Damage Mechanisms in High-Temperature Superconducting (HTS) Tapes

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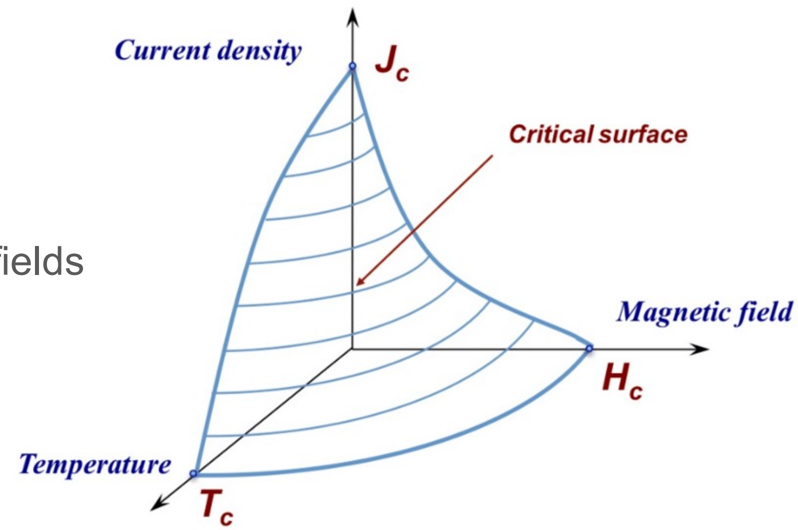
Outline

1. Superconducting material
2. Motivations: one failure case example
3. The HiRadMat-37 experiment
4. Critical current measurement
5. Conclusion

Superconducting material

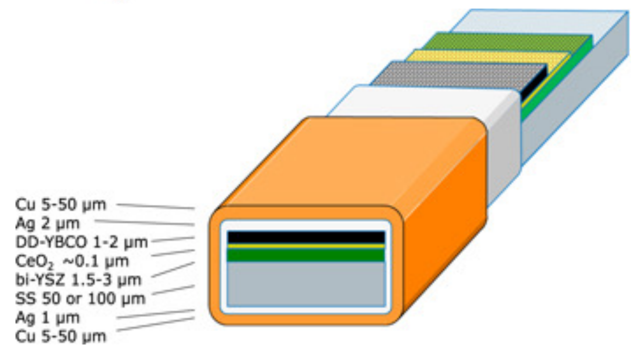
Superconductivity

- Operation below the critical surface → No resistance
- Typically implies cryogenic temperature operation
- Used in accelerator magnets to provide high magnetic fields
  - NbTi used on LHC magnets
  - Nb_3Sn used for the new HL-LHC triplet quadrupoles
- Newly developed materials provide
  - High-Temperature Superconductors (HTS) (if $T_c \geq 77K$)
  - Room temperature superconductors [1]



HTS REBCO Tape

- Operation at 77K or at 4K with higher external magnetic field
- 0.2mm thick multilayer tape
- Considered for future colliders

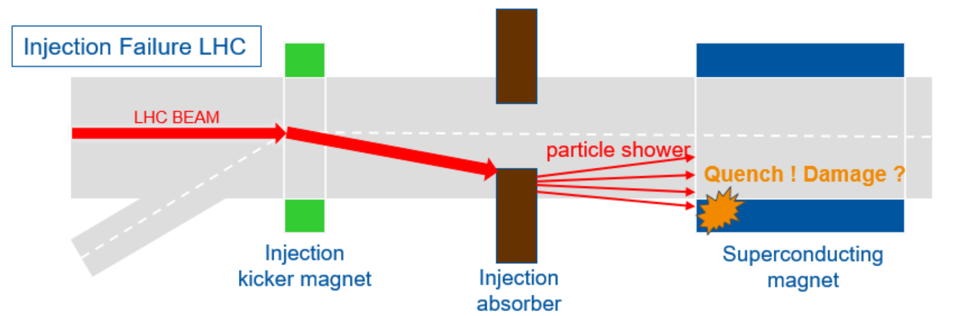


[1] S. Lee and al., The First Room-Temperature Ambient-Pressure Superconductor, 2023
https://doi.org/10.48550/arXiv.2307.12008

Motivations: one failure case

Accelerator failure scenarios

- Beam losses: quenches → Availability issue
- Failure scenarios: possible long-term degradation of magnet coils? → Machine protection issue

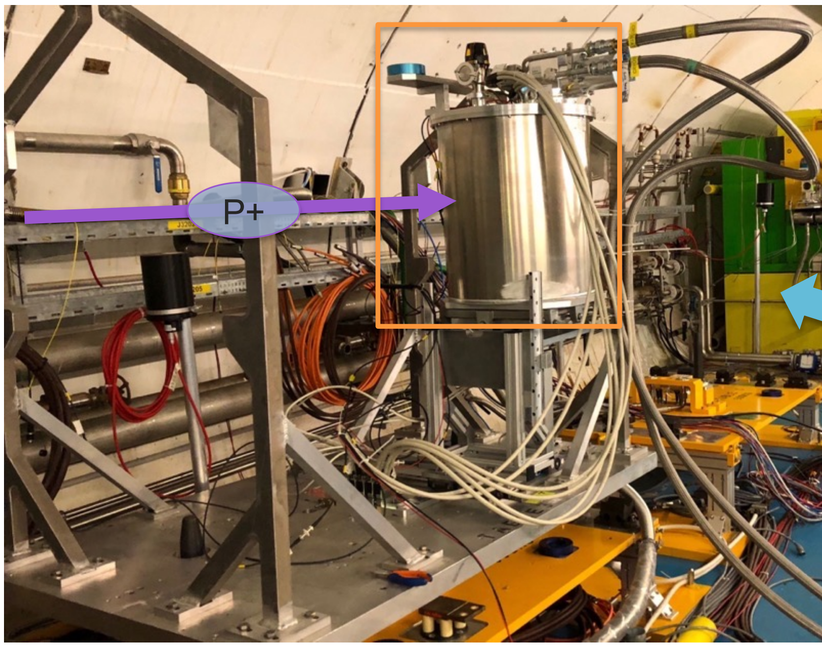


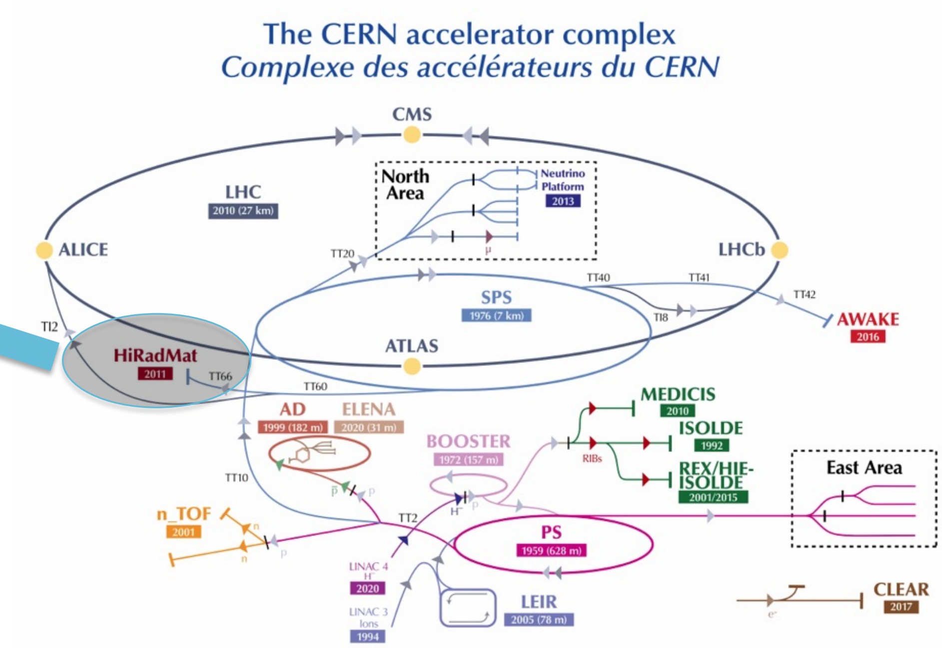
Courtesy V. Raginel

A large experimental campaign was started to assess the damage mechanisms and to quantify the damage limits of the different superconductors: LTS and HTS

The HiRadMat-37 experiment

Experimental table setup in the HiRadMat tunnel

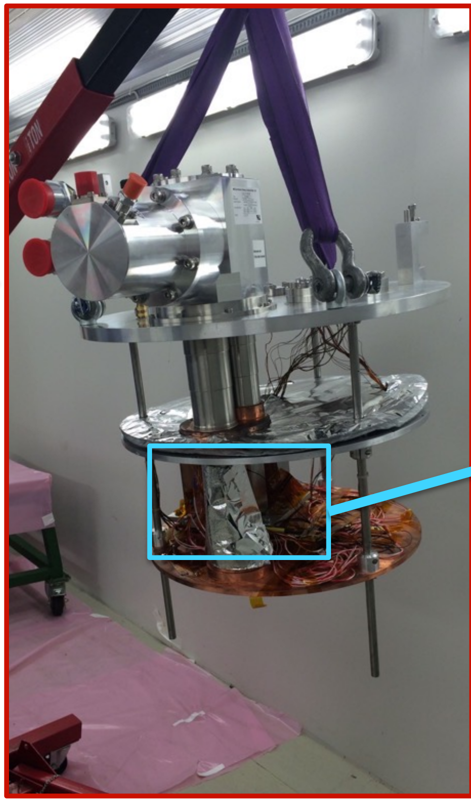




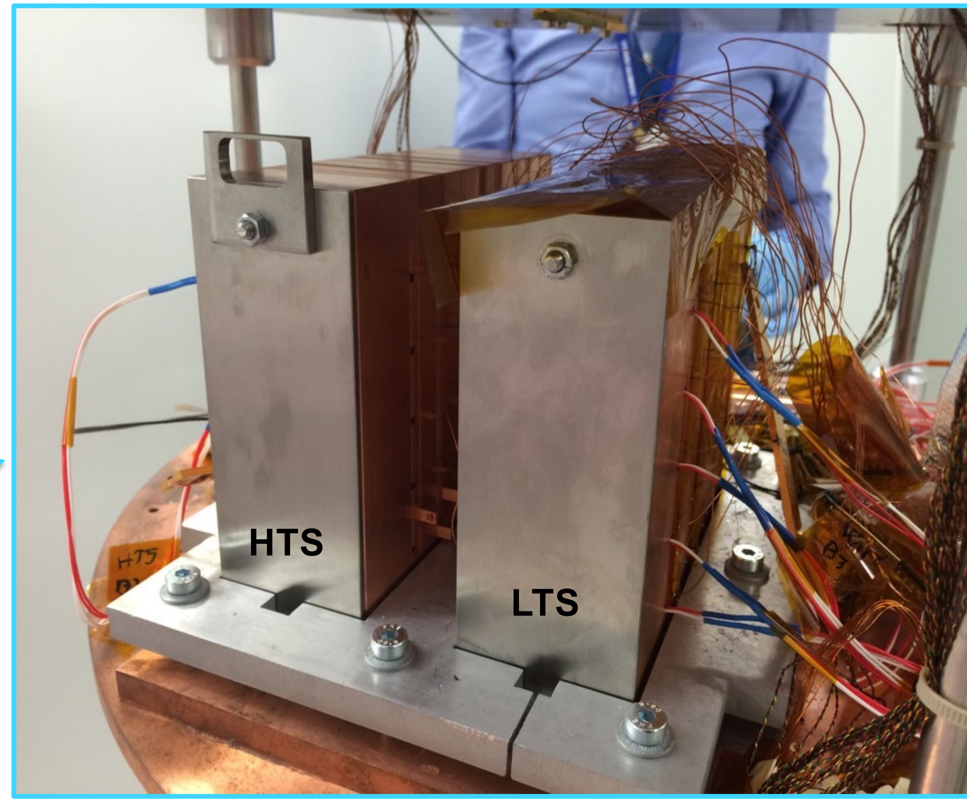
The HiRadMat-37 experiment

Cryostat

Second layer removed

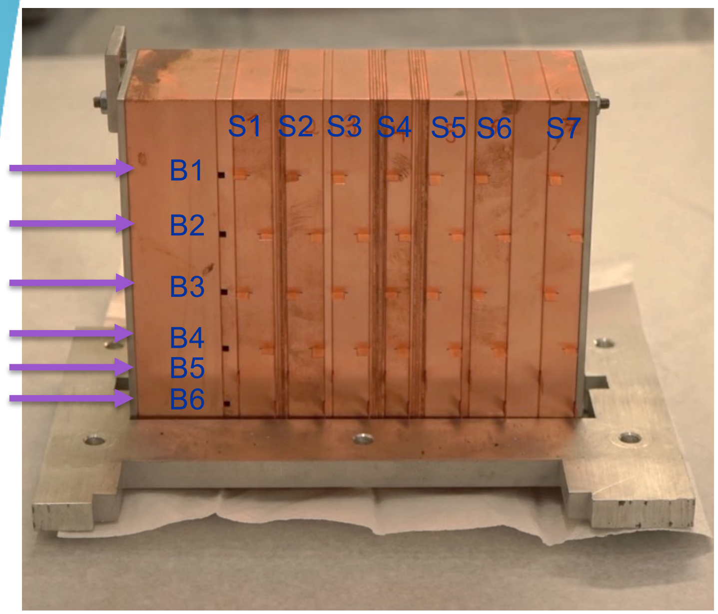


Sample holders placed on the cryostat

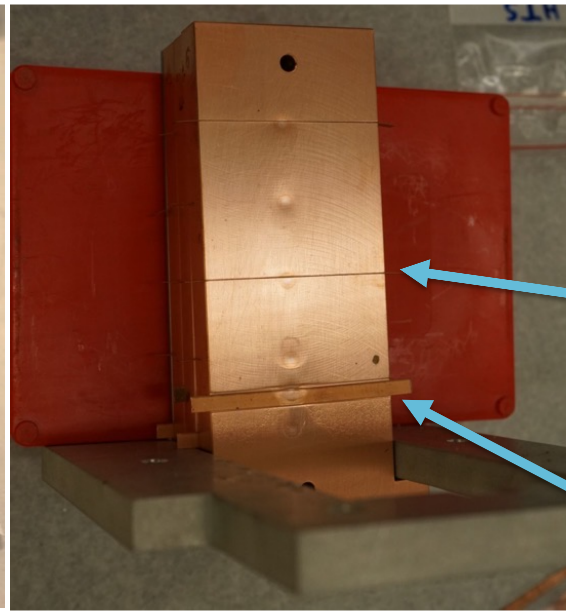


The HiRadMat-37 experiment

HTS samples holder
6 batches of 7 samples



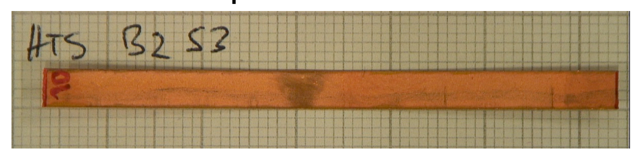
HTS samples holder after beam impact



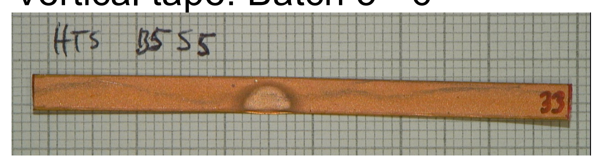
HTS tape

Dimensions:
- Length: 60mm
- Width: 4mm
- Thickness: 0.2mm

Horizontal tape: Batch 1 - 4



Vertical tape: Batch 5 - 6



HiRadMat-37: Post-beam-impact analysis

HiRadMat-37

- Tapes impacted
- Tapes removed from the sample holder
- First visual inspection

Study physical characteristics during the experiment

- Beam position
- Beam size
- Beam intensity
- Temperature inside the cryostat

Study superconducting characteristics degradation

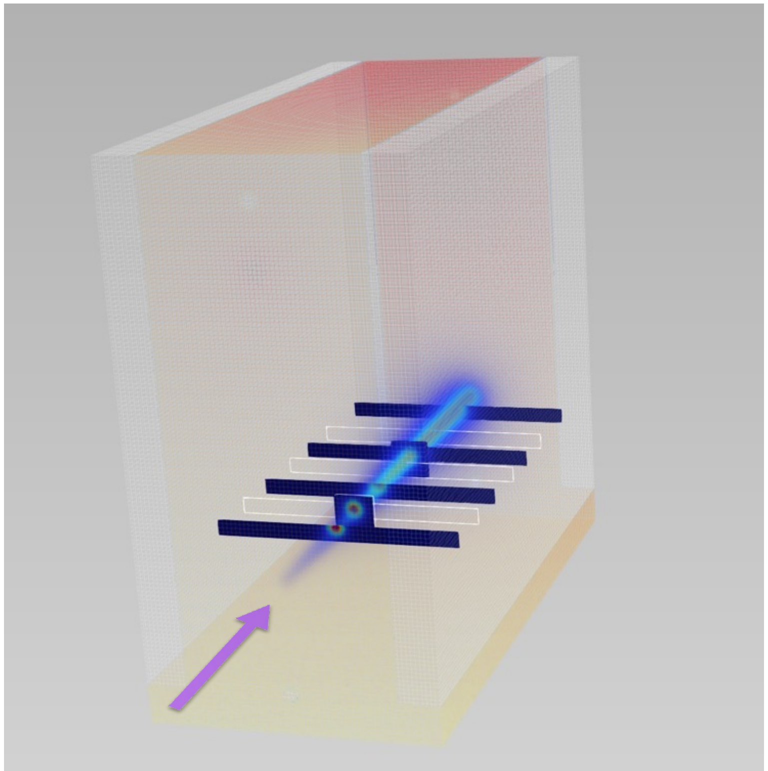
- Measurement of critical current at the University of Geneva
- Comparison and analysis

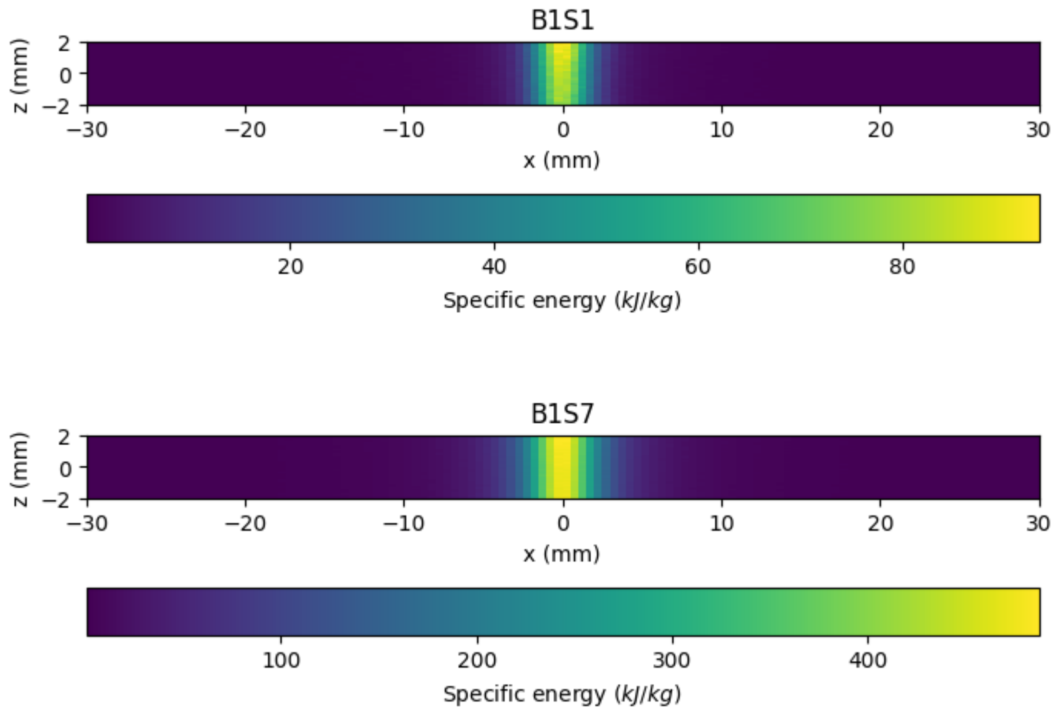
Determination of thermal conditions reached in the tapes

- Monte Carlo simulation
- Energy → Temperature
- Hotspot and gradient

Assessment of damage mechanisms and quantitative analysis of damage limits

HiRadMat-37: Monte Carlo simulation

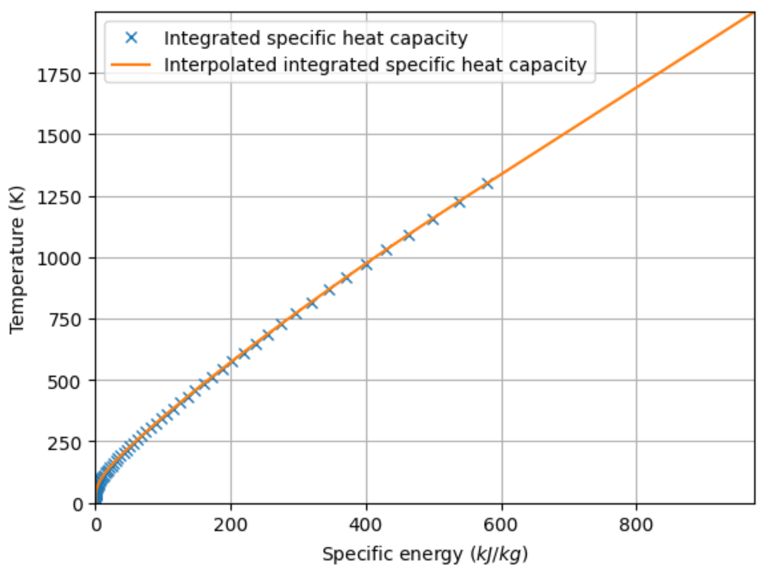


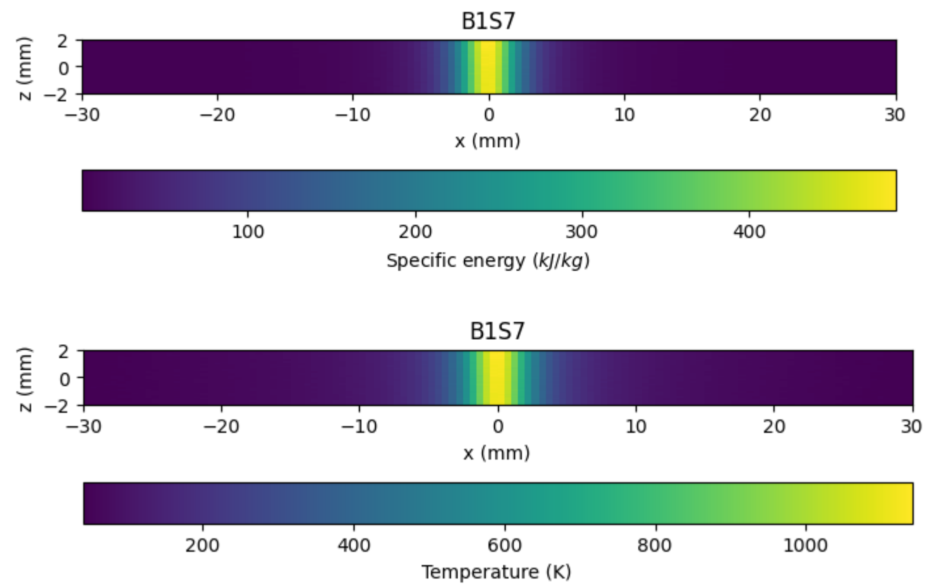


HiRadMat-37: Monte Carlo simulation

From specific energy to temperature

$Q = \int_T C_p(T)\, dT$ with C_p specific heat capacity $[\, J \cdot kg^{-1} \cdot K^{-1}\,]$

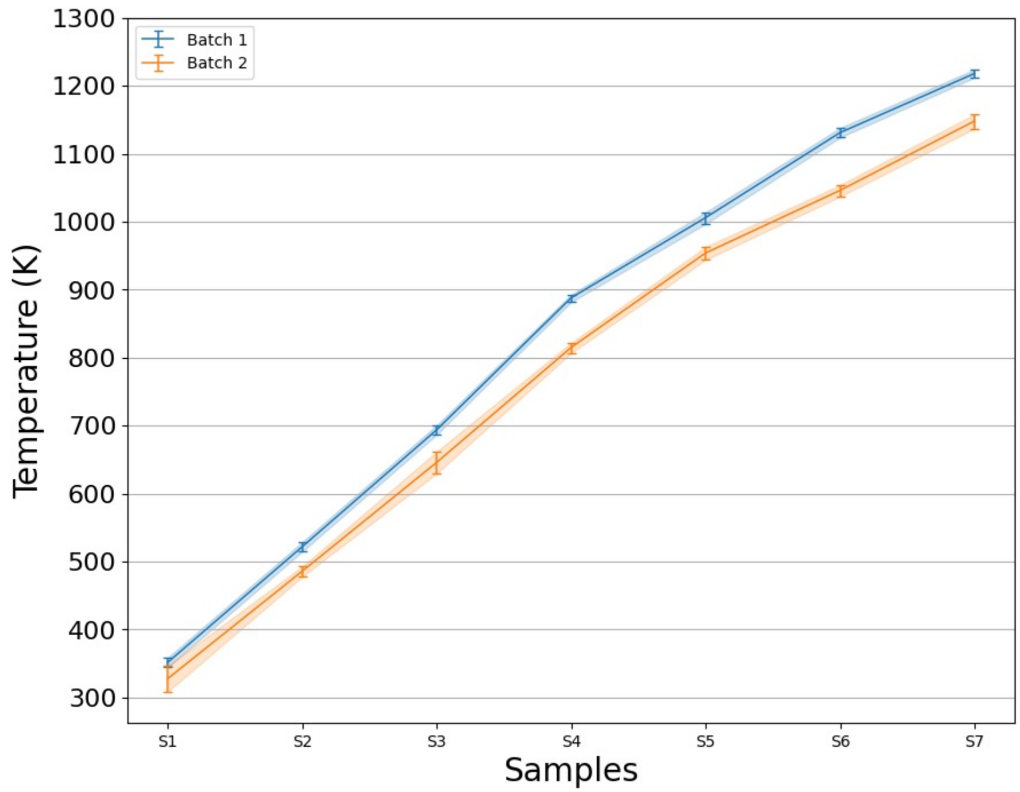




HiRadMat-37: Monte Carlo simulation

Hotspot values for Batch 1 and Batch 2

Sample	Hotspot Temperature [K]	Relative error -	Relative error +
B1S1	352	1.99%	1.99%
B1S2	522	1.34%	1.34%
B1S3	694	1.01%	1.01%
B1S4	888	0.68%	0.56%
B1S5	1006	0.89%	0.80%
B1S6	1131	0.62%	0.62%
B1S7	1218	0.49%	0.49%
B2S1	328	5.79%	5.79%
B2S2	486	1.65%	1.44%
B2S3	646	2.48%	2.48%
B2S4	815	0.98%	0.86%
B2S5	954	1.05%	0.94%
B2S6	1046	0.86%	0.76%
B2S7	1148	0.96%	0.87%

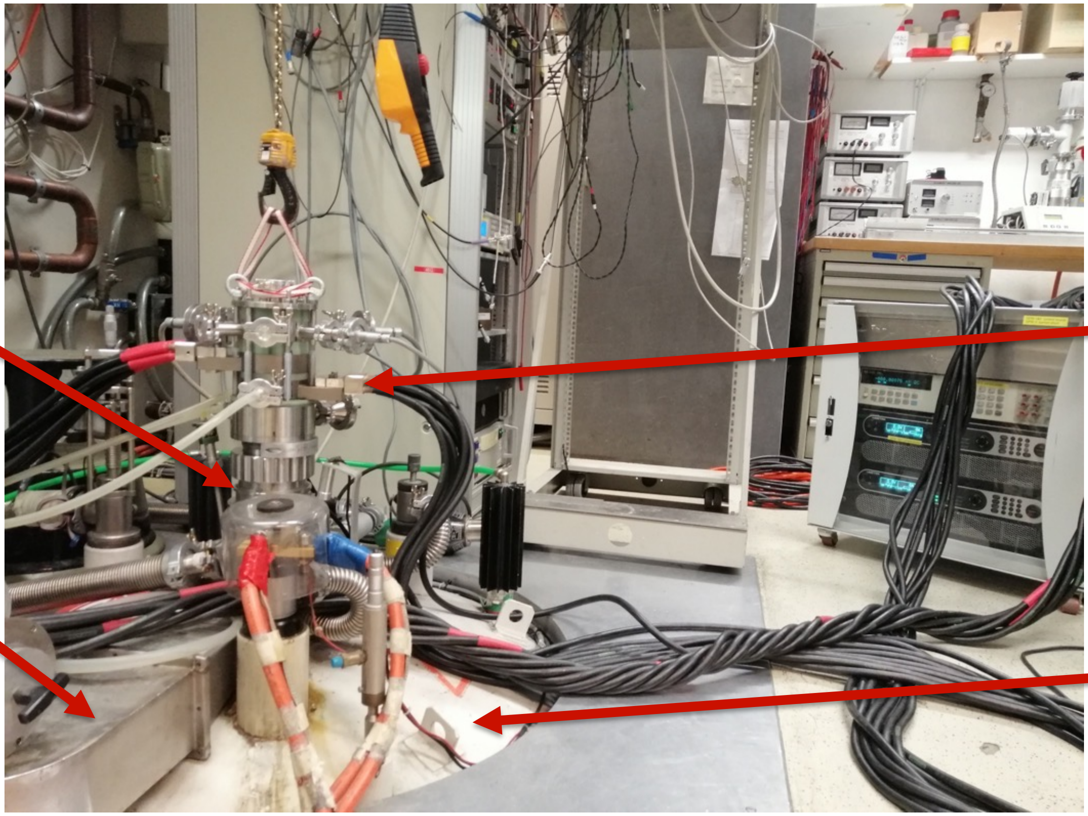


Critical current measurement

Setup of the University of Geneva Lab

Removable tube on which the sample is fixed

Electro-magnet for the external magnetic field

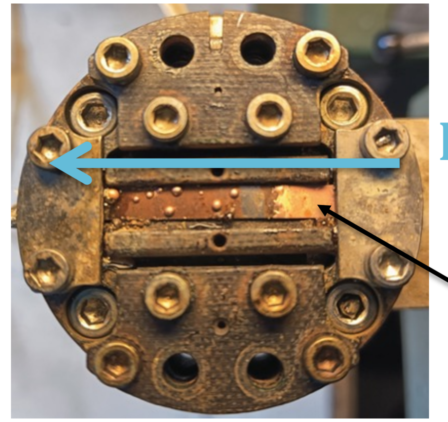


Current supply

Cryostat with liquid helium: Measure at 4K or 77K

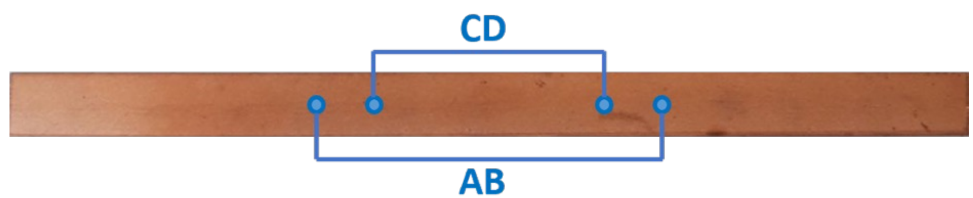
Critical current measurement

Removable tube on which the sample is fixed via the sample holder



Sample holder

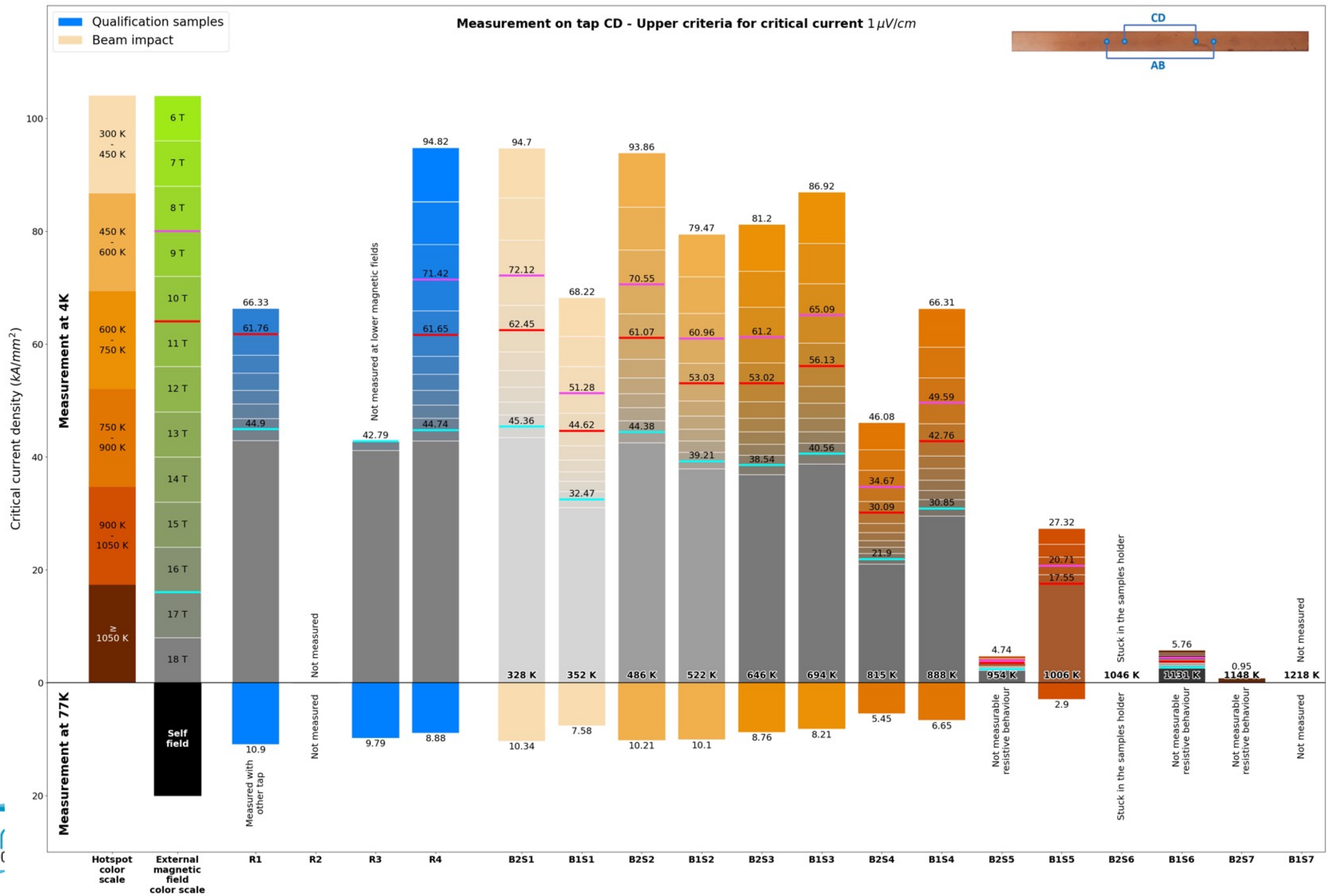
HTS tape



Voltage tap for the measurement

$AB \approx 20\,mm$

$CD \approx 15\,mm$



Measurement on tap CD - Upper criteria for critical current 1 μV/cm
Qualification samples
Beam impact
CD
AB
Critical current density (kA/mm²)
Measurement at 4K
Measurement at 77K
Hotspot color scale
300 K - 450 K
450 K - 600 K
600 K - 750 K
750 K - 900 K
900 K - 1050 K
≥ 1050 K
External magnetic field color scale
6 T
7 T
8 T
9 T
10 T
11 T
12 T
13 T
14 T
15 T
16 T
17 T
18 T
Self field
R1
66.33
61.76
44.9
10.9
Measured with other tap
R2
Not measured
Not measured
R3
Not measured at lower magnetic fields
42.79
9.79
R4
94.82
71.42
61.65
44.74
8.88
B2S1
94.7
72.12
62.45
45.36
328 K
10.34
B1S1
68.22
51.28
44.62
32.47
352 K
7.58
B2S2
93.86
70.55
61.07
44.38
486 K
10.21
B1S2
79.47
60.96
53.03
39.21
522 K
10.1
B2S3
81.2
61.2
53.02
38.54
646 K
8.76
B1S3
86.92
65.09
56.13
40.56
694 K
8.21
B2S4
46.08
34.67
30.09
21.9
815 K
5.45
B1S4
66.31
49.59
42.76
30.85
888 K
6.65
B2S5
4.74
954 K
Not measurable resistive behaviour
B1S5
27.32
20.71
17.55
1006 K
2.9
B2S6
Stuck in the samples holder
1046 K
Stuck in the samples holder
B1S6
5.76
1131 K
Not measurable resistive behaviour
B2S7
0.95
1148 K
Not measurable resistive behaviour
B1S7
Not measured
1218 K
Not measured