Damage limits studies with sc. coil samples - experimental preparations and setup

- Motivation & Scientific goals
- Re-cap of key results from previous beam experiments
- Sample coil design
- Experimental Setup
- Schedule

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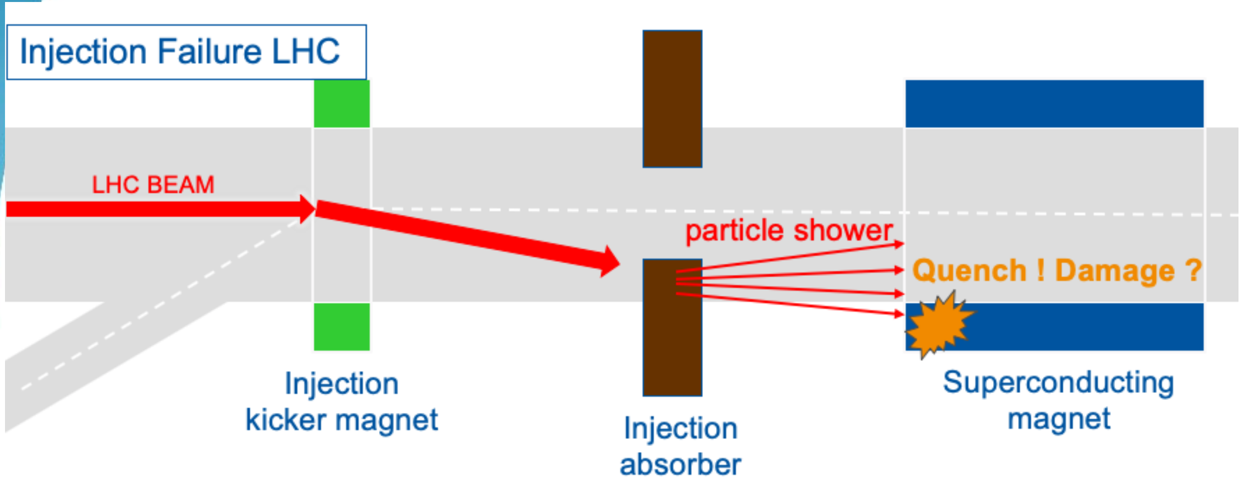
12th HL-LHC Collaboration Meeting, Uppsala (Sweden), 19.-22. September 2022

Motivation of the studies on sc. magnet components

Ultra-fast failures in HL-LHC



- One such event per year in today's LHC. No damage.
- HL-LHC:
  - **increased bunch intensity** from 1.15 x 10^{11} ppb to 2.2 x 10^{11} ppb
  - **reduced emittance** (3.75 um rad → 2.5 um rad)
  - **Increased stored beam** energy from 360 MJ to 690 MJ
  - Failures become **more critical**

- For HL-LHC beam, a peak energy deposition of 100 Jcm^{-3} is expected in the D1 magnet without mask[1] due to an injection failure. Similar values are expected in Q5 in case of an asynchronous beam dump[2].
- Will the **magnets survive**?
- What are the **damage mechanisms and limits** of superconducting magnets due to **high intensity beam impact**?

[1] A. Lechner et al., Protection of superconducting magnets in case of accidental beam losses during HL-LHC injection, In Proceedings of IPAC15
[2] B. Auchmann et al., Quench and Damage Levels for Q4 and Q5 Magnets near Point 6, CERN EDMS 1355063, 2014

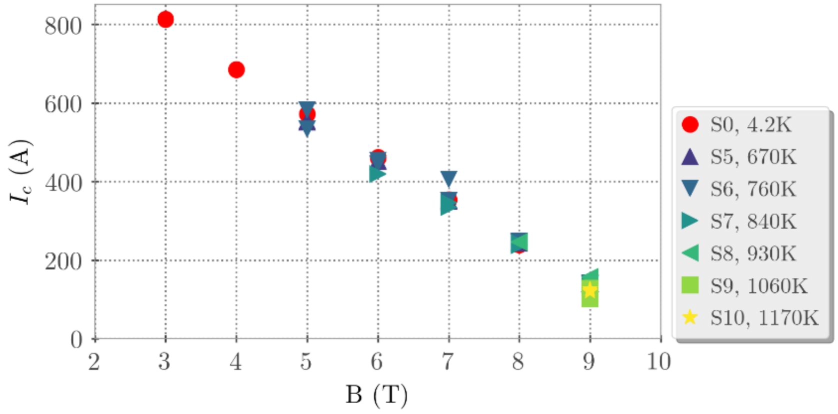
Staged Experimental Program by TE-MPE

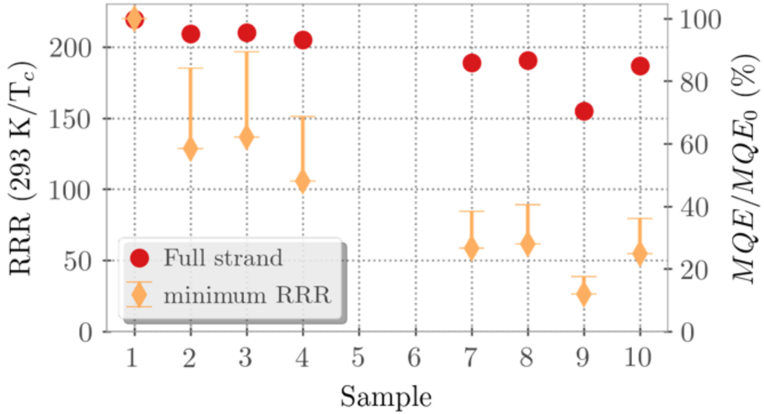
- 08.2014 – Project start
- 04.2016 – I. Polyimide insulation degradation due to hour long heating
- 09.2016 – II. Insulation & I_c degradation - beam impact @ RT
- 12.2016 – III. Degradation of critical current due to ms-heating
- 03.2017 – IV. Degradation of polyimide insulation (ms-heating)
- 08.2018 – V. I_c degradation in sc. strands - beam impact @ LHe
- 10.2022 – VI. I_c degradation in sc. sample coils – beam impact @LHe

HiLumi HL-LHC PROJECT

Re-cap: Key results of cryogenic beam experiment (HiRadMat37 - 2018) for Nb-Ti

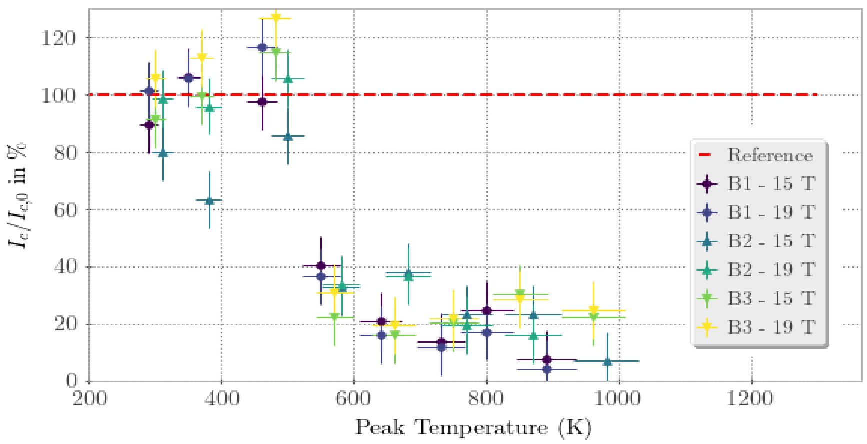
- **No degradation** of I_c observed
- Measurements indicate significant **reduction of RRR at beam impact position**
  - Reduced minimum quench energy (MQE) → potentially causing **thermal instability** of the strands / magnets
  - RRR **locally reduced** below 100 for samples with hot spots > 800 K

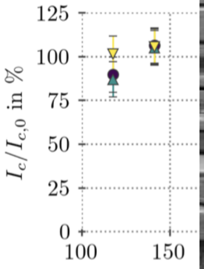


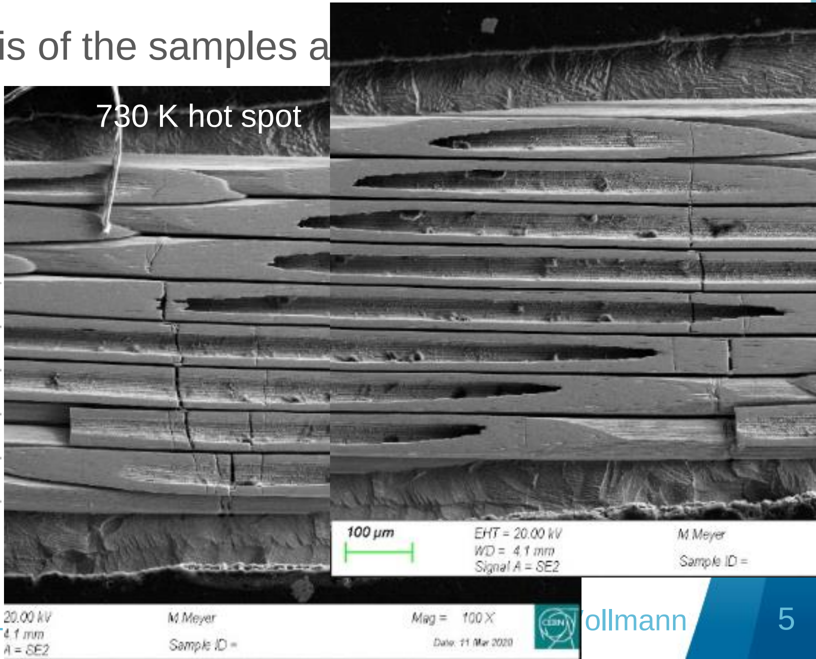


Re-cap: Key results of cryogenic experiment (HiRadMat37 -2018) for Nb_3Sn

- Significant I_c **degradation** was observed in samples, which experienced a hot spot temperatures **> 460 K** and temperature gradients **> 200 K/mm** due to the beam impact
- **Thermo-mechanical simulations** allowed to identify the two main damage mechanism:
  - **Filament breaking** due to too high axial strain → dominating factor for I_c degradation
  - B_{c2} **degradation** due to residual strain from copper matrix and other copper/ bronze phases causing additional degradation of I_c
- Damage mechanisms were **confirmed by SEM** analysis of the samples a… **magnetisation measurements**







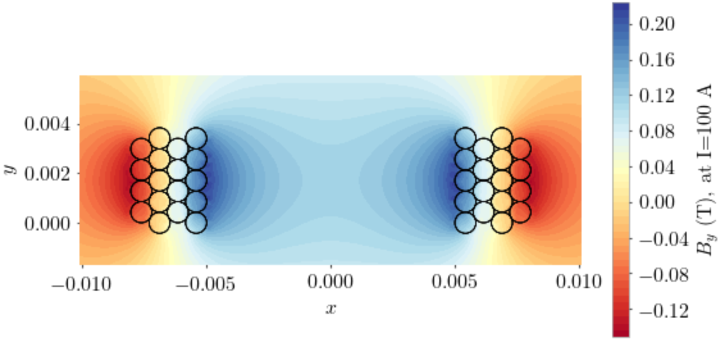
Scientific goals for the upcoming experiment

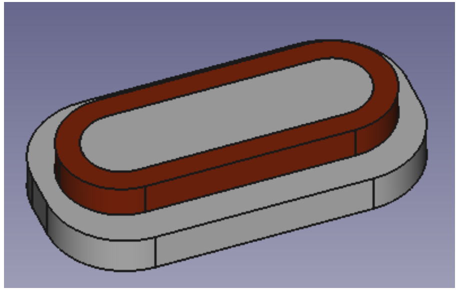
- **Validate** damage limits and mechanisms derived from previous **strand** damage experiments with Nb-Ti and Nb_3Sn **racetrack coils**.
- Identify **additional damage mechanisms** in multilayer, impregnated coils due to instantaneous beam impact.
- Study the impact of **radiation ageing** on the observed damage limits and mechanisms
  - This part had to be dropped for the upcoming experiment due to time limitations.

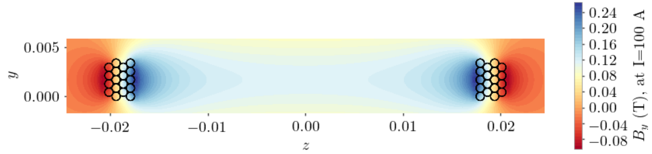
HiLumi HL-LHC PROJECT

Sample coil design for upcoming experiment

- Racetrack coils:
  - 43 mm x 21.25 mm
  - 4 layer winding: 5|4|5|4
  - Strand diameter: 0.85 mm
  - Nb_3Sn: RRP HL-LHC triplet strand, impregnated with CDT101K
  - Nb-Ti: LHC dipole inner layer strand
- The coils have been built at KIT, Germany



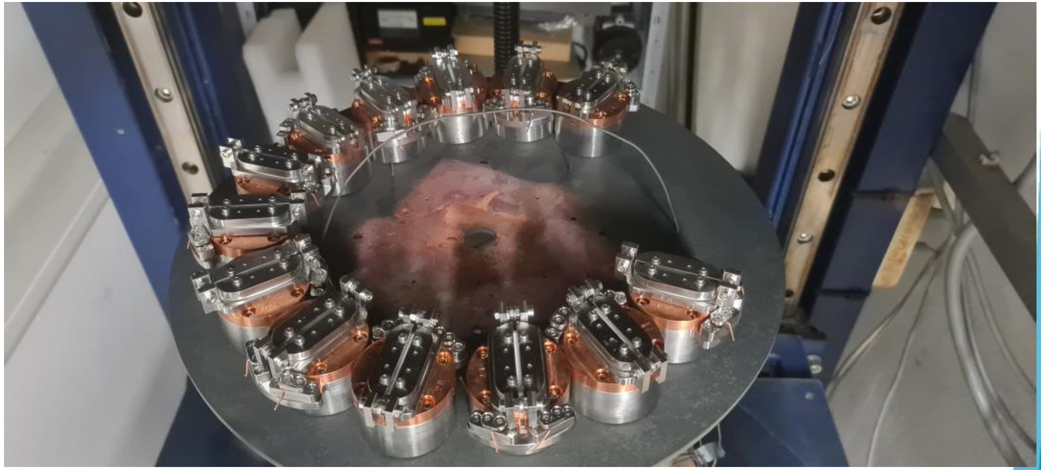


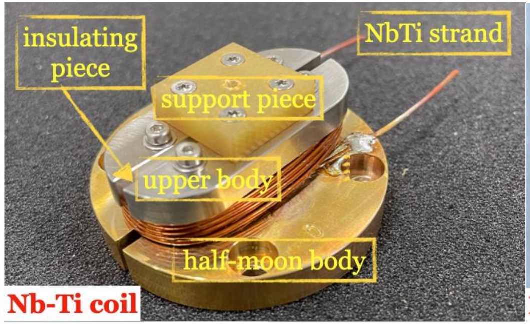


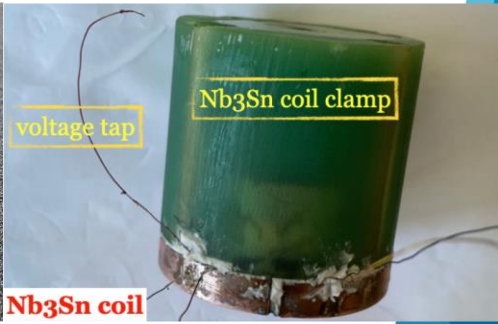
Nb_3Sn coil on winding body

Sample coils: treatment and final structure

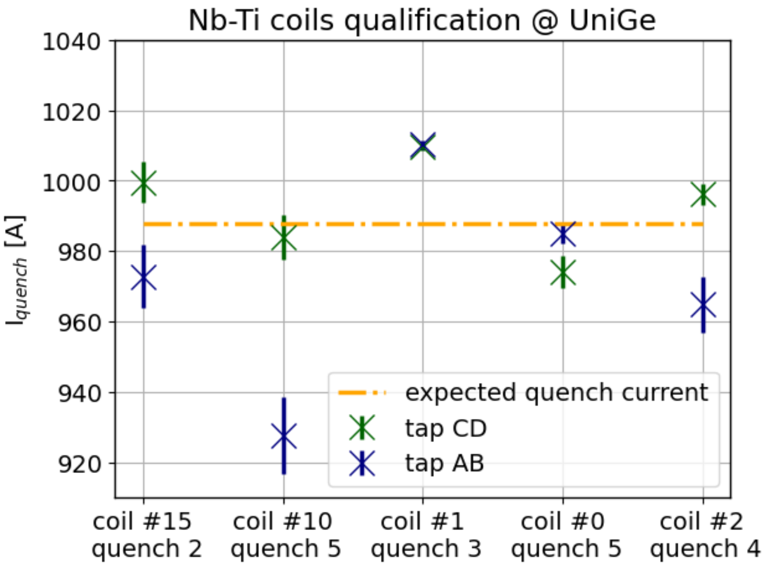
- Nb_3Sn coils
  - underwent heat treatment at University of Geneva;
  - were equipped with a G10 clamp;
  - were impregnated with CDT101K in CERN's Polymer Lab.
- The coils are currently being qualified at the **University of Geneva**.





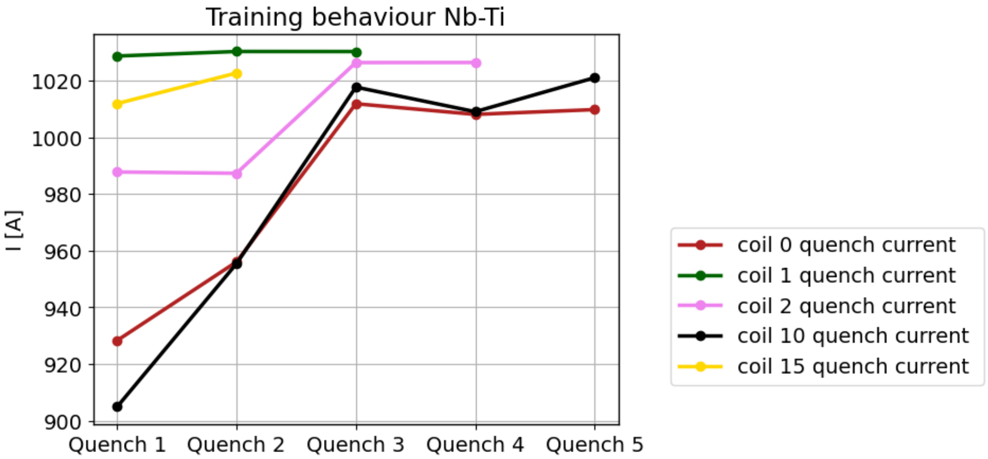


Results of Nb-Ti coil qualification



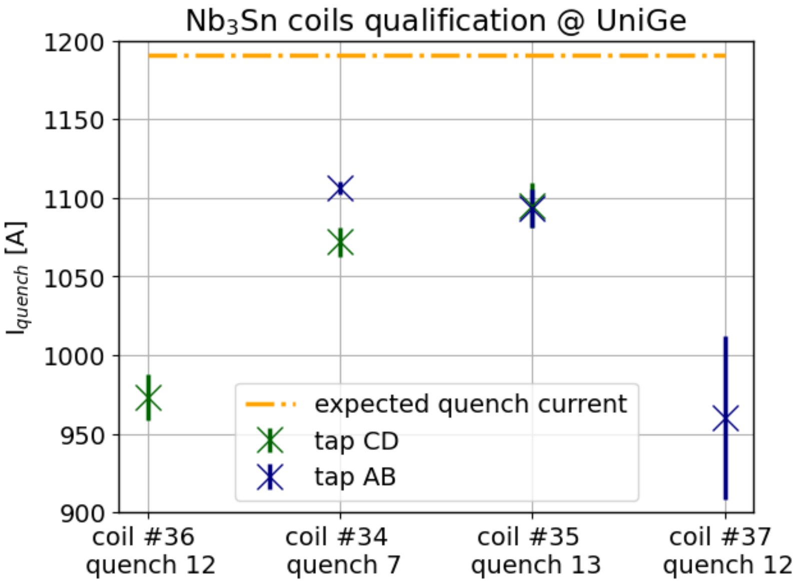
I_{quench} derived from fitting of sc. to normal conducting transition

- 5 coils measured @ 4.2 K in liquid Helium @ Uni-Ge.
- All reaching critical current close to short sample limit → **excellent performance**.
- Up to 5 training quenches observed.
- **Very reproducible** results → we will also install 5 un-tested Nb-Ti coils.



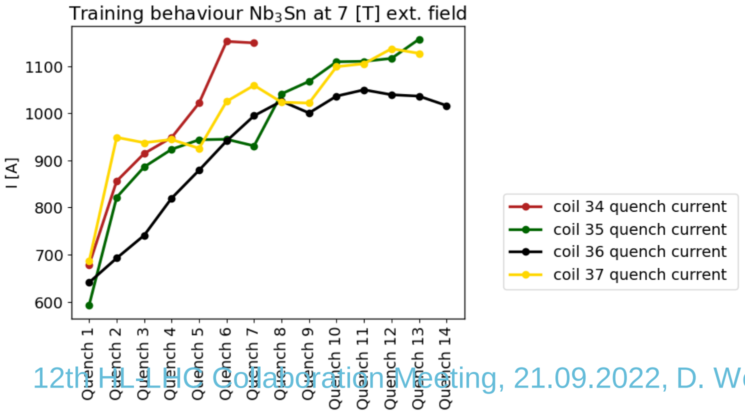
Courtesy D. Gancarcik & M. Bonura

Results of Nb_3Sn coil qualification

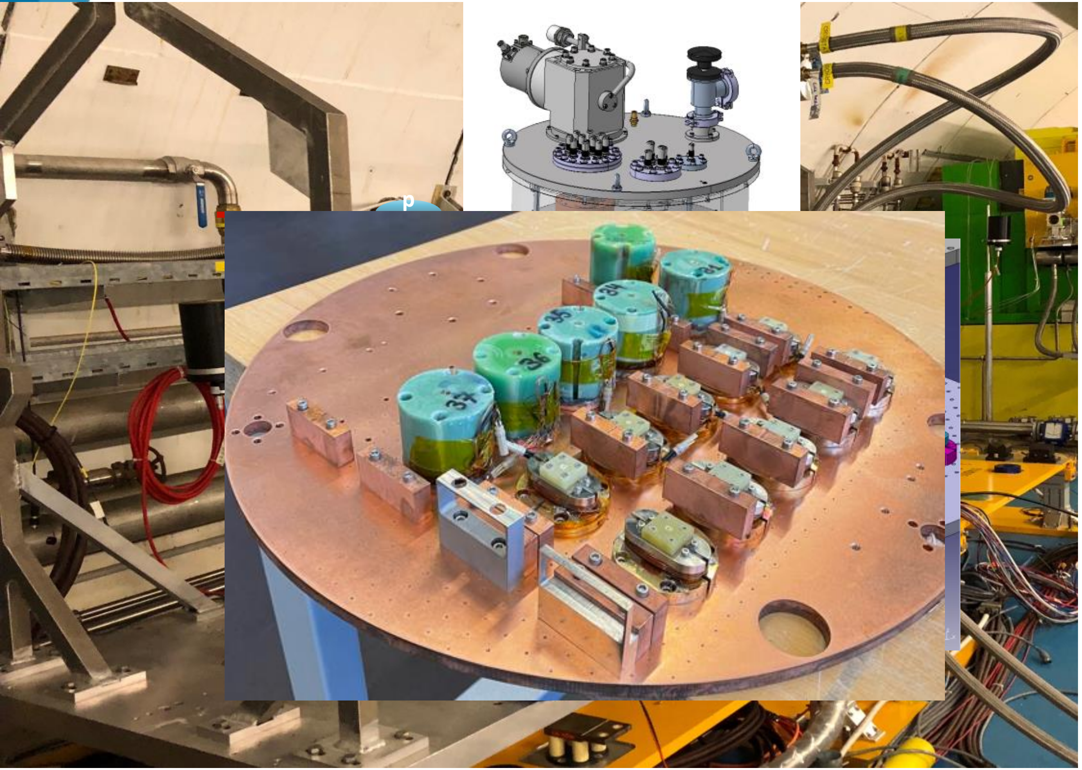


I_{quench} derived from fitting of sc. to normal conducting transition

- 6oo13 coils measured so far @4.2 K and with 7 T external field.
- **4 coils performing well**, reaching between 80 and 90 % of short sample critical current level.
- One coil showed **damage of conductor** (quenching at 20-30% of short sample limit) after heavy handling (prototype of impregnation).
- One coil has **developed a short.**
- ➢ **Less reproducible** than Nb-Ti (as expected), **good performance** of functioning coils.
- 2-3 coils still to be measured before the experiment.

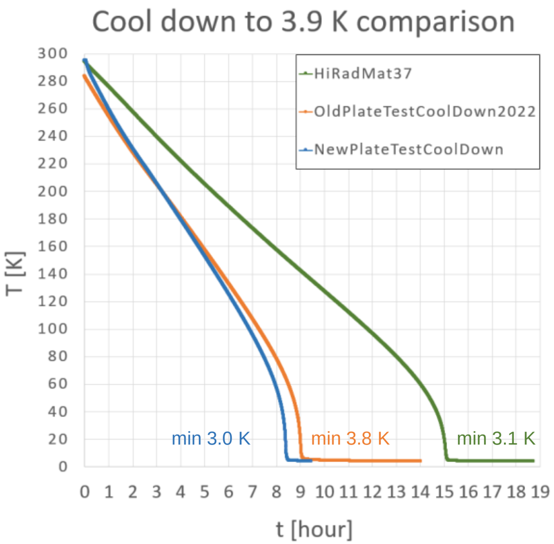


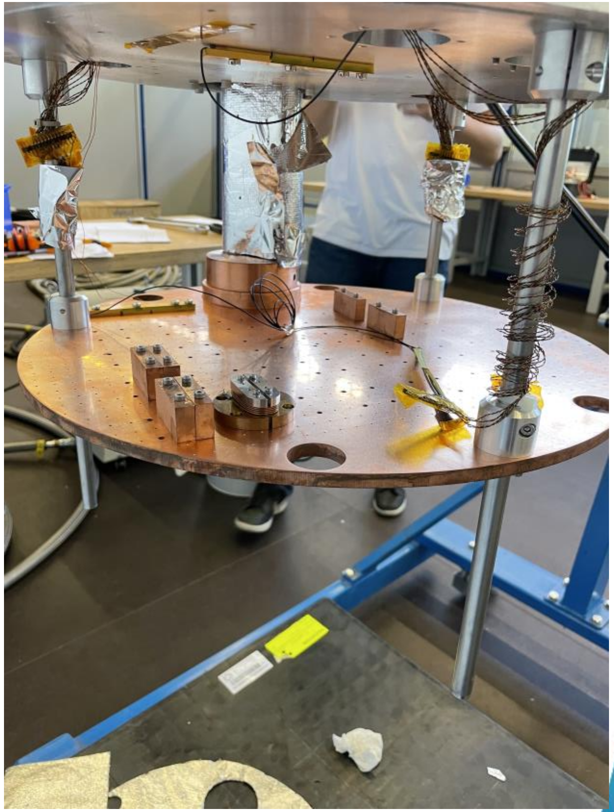
Experimental setup



- **Cryocooler based** cryostat from previous experiment
- Sample coils arranged in **batches of 5** to reach hot spot temperatures between 200 K and 950 K.
- Two batches of 5 Nb-Ti coils.
- Two batches of 5 Nb_3Sn coils.
- Vertical pillar and horizontal stage to switch between batches, move target **out of beam** and perform **beam based alignment**
- Diamond detector for **beam based alignment with pilot bunches.**
- Temperature sensors on plates connect to first and second stage of the cryocooler.
- Shots of **3.6 x 10^{12} p^+ for Nb-Ti** batches and **2.4 x 10^{12} p^+ for Nb_3Sn** batches @ 440 GeV

Modification and Testing of cryostat setup



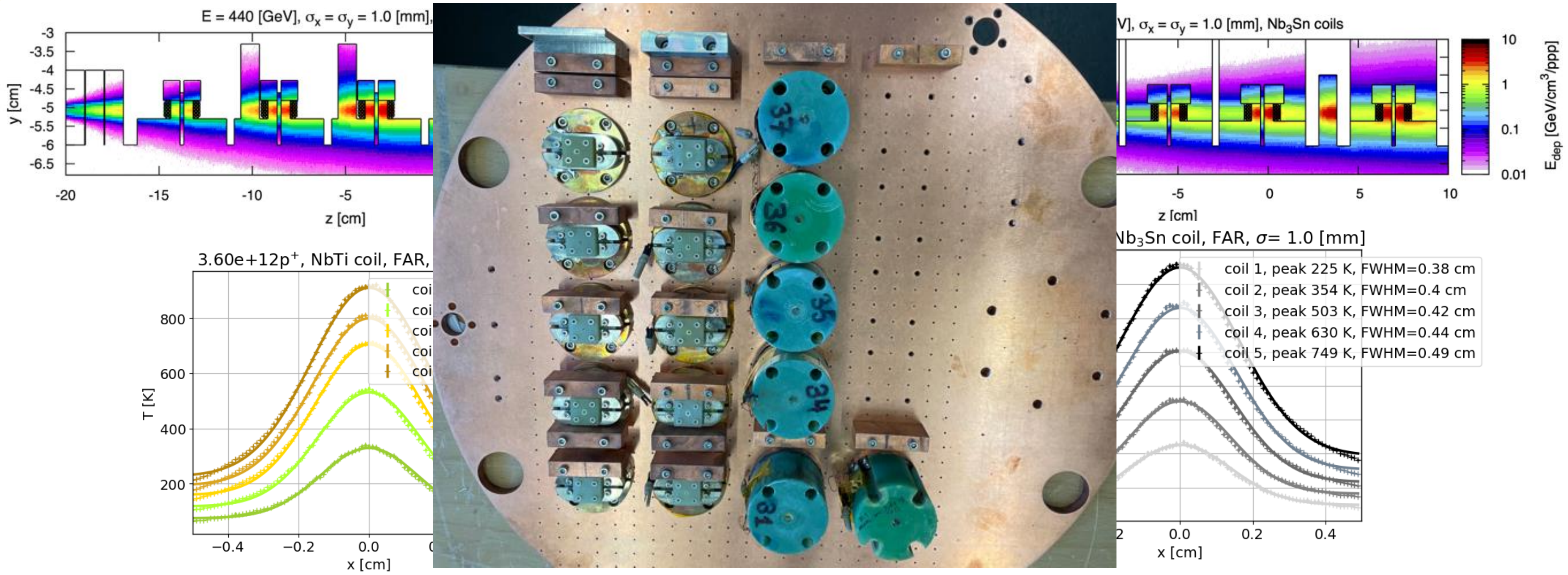


- Two successful and efficient cool-downs of the cryostat after 4 years in the radioactive storage, without issues: < 5 K after ~9h of cool-down, minimum temperature of 3 K reached.
- New second stage copper plate for coil setup successfully installed and tested.

Energy deposition & expected hot spots

Nb-Ti

Nb_3Sn



Expected hot spots (coils 1-5):

- 329 K, 530 K, 704 K, 799 K, 910 K

Expected hot spots (coils 1-5):

- 225 K, 354 K, 503 K, 630 K, 749 K

Schedule until beam experiment

- Week 39: Installation of coil setup in cryostat
- Week 40: Metrology of cryostat setup & final cool-down test
- Week 41: Alignment of cryostat in BA7 on HiRadMat table (survey)
- Week 42: Installation of cryostat in HiRadMat tunnel
- Week 43: Beam experiment in HiRadMat

Post-irradiation analysis

- The sample coils will be **visually inspected** for indication of damage to the sc. strands, cracks in the epoxy etc. after removal from the cryostat
- The sample coils will be qualified with **critical current measurements** at the University of Geneva
- The stresses in the sc. strands of the coils will be **simulated with ANSYS** and the simulation results compared to the measurement results
- Finally, some sample coils might be cut open to allow for **microscopic inspections** at the level of the filaments of the superconducting strands

Conclusion

- A **cryogenic** beam experiment with dedicated **sample coils** is scheduled for end of October 2022 to validate the results from previous experiments and identify potentially further damage mechanisms.
- Coils have been wound, reacted and impregnated. Their qualification is ongoing.
- The Nb-Ti sample coils show **excellent performance**.
- 2oo6 coils lost so far from in total 13 Nb3Sn coils, the others show **very good performance**.
- Modifications of the cryostat have been implemented and performance **successfully tested**.
- Final preparations for the beam experiment are ongoing.

Acknowledgments

- A. Bernhard, B. Bordini, L. Bortot, M. Favre, A. Liakopoulou, B. Lindstrom, D. Kleiven, K. Kulesz, M. Mentink, A. Liakopoulou, B. Lindstrom, M. Meyer, A. Monteuuis, A.-S. Mueller, Y. Nie, A. Oslandsbotn, V. Raginel, R. Schmidt, D. Schoerling, J. Schubert, C. Scheuerlein, A. Siemko, K. Stachon, M. P. Vaananen, A. Verweij, A. Will
- Measurements of I_c were performed by the University of Geneva – M. Bonura, C. Senatore - who also provided strong support for the interpretation of the experimental results
- This work was supported by the High Luminosity LHC Project

Notes, publications and theses

V. Raginel, B. Auchmann, R. Schmidt, D. Schoerling, A.P. Verweij, D. Wollmann, "Experimental Setups to Determine the Damage Limit of Superconducting Magnets for Instantaneous Beam Losses", Proceedings IPAC 2015.

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V. Raginel, D. Kleiven, K. Kulesz, M. Mentink, R. Schmidt, A. Verweij, and D. Wollmann, “Change of critical current density in Nb-Ti and Nb3Sn strands after millisecond heating”, Proceedings IPAC 2017

V. Raginel, M. Bonura, D. Kleiven, K. Kulesz, M. Mentink, C. Senatore, R. Schmidt, A. Siemko, A. Verweij, A. Will, and D. Wollmann, "First Experimental Results on Damage Limits of Superconducting Accelerator Magnet Components Due to Instantaneous Beam Impact", IEEE Trans. Appl. SC, Vol 28(4), June 2018

V. Raginel, "Study of the Damage Mechanisms and Limits of Superconducting Magnet Components due to Beam Impact ", TU-Wien, Austria, CERN-THESIS-2018-090

A. Oslandsbotn, A. Will and D. Wollmann, Beam Impact on Superconductor short samples of Nb3Sn, Nb-Ti and YBCO, CERN Internal Note, 2018, EDMS 2068064

A. Will, A. Bernhard, M. Bonura, B. Bordini, L. Bortot, M. Favre, A. Liakopoulou, B. Lindstrom, M. Mentink, A. Monteuuis, A.-S. Mueller, A. Oslandsbotn, R. Schmidt, C. Senatore, A. Siemko, K. Stachon, M. P. Vaananen, A. Verweij, D. Wollmann, "Beam impact experiment of 440GeV/p Protons on superconducting wires and tapes in a cryogenic environment", Proceedings IPAC 2019

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M. S. Meyer, "Characterization of Nb3Sn strands impacted at 440GeV at 4K", EDMS 2363700

J. Schubert, "Damage Study on Single Strand Nb3Sn Ultra-Fast Beam Impact in Cryogenic Environment Simulation with Finite Element Method", University of Jena, Germany, CERN-THESIS-2020-072

A. Will, “Damage Mechanisms in Superconducting Particle Accelerator Magnets Due to the Impact of High EnergyParticles”. Karlsruher Institut für Technologie (KIT), Karlsruhe, Germany, 2021, CERN-THESIS-2021-187

Questions?