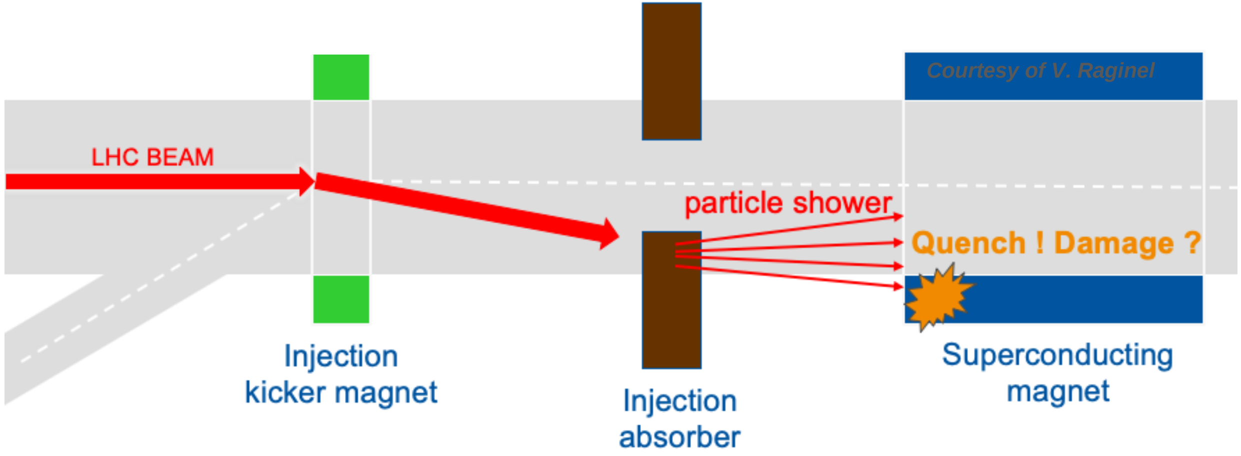
Damage of superconducting sample coils due to beam impact

David Gancarcik, Cedric Hernalsteens, Daniel Wollmann
(TE-MPE-CB, WP7) and many more (see acknowledgements)

14th HL-LHC Collaboration Meeting, Genoa (Italy), 10 October 2024

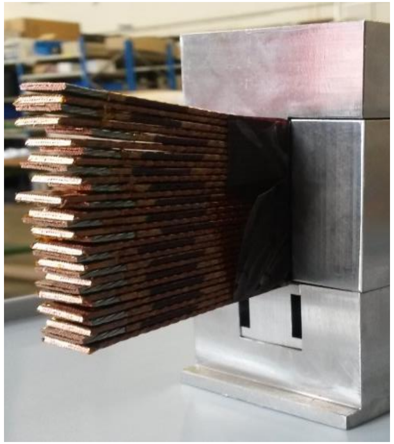
Motivation of the studies on sc. magnet components

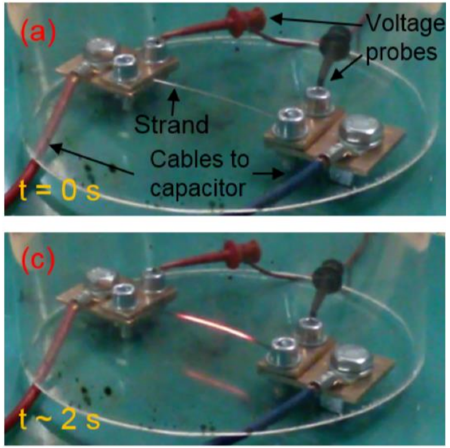
Ultra-fast failures in HL-LHC: Injection kicker failure case



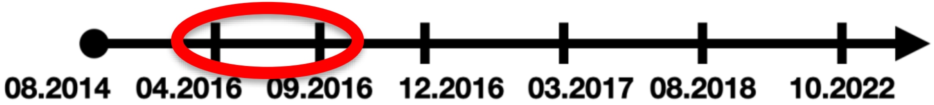
- Will the **magnets be permanently damaged**?
- What are the **damage mechanisms and limits** of superconducting magnets due to **high-intensity beam impact**?
- Ongoing studies within WP7 in past decade
  - **Nb-Ti** and **Nb_3Sn strands** and **cables** and **coils**, polyimide insulation (Nb-Ti), CTD101K epoxy (Nb_3Sn)

Experimental campaign





- Different timescales (**hours-µs**), heating in furnace [1], discharge[2],



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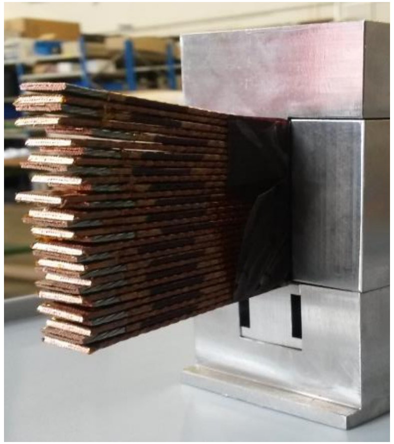
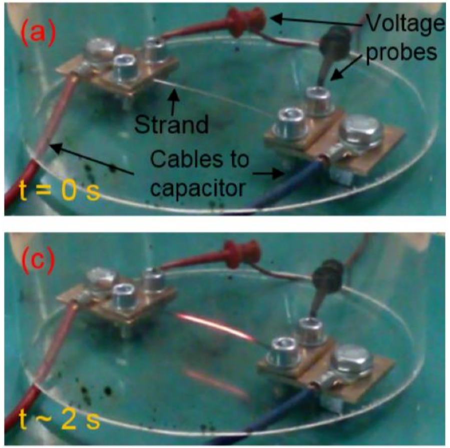
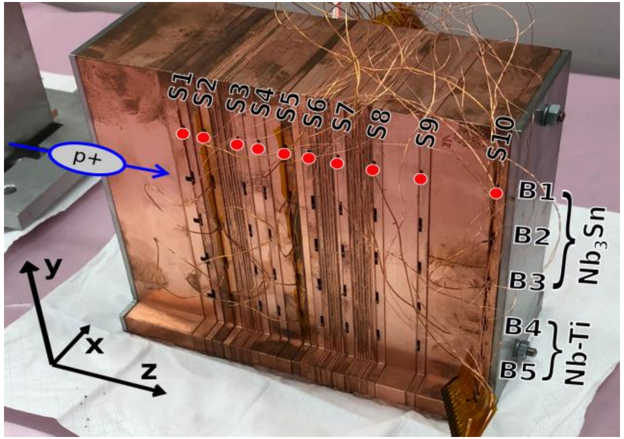
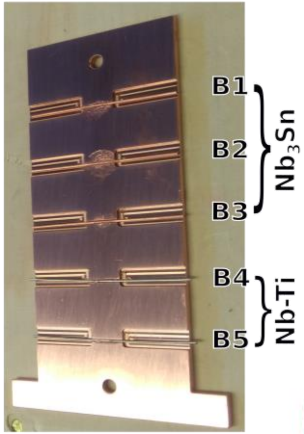
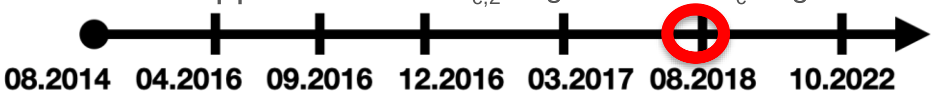








- Different timescales (**hours-µs**), heating in furnace [1], discharge[2], beam at RT [3]
- **HRMT37** [4] – 1st **beam experiment at 4K**, strands in copper sample holder
- Two main damage mechanisms in Nb_3Sn identified
  - Filament breaking caused by the excessive strain → I_c degradation
  - Residual strain from the copper matrix → $B_{c,2}$ degradation → I_c degradation



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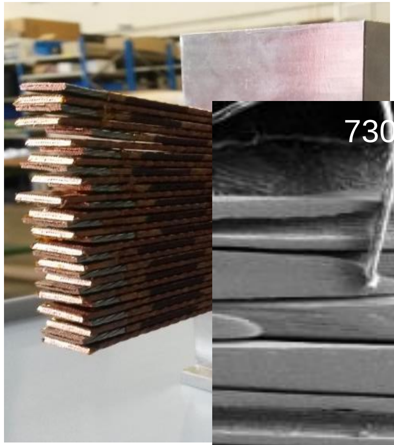
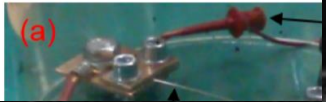
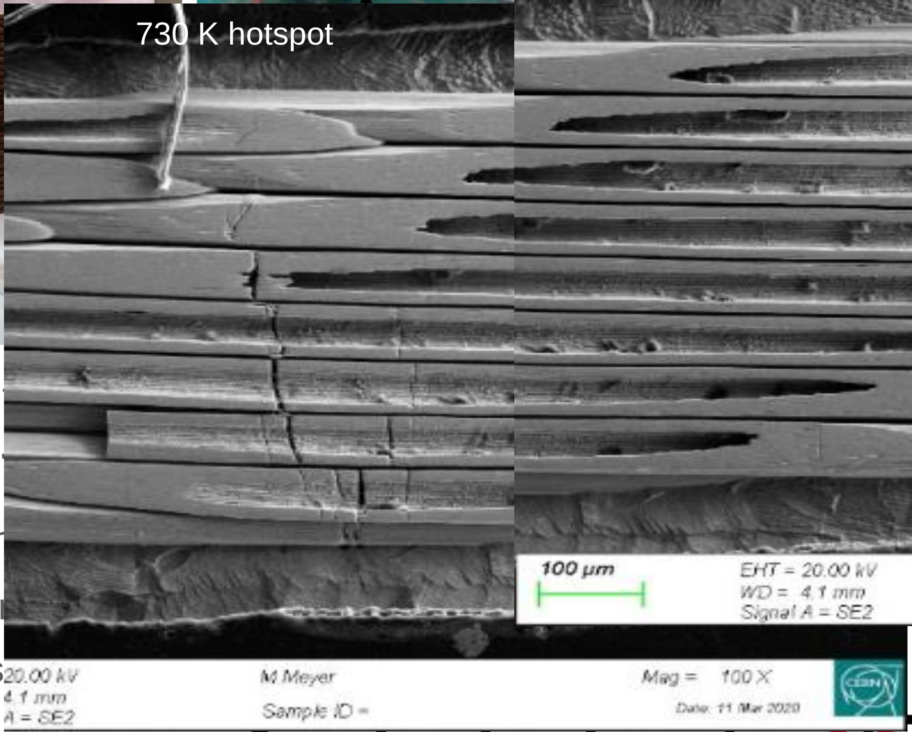
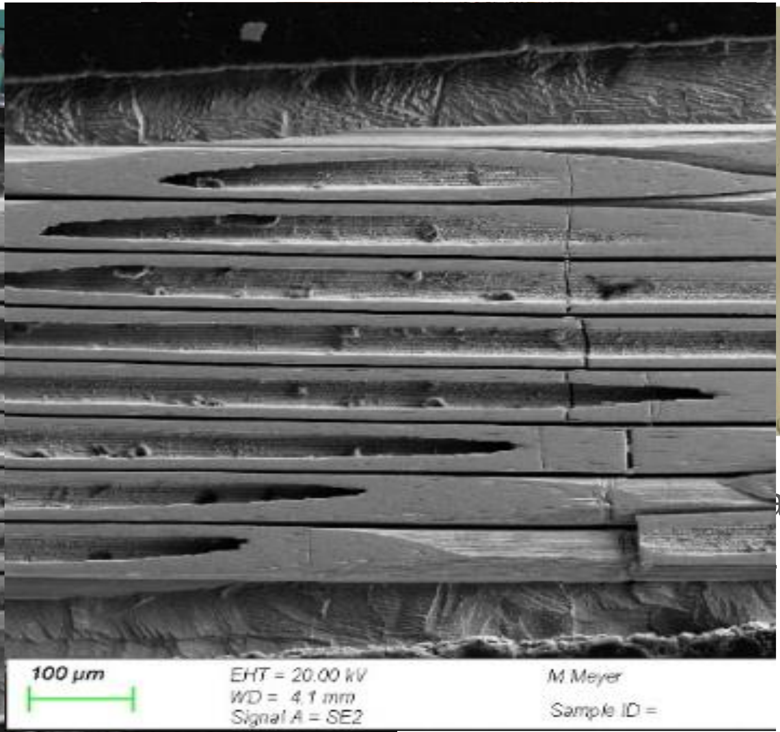
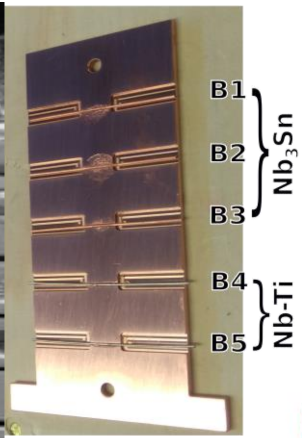


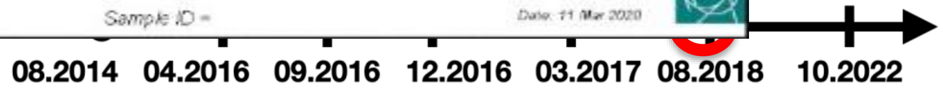






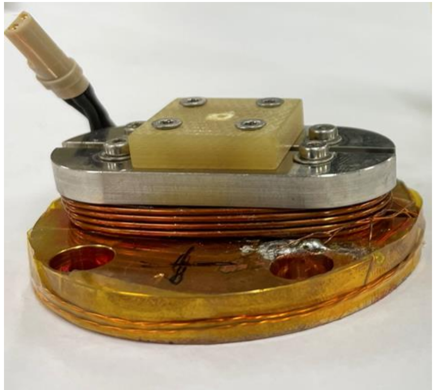


- Differen… at RT [3]
- **HRMT3…**
- Two dar…
  - Fila…
  - Res…



Sample racetrack coils

- Copper base Ø 48mm
- Nb-Ti sample coil:
  - Ø 0.825mm **LHC dipole** inner layer **strand**



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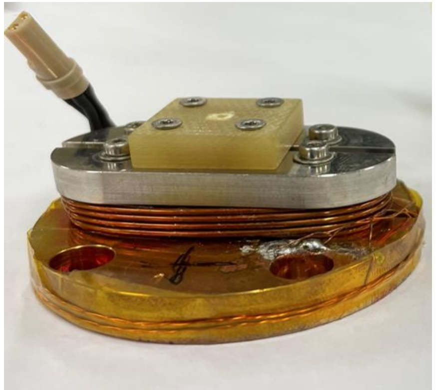
- Nb_3Sn sample coil:
  - Ø 0.85mm RRP **HL-LHC triplet strand**
  - Reacted with HL cycle (same as MQXF)
  - Impregnated with **CTD101K epoxy**
  - Equipped with G10 clamp



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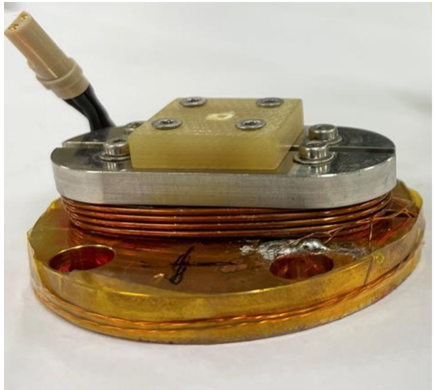
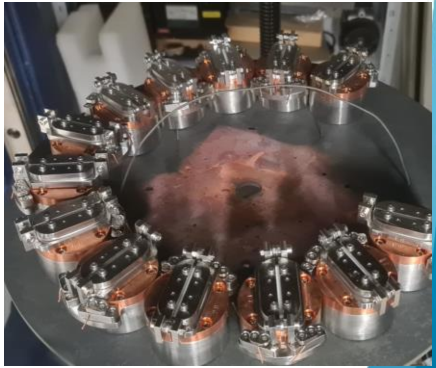
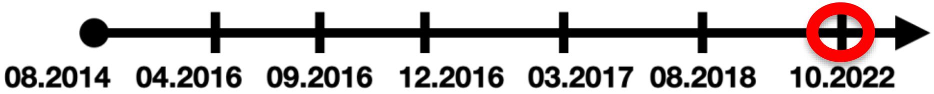
- Coils were **wound @ KIT**, **reacted @ University of Geneva** and **impregnated @ CERN polymer lab**

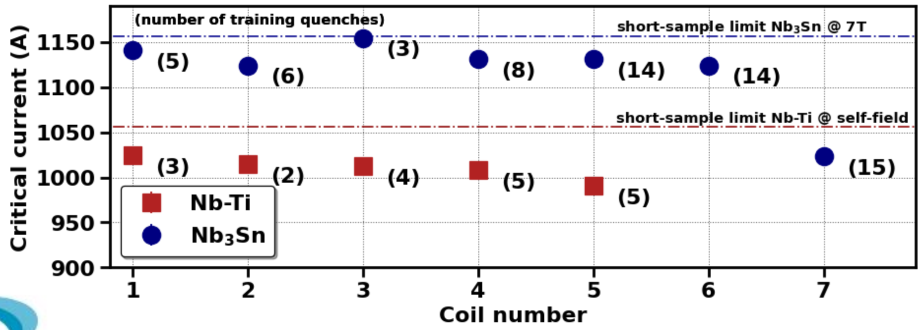


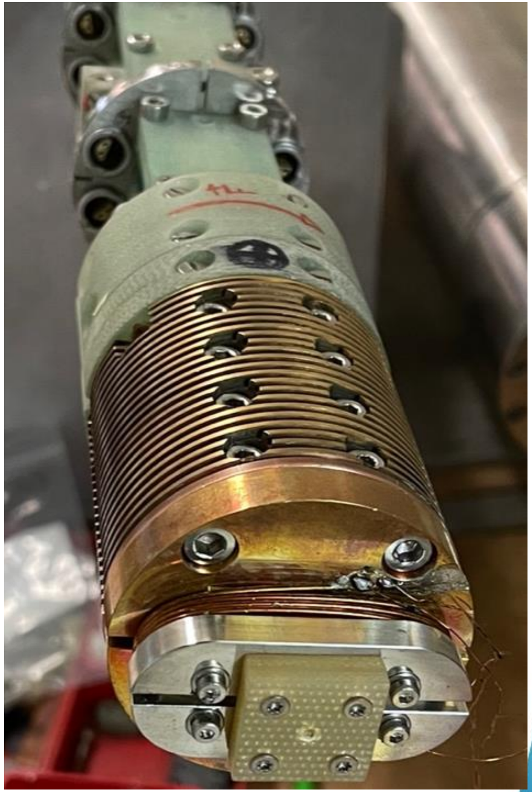




Qualification of sample coils

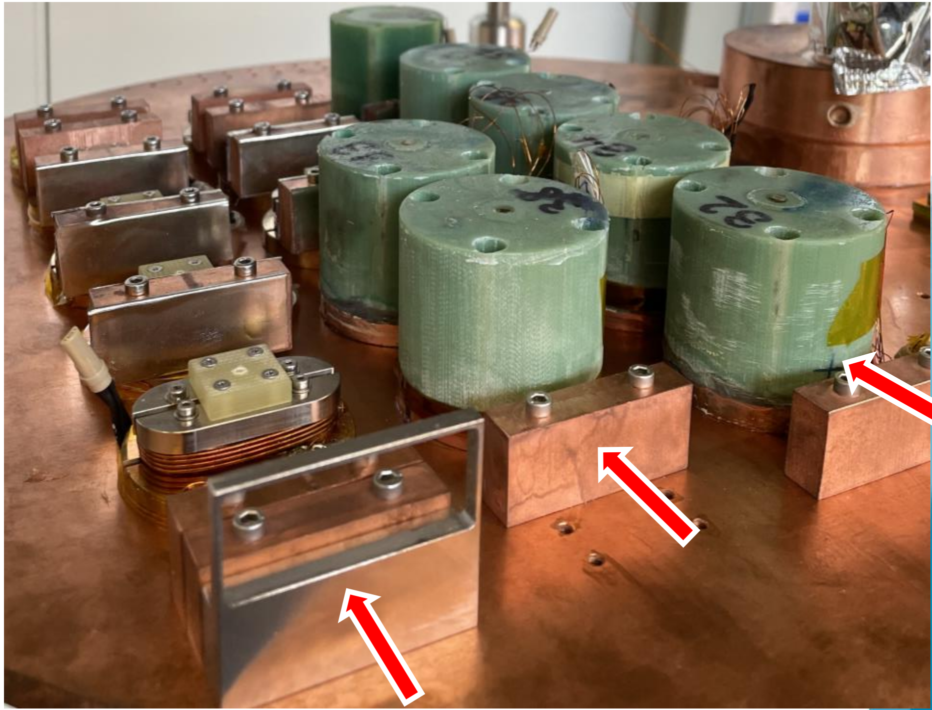
- Ramping of current, quench detection
- Qualification performed for:
  - **Nb-Ti samples** @ **self-field:** show similar performance, **reached 94-98%** of short-sample limit **(**built:15, **used:8, qualified:5)**
  - **Nb_3Sn samples** @ **7T** ext. field: more training quenches, larger differences between quench current compared to Nb-Ti, **reached 91-100%** of short-sample limit **(**build:15, **used:7, qualified:7)**





Experiment setup for coils experiment

- **Three batches of five coils**
  - Batch 1 (Nb-Ti): qualified Nb-Ti
  - Batch 2 (mixed): $2xNb_3Sn+3xNb$-Ti
  - Batch 3 (Nb_3Sn): qualified Nb_3Sn



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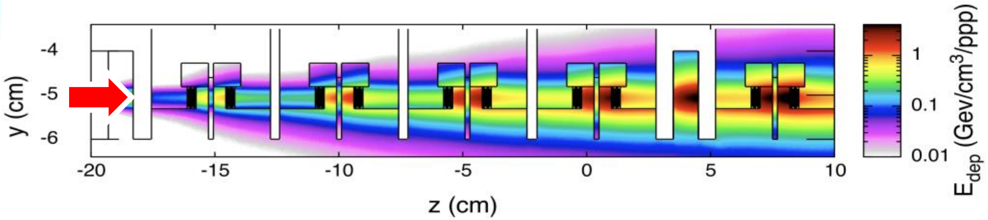

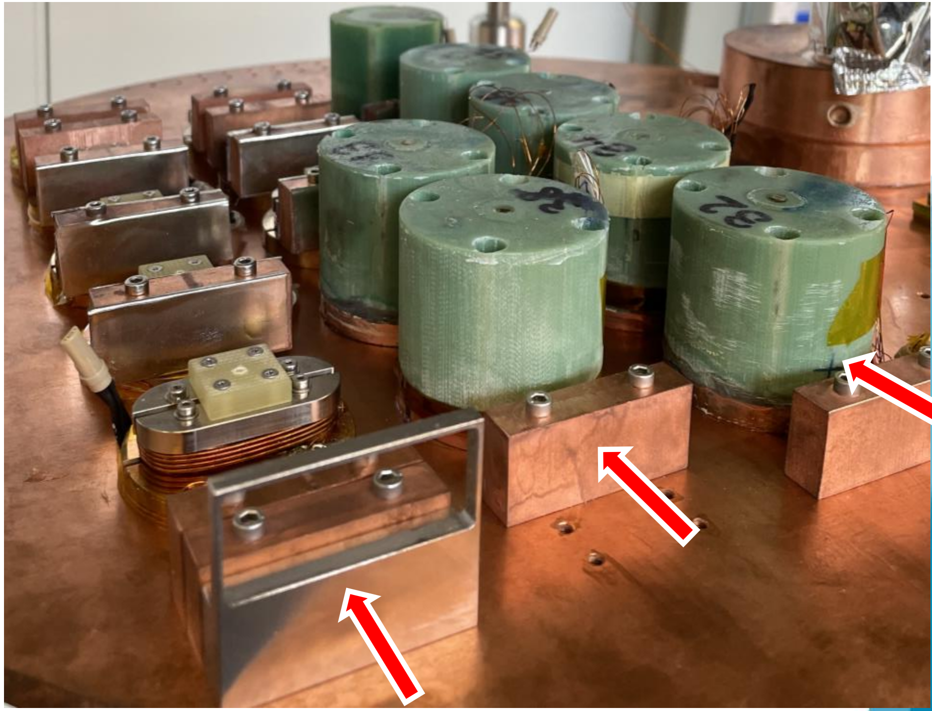

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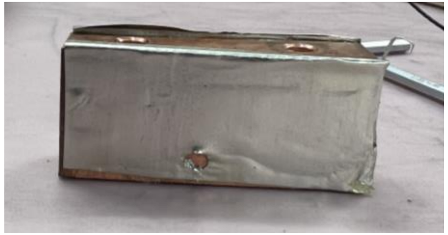
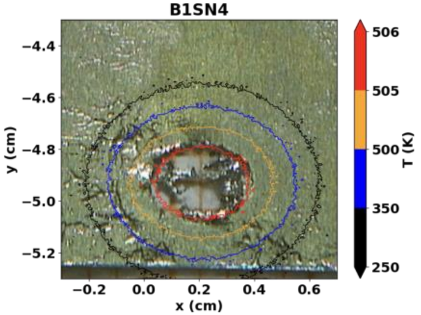
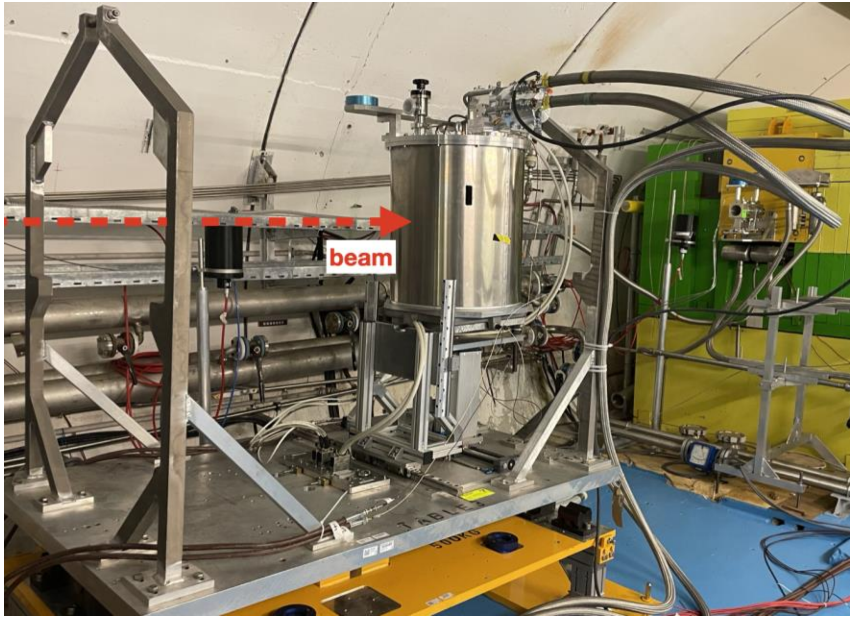


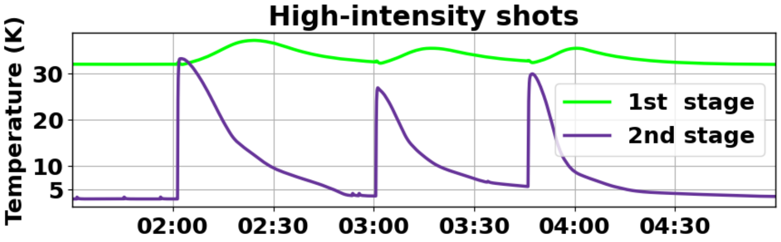


Coil	T (K)	G_T (K/mm)	G_A (K/mm)
Nb-Ti	300 - 910	80 - 260±30	80 - 240±30
Nb_3Sn	200 - 680±40	50 - 200±20	70 - 190±20

Experimental setup in HiRadMat tunnel



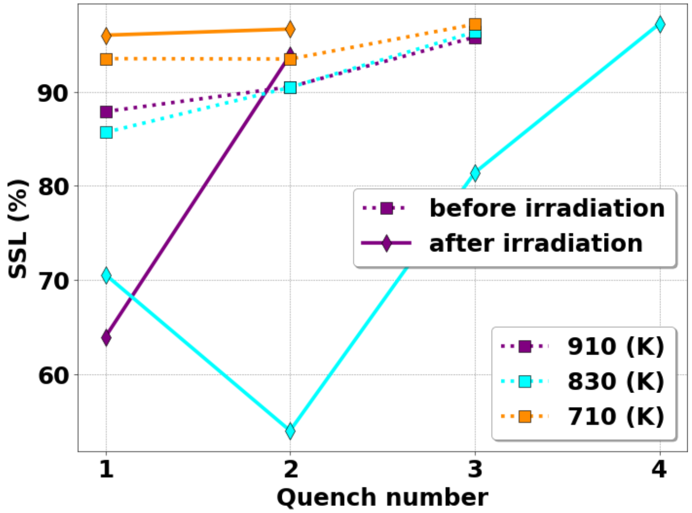
Batch	Intensity (10^{12} p^+)	σ_x, σ_y (mm)
1	3.9±2%	1.33±5%, 1.05±5%
2	2.6±2%	1.33±5%, 1.05±5%
3	2.6±2%	1.33±5%, 1.05±5%



- Placed in **vacuum vessel** with cryogenic device → experiment conducted **at 4K**
- Horizontal and vertical **movable stages** to switch in between batches
- **Beam-based alignment** prior to high-intensity shots to validate the correct alignment

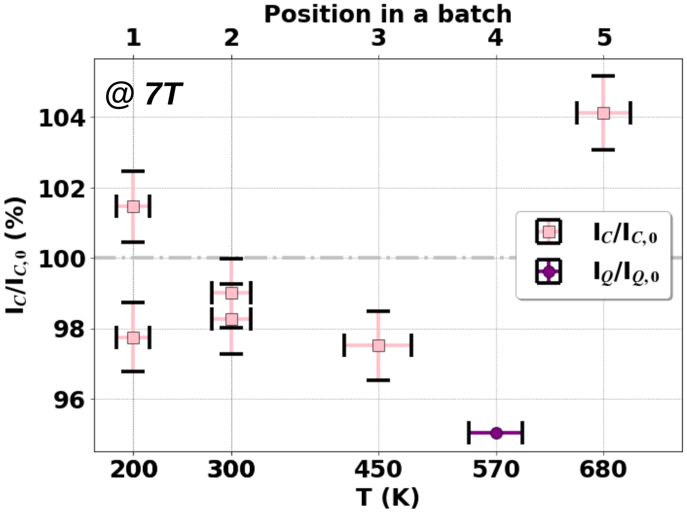
Post-irradiation I_c measurement (Nb-Ti coils)

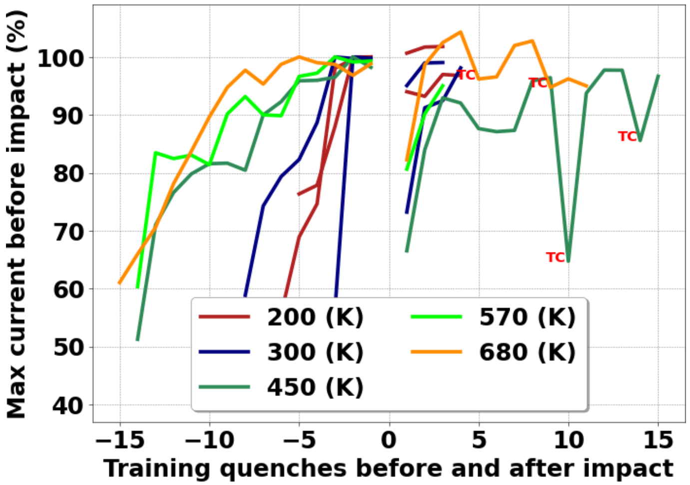
- **No permanent degradation** in coil observed **up to 910K**
  - Consistent with previous findings → no new damage mechanism
- Temporary **memory loss** for hotspots above 710K
  - Strong de-training observed after the beam impact
  - Likely caused by tension in the winding from the beam heating
  - Tension is released during few first training quenches



Post-irradiation I_c measurement (Nb_3Sn coils)

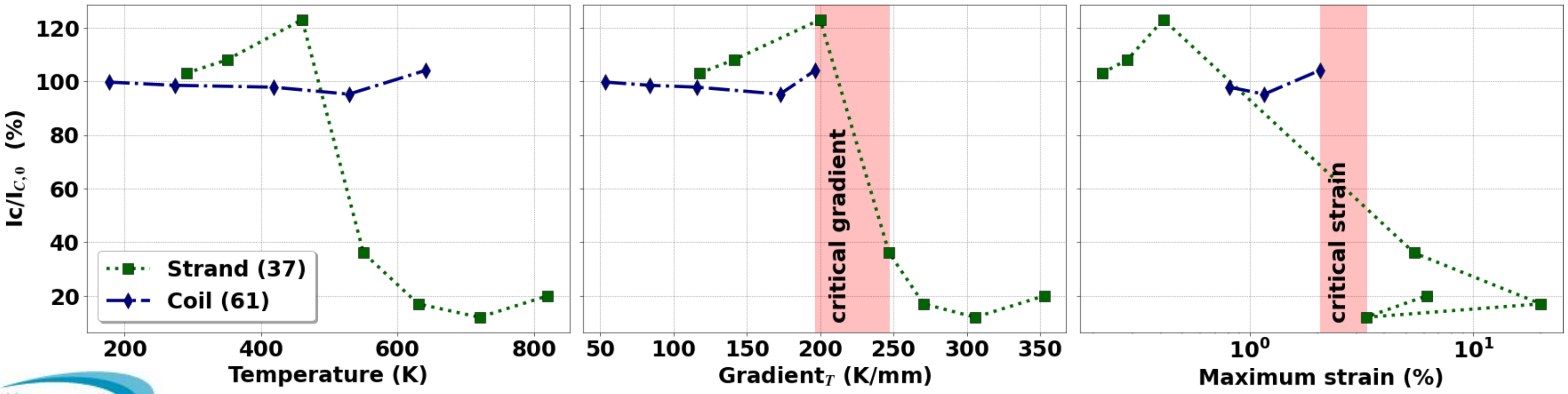
- **No permanent degradation** observed up to **680K**
- No additional memory loss after beam impact as compared to effect of thermal cycle





Comparison between strand and coil experiment

- **No degradation** in coils **up to 680K** as opposed to degradation in strands above 460K
- Seems contradictory but looking at the transverse **thermal gradient** the coil **results agree with the strands** results → supported by the physics, as thermal gradient is more relevant for the strain in the strands / filaments
- Confirmed by comparing the **maximum strain** as derived from ANSYS simulations



Conclusion

- Extensive and successful experimental campaign has been conducted to identify the **damage limits and mechanisms of superconducting magnet** components due to direct beam impact.
- The results of the sample coil experiment are in agreement with the previous strand experiment
  - **Nb-Ti: No permanent degradation** of critical current if hot spot in coil **up to 910K** (up to 1130K in strand experiment)
  - **Nb_3Sn: No permanent degradation for gradients up to 200K/mm or** in **maximum strain up to 2%**
  - Coil experiment reveals **memory loss** for hotspots above **710K in Nb-Ti** coils
- Damage studies (simulations & experiments) are essential to identify the criticality of failure cases, to design protection methods and equipment and to specify interlock systems

Acknowledgments

- A. Bernhard, S. Bolton, M. Bonura, B. Bordini, L. Bortot, B. Bulat, E. Calvo, A. Cherif, B. Descargues, S. Clement, E. Effinger, M. Favre, N. Glamann, A. Grau, D. Jauregui, D. Kleiven, T. Koettig, K. Kulesz, M. Mentink, A. Liakopoulou, B. Lindstrom, M. Meyer, A. Monteuuis, A.-S. Mueller, Y. Nie, A. Oslandsbotn, V. Raginel, F. Rodriguez Mateos, R. Schmidt, D. Schoerling, J. Schubert, C. Scheuerlein, C. Senatore, J. Sestak, A. Siemko, P. Simon, K. Stachon, D. Tommasini, C. Urscheler, M. P. Vaananen, A. Verweij, A. Will
- Presented experiments and results are part of V. Raginel's and A. Will's PhD theses.
- Measurements of I_c, T_c, B_{c2}, Magn., were performed by the University of Geneva, who also provided strong support for the interpretation of the experimental results
- The Nb_3Sn sample coils have been impregnated at CERN's polymer lab.
- This work is supported by the High Luminosity LHC Project

HiLumi HL-LHC PROJECT