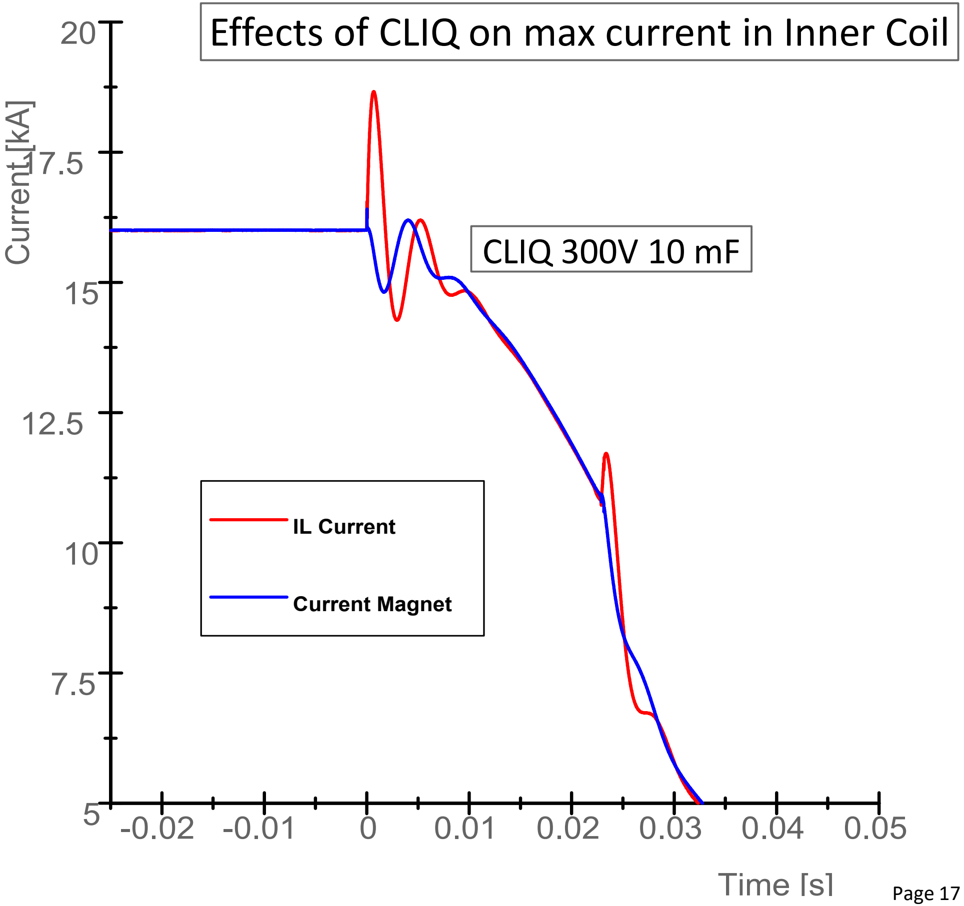

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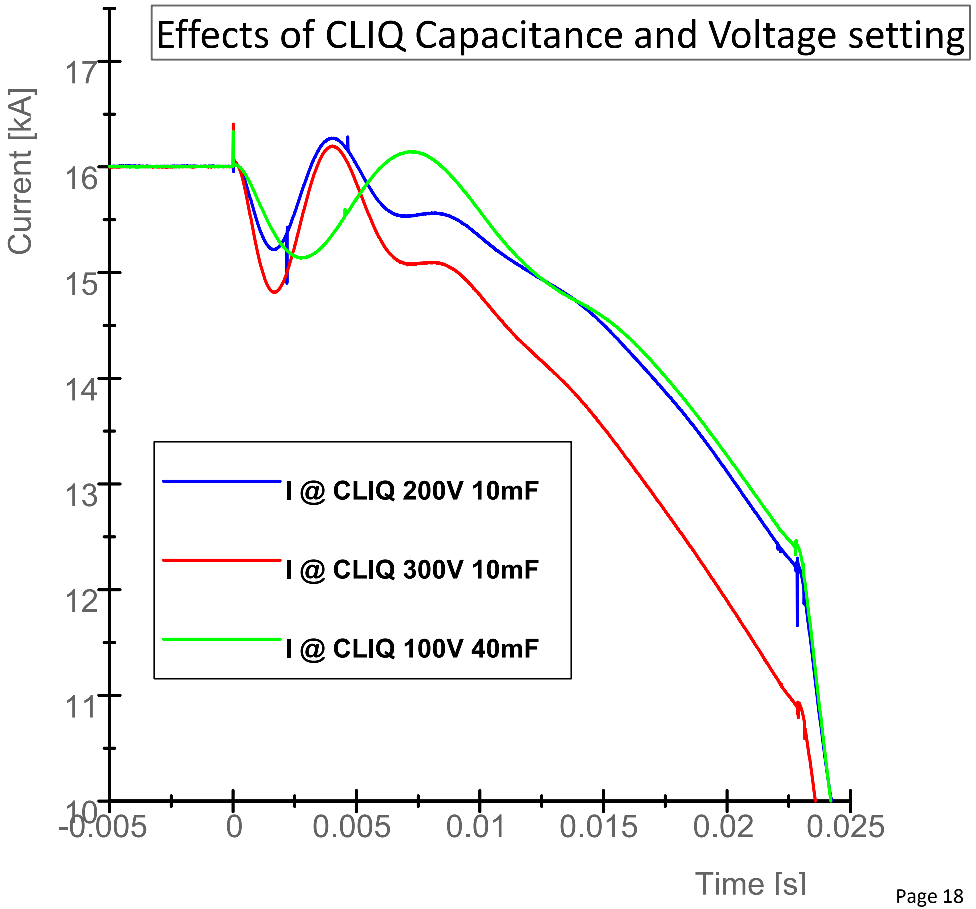

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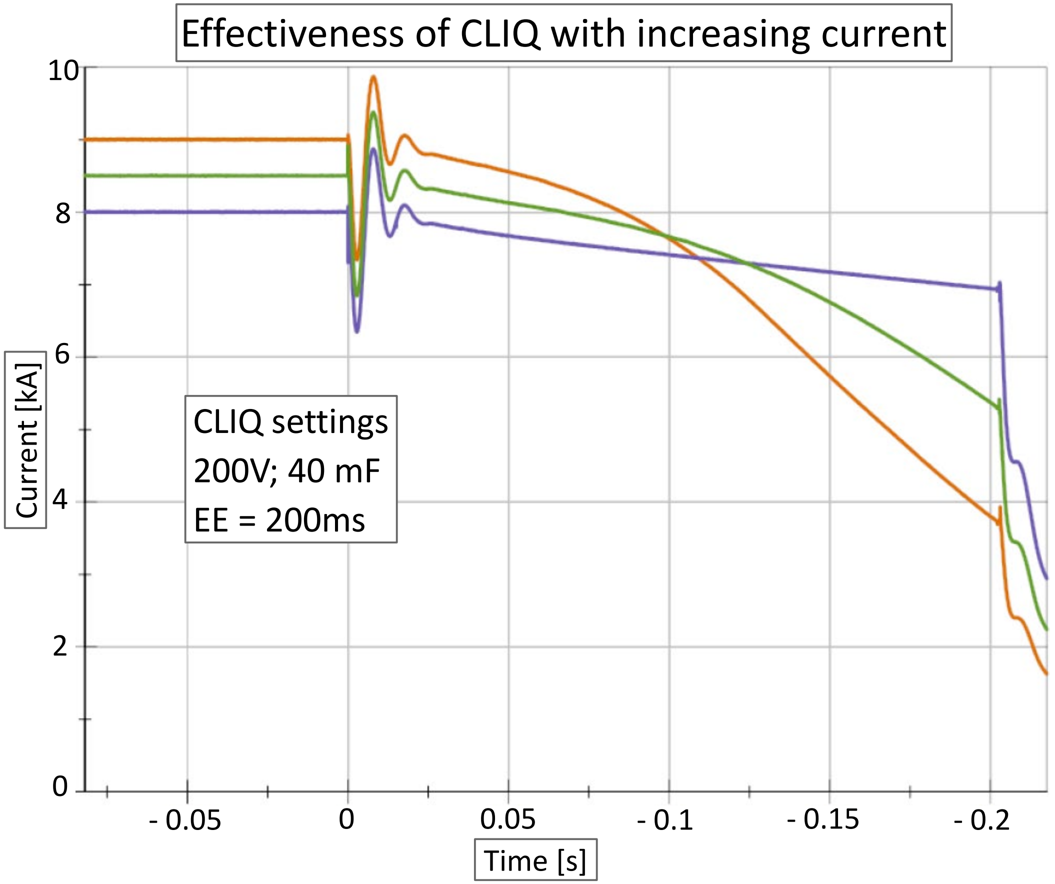

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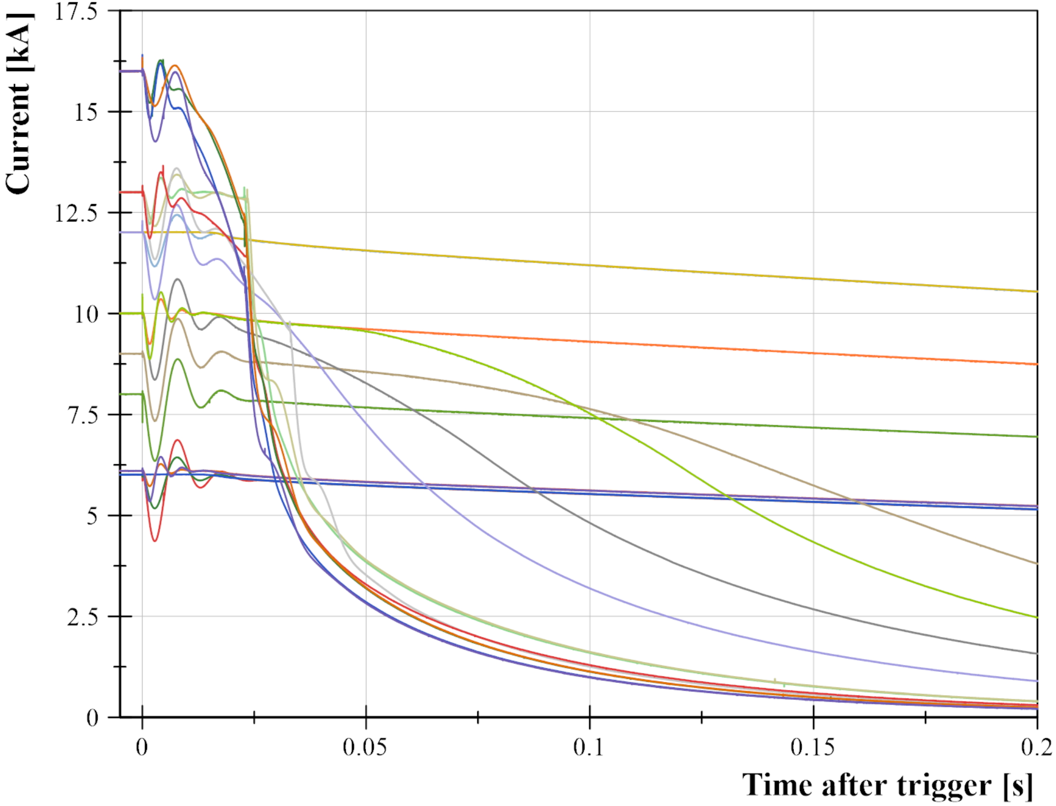
Overall Selection of CLIQ Quenches



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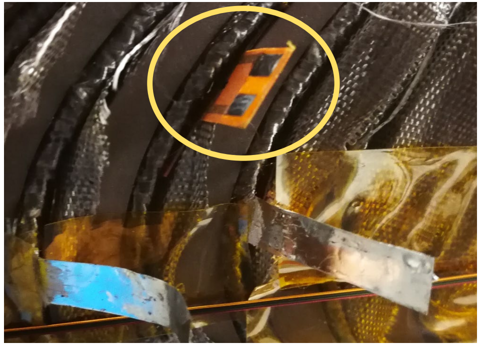
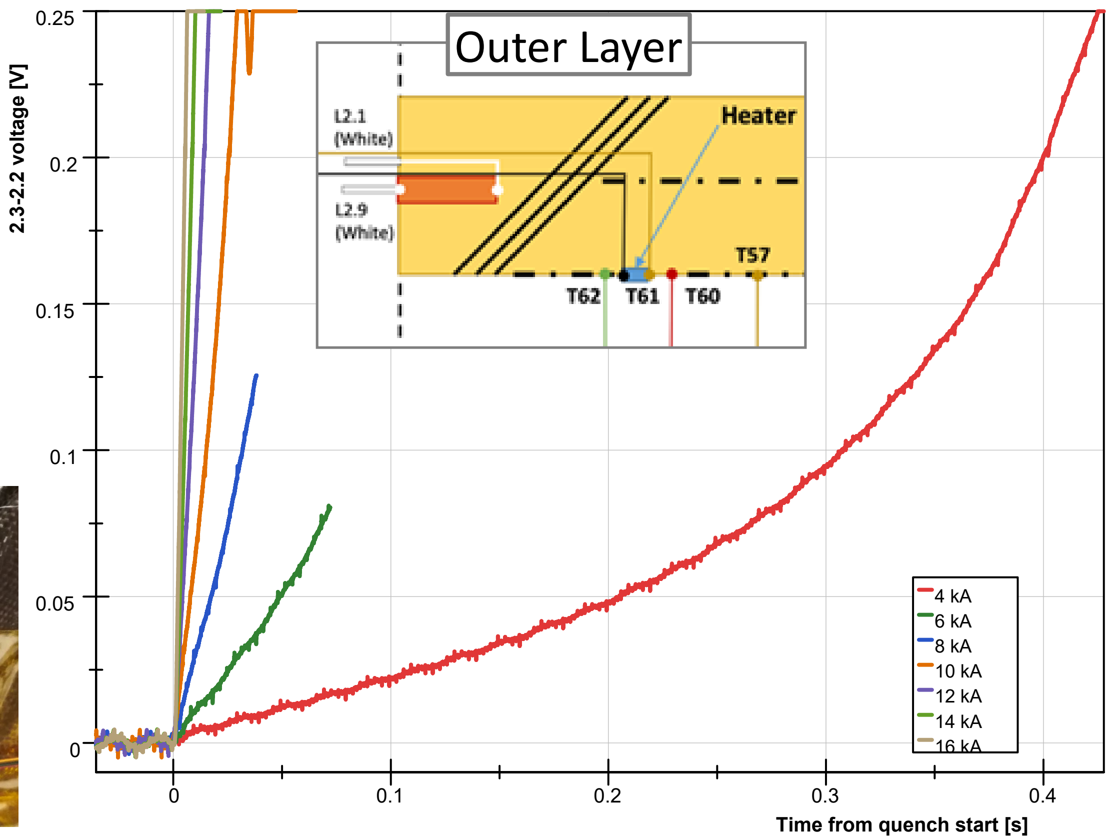
CD1 Spot Heater Test

- All tests at 4.5 K
- Circuit: 10 mF capacitor and $R_{heater} \approx 11$ Ohm (at 4.5K):
  - 27 V (8 kA and above)
  - 35 V (6 kA)
  - 45 V (4 kA)
- Example: At 4 kA with EE delay of 20ms -> 8.5 J deposited

I [kA]	t_{100mV} [ms]
4	310
6	100*
8	32
10	15
12	7.0
14	4.1
16	2.3

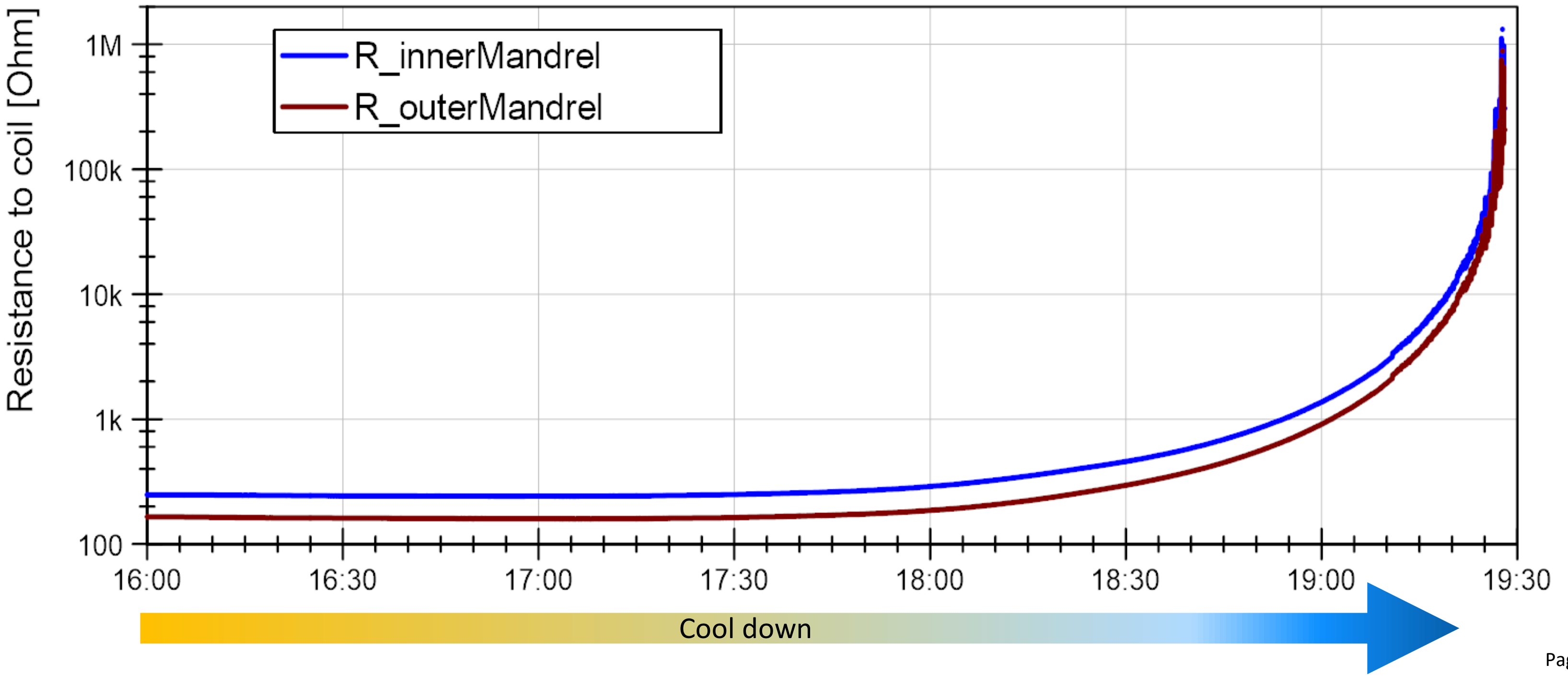


** Extrapolated to 100mV*



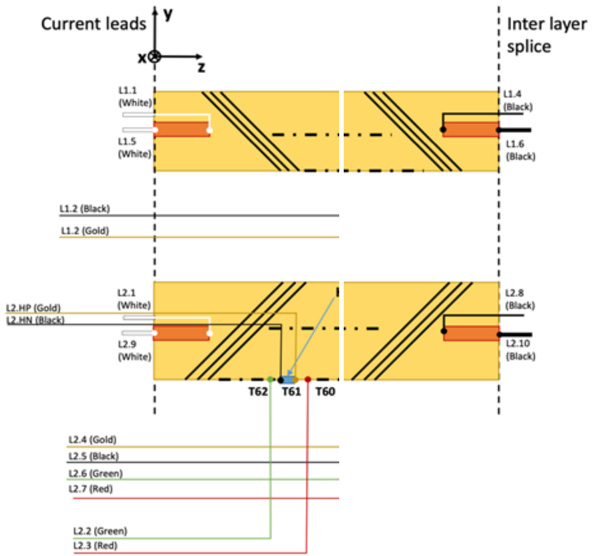
Resistance to Mandrel

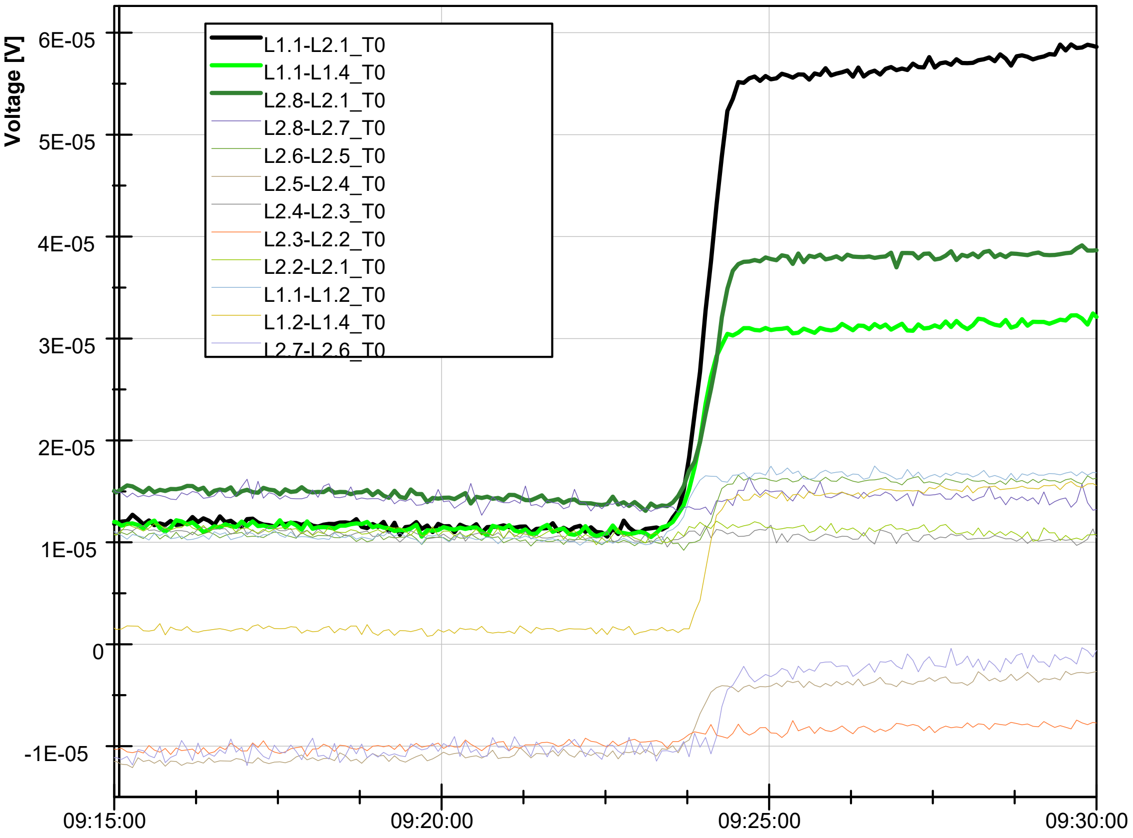
- CD1, after reaction and impregnation, had a resistance of approx. 3 Ohms to the mandrel.
- Coil to mandrel resistance greatly improves when cold (similar to CCT 5)
- This transition was noticed for each thermal cycle.



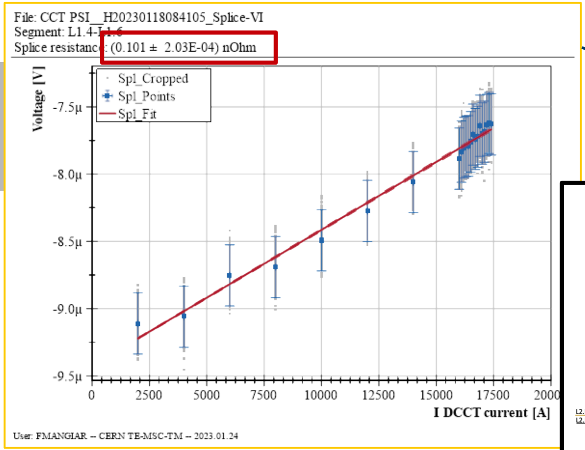
RRR measurements

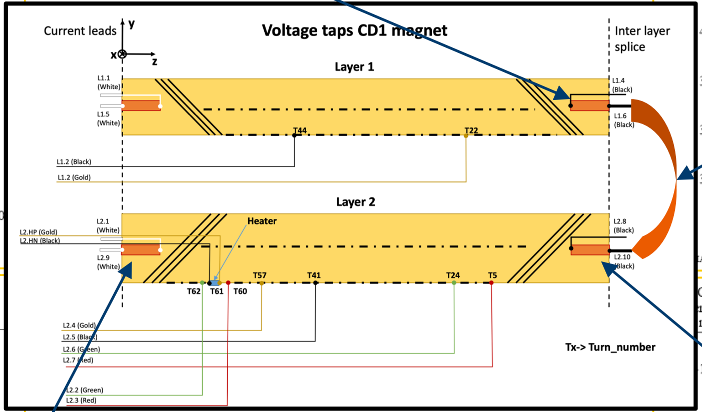
- Fast and uniform transition
- RRR (293/20) values:
  - All magnet: 270 +- 6
  - Outer layer: 290 +- 10
  - Inner layer: 250 +- 10

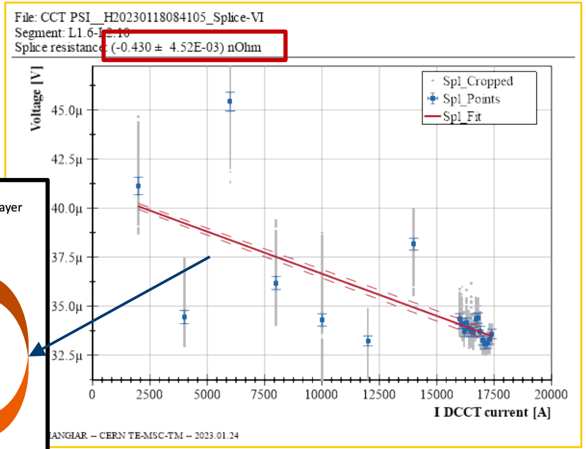


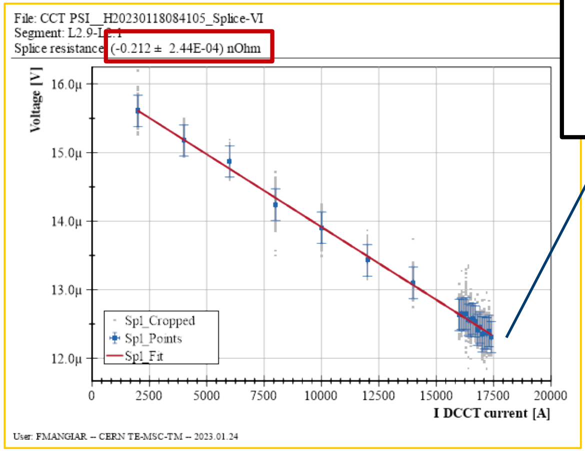


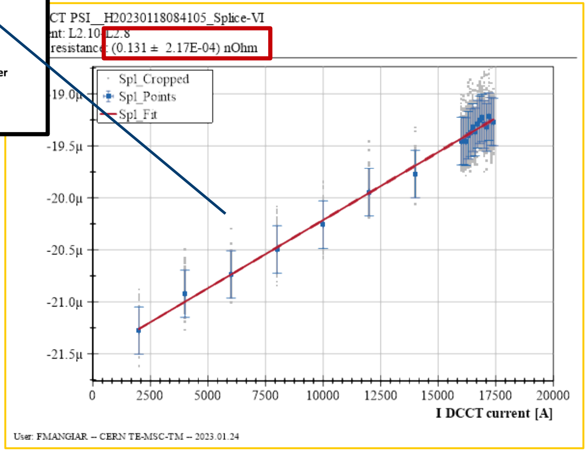
CD1: Splice Resistance











- No particular issues with splices
- Vtap 1.5 lost - IL not measured
- Results typically below 1 nOhms
- Splicing method adopted from LBNL

CD1 Test campaign: Concluding Remarks

- CD1 trained heavily (76 quenches to I_{SSL}) but reached ≈ 100% I_{SSL} at 4.5 K
- Training seems to have been accelerated by 1.9 K and/or CLIQ
  – Importantly, memory of training at 1.9 K allowed to reach 100% I_{SSL} when back to 4.5 K.
- Models for CLIQ protection need to be re-evaluated as models do not match with test results.
- Overall, similar behaviour to LBNL's CCT5 – PSI can build a working HF Magnet.
- Stress management i.e. CCT, is a "forgiving" design: issues during production were not particularly limiting performance.
- Much more information to analyse and models to validate (Strain Gauges, Acoustics, CLIQ).
- What to do with CD1: post-mortem analyses on CD1 ?!?!

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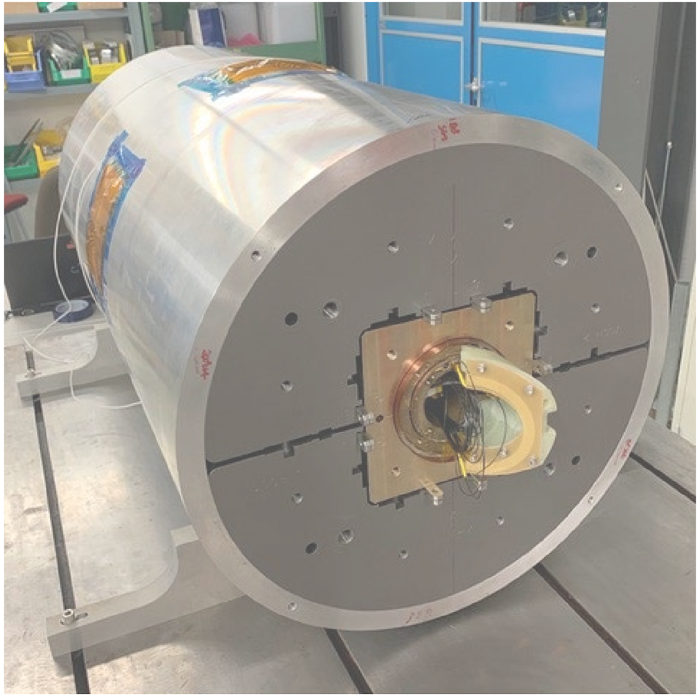
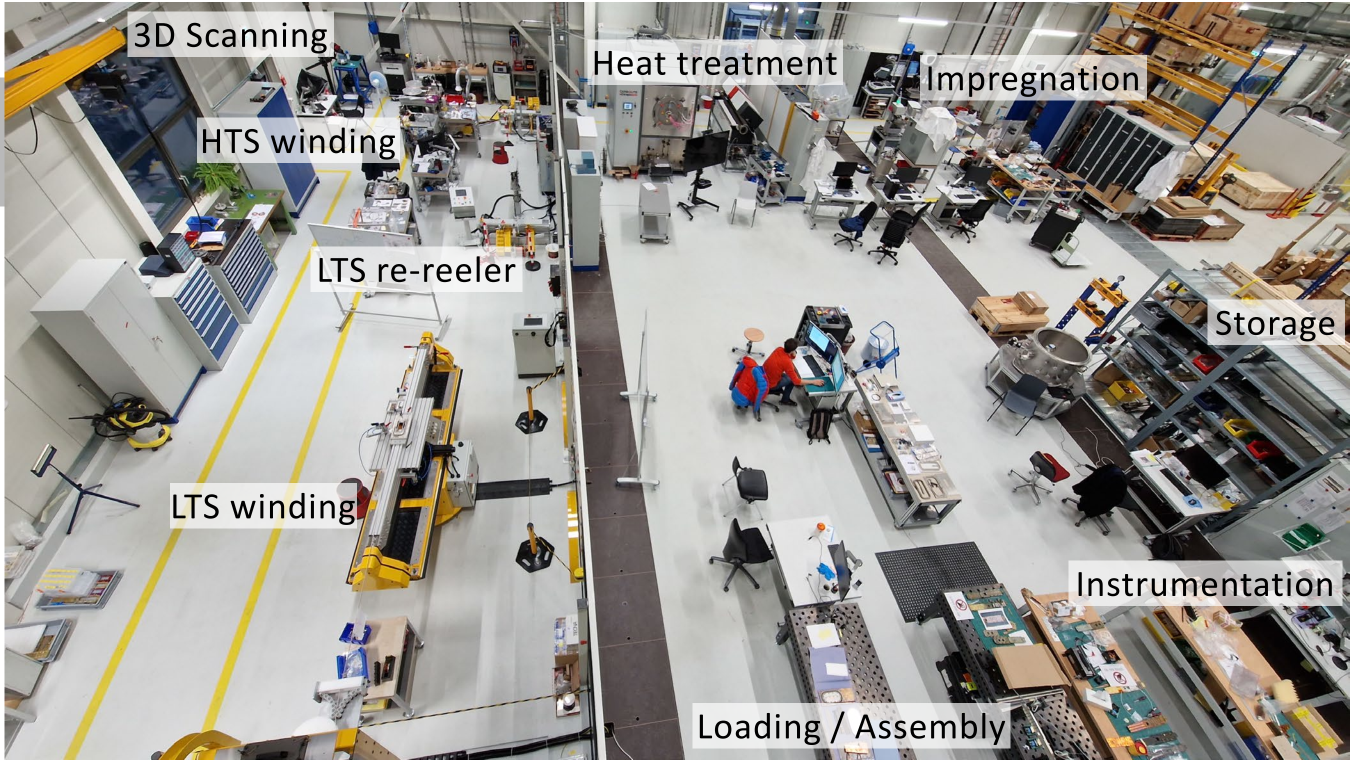
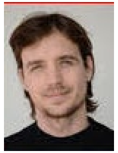


Superconducting Magnets at PSI





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P3 Project, Magnet Section

UNIVERSITÉ DE GENÈVE FACULTÉ DES SCIENCES

WireChar, WireDev

ETH zürich

MagNum (D-ITET)

ETH zürich

MagRes (D-MAT SMG)

ETH zürich

MagAM (pd|z, inspire AG)

ETH zürich

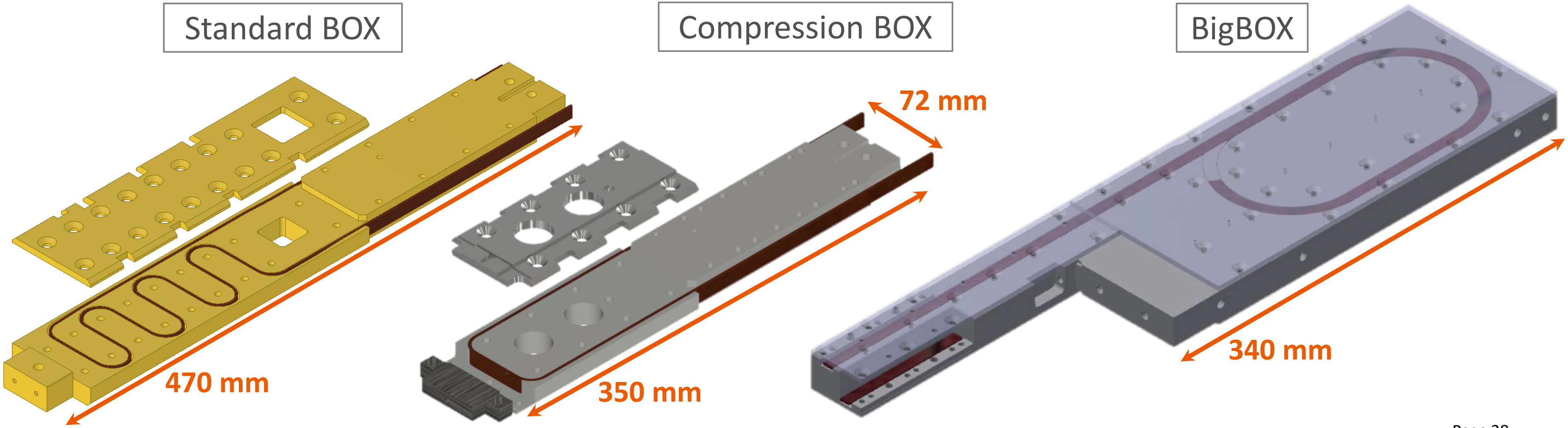
MagComp (D-MAT SMG)

Empa Materials Science and Technology

Acoustics/Noise Control

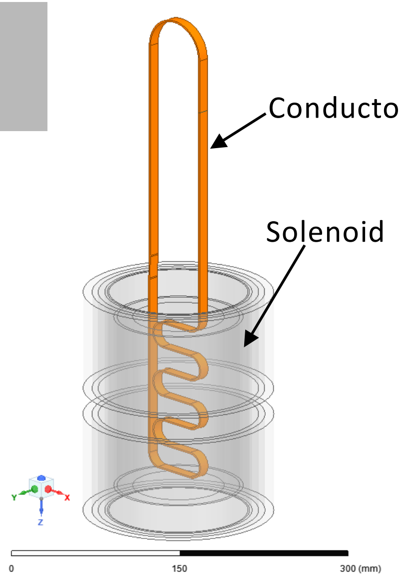
BOX: BOnding eXperiment Samples

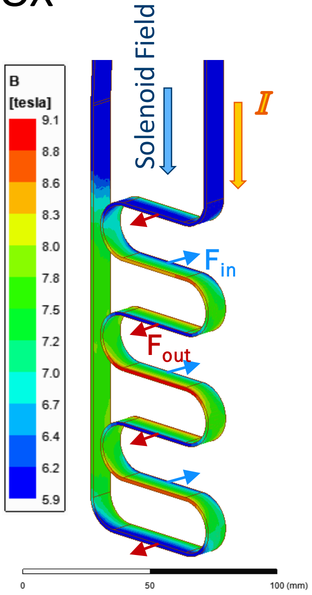
- BOX “Standard”
  - Assess Training
- BOX for Transverse Pressure (TP) “Compression”
  - Assess a direct load/stress on broad face of cable
- BigBOX (Cable supplied by US-MDP/BNL)
  - Assess cable “stack” in racetrack (wax impregnated) in realistic conditions



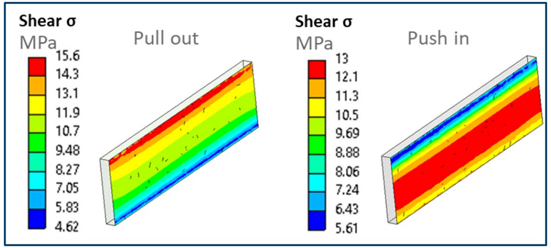
BOX: Standard and Compression (TP BOX)

Standard BOX

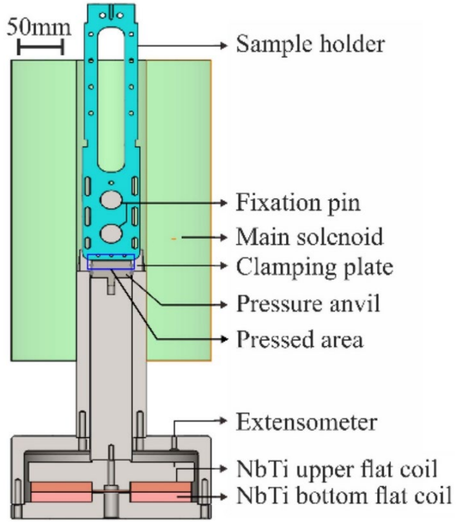




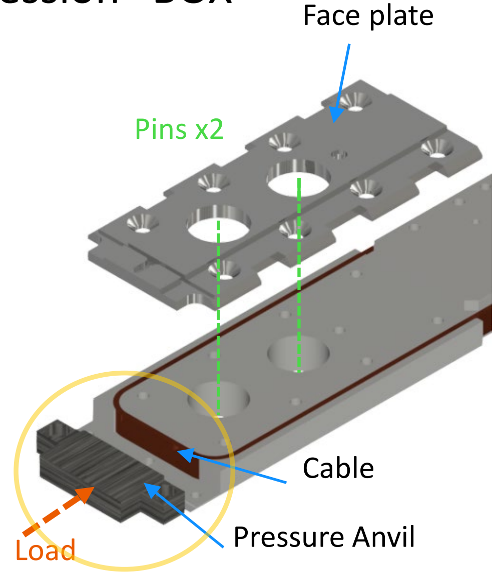
When bonded to channel walls

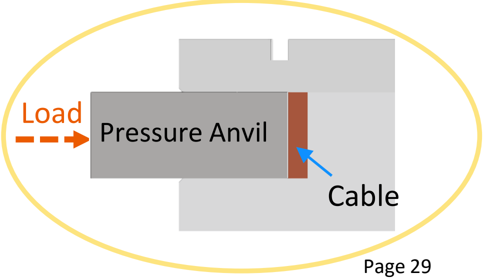


TP "Compression" BOX

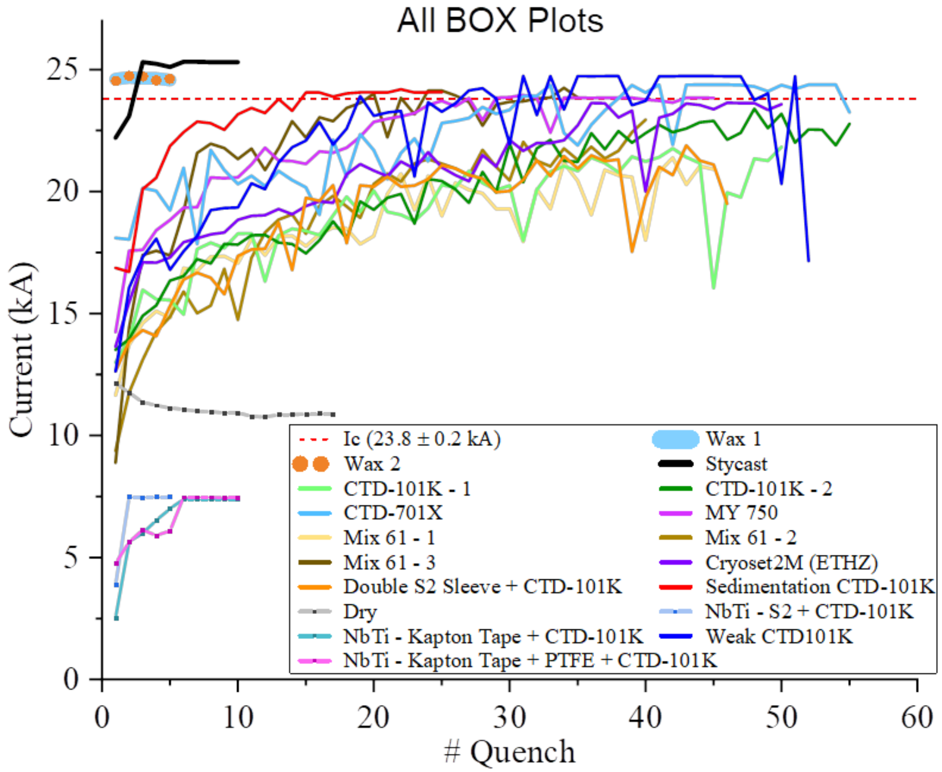


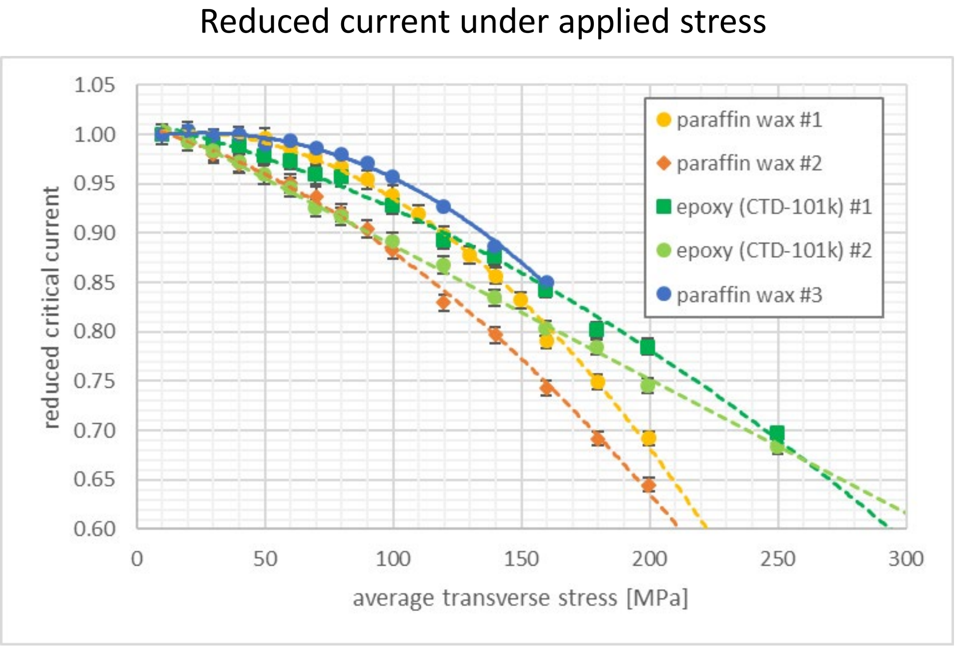
Drawing by Peng Gao (UTwente)





Results from BOX and TP BOX

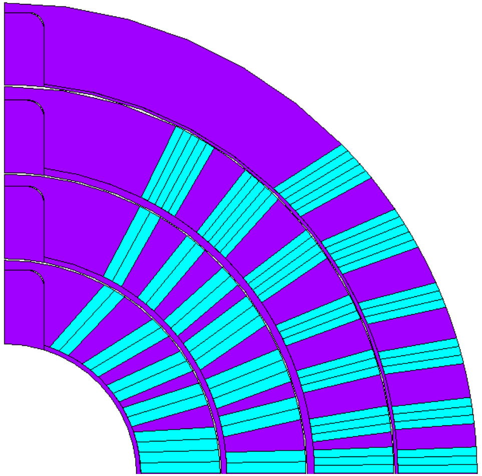


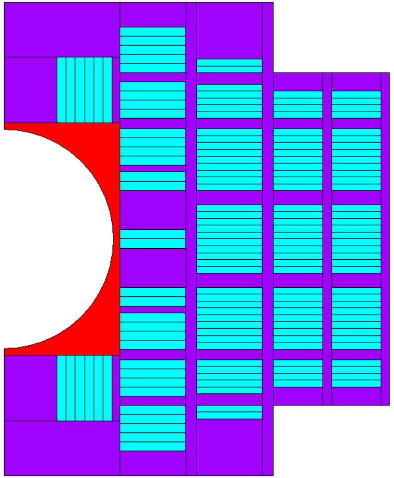


BOX samples made from the remaining cable of CD1 (Supplied by LBNL)

Stress Management alternatives to CCT

- CCT for Nb_3Sn promised reduced conductor stress by introducing stress management.
- The BOX program provided a handle on the vexing interface problem.
- Other difficulties intrinsic to CCT technology remain for FCC-hh main dipoles.
- **Stress-managed on other geometries promise to combine the benefits of SM with the (relatively) easier manufacturability.**

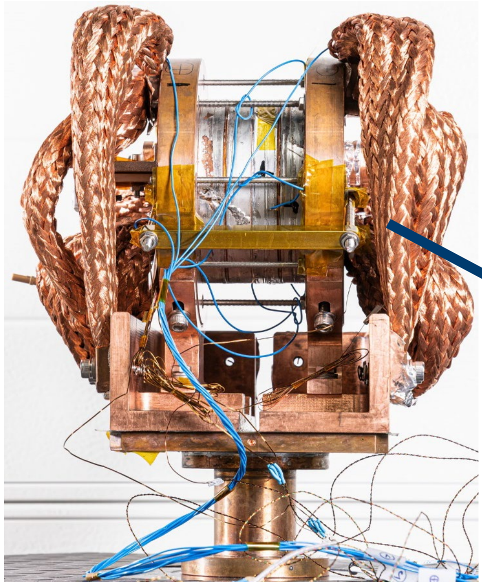




Courtesy of D. M. Araujo – images show snapshots of design studies for illustration purposes.

HTS and More

- Successful test in cryogen-free test station of 4-pancake HTS NI solenoid, built in-house at PSI and using licensed Tokamak Energy Ltd technology.
- Coil reached **18.2 T** in the center, **20.3 T** on the conductor at the maximum current of the power converter of 2 kA.



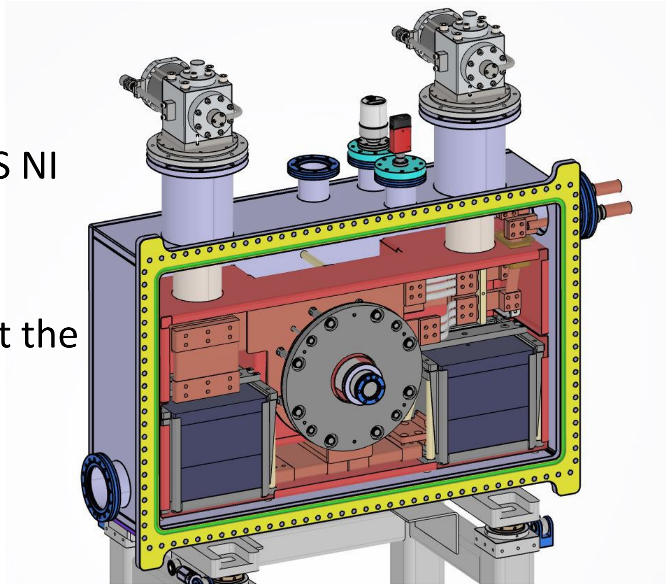
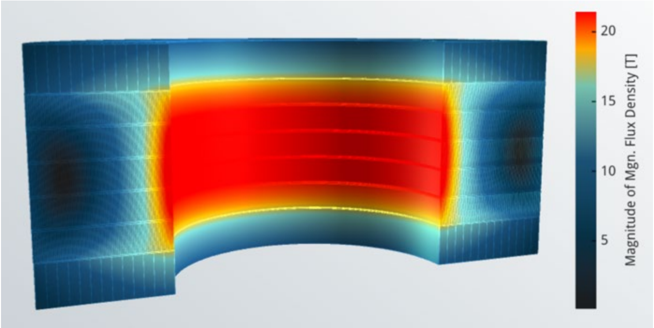
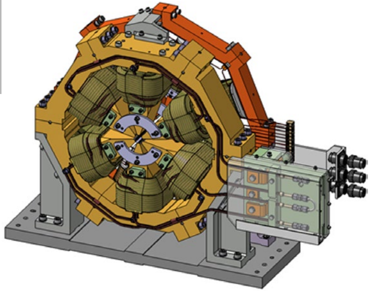


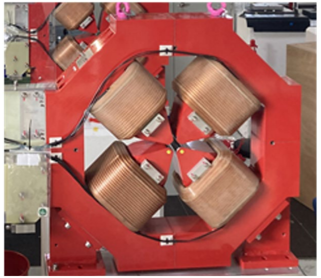
CHART2 FCCee Injector Study: P3 (PSI Positron Production) Project

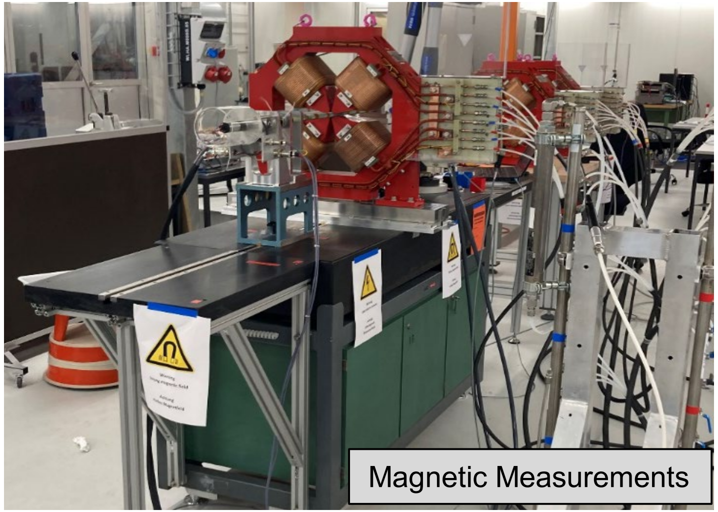


PSI Magnet Section: Upgrades and Projects

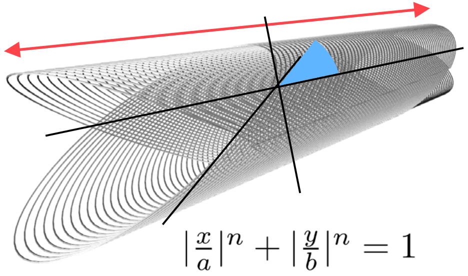
SLS 2.0 Upgrade Magnets

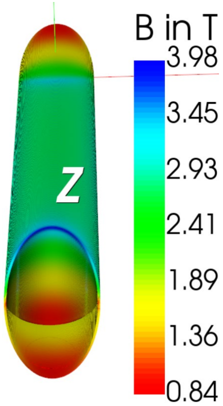




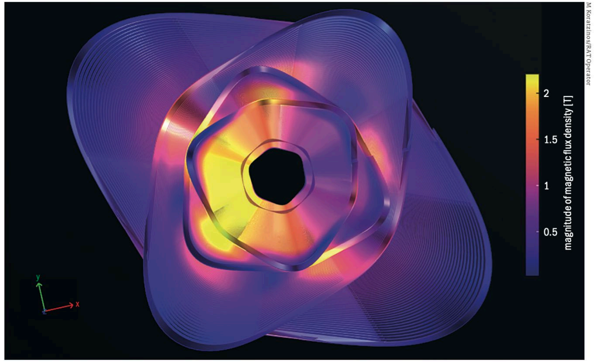


Proton Therapy Upgrade





FCC-ee Quad-Sextupole



Innovative *The magnetic flux density of a nested main sextupole–quadrupole system for FCC-ee, looking along the direction of the electron beam.*

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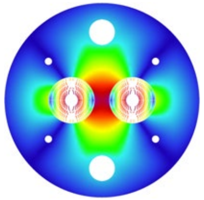
PSI CHART Team: Michael Daly, Bernhard Auchmann, Douglas Araujo, André Brem, Christoph Hug, Oliver Kirby, Thomas Michlmayr, Jaap Kosse, Henrique Rodrigues, Michal Duda, Dmitry Sotnikovs, Sergei Sidorov, Giuseppe Montenero.
CERN Team: Franco Mangiarotti, Jean-Luc Guyon, Daniel Molnar, Jerome Feuvrier
US-MDP Support: Diego Arbelaez, Lucas Brouwer, Schlomo Caspi, Jim Swanson, to name a few…

Additional Slides

CCT for FCC: Pros and Cons



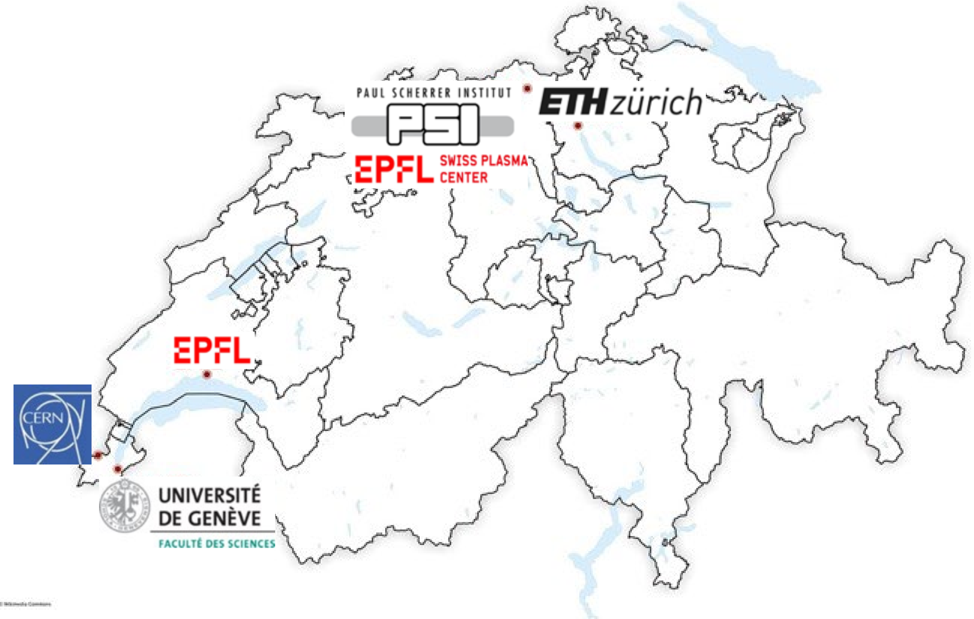
- Design:
  - **Mechanical support** of each turn → reduced coil stress and avoidance of stress-induced degradation.
  - Easy field quality (on paper).
  - Ideally suited for LTS/HTS **hybrid magnets** due to easy stacking of heterogeneous layers.
  - Simpler external mechanical structure → more iron between the apertures and better magnetic separation → less cross-talk.
  - **Hope to fix training:** getting one turn “right”, the entire magnet would work; no discontinuities towards the end regions
- Fabrication:
  - Simple and safe coil-manufacturing process; little tooling needed; coil always protected by former.
- Instrumentation and protection:
  - Efficient CLIQ protection as every turn is a high-field turn.
  - Co-winding of instrumentation (fibers, wires, etc.) is supposedly easy.

- Design:
  - Every turn must be **glued to metal surfaces**; delamination would preclude good performance.
  - *Reduced efficiency* by winding angle, rib thickness, and spar thickness.
  - Check FQ variation along z-axis due to lack of control on turn position.
  - Some axial strain on cable in every turn.
  - No radial pre-compression possible.
- Fabrication:
  - Tricky ***winding*** on small ID with wide cable.
  - Difficult to obtain *reliable insulation*.
  - Difficult to ***keep cable in groove*** on small IDs.
  - Interplay between former and cable during reaction.
- Instrumentation and protection
  - No heater protection possible.
- Scaleup:
  - Involved ***former manufacturing***; cost and time consuming; difficult to scale to 15 m.
  - Difficult **assembly and alignment** for long magnets – assembly gaps reduce performance.

CHART Network and ESPPU

- "CHART, the Swiss Center for Accelerator Research and Technology, was founded to support the future oriented accelerator project Future Circular Collider (FCC) at CERN and the development of advanced accelerator concepts in Switzerland beyond the existing technology. […] The high field magnet R&D has strong synergies with PSI projects […]"
  [Application for support of the Swiss Accelerator Research and Technology Initiative, 2018]

- Swiss national centers of competence in HFM:
  - EPFL Swiss Plasma Centre*: Infrastructures and Instruments, Materials
  - ETHZ: Materials, Models, Powering
  - PSI: LTS and HTS Magnet R&D, Infrastructures, Materials
  - UniGE: LTS and HTS Conductors



* … no projects in current CHART2 period.

http://chart.ch

CHART – What, Who How?

- Topics and FTEs of ongoing **ASC projects** in CHART:
  - WireChar – SC wire and tape characterization (1 FTE)
  - WireDev – Nb_3Sn wire development (3 FTE)
  - MagRes – resin development (1 FTE)
  - MagComp – coil composite characterization and constitutive modeling (1 FTE)
  - MagAM – additive manufacturing for coil components (1 FTE)
  - MagNum – model-based systems engineering for magnets (1 FTE)
  - FCCee CPES – cryogenic power supply development (1 FTE)
  - MagDev1/2 – SC magnet development (8 FTE)
  - HTS Bulk Undulator – Bulk REBCO undulator technology (2 FTE)
  - FCCee Injector –NI solenoid for injector test at SwissFEL (1 FTE on ASC)
  - FCCee HTS4 – HTS Short Straight Section Demo for FCCee (4 FTE)
  - Total: 24 FTE
- Other ongoing CHART projects:
  - FCC / LHC Lumi
  - FCCee Beam Dynamics Simulation
  - FCChh Stability
  - FCCEe SPIN POL
  - FCCee Lumi
  - Muon Collider Feasibility Studies
  - FCCee Injector
  - FCC Geodesy
  - FCC Geology 3D Model

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