Damage mechanisms and limits of Nb_3Sn due to direct high energy proton beam impact

Project overview and status

A. Will, J. Schubert, D. Wollmann, *et al.*

Superconducting wires/ tapes

Nb-Ti strand (LHC)

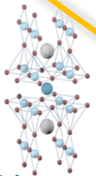
Nb_3Sn strand (HL-LHC)

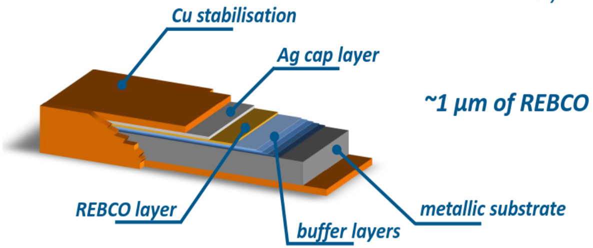
HTS tapes
(future acc. magnets..?)

RE = Rare Earth

YBCO (REBCO) coated conductors

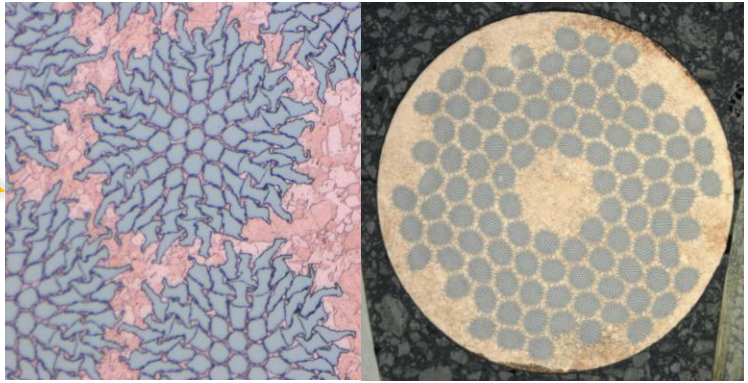
Iijima et al., APL 60 (1992) 769
Goyal et al., APL 69 (1996) 1795





~1 µm of REBCO in a ~100 µm thick tape

Image from C. Senatore, Lecture on Superconductivity, 2018



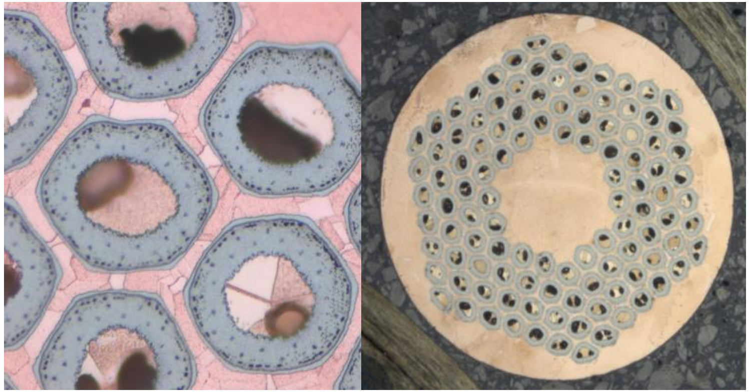
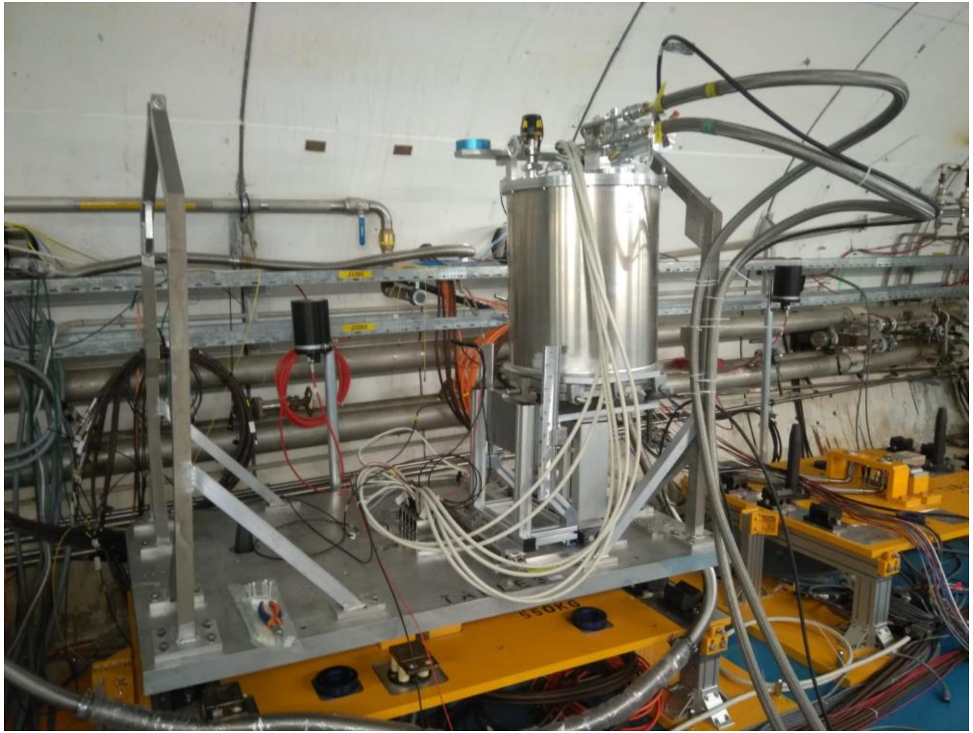


Image courtesy M. Meyer, CERN

Beam impact experiment at cryogenic temperatures

- First **cryogenic beam impact experiment** was performed in August 2018

- Irradiation facility **HiRadMat** provides 440 GeV proton beams towards fixed targets
  - 1.2 x10^{11} ppb
  - 25 ns bunch spacing
  - 3.4 MJ max. per pulse
  - beam size ~1mm



Sample Holder

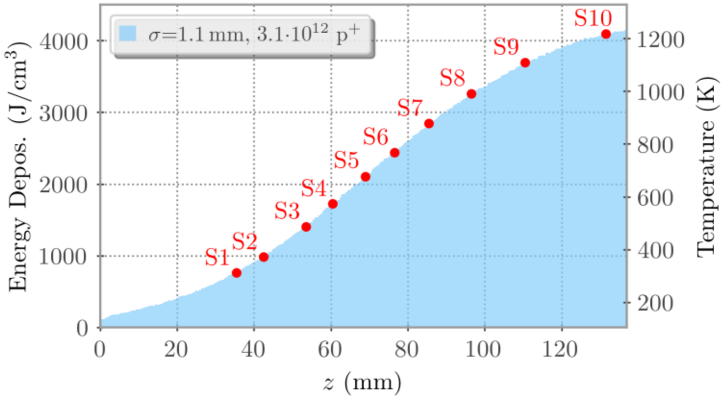
Energy deposition

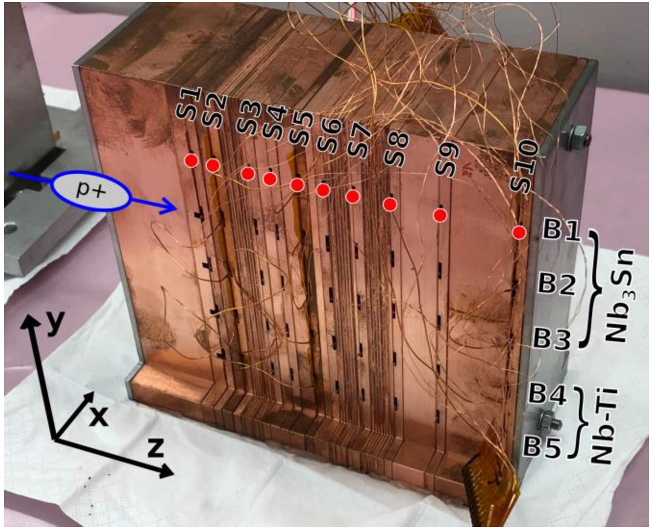
- **Temperature** reached along a **block of copper** for 440 GeV proton beam, simulated with FLUKA

- Embedded samples along beam axis reach various hot spot temperatures

As in real failure case

- proton beam interacts with matter before impacting superconductors





Nb3Sn Strain dependence

Mentink, Goedeke et al.

- Scaling law for Nb_3Sn from literature

$$J_c(B,T,\varepsilon) = C_1\ (1-t^2)\ b^{-0.5}\ (1-b)^2$$

$$t = \frac{T}{T_c \cdot s(\varepsilon)^{\frac{1}{3}}}$$

$$b = \frac{B}{B_{c2}(T,\varepsilon)}$$

$$B_{c2}(T,\varepsilon) = B_{c2,0} \cdot s(\varepsilon) \cdot (1-t^{1.5})$$

- normalized strain dependent function s(ε)
  - $s(0) = 1$
  - monotonic decreasing towards zero for higher strains
  - simplest assumption s(ε)=$1-\varepsilon^n$

- Kramer form linearizes the I_c curve

$$f_K = J_c^{0.5} \cdot B^{0.25} \quad \propto \quad (1-b) = \frac{B_{c2}-B}{B_{c2}}$$

- Flux-pinning force

$$\vec{F}_p = \vec{J}_c \times \vec{B}$$

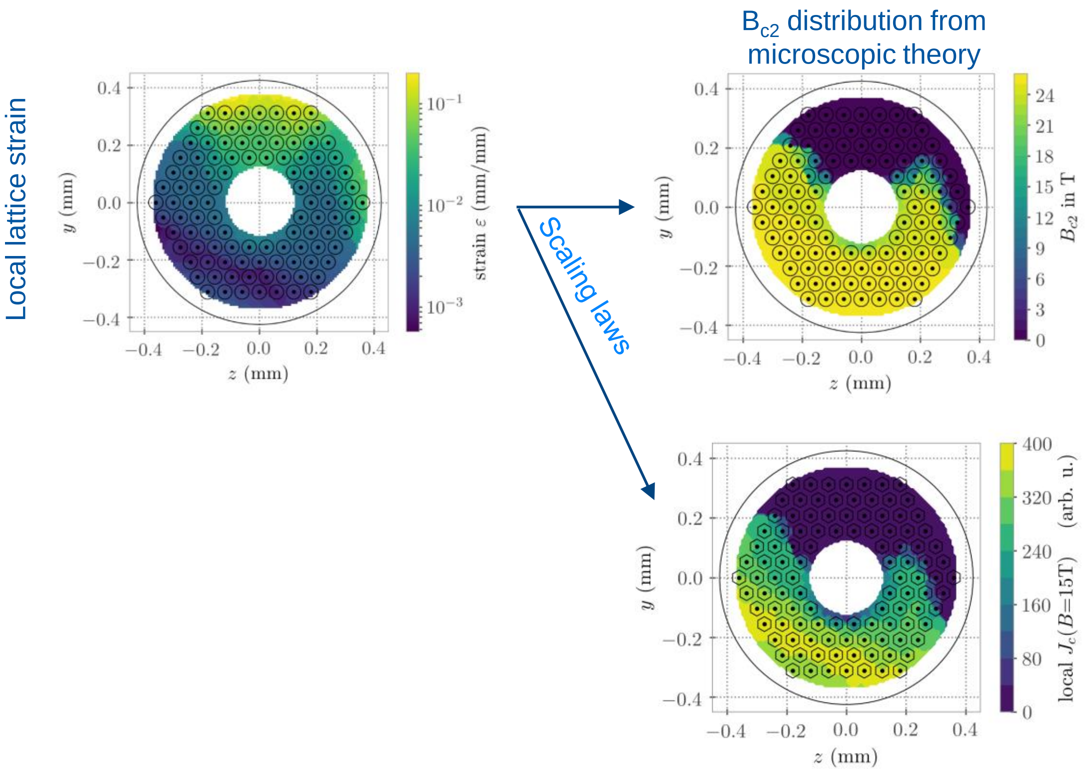
Results of thermo-mechanical simulations

Thermo mechanical simulations performed* with ANSYS

- study the stresses within the strand cross-section due to thermal gradients and expansion
- study the interaction of the strands with the sample holder

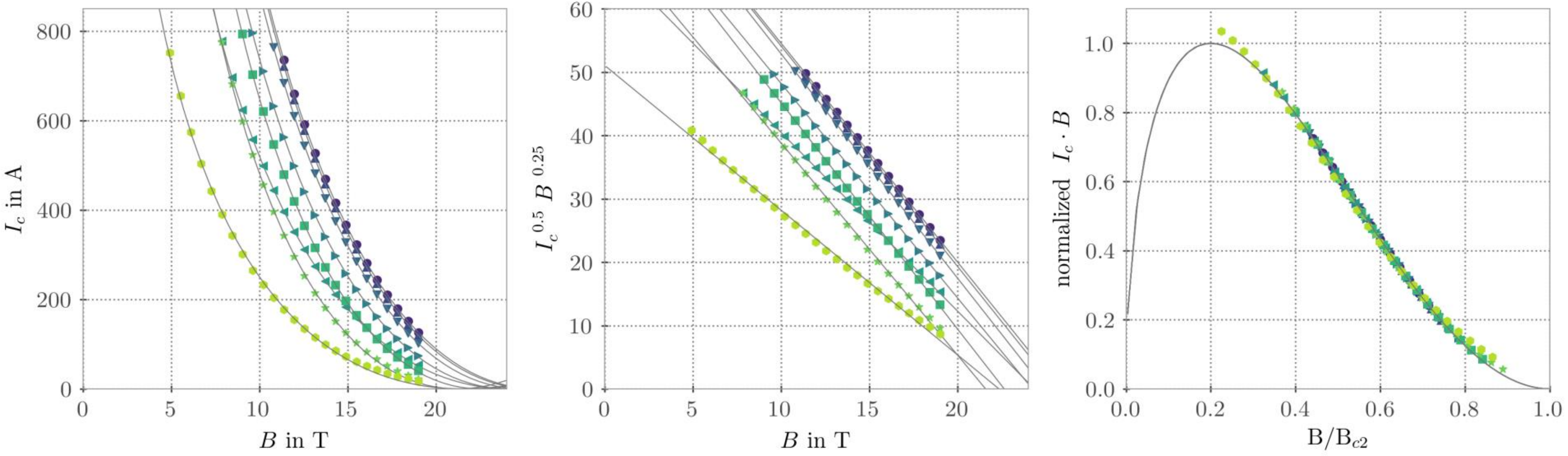
Use scaling laws from literature to predict I_c degradation of full strand

Filament cracking via “strain irreversibility cliff” model (Cheggour et al.)

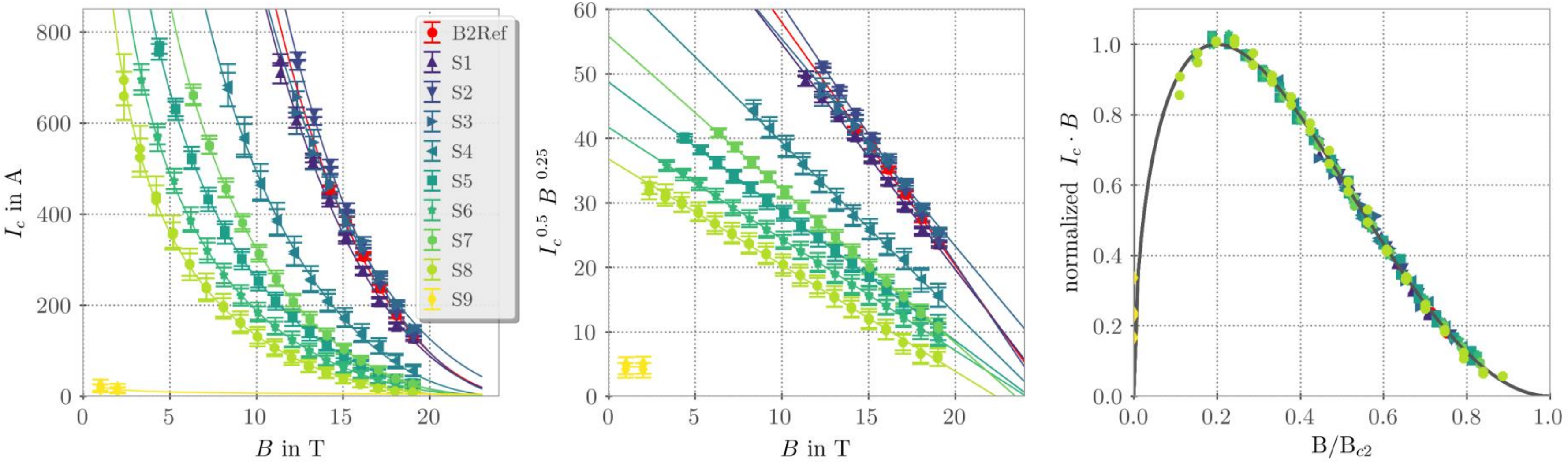


*Bachelor Thesis J. Schubert, to be submitted soon

Simulations



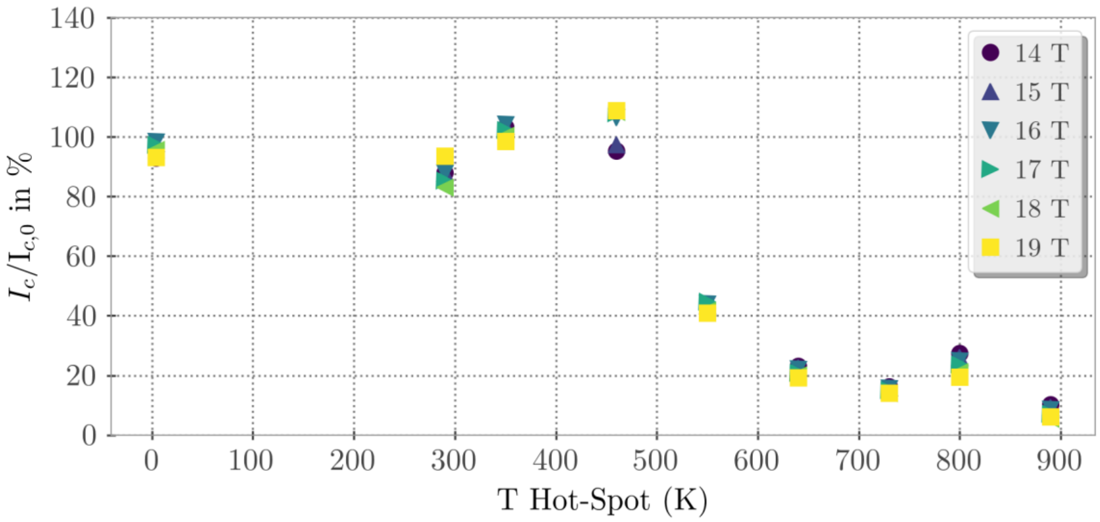
Measurements



Absolute I_c degradation

- Absolute I_c degrades strongly above hot-spot temperature of ~450K

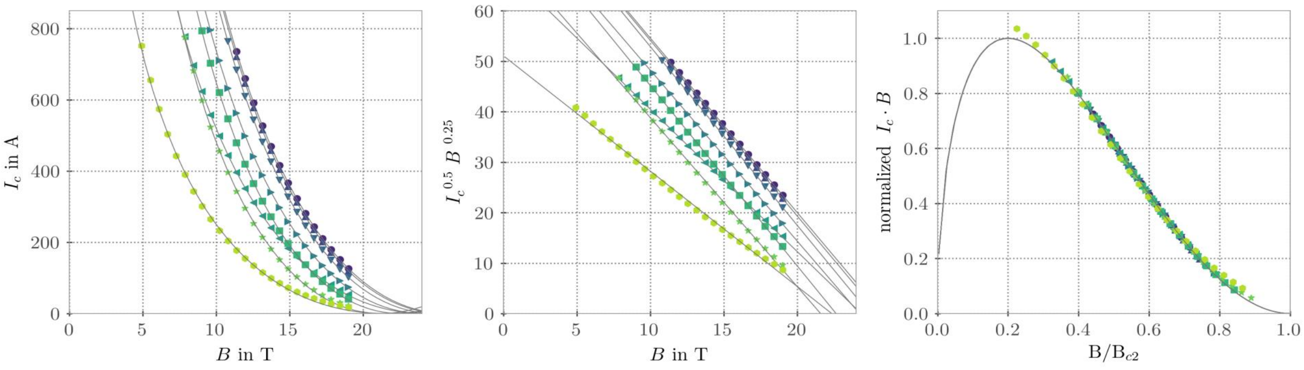
- Almost independent of magnetic field



Comparison

- I_c of S1-3 barely affected by strain dependent degradation (both Simulation and Measurement)
- From S4 much stronger degradation is observed than predicted by strain scaling only
- Shift in B_{c2} in all type of fits
- Pinning force maximum unaltered

Simulation



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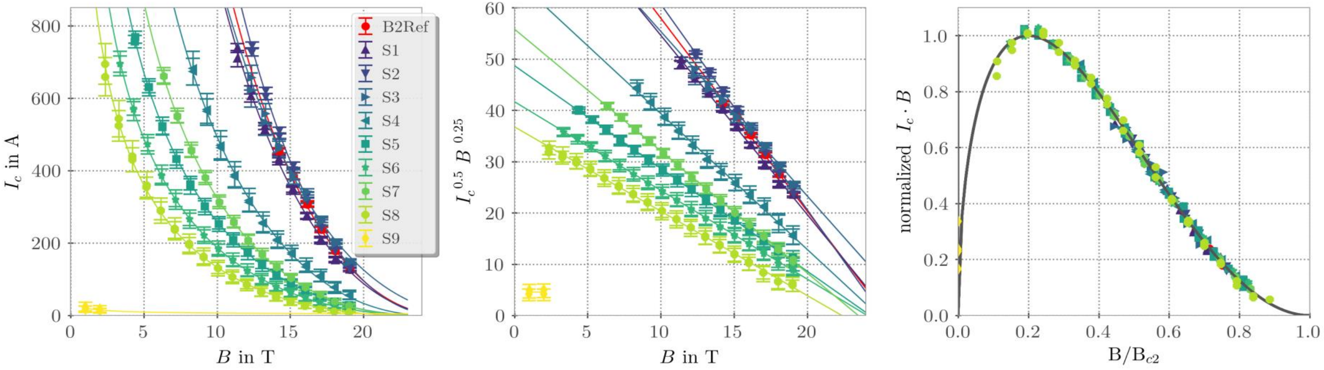

Fit-results comparison

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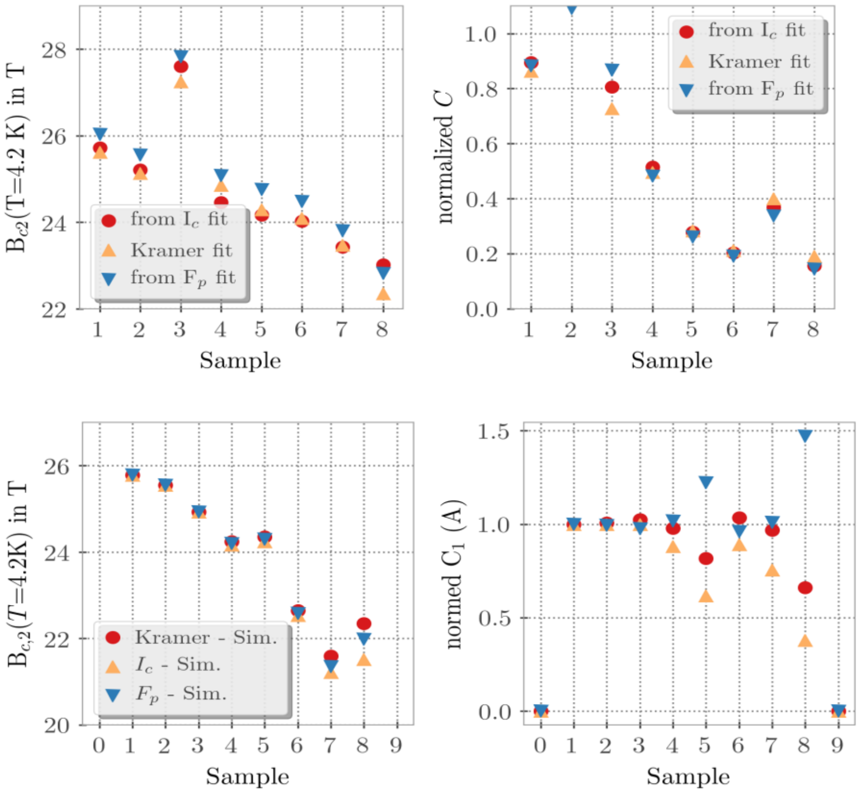
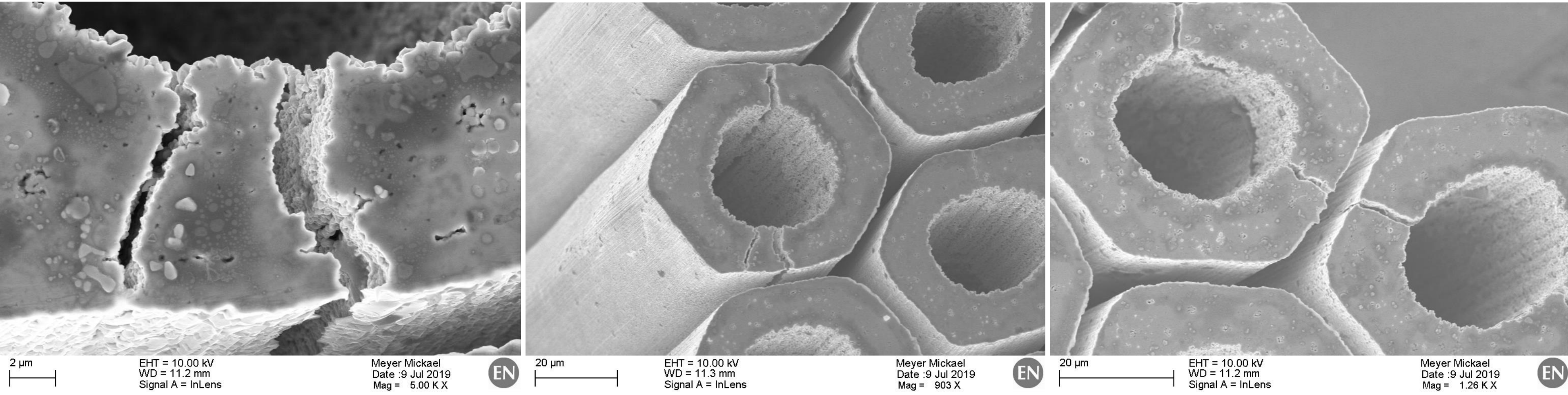


Filament Cracking

- strain alone can not explain the large reduction in absolute I_c (independent of T and B)
- Reduction in superconducting cross section could explain
  - Filament cracking due to too large strain?

$$J_c(B, T, \varepsilon) = C_1 \left(1 - t^2\right) b^{-0.5} \left(1 - b\right)^2$$

Nb3Sn samples from HRMT31 Experiment, Thanks to M. Meyer from the SEM Lab



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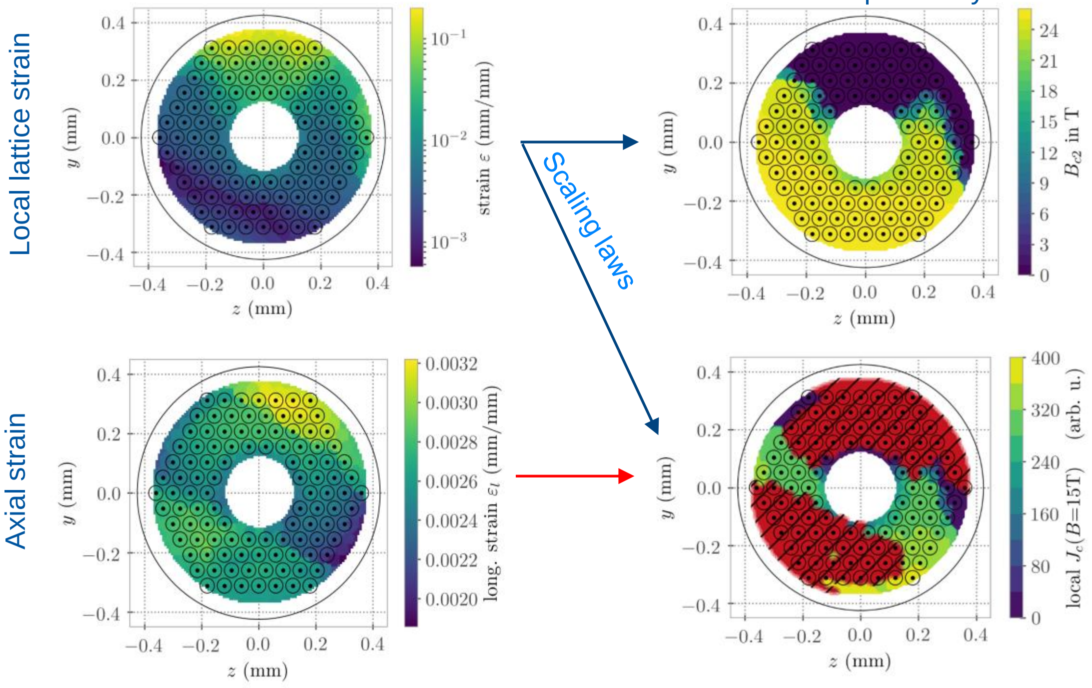
B_{c2} distribution from microscopic theory



J_c distribution from microscopic theory + cracked filaments

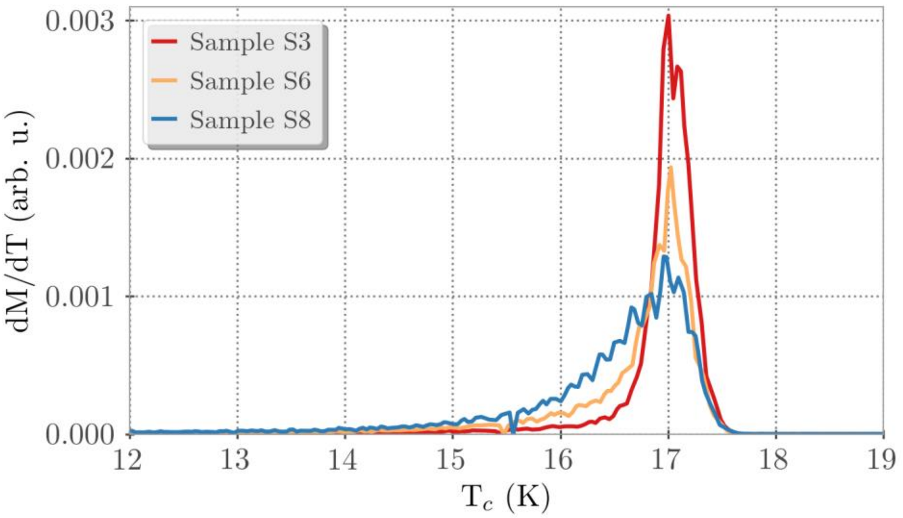
*Bachelor Thesis J. Schubert, to be submitted soon

Conclusion and further actions

$$T_c(\varepsilon) = T_{c,0} \cdot s(\varepsilon)^{\frac{1}{3}}$$
$$B_{c2}(T,\varepsilon) = B_{c2}(T) \cdot s(\varepsilon)$$

B_{c2} and T_c degradation dominated by lattice strain

- ➢ Measured T_c distribution:
- • Broadening of T_c distribution towards lower values as predicted: with higher exposed energy deposition, higher strains are expected.
- • Due to strain gradient, distribution is widened and no sharp peak
- ➢ Well reproduced with Simulations!



I_c degradation is a combination of lattice & axial strain, major part due to filament cracking

- ➢ Filament Cracking is difficult to predict due to nature of Nb_3Sn
- ➢ Continue optical analysis with SEM! (as seen before)

Thank you for your attention

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Backup Slide I
Experimental challenges

Ic measurements on short wires are challenging
for highly inhomogeneous Jc wires
very low n-values
Sample holders add a lot of copper
Current sharing