HiLumi
HL-LHC PROJECT

Studies on damage limits of superconducting magnet components due to instantaneous beam impact – recent results and future plans

- Motivation for experimental studies on damage limits
- Experimental program & Results
- Future plans

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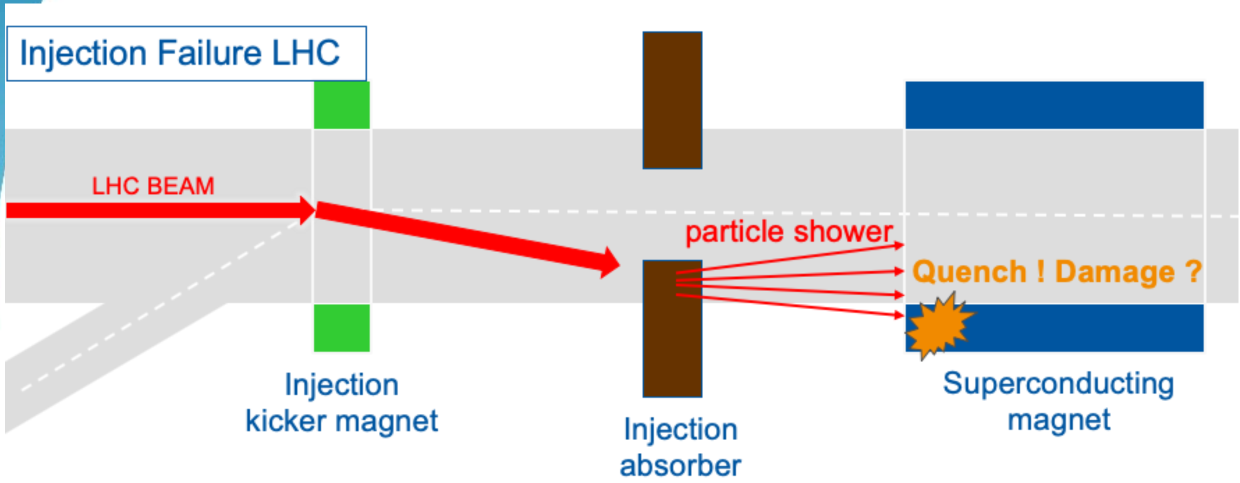
MSC Seminar 10.11.2020, CERN

Motivation of the studies

Ultra-fast failures in HL-LHC



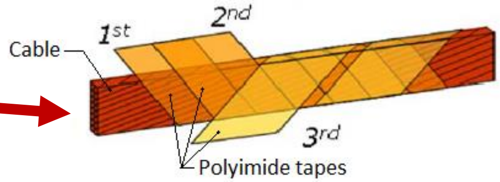
- One such event per year in today's LHC. No damage.
- HL-LHC:
  - **increased bunch intensity** from 1.15 x 10^{11} ppb to 2.2 x 10^{11} ppb
  - **reduced emittance** (3.75 um rad → 2.5 um rad)
  - **Increased stored beam** energy from 360 MJ to 690 MJ
  - Failures become **more critical**

- For HL-LHC beam, peak energy deposition of 100 Jcm^{-3} in the D1 magnet without mask[1] and similar in Q5 are expected 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**?

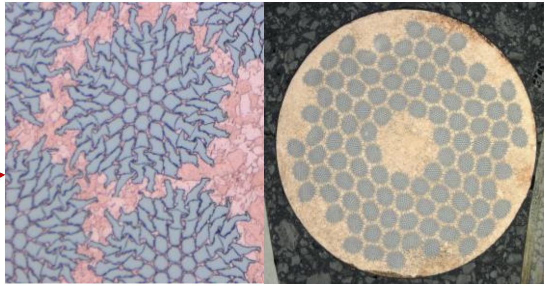
[1] A. Lechner et al., Protection of superconducting magnets in case of accidental beam losses during HL-LHC injection, In Proceedings of IPAC15
[2] B. Auchmann et al., Quench and Damage Levels for Q4 and Q5 Magnets near Point 6, CERN EDMS 1355063, 2014

Critical parts of superconducting magnets

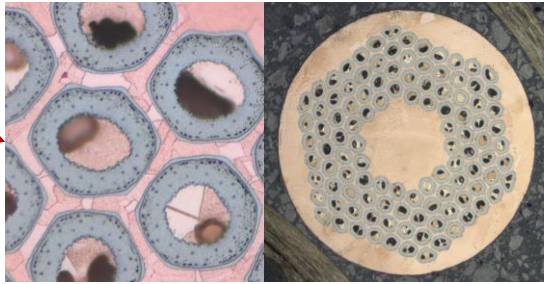
- Polyimide insulation (Nb-Ti magnets)
  - Decomposition when exposed to high temperature
  - Reduction of the dielectric strength



- Nb-Ti strand/cables (LHC)



- Nb_3Sn strand/cables (HL-LHC)
  - Reduction of the J_c induced by:
  - High temperature (e.g. diffusion)
  - Mechanical stress, deformation and cracks

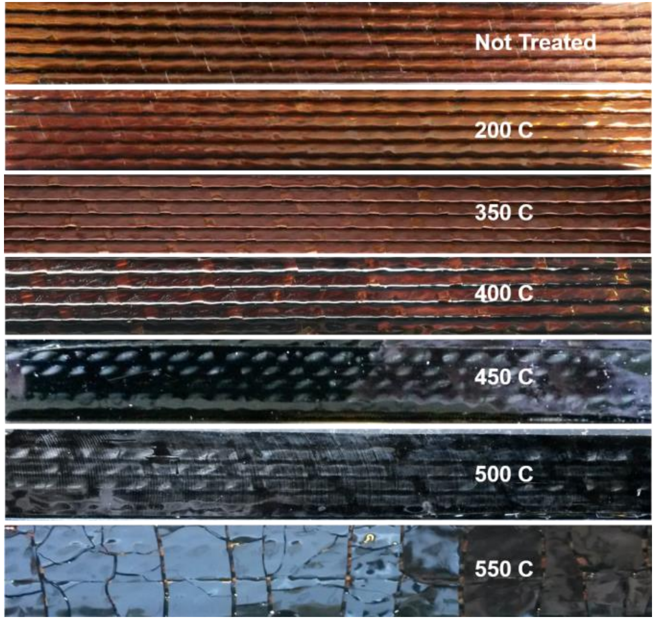


Staged Experimental Program in TE-MPE

Staged approach to study the damage limits of superconducting magnet components due to beam impact / heating

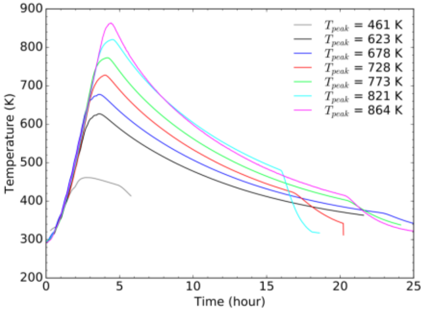
I. Polyimide insulation degradation due to heating
II. Degradation of critical current due to ms-heating
III. Degradation of polyimide insulation (ms-heating)
IV. Insulation & I_c degradation - beam impact @ RT
V. I_c degradation - beam impact @ LHe

I. Polyimide insulation degradation due to heating



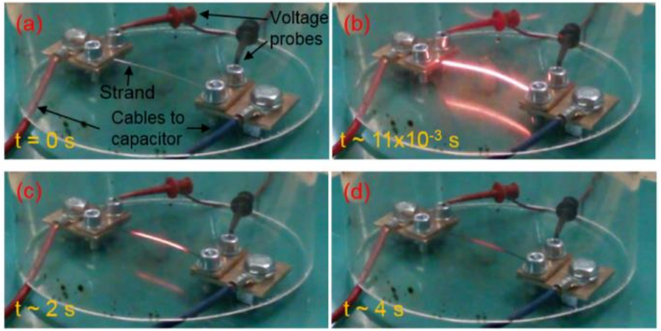
Side view of the cable stacks before and after the heat treatment with different peak temperatures

LHC cable samples heated under pressure over several hours in a furnace:
3 - 5 hours heating & ~7 hours cool-down

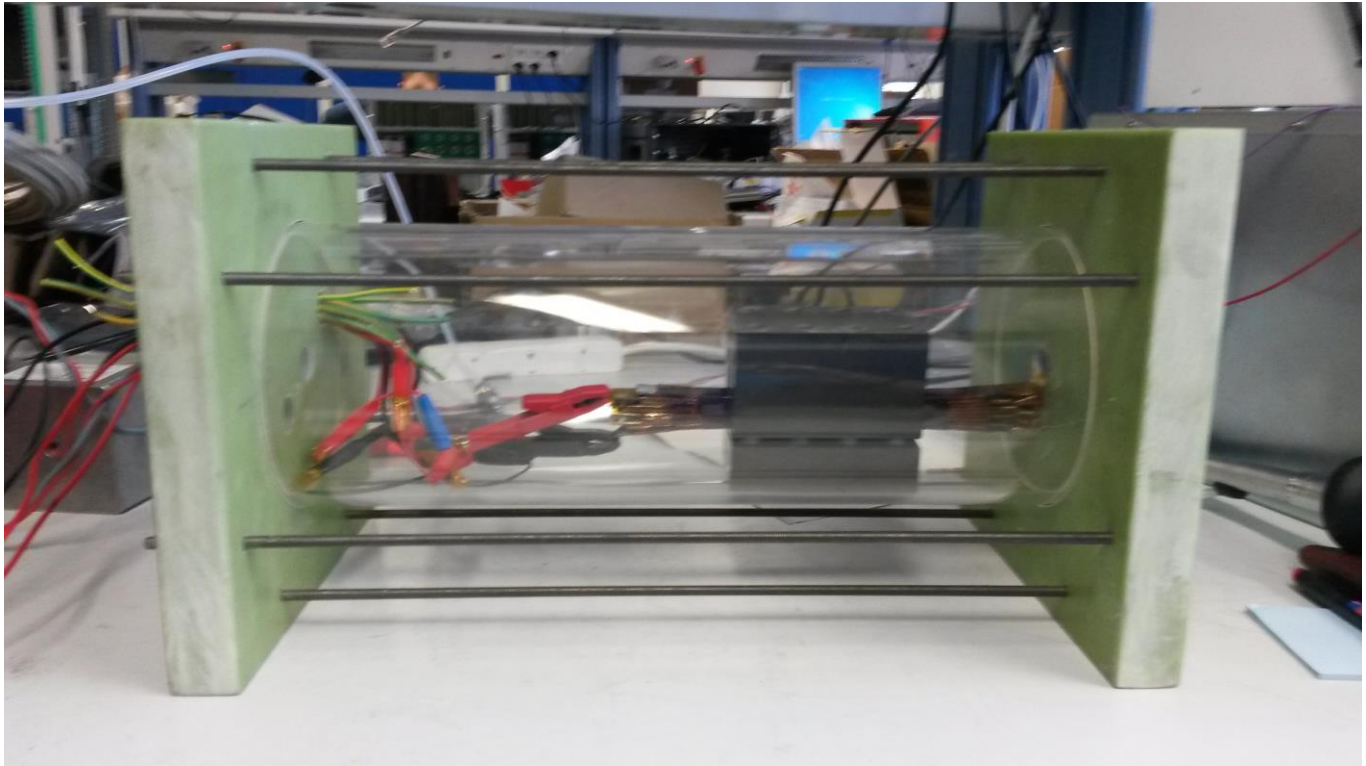


II. Degradation of critical current due to ms-heating

- Capacitive discharge into Nb-Ti and Nb_3Sn strands at room temperature → ms heating → cool-down over seconds
- Magnetisation measurements after heating of strands (@Uni-Ge)



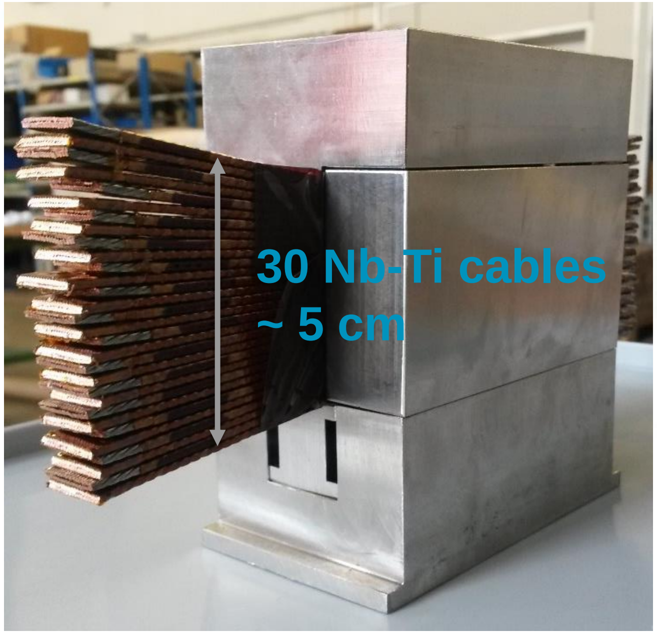
III. Degradation of polyimide insulation (ms-heating), due to capacitive discharge

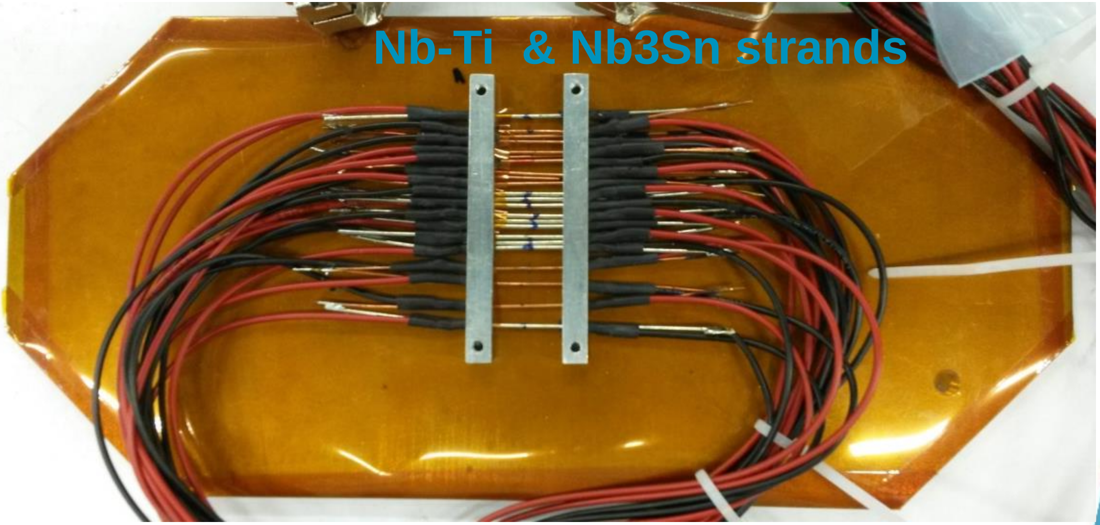


Capacitive discharge into Nb-Ti Rutherford cables under pressure at room temperature → ms heating

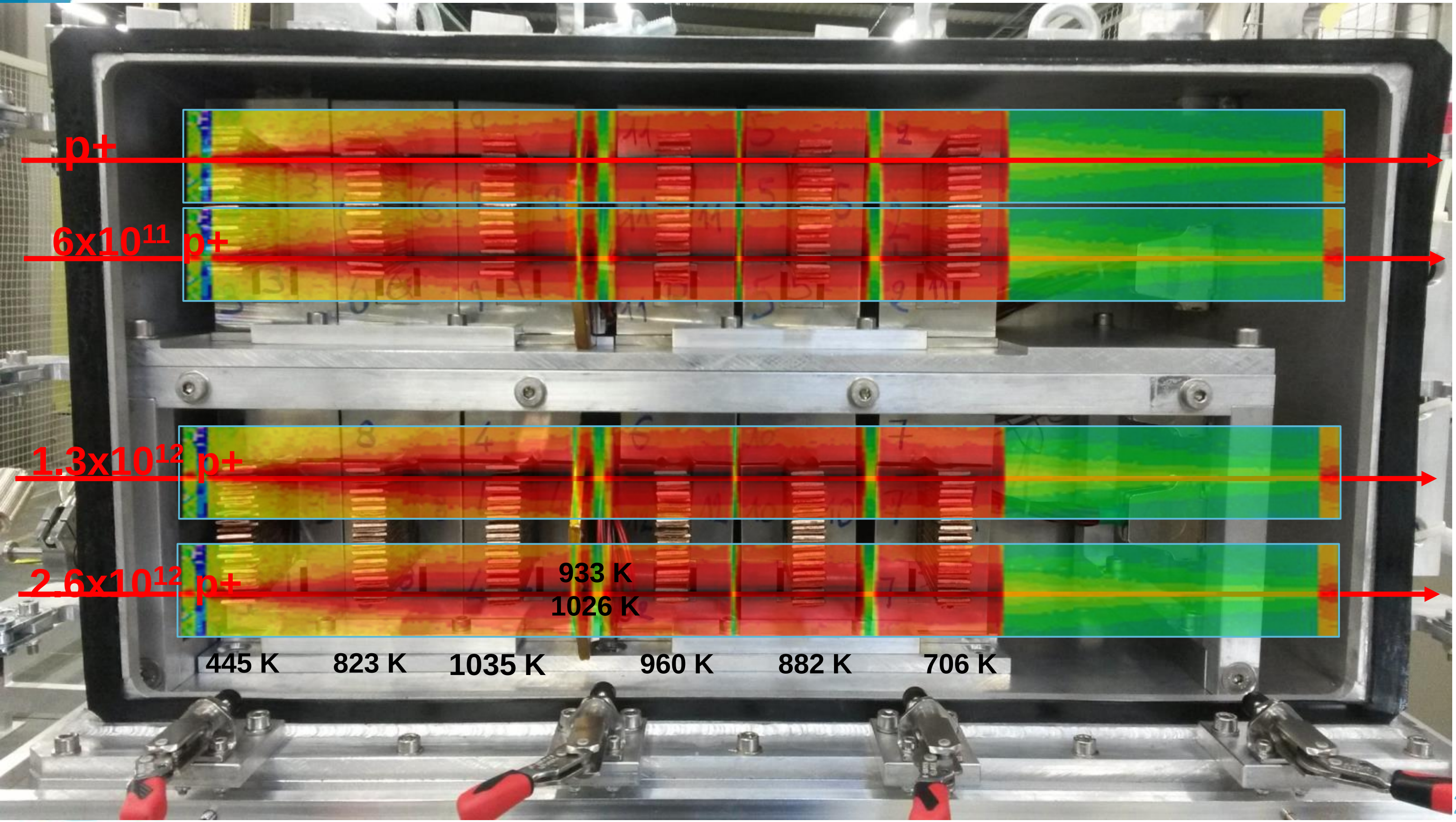
IV. Insulation & I_c degradation - beam impact @ RT

HiRadMat experiment HRMT31 - Samples





IV. Insulation & I_c degradation - beam impact @ RT experimental setup

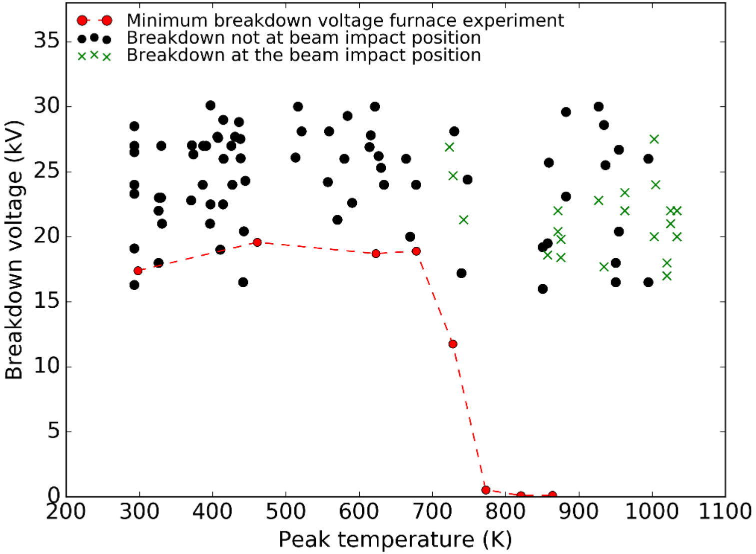


- Argon atmosphere
- 440 GeV protons (HiRadMat):
  - 6 x 6×10^{11} p^+
  - 6 x 1.3×10^{11} p^+
  - 6 x 2.6×10^{12} p^+

Main results of room temperature experiments (1/2)

Polyimid insulation:

- **Chemical decomposition** due to exposure to high temperature
- Significant **reduction of insulation strength** after heating in furnace **> 700 K**
- **No degradation** measured after beam impact – temperature up to ~1050 K
- **Weakening** of the insulation at the point of the beam impact was observed for **T > 850 K**



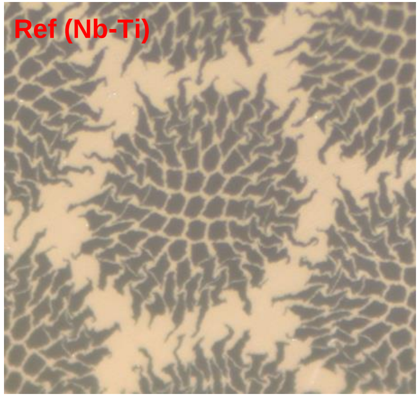
Main results of room temperature experiments (2/2)

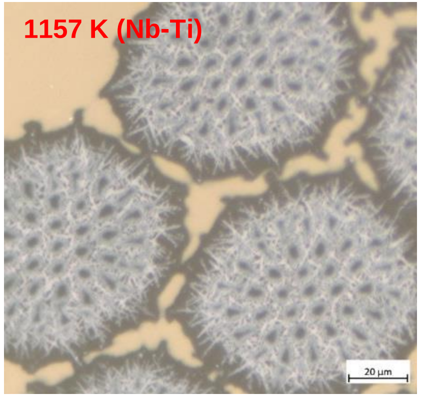
Nb-Ti strands:

- J_c decreases with increasing exposure time caused by
  - **Diffusion** process & change of **pinning** behaviour
  - Variations of α-Ti precipitates size and spacing
- At T=1157 K (capacitive discharge), filament merging was observed
- J_c degradation for hotspot temperatures **> 880 K** after beam impact

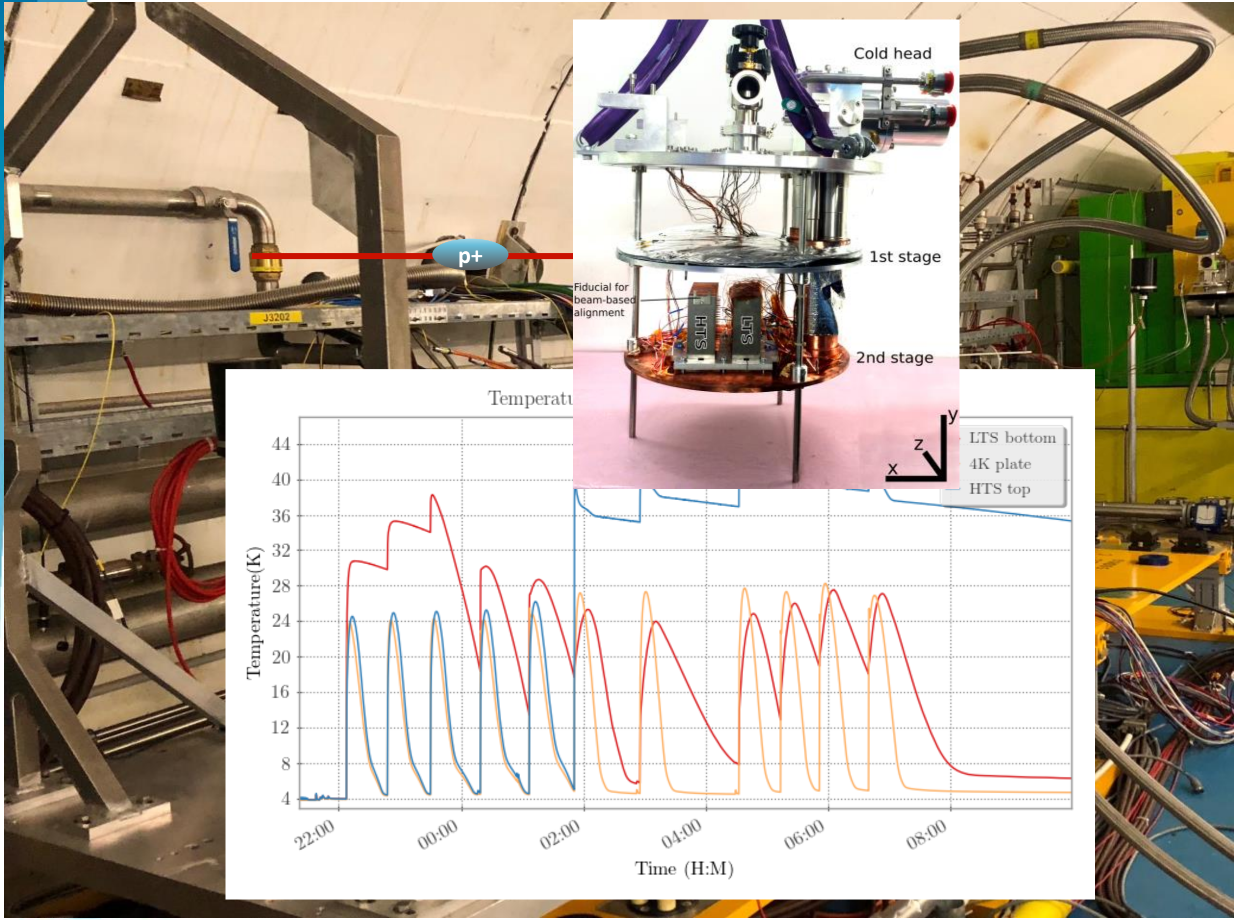
Nb_3Sn strands:

- J_c degradation observed in **all samples** T ≥ 700 K



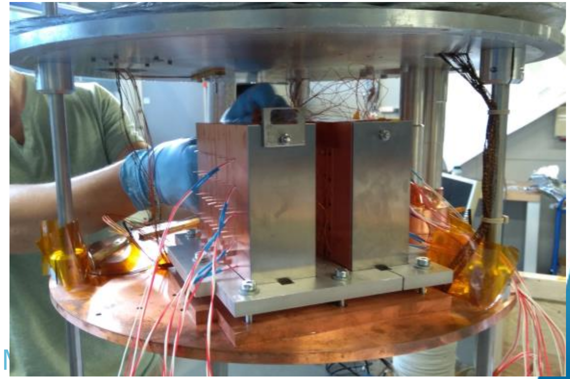


V. I_c degradation - beam impact @ LHe



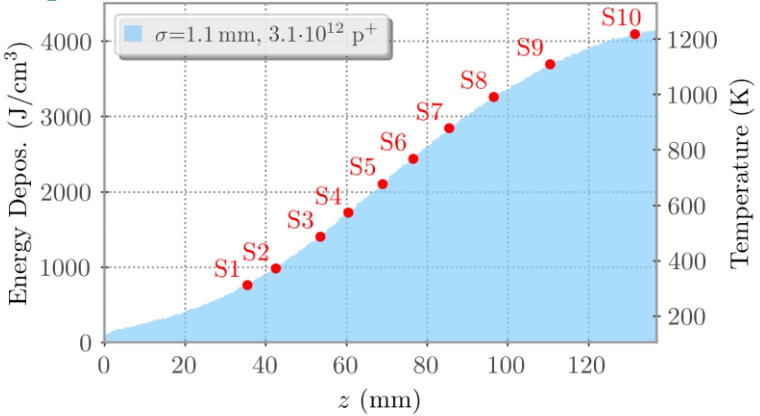
- 20 Nb-Ti short strand samples: 50 mm, Ø 0.825 mm
- 30 Nb_3Sn short strand samples (RRP type): 50 mm, Ø 0.85 mm
- 40 YBCO tape samples: 60 mm x 4 mm x 0.2 mm

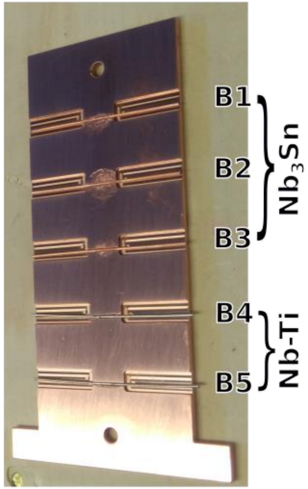
- 11 x 24 b **(~3e12 p**, sigma$_{x,y}$= 1.1 mm) @ **440 GeV**
- Hotspots **up to 1250 K** reached in strands

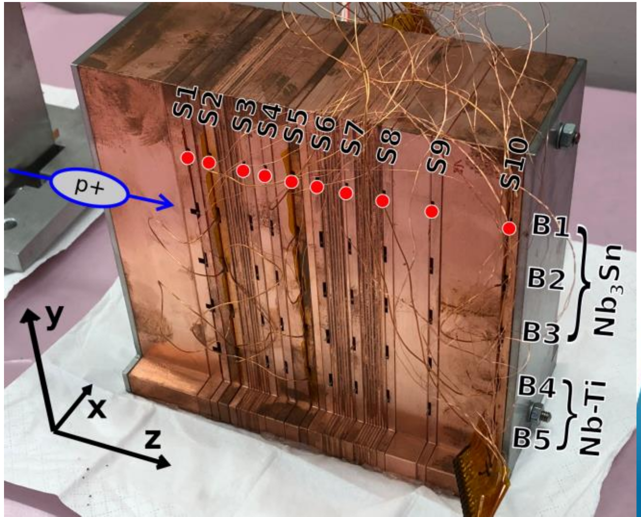


Sample holder & hotspots

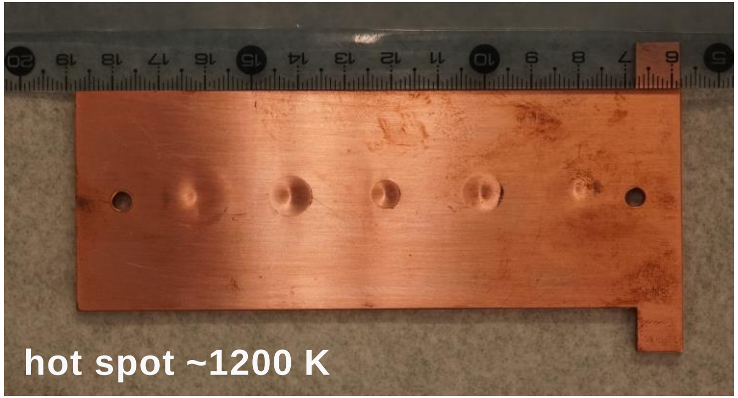
- Superconducting strands **embedded** in sheeted **copper sample holder** (held by vacuum grease)
- Samples from one batch see the **same beam**
- Hadronic showers cause **increasing energy deposition** when protons pass through the sample holder → similar to a failure case when **beam-showers impact on a sc. magnet**
- Energy deposition and hotspots **calculated** with FLUKA based on measured beam parameters (intensity, beam size, offset)







Sample holder and samples after beam impact visual inspection



B3 S6

B1 S6

Nb_3Sn, peak ~ 730 K /760 K

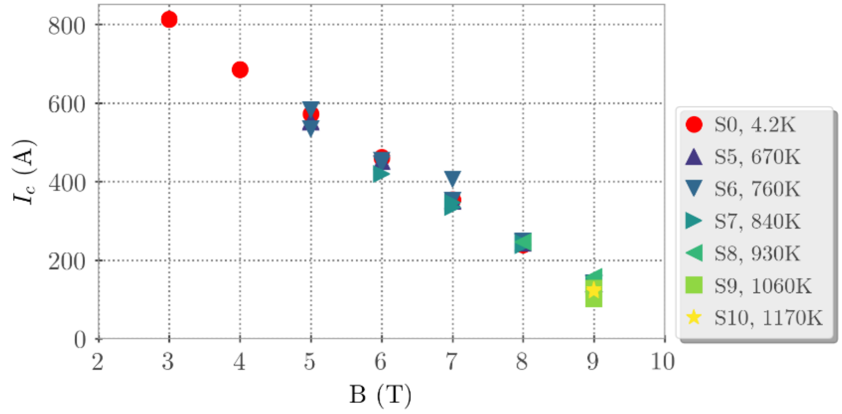
B2 S8

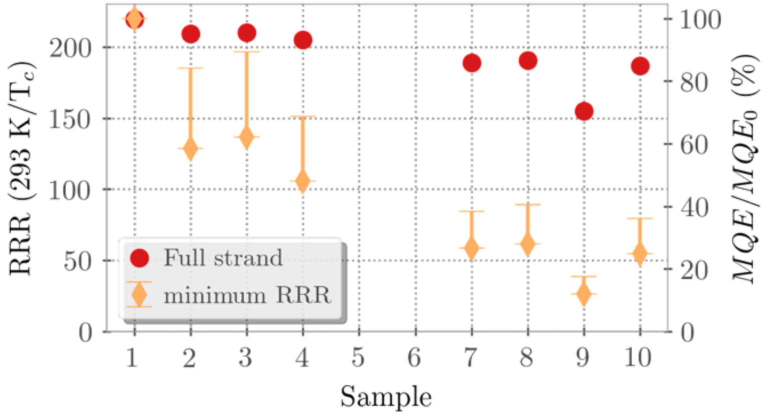
Nb_3Sn, peak ~ 950 K

- Beam imprints clearly visible in sample holder plates
- Nb-Ti strands: no deformation observed after beam impact
- Nb_3Sn strands:
  - Beam impacted with slight offset → **visible bending** of samples for **hotspots > ~700 K**
  - **Breaking of copper matrix** in some samples with hotspots > ~ 900 K

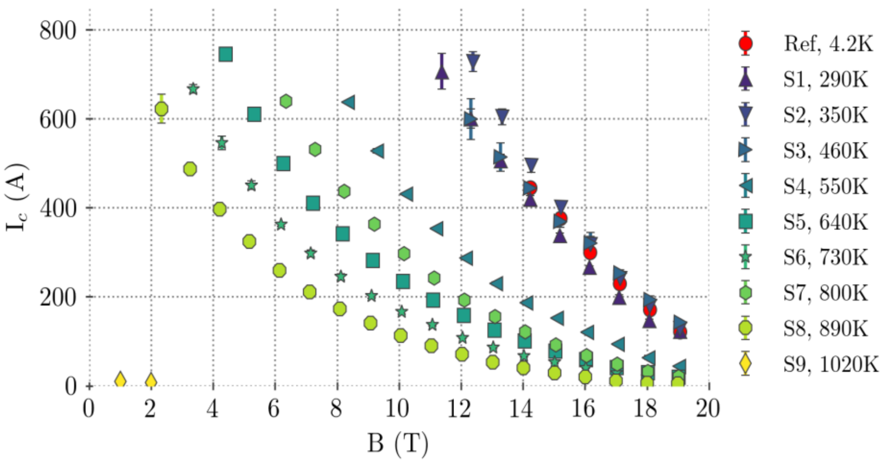
Key results of cryogenic beam experiment: Nb-Ti

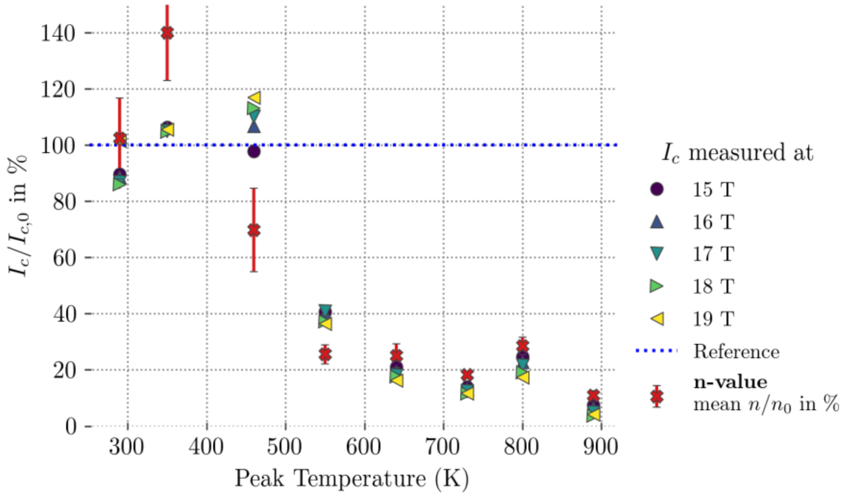
- **No degradation** of I_c observed
- Measurements indicate significant **reduction of RRR at beam impact position**
  - Reduced minimum quench energy (MQE) → potentially causing **thermal instability** of the strands / magnets
  - RRR **locally reduced** below 100 for samples with hot spots > 800 K





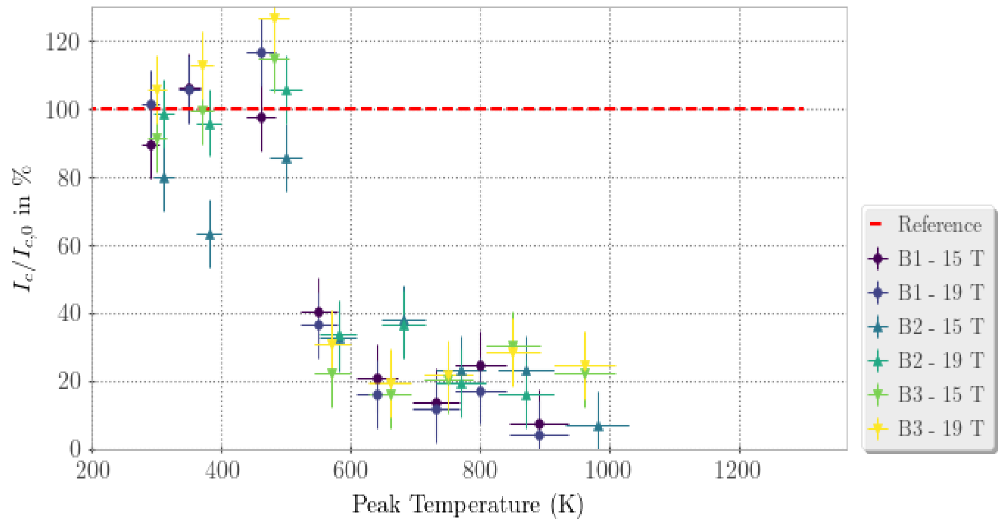
Nb_3Sn: I_c degradation after beam impact (1/2)





- **Significant I_c degradation** from Sample S4 with peak temperatures **> 460 K**
- No measurable transport current for peak temperatures **> 890 K** → samples S9 and S10 **destroyed**
- **Inversion of degradation** order (S4, S7, S5, S6, S8) due to effect of different **sample holder design** around sample S7 (thin copper sheets versus thick copper blocks) → reproduced in thermo-mechanical simulations

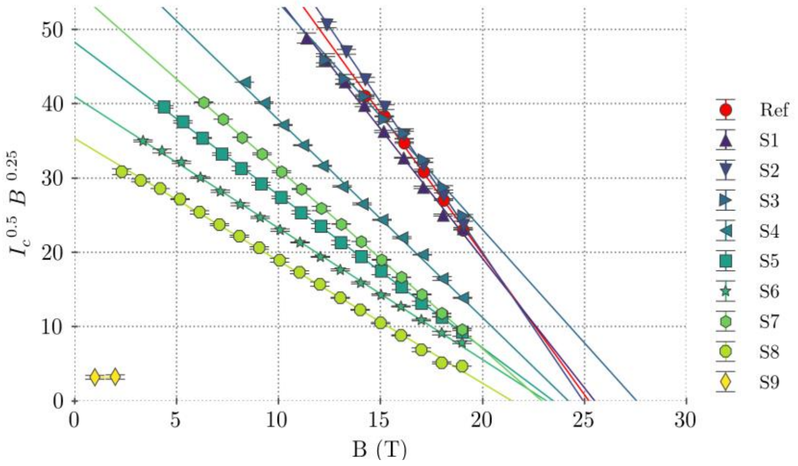
Nb_3Sn: I_c degradation after beam impact (2/2)

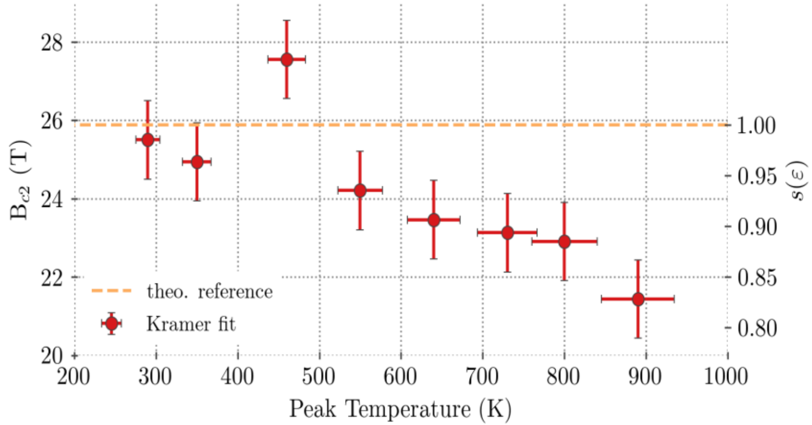


- **Similar behaviour** observed in all three batches of strands (within the uncertainty of the experimental setup and the measurements)

Nb_3Sn: B_{c2} degradation after beam impact

- B_{c2} derived from I_c measurements via the KRAMER form
- **B_{c2} degrades** with increasing peak temperatures due to **residual strain** in the strand
- Errors fairly large as samples are very inhomogeneous after the beam impact
- Observation **confirmed by magnetization measurements** on a subset of samples





Thermo-mechanical simulations

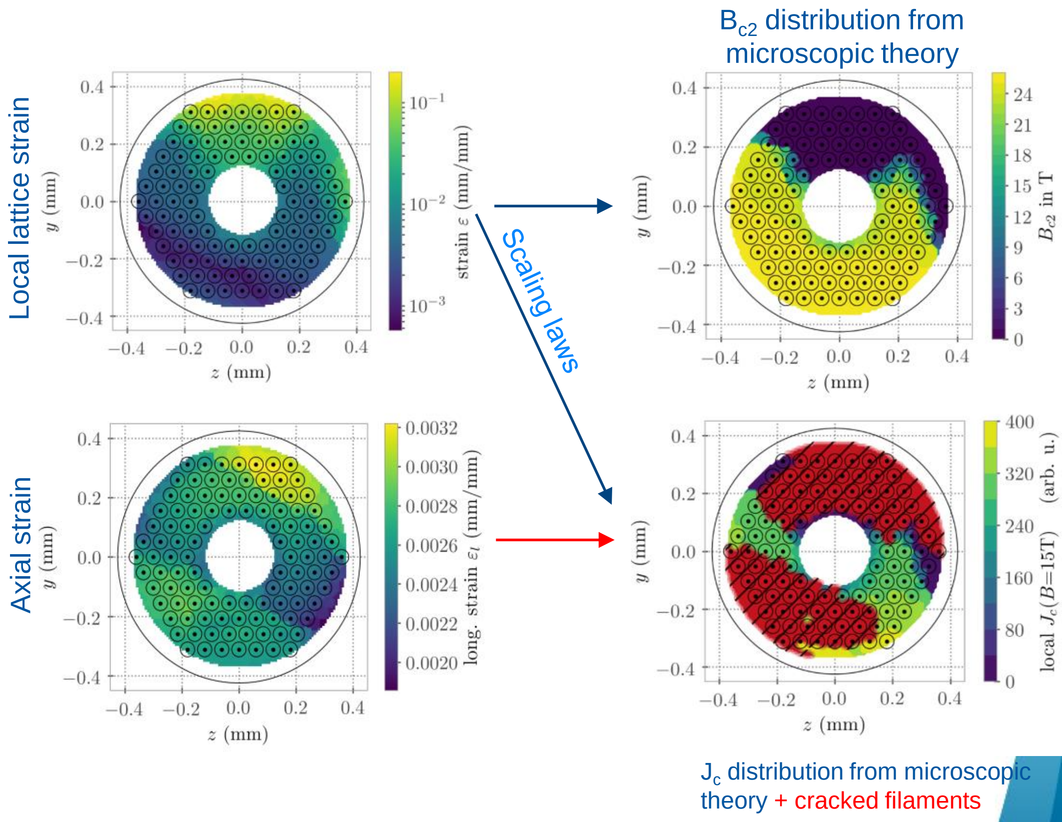
Simulation of stresses within the strand cross-section due to

- **thermal gradients** and expansion caused by beam heating
- the **sample holder impacting** on the strand due to its thermal expansion

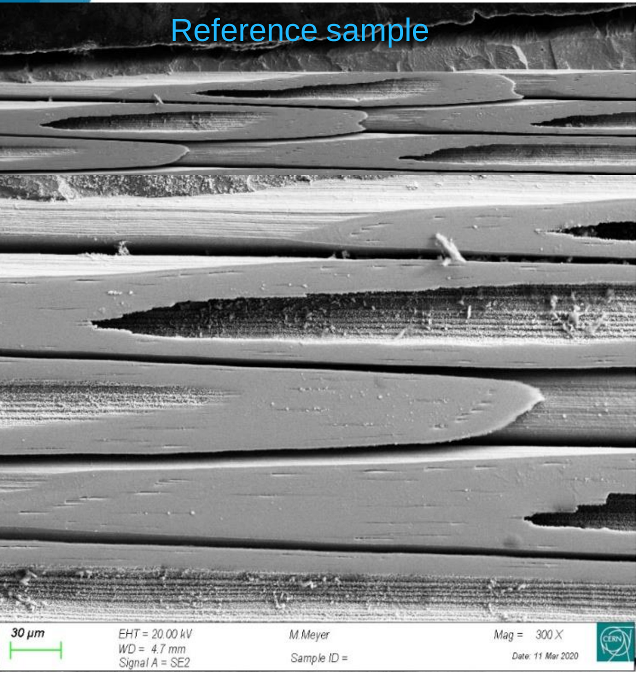
Derive expected I_c for each strand based on literature scaling laws (Uni Twente Model, filament breaking limit, etc.)

Results:

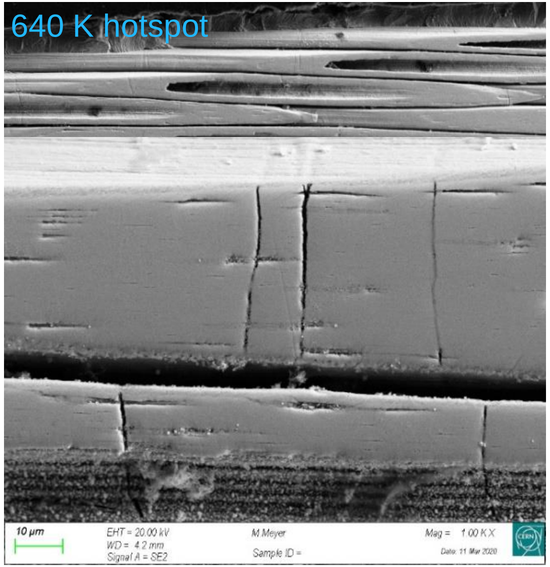
- Measured I_c degradation can be explained by the **residual strain in the strands and the breaking of filaments**.
- Filament breaking can be observed for hotspots **> 450 K** (from sample S4) and is **dominating** the I_c degradation with increasing hotspot temperature

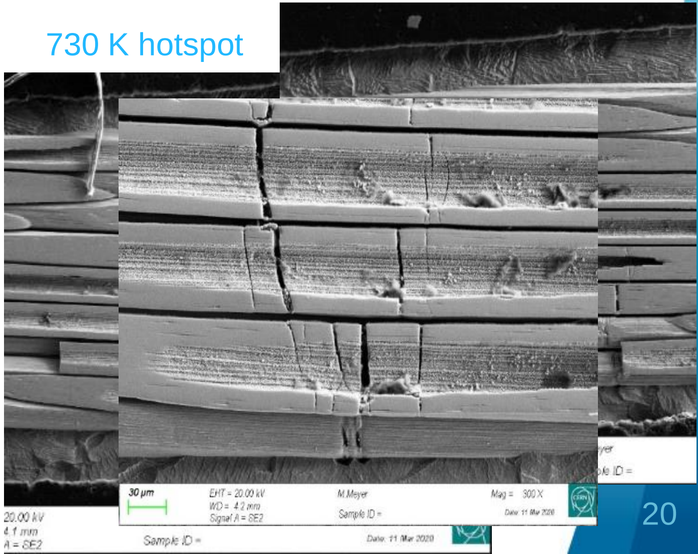


Results from SEM analysis of Nb_3Sn samples



- Network of **transverse cracks** developing with **increasing hotspot** temperatures in the sample
- Last sample with no cracks: hotspot of 350 K
- First sample with cracks: hotspot of 550 K





Courtesy M. Meyer, EDMS 2363700

Key results of cryogenic experiment for Nb_3Sn

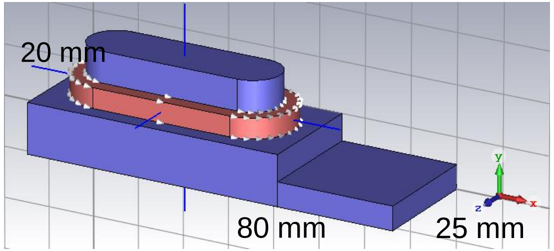
- Significant **I_c degradation** was observed in samples, which experienced a hot spot temperature **> 460 K** due to the beam impact
- **Thermo-mechanical simulations** allowed to identify the two main damage mechanism:
  - **Filament breaking** due to too high axial strain → dominating factor for 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 and **magnetisation measurements**

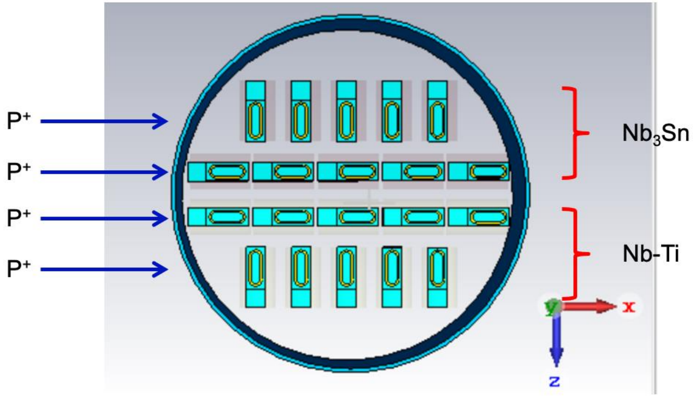
Future plans

1) Experimentally **verify damage limits** derived for sc. strands using **dedicated sample coils** made from Nb-Ti (LHC like) and Nb_3Sn (HL-LHC like)
   - Design & construction and qualification of sample coils
   - Design & construction of cryostat
   - Beam experiment foreseen for first part of 2022 in CERN’s HiRadMat facility
   - Work has started in collaboration with Karlsruhe Institute of Technology

2) In-situ experimental studies of the damage limits of **magnet coils representative for HL-LHC** with beam impact **during powering**
   - Follow-up of 1)
   - Beam experiment tentatively foreseen for 2024 (end of LHC Run3)

Conceptual design of coil samples and setup 1)





Courtesy Y. Nie, KIT

- Potted **racetrack coils** (11 turns, 3 layers), made of
  - LHC dipole strand
  - HL-LHC RRP Nb_3Sn strand
- Testing **virgin** and (radiation) **aged** sample coils
- Re-use **cryocooler based cryostat** for irradiation in HiRadMat
- Perform **in-situ near T_c measurements** during beam experiment
- Full qualification of coils after beam impact in specialised cryostat setup

Conclusions

- Over the past years TE-MPE has performed a comprehensive **study of the damage limits** of sc. magnet components due to shock heating through an **instantaneous beam impact**
- **Several experiments** were performed including two with 440 GeV **protons** at HiRadMat, one at room temperature and one **at 4 K**
- **Nb-Ti** strands
  - **No degradation of I_c** observed after beam impact
  - Significant **local RRR reduction** at beam impact for hotspots **> 800 K**
- **Nb_3Sn** strands
  - Significant **degradation of I_c** observed for **hotspots > 460 K** caused by **filament breakage** and **degradation of B_{c2}**
  - Damage mechanisms were studied in **detailed thermo-mechanical simulations** and confirmed with **microscopic analysis** and **magnetisation measurements**
- **Follow-up** project has started in collaboration with KIT to **verify the damage limits** in strands experimentally using **dedicated sample coils** (including epoxy and insulation)

Acknowledgments

- A. Bernhard, M. Bonura, 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, C. Senatore, A. Siemko, K. Stachon, M. P. Vaananen, A. Verweij, A. Will
- Presented experiments and results are part of V. Raginel's and 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
- This work was supported by the High Luminosity LHC Project

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Questions?