Beam Damage Experiments on Superconducting Coils

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with contributions of many and many others (see acknowledgements)

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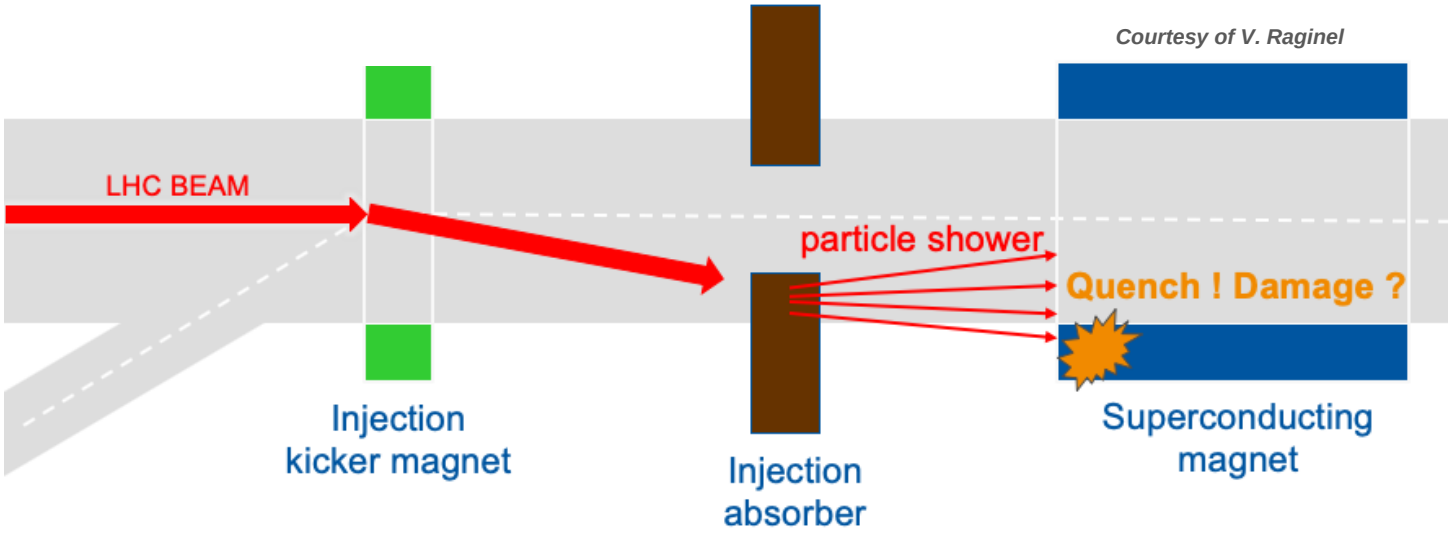
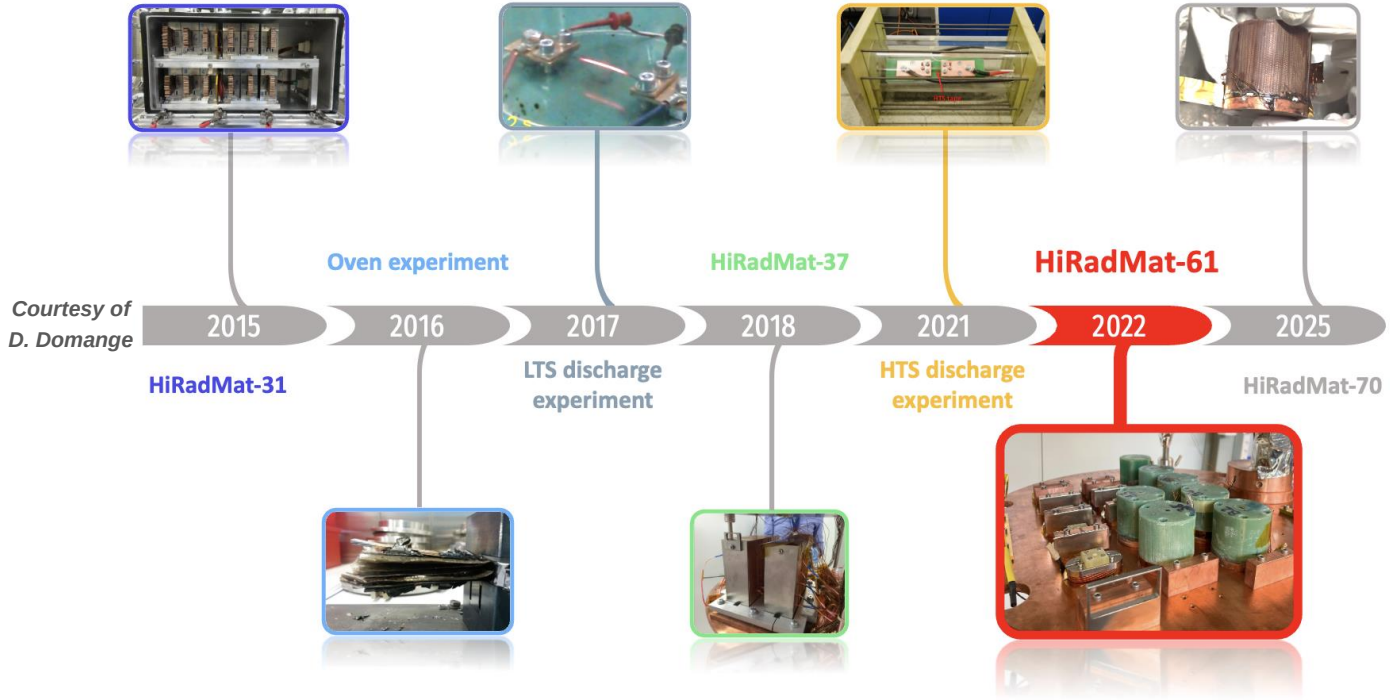
Motivation of the studies on sc. magnet components

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



- What are the **damage mechanisms and limits** of superconducting magnets due to **high-intensity beam impact?** Will the **magnets be permanently damaged**?

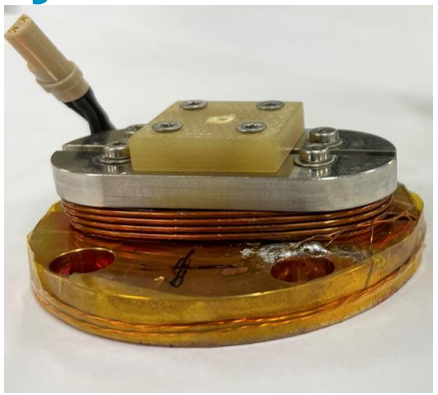
Timeline of the studies on sc. magnet components



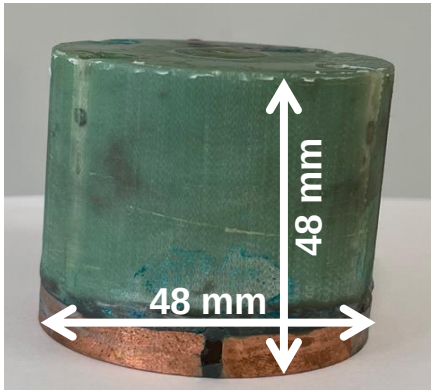
- From studying damage in strands, insulation, and cables across different temperature ranges and timescales → **impact of racetrack sc. coils at 4K with 440 GeV beam**

Sample racetrack coils impacted by the beam

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

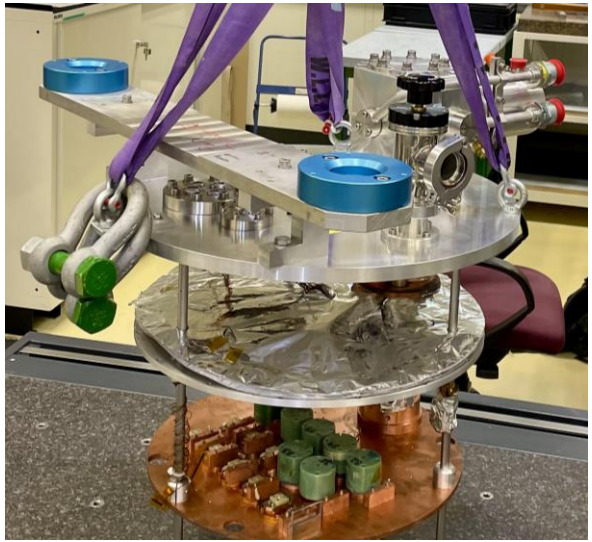


- Nb_3Sn sample coil:
  - Ø 0.85mm RRP **HL-LHC triplet strand**
  - Heat-treated with HL-LHC temperature profile and impregnated with **CTD101K epoxy (same as MQXF)**



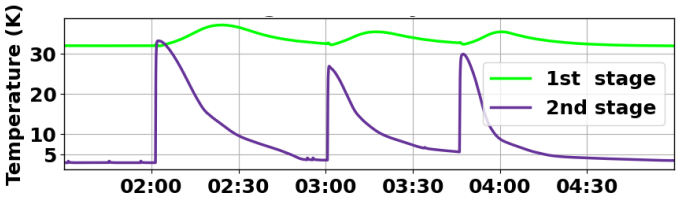
- Pre-irradiation qualification was performed at University of Geneva (critical transport current measurement)

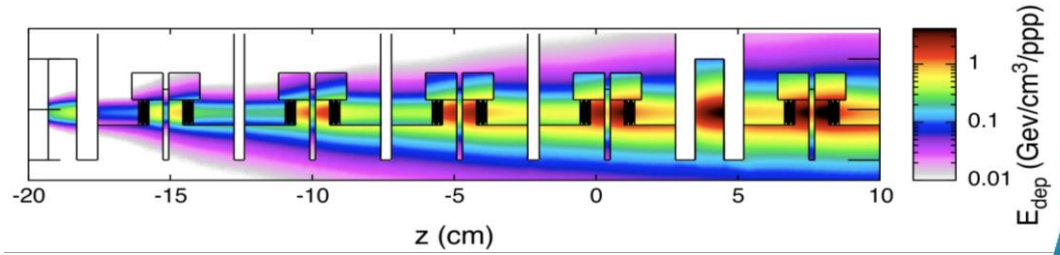
Experimental setup in HRMT facility



Samples arranged in vacuum vessel

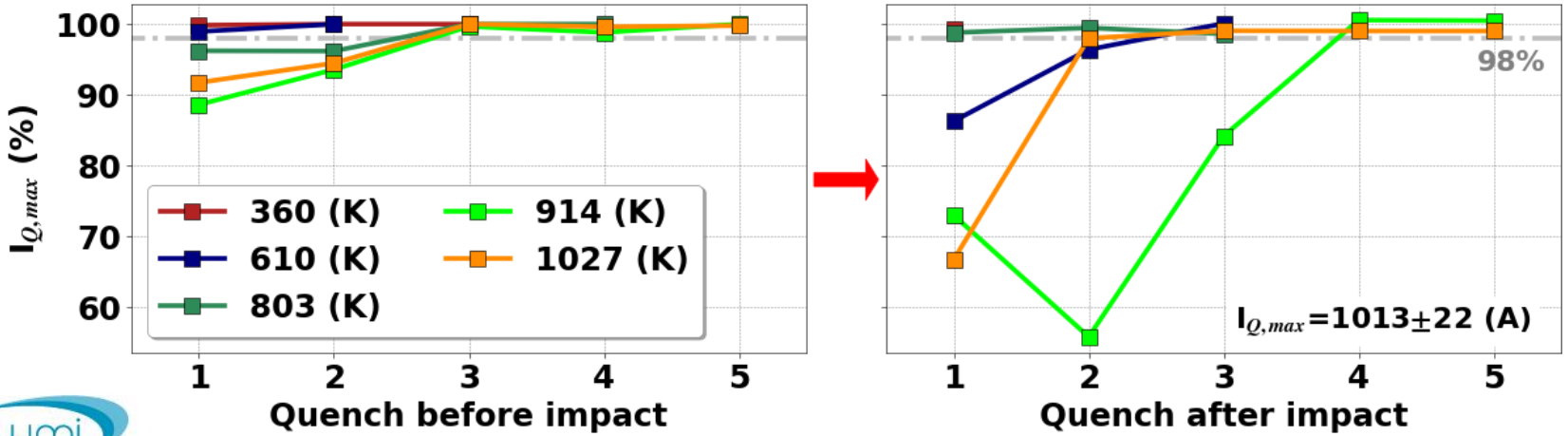
Vacuum vessel cooled to 4K impacted by beam in HRMT tunnel





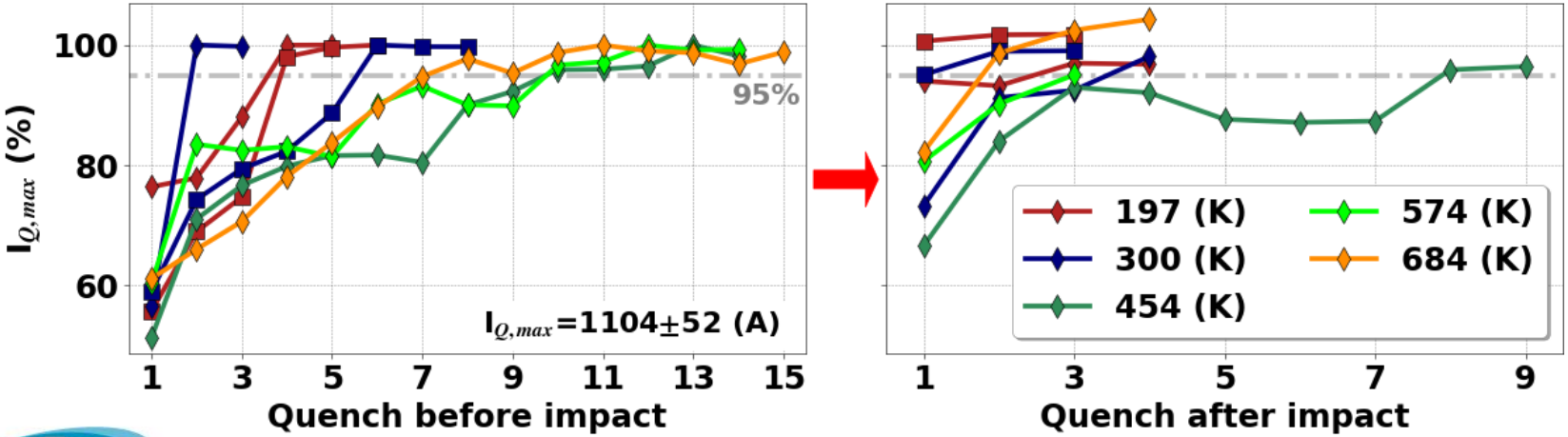
Post-irradiation I_c measurement (Nb-Ti coils)

- **All samples reached more than 98% of pre-irradiation current**
  → **No permanent degradation** was observed **in Nb-Ti** coils
- Temporary **memory loss** for samples at or above 610K
  - Strong de-training observed after irradiation compared to the effect of a thermal cycle
  - Likely caused by tension in the winding due to beam heating => tension is released during a few first training quenches (up to 3, usually 1)



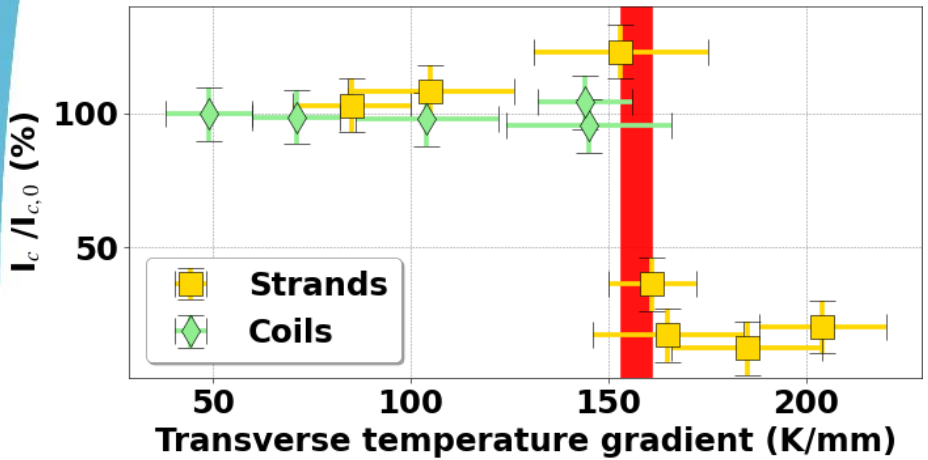
Post-irradiation I_c measurement (Nb_3Sn coils)

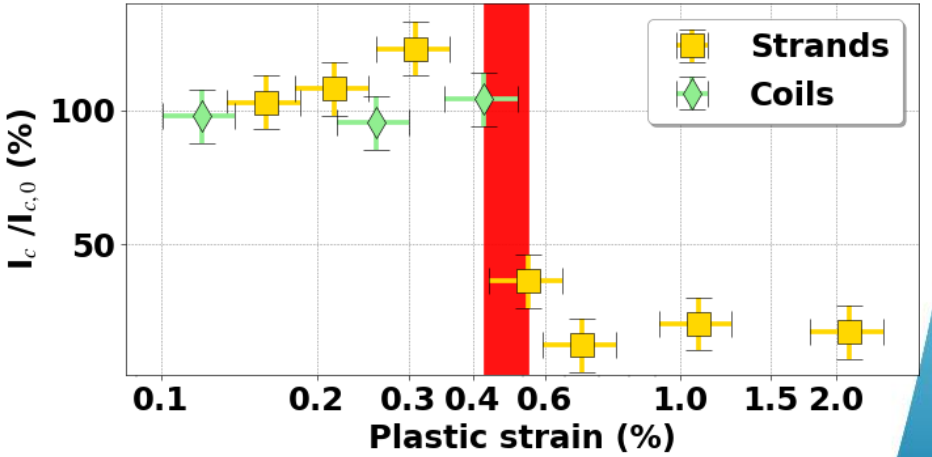
- **All samples reached more than 95% of pre-irradiation current**
  → **No permanent degradation** was observed **in Nb_3Sn** coils
- Temporary memory loss was also observed, but at the level of a thermal cycle. Due to the small statistics, this cannot be reliably attributed to the beam impact



The main damage mechanism due to beam impact

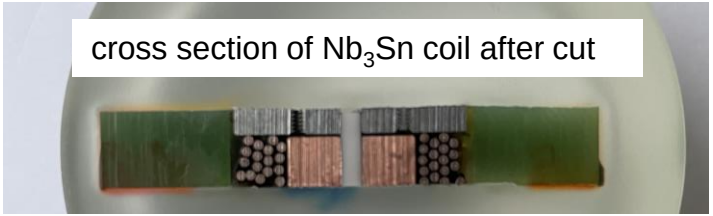
- **Filament breakage**: not observed in coils as the transverse gradient (and the plastic strain, simulated with dedicated ANSYS simulations) did not reach the critical value of 153 K/mm (or plastic strain of 0.51%)



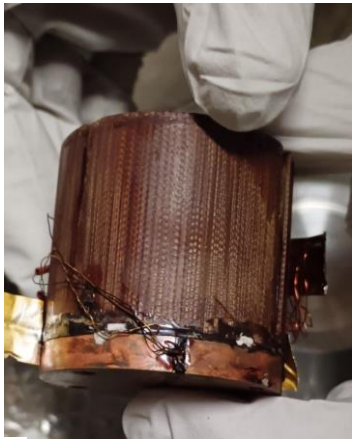


Conclusion and outlook

- No additional damage mechanism has been identified
- Destructive testing in progress
- The upcoming experiment (October 2025) will investigate:
  - additional damage mechanisms in coils irradiated with gamma-rays to 25 and 30 MGray (integral dose levels expected in HL-LHC inner triplets) and subsequentially impacted by the proton beam
  - region of higher transverse gradients (plastic strain)



Nb_3Sn coil



Nb_3Sn coil at 25MGray

Acknowledgments

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- Presented results of strand experiment are part of A. Will's PhD thesis
- Measurements of I_c were performed by the University of Geneva
- The sample coils were wound in KIT campus north
- The Nb_3Sn sample coils have been impregnated at CERN's polymer lab
- **This work is supported by the High Luminosity LHC Project**