Beam impact experiment of 440 GeV/c protons on Nb_3Sn filaments and YBCO tapes at cryogenic temperatures

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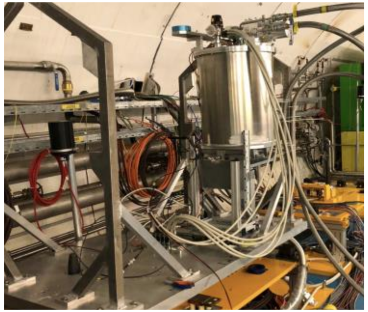
13th August 2020

http://sc-damage-limits.web.cern.ch

Outline

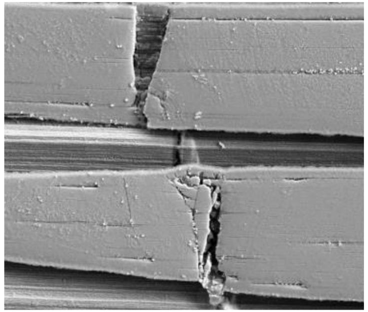
Timeline review



SC Damage experiments

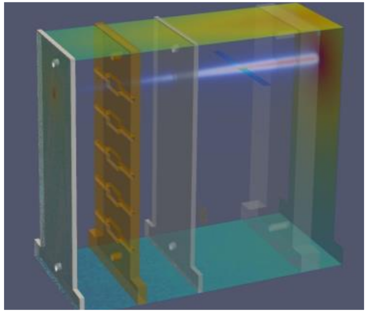
- Furnace heating
- CLIQ discharge heating
- HiRadMat-31 (room temperature)
- HiRadMat-37 (cryogenics temperature)

HiRadMat-37: Nb_3Sn



- Update on new results
- Microscopic damage analysis
- Post-irradiation performance measurements at UNIGE

HiRadMat-37: YBCO



- Detailed modelling
- Overview
- Energy deposition simulations
- Thermo-mechanical analysis

Superconductor damage experiments

HiRadMat-31

Cable stacks furnace heating
- Polyimide insulation degradation
- Measurement of dielectric strength

Capacitive discharges (seconds)
- Magnetization measurement and dielectric strength (insulation)

Irradiation at room temperature
- Degradation of polyimide insulation
- Degradation of critical current density
- Microscopic analysis

Irradiation at cryogenics temperature

NbTi + Nb_3Sn
- Energy deposition and thermo-mechanical analysis (FLUKA)
- **Jc & magnetization measurements (UNIGE)**
- **RRR measurements**
- **Microsopic analysis (optical, polishing & etching, SEM)**

Today

YBCO
- **Energy deposition**
- **Thermo-mechanical analysis**

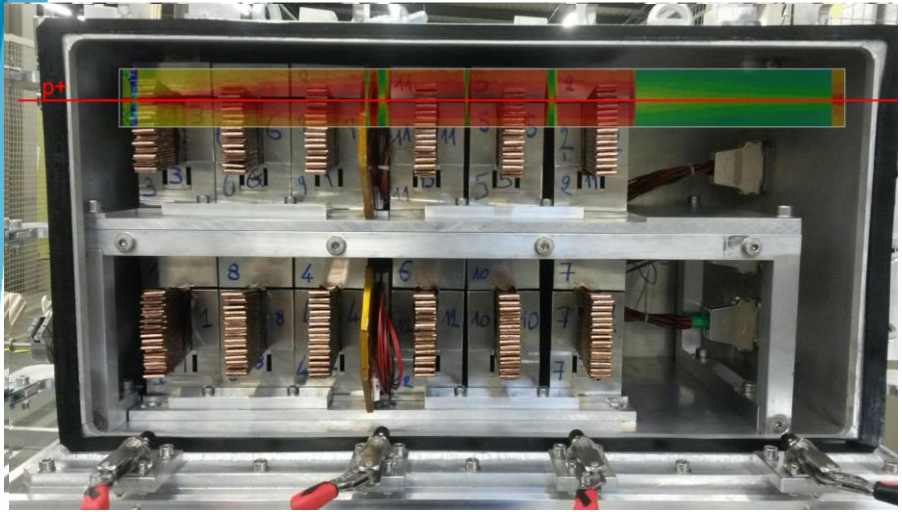
Nb3Sn
- SEM analysis of batch 3

YBCO
- Jc measurement (UNIGE)
- Microscopic analysis

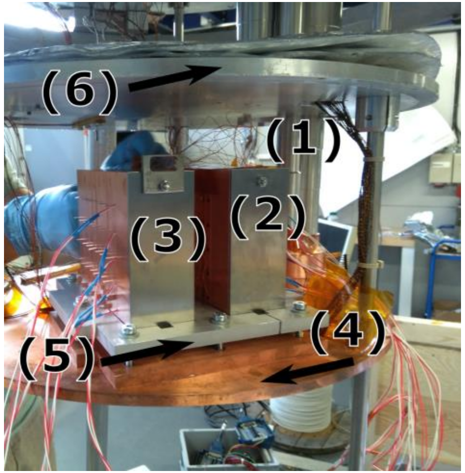
2016 — 2018 — 2019 — 2020

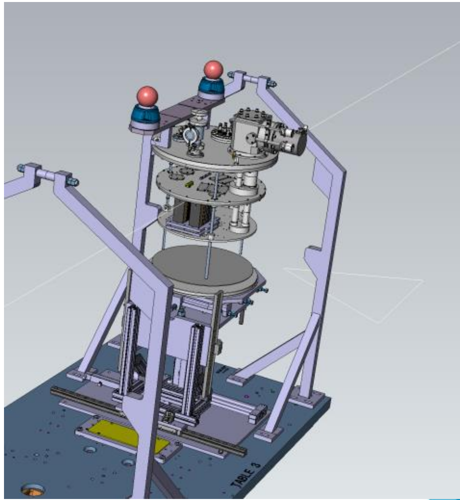
HiRadMat-37

HiRadMat-31 & HiRadMat-37



Room temperature experiment





Crygen-free 4K cryostat

Table 1: Overview of samples and sample dimensions used in the experiment.

Sample type	Diameter/cross section	length
LTS Nb_3Sn RRP	0.85 mm	50 mm
LTS NbTi	0.825 mm	50 mm
HTS YBCO	0.2 mm × 4 mm	60 mm

HiRadmat-37

Beam impact
- Thermal gradients
- Thermal stresses
- Sample and sample holder deformation

→

Changes in micro-structure
- Micro-cracking
- Cracking / breaking

→

Damages to filaments
- Reduced number of filaments contributing to the transport current

→

Degradation of SC properties
- Critical current
- Magnetic moment
- B_{c2}

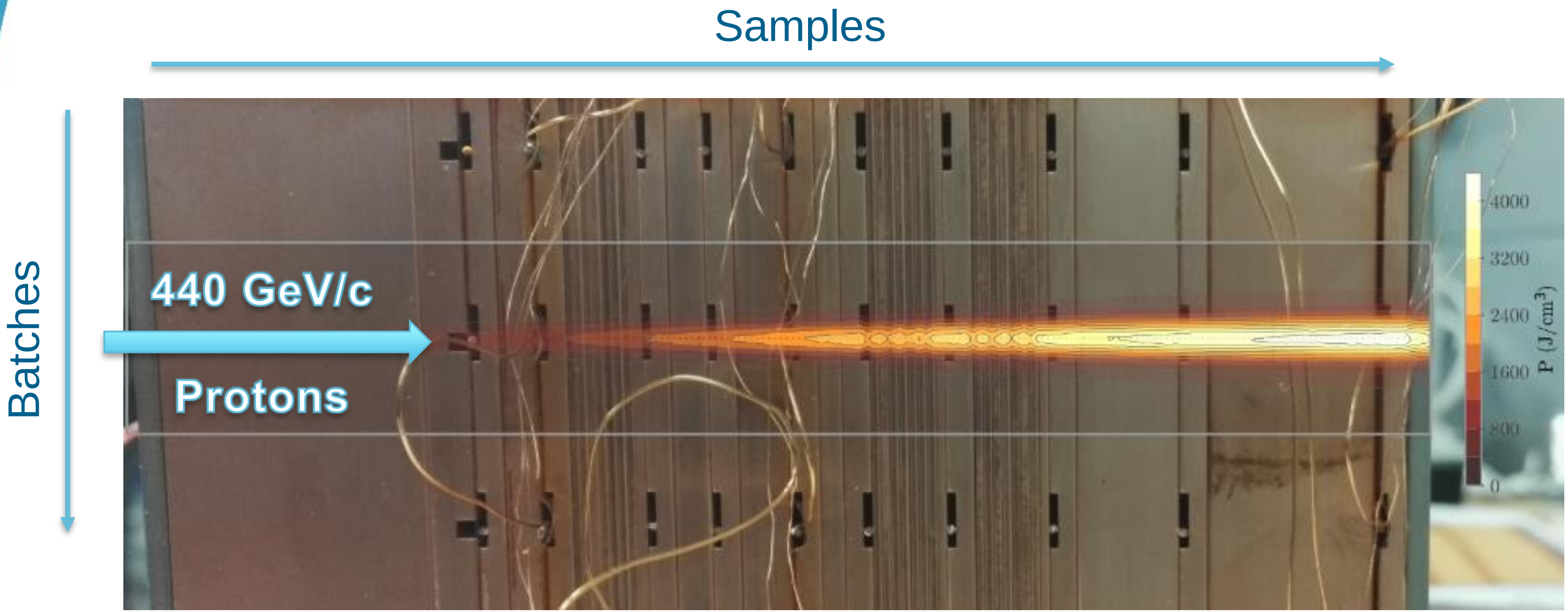
FLUKA / Geant4
Ansys

Microscopic analysis

Post-irradiation performance measurements (UNIGE)

→ **Determination of the damage mechanisms**

HiRadmat-37 - Nb3Sn samples



Fluka simulation in simplified geometry (courtesy A. Will)

HiRadmat-37 - Nb3Sn samples

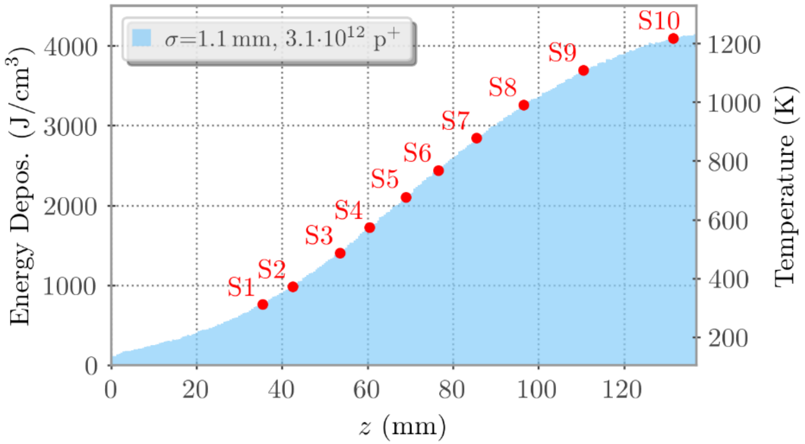
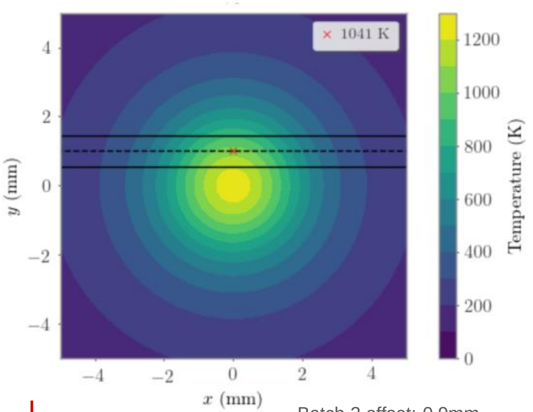


Table 13: Peak temperatures for the LTS samples. The batches are marked in the first column as B# and the sample segments are noted in the top row as S#.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
B1	302 K	361 K	474 K	552 K	644 K	728 K	803 K	893 K	1019 K	1131 K
B2	316 K	383 K	501 K	580 K	680 K	766 K	846 K	943 K	1070 K	1185 K
B3	311 K	373 K	490 K	570 K	667 K	753 K	829 K	924 K	1051 K	1166 K
B4	313 K	380 K	497 K	575 K	674 K	759 K	838 K	934 K	1060 K	1174 K
B5	311 K	374 K	490 K	571 K	668 K	753 K	830 K	925 K	1052 K	1167 K

Peak temperature is not the only factor: the impact parameter (beam offset) also plays a crucial role



Batch 2 offset: 0.9mm

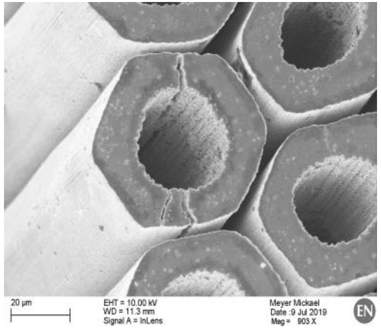
Large temperature gradient!

Batch 2 selected for longitudinal cross-section microscopic analysis

No major differences in peak temperatures between batches

Nb3Sn samples – Microscopic analysis

Cross sectional observations (HiRadmat-31)



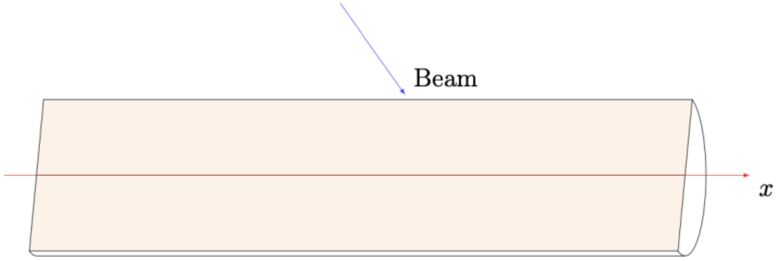
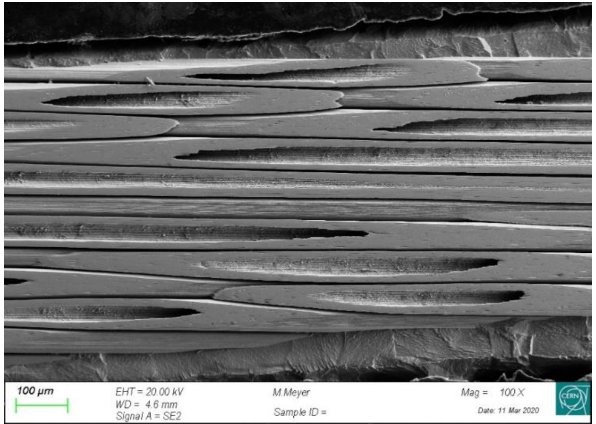


Figure 4.4: Schematic view of the ideal surface used for the microscopic analysis.

Courtesy A. Schubert

Longitudinal observations (HiRadmat-37)



Nb3Sn samples – Microscopic analysis

EDMS 2363700

- Optical observation of polished samples

Reference sample

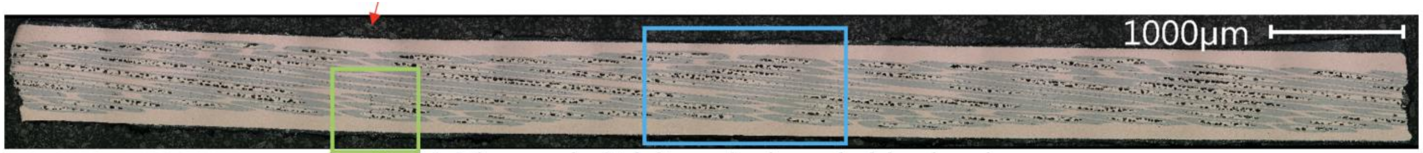


Figure 4 – Reference sample – Stitched image – Sample seems bend above the crack

Figure 5 – a) Magnified view of the stitched image, crack in the Nb3Sn phase – b) Centre of the sample, no crack observed – c) Magnified view of 5b)

Nb3Sn samples – Microscopic analysis

EDMS 2363700

- Optical observation of polished samples

Sample 4 (550K)

Figure 10 – S4 – 550 K – Sample is bend on cracks location

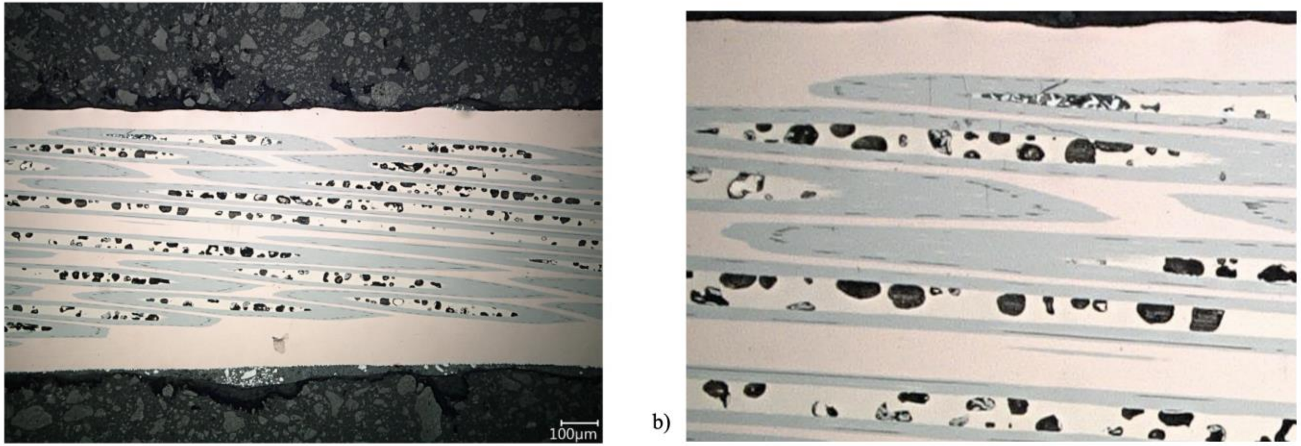


Figure 11 a) The location of the cracks is shifted from the middle of the sample, , b) Magnified view of 11a), cracks in the Nb_3Sn phase

Nb3Sn samples – Microscopic analysis

- Optical observation of polished samples

Sample 6 (790K)

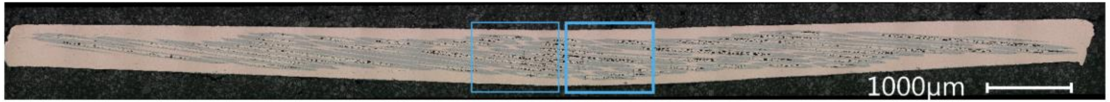


Figure 15 – S6 – 790K - Sample is bend in the missle

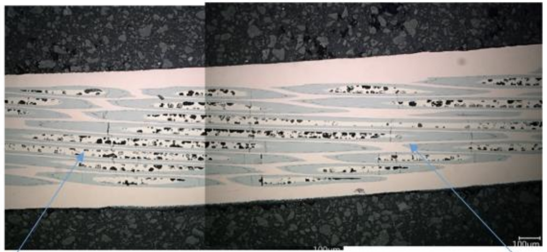


Figure 16 - Stitched image

a) b)

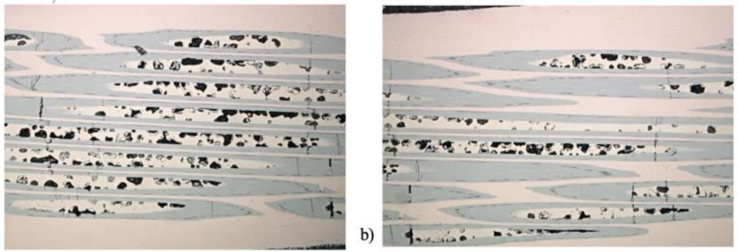


Figure 17 – a), b) Magnified views of figure 16, The location of the cracks is in the middle of the sample and spread over 1 mm on both sides

Nb3Sn samples – Microscopic analysis

EDMS 2363700

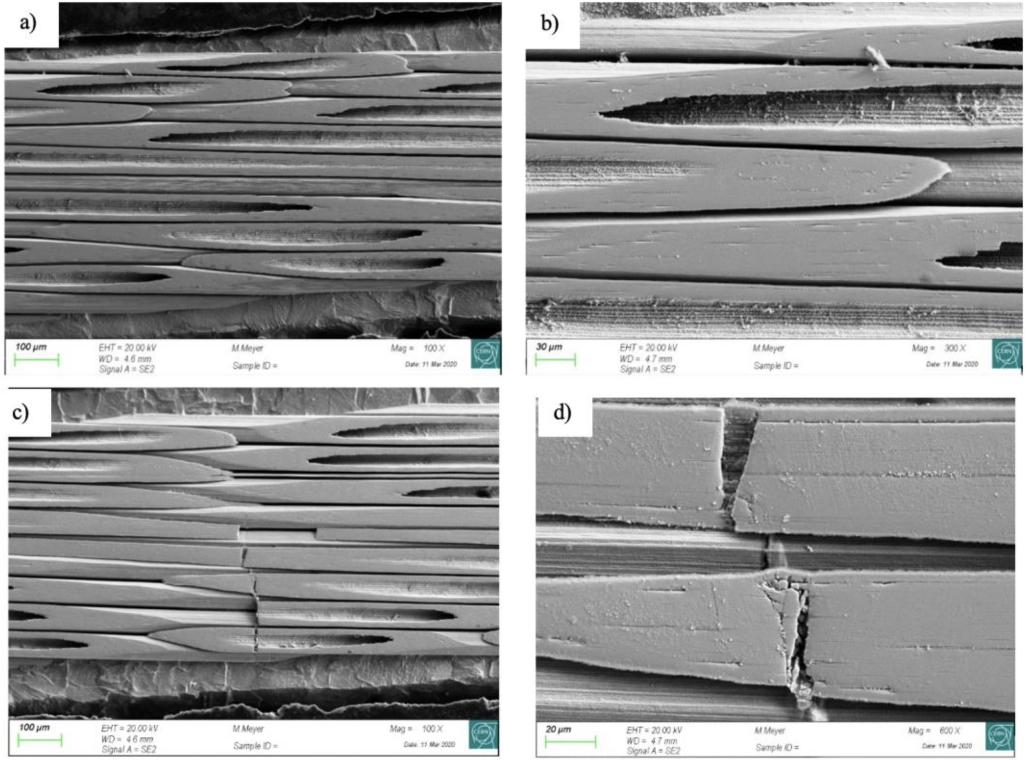
- SEM observation of etched samples
- Macro etching using HNO_3 (Cu removal)
- SEM observation (large field depth) to see the ”3D” structure of the filaments

Nb3Sn samples – Microscopic analysis

EDMS 2363700

Reference sample

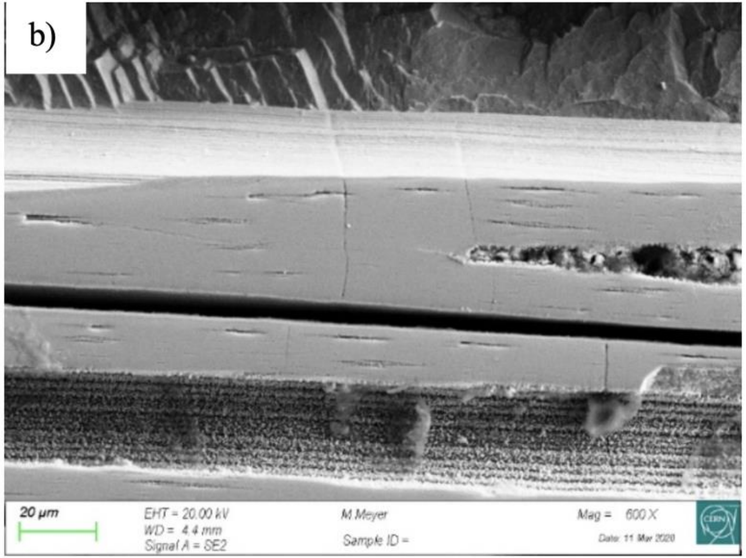
“Handling” crack observed

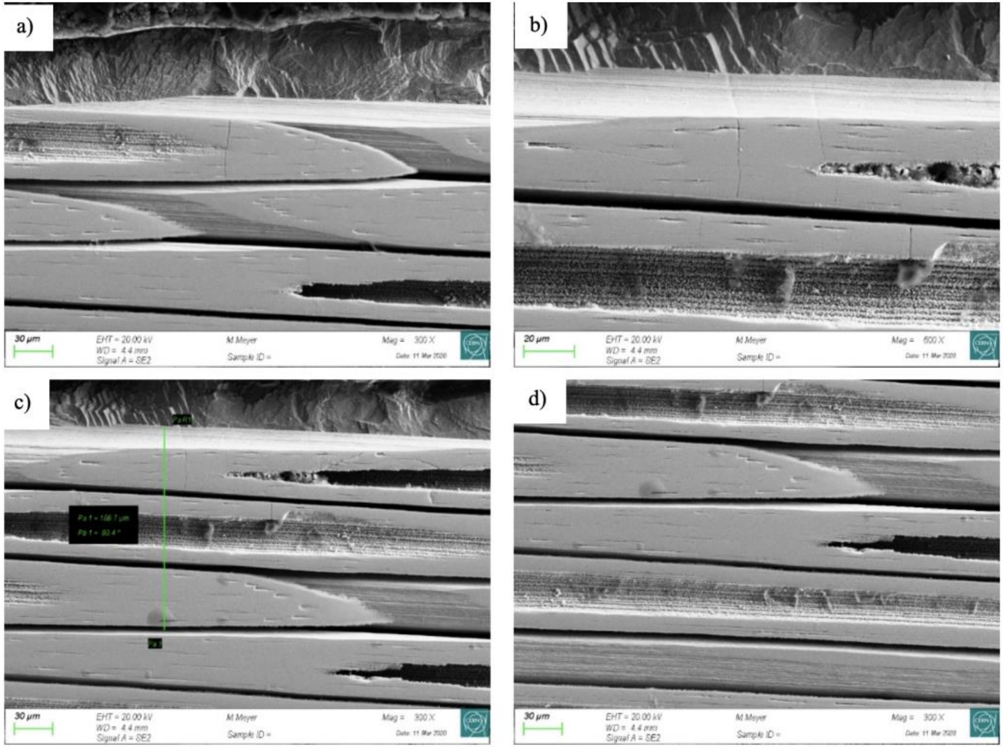


Nb3Sn samples – Microscopic analysis

EDMS 2363700

Sample 4 (550K)



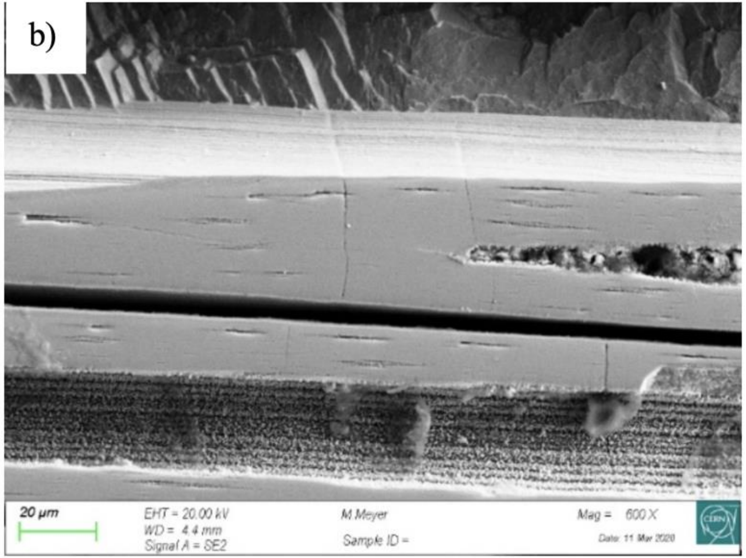


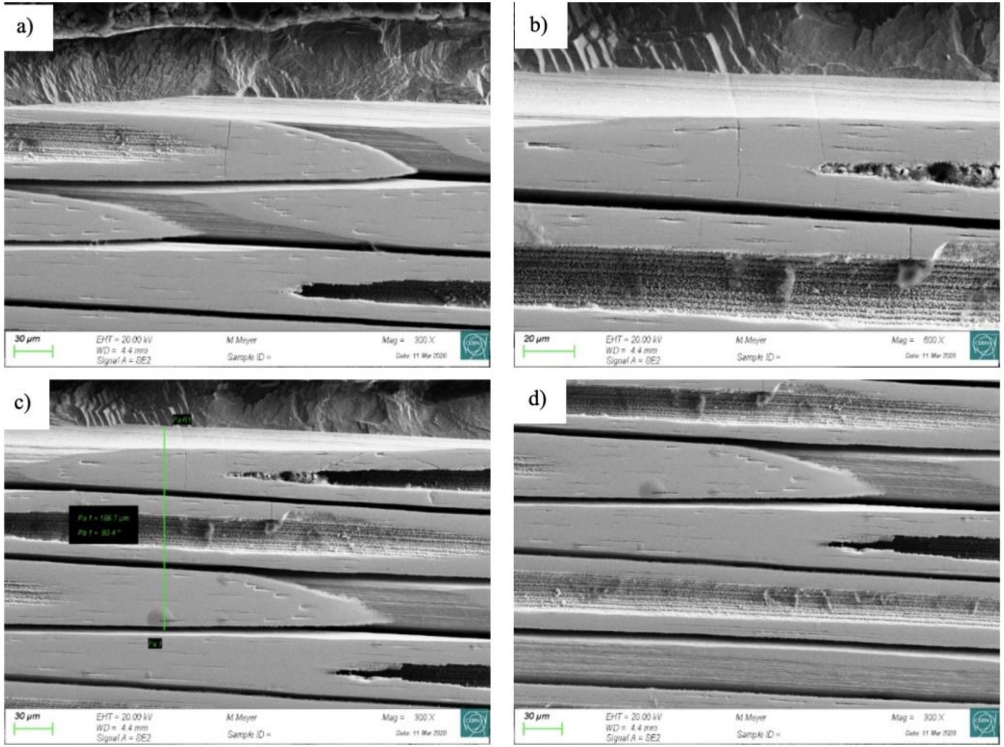
Network of transverse cracks

Nb3Sn samples – Microscopic analysis

EDMS 2363700

Sample 4 (550K)



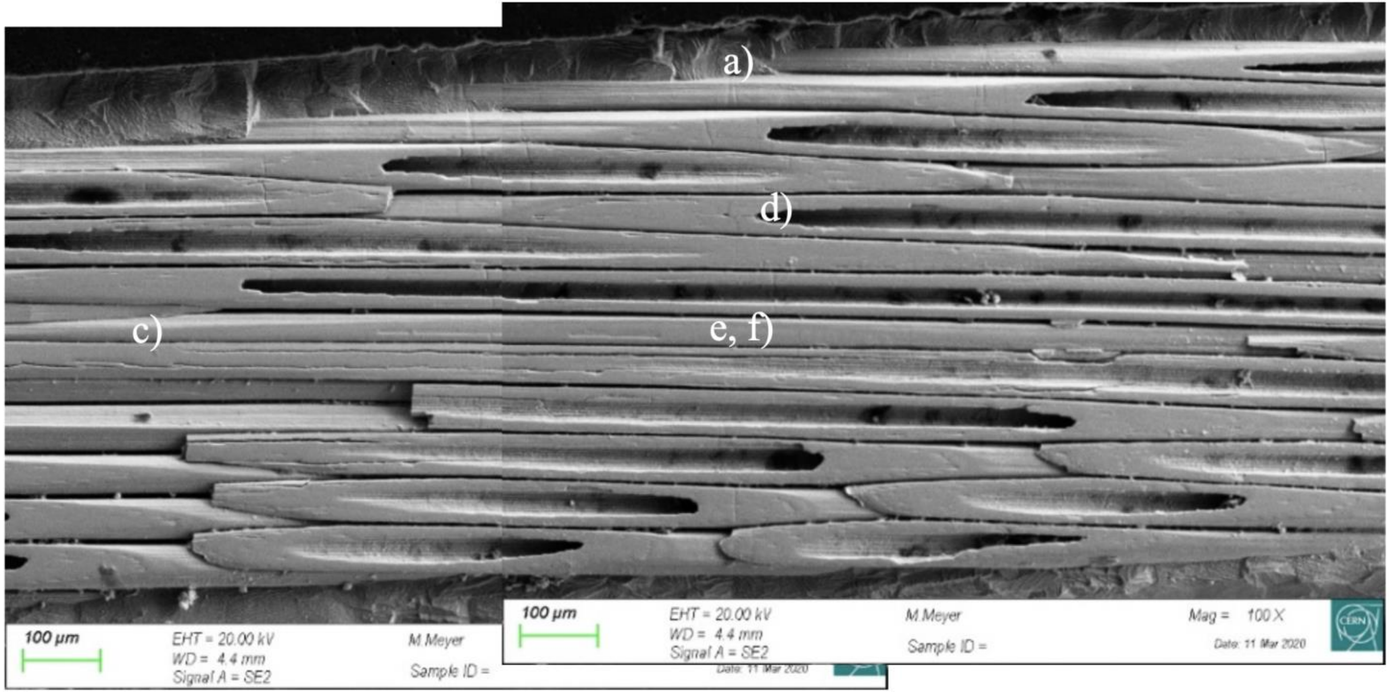


Network of transverse cracks

Nb3Sn samples – Microscopic analysis

EDMS 2363700

Sample 5 (640K)



Network of transverse cracks
and **longitudinal crack**

Nb3Sn samples – Microscopic analysis

EDMS 2363700

- Cracks appear on S2 (383K) and increase in number for S4, S5 and S6 (766K)
- Cracks are located in the Nb3Sn brittle phase and do not penetrate the soft Nb layer
- Only S5 exhibited longitudinal cracks
- The very large gradients (due to the small sample size compared to the beam size *and* due to the beam impact offset) induce a pronounced bending of the samples

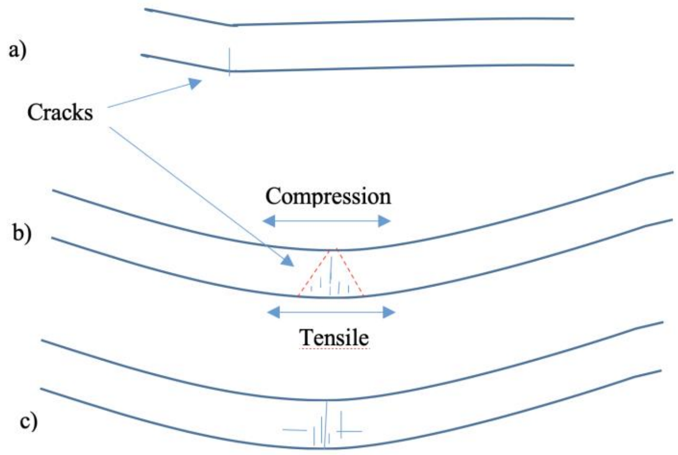
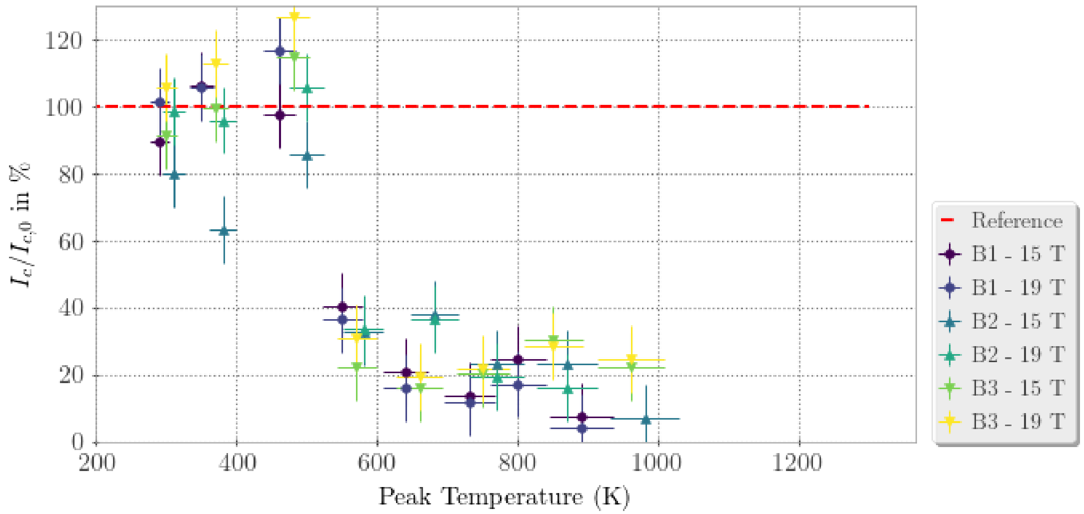


Figure 20 - a) pattern of cracks observed for the reference sample – b) pattern of cracks observed for sample S6, S8 - c) pattern of cracks observed for sample S5 (Fan shape highlight by red dash line)

Nb3Sn samples – SC properties

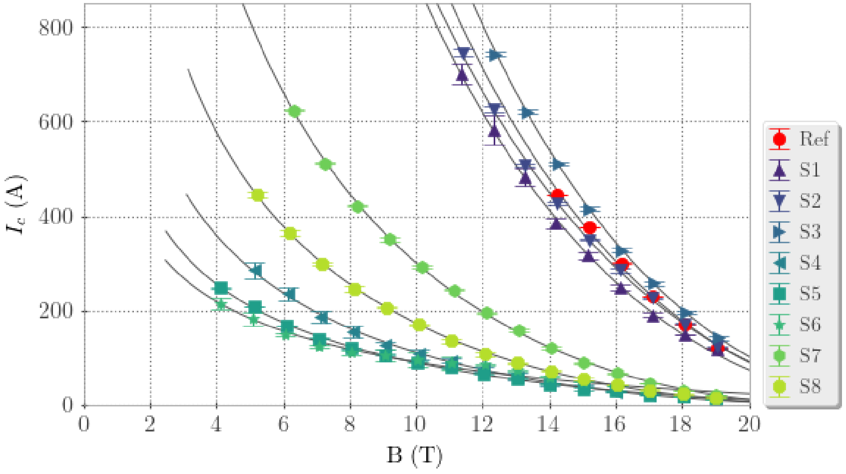
- **Batch 3** has been measured at UNIGE
- Results are consistent with other batches (1 and 2)

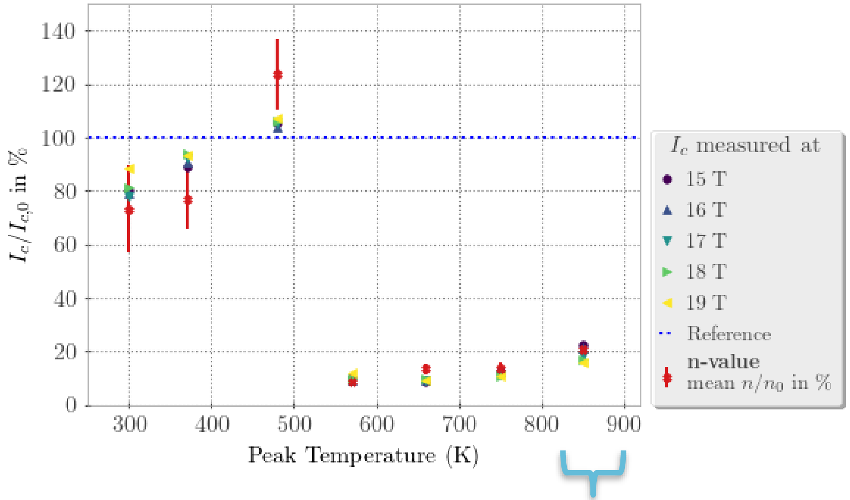


Nb3Sn samples – SC properties

- **Batch 3** has been measured at UNIGE
- Results are consistent with other batch

Plots courtesy A. Will





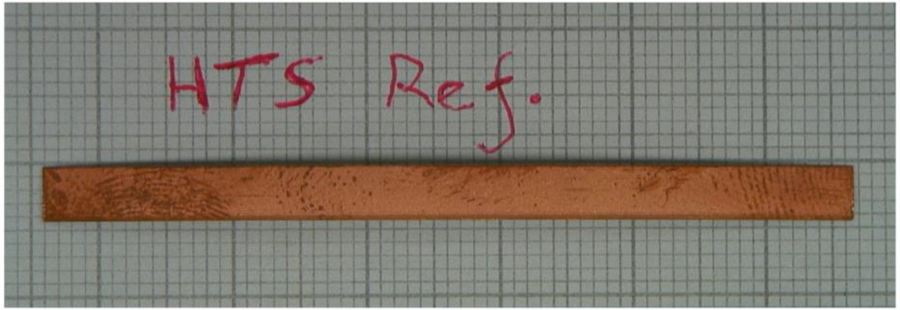
S7 consistently better
Due to sampler holder geometry (blocks and foils) and/or beam impact offset

HiRadmat-37 - HTS samples

- Tape composition
- Experimental setup and geometry
- Detailed Geant4 modelling energy deposition simulations
- Thermo-mechanical analysis

HiRadmat-37 - HTS samples

- Tape composition



(a) HTS Reference frontside.

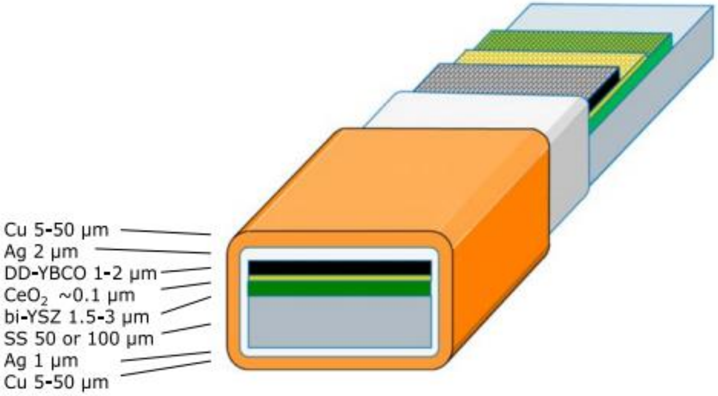


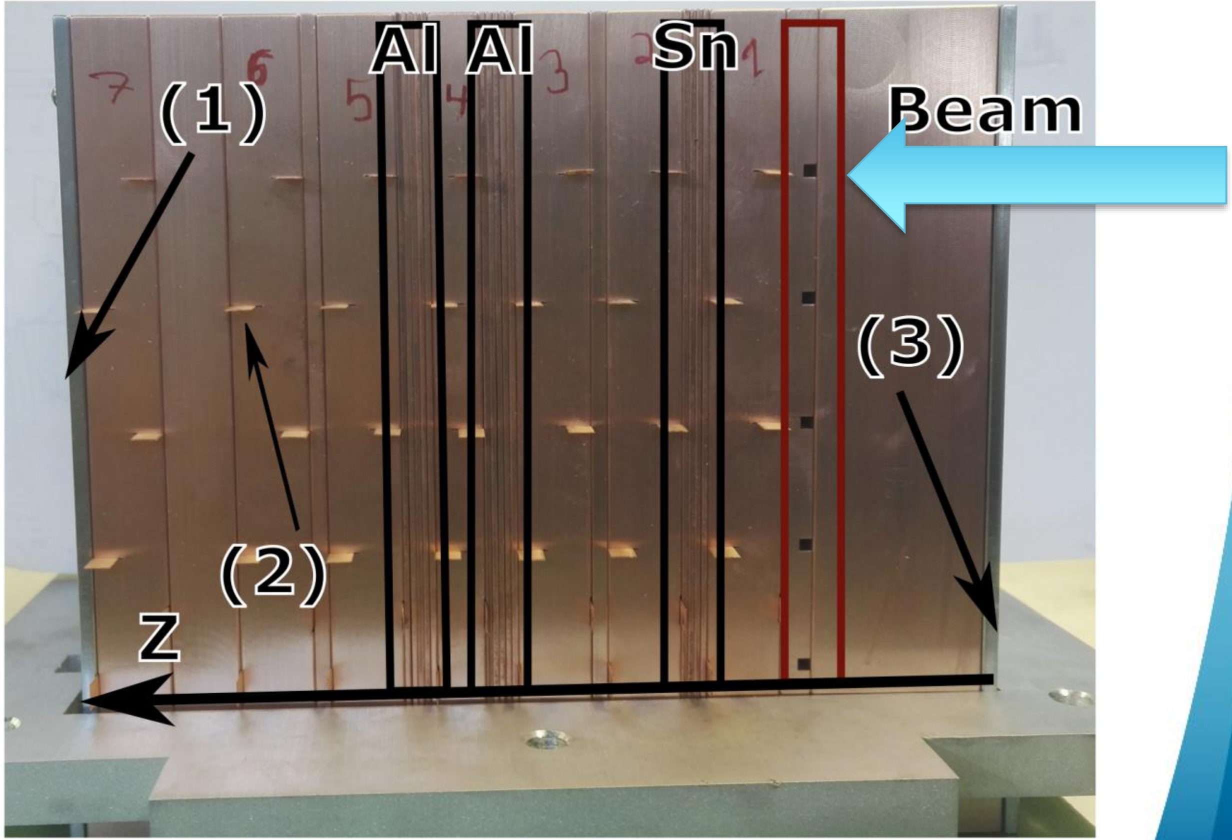
Figure 1. Cross-sectional design of HTS coated tape manufactured at Bruker HTS GmbH with length of 600 m. SS denotes CrNi stainless steel (or Hastelloy) used as a substrate material, bi-YSZ: bi-axially textured yttria-stabilized zirconia buffer layer deposited via ABAD, CeO: CeO_2 buffer cap layer deposited via PLD. DD-YBCO: double disordered superconducting layer [3] based on $YBa_2Cu_3O_{7-\delta}$ deposited via PLD. Ag: silver protection layer deposited by thermal vacuum evaporation, Cu: copper layer deposited via galvanic plating.

HiRadmat-37 - HTS samples

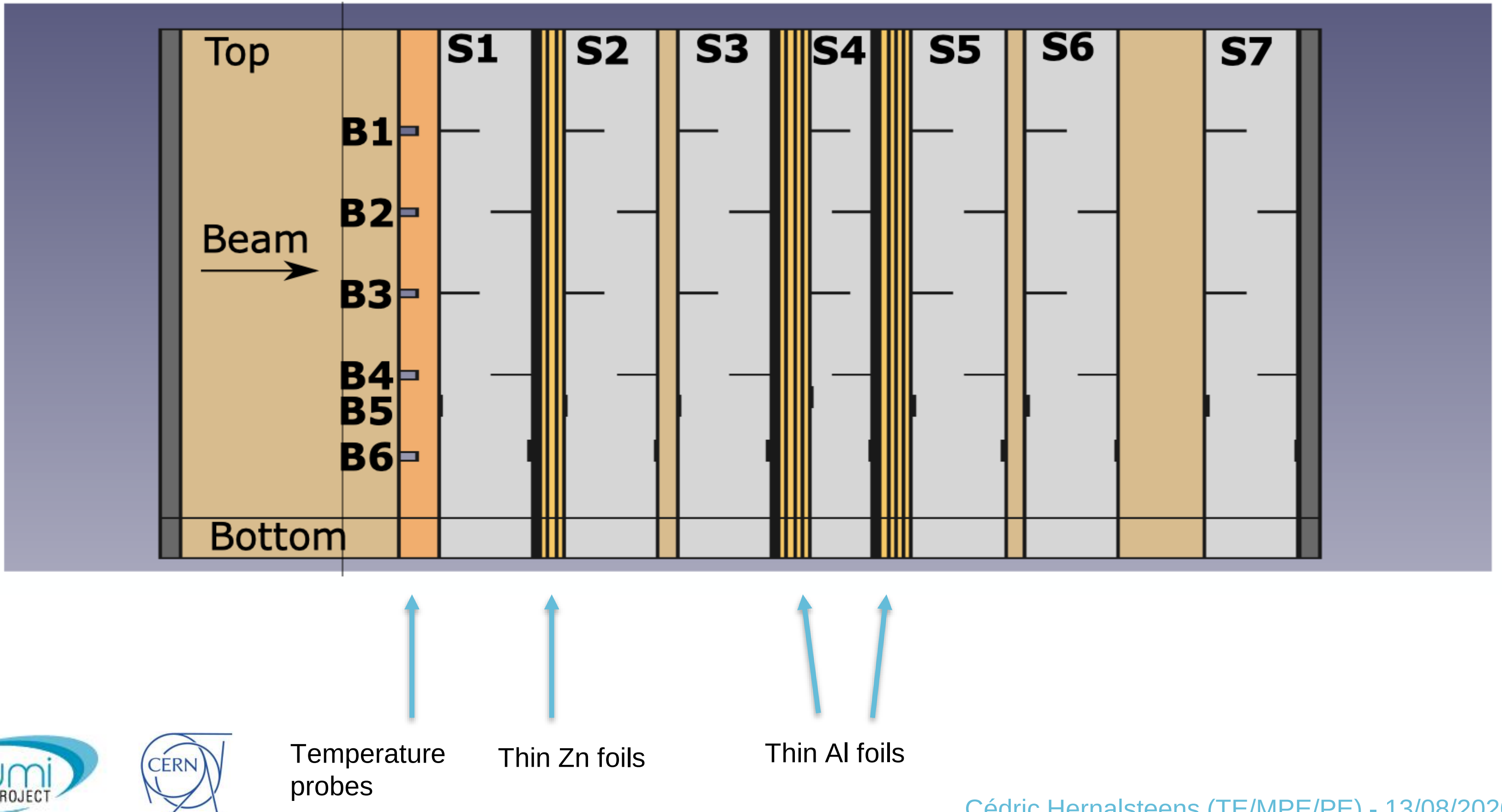
Longitudinal positions are interleaved

Batches 1-4 “side” beam incidence

Batches 5-6 “front” beam incidence



HiRadmat-37 - HTS samples

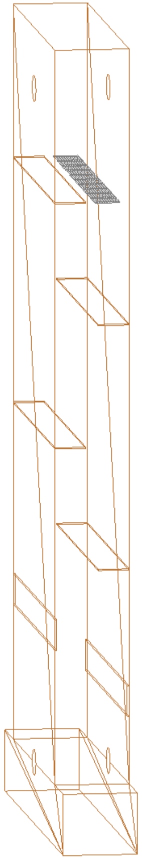


HiRadmat-37 – Geant4 simulations

- Detailed modelling of the experiment performed with pyg4ometry

  S. Boogert *et al*, Pyg4ometry: a tool to create geometries for Geant4, BDSIM, G4Beamline and FLUKA for particle loss and energy deposition studies, IPAC'19

  - Sampler holder including all features (from 2D drawings)
  - HTS tape with each layer included
  - Python tool: ease of use, cross platform, versioning, debugging, modular approach to build and reuse complex geometries
  - Allows subsequent comparison between codes with no "conversion effort" and exact same geoemtries



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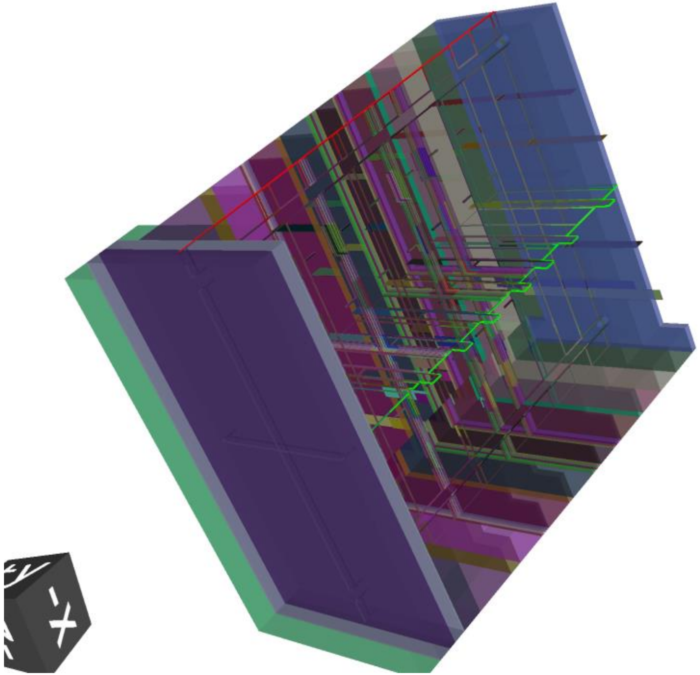
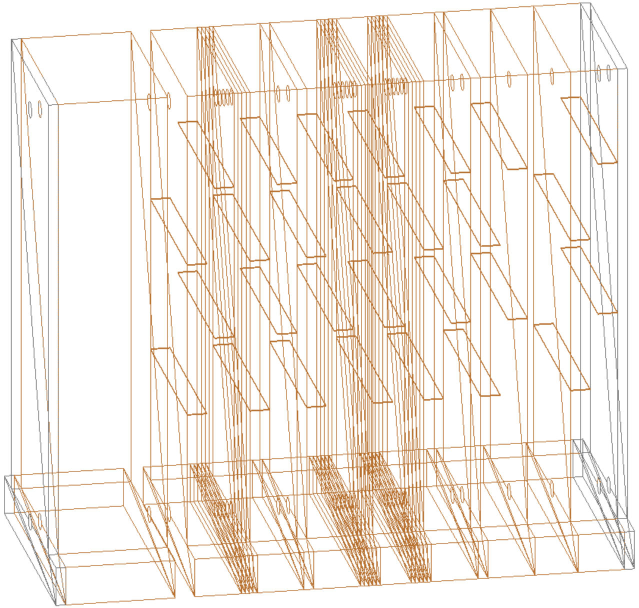
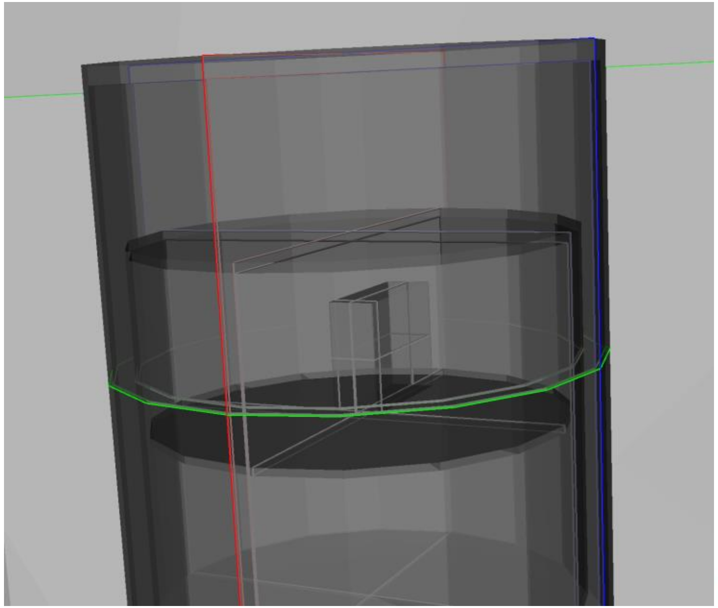




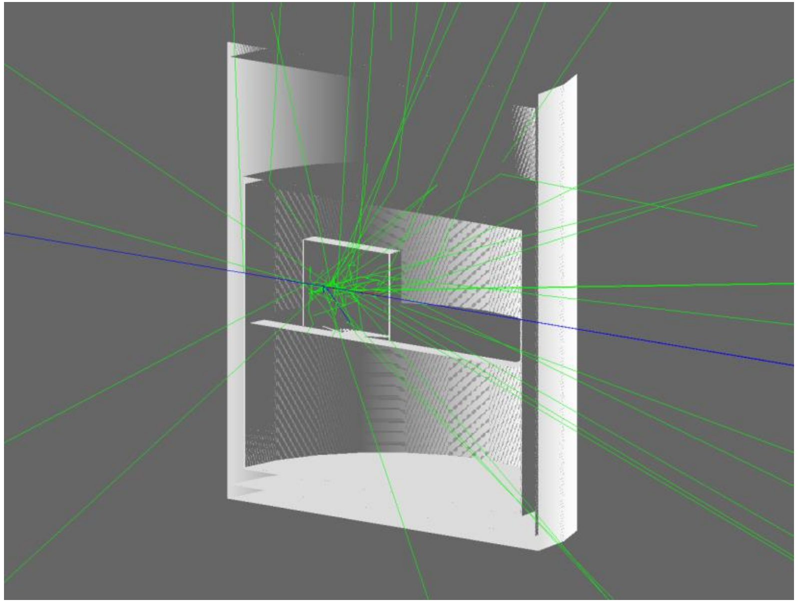
HiRadmat-37 – Geant4 simulations

- Detailed modelling of the experiment performed with pyg4ometry
- Optional inclusion of the vacuum vessel and thermal shields



HiRadmat-37 – Geant4 simulations

- Automatic conversion from FLUKA input files to GDML (Geant4 geometry persistency format)
- No manual operation
- Less detailed model from A. Will converted

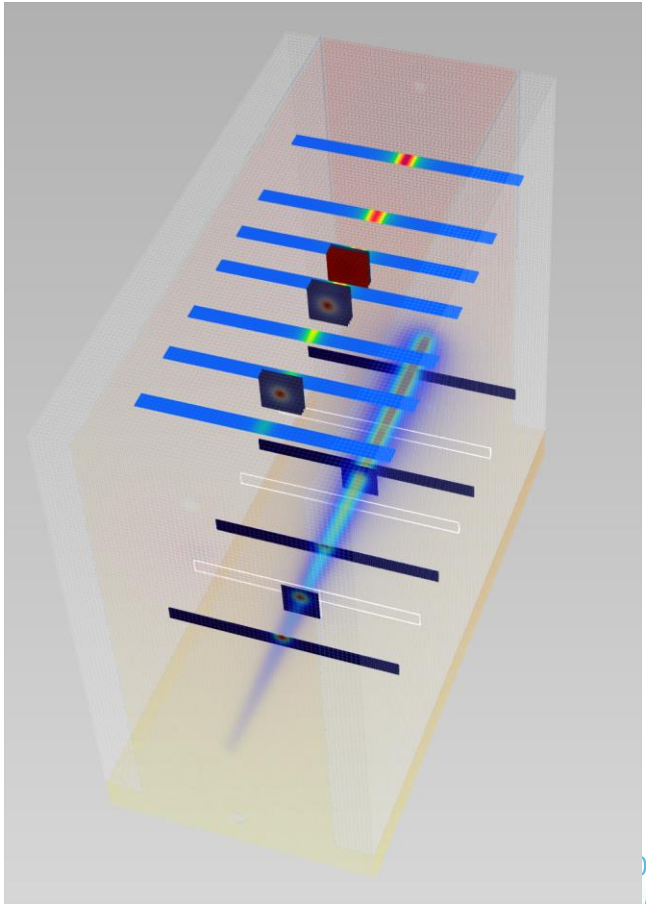


HiRadmat-37 – Geant4 simulations

- Energy deposition simulations performed with BDSIM

L.J. Nevay *et al*, BDSIM: An accelerator tracking code with particle-matter interactions, Computer Physics Communications, 252, 2020

- Created a complete pipeline (managed in Python) for 3D visualization of input geometry, Geant4 simulation results and Ansys meshes and physics results using Paraview



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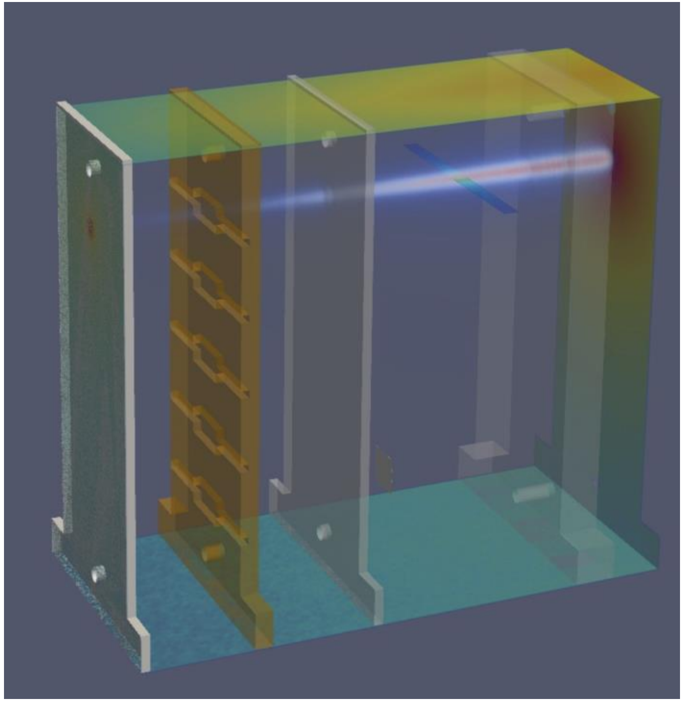

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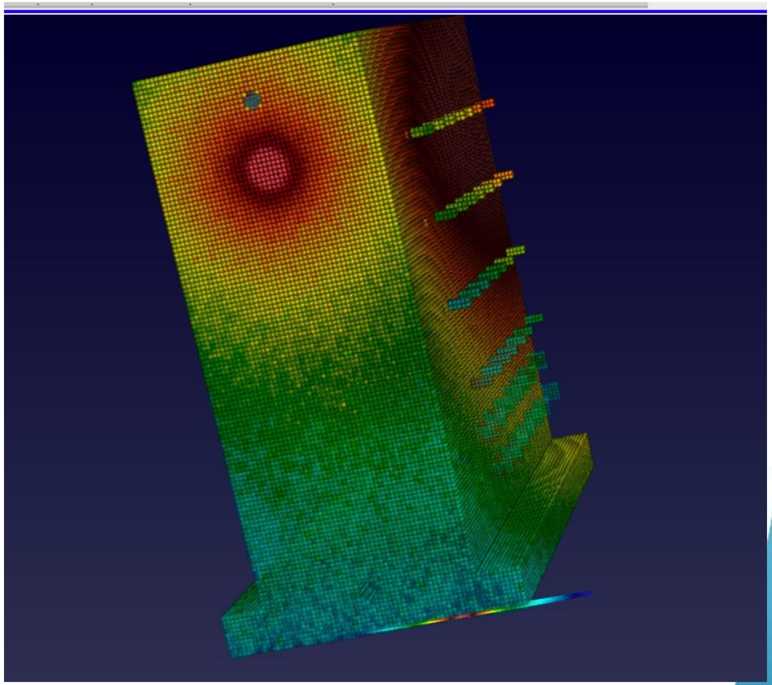
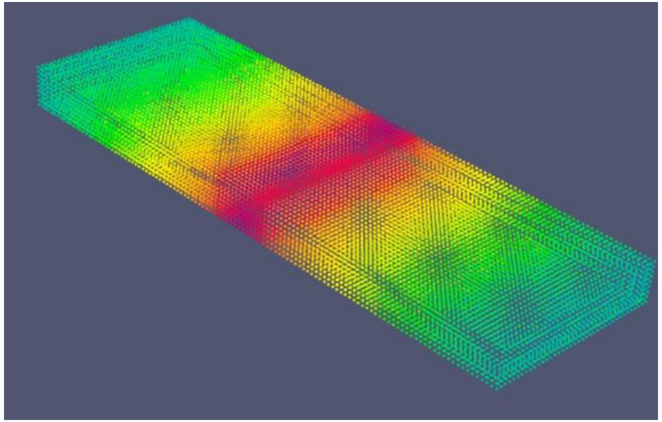


HiRadmat-37 – Geant4 simulations

- Energy deposition scored on multiple meshes
  - Coarse (milimeters) global mesh
    - Overal temperature profile agrees with prior FLUKA studies
    - Small features differs due to the more detailed geometry (grooves, etc.)
  - Fine transverse mesh of the Zn and Al foils to determine if melting point has been reached
  - Refined mesh for each tape

	Size (mm)	Bins
Length	60	120
Width	4	40
Thickness	0.1809	10



HiRadmat-37 – Ansys modelling

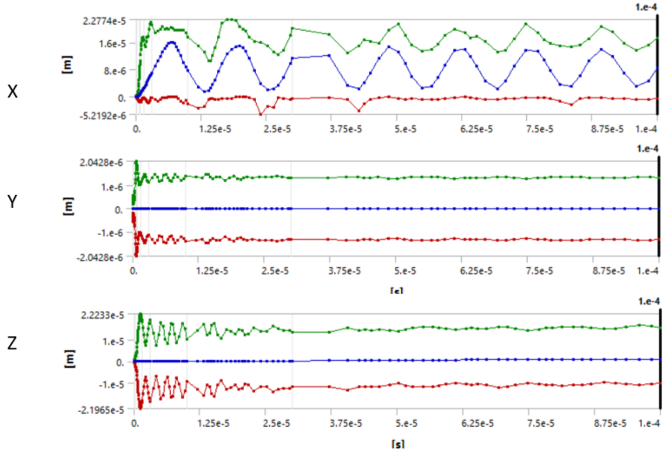
- All meshes data exported in a format suitable for Ansys import (all data on *gitlab* and *cernbox*)
- Critical need of material properties data at low temperatures
  - Data from multiple sources extracted, cleaned and used in Ansys * for
    - Hastelloy
    - YBCO
    - YSZ
    - Ag
    - Cu

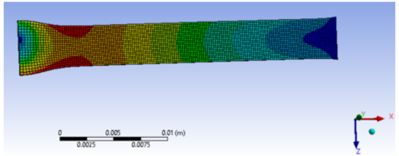
(*) Summary Excell sheet available on CERNbox

HiRadmat-37 – Ansys modelling

- First model using a single stainless steel layer
- Effort to better understand the required meshing details in Ansys

Movement of Batch 1 Sample 5.
With symmetry and constrained in one end





Conclusions and futures steps

- **Nb_3Sn**
  - Microscopic analysis confirmed the damage mechanisms
    - ➢ Second batch to be analyzed to finalize the analysis of Nb_3Sn
  - Post-irradiation performance behaviors confirmed with 3 batches (see A. Will's thesis)

- **HTS**
  - Detailed energy deposition patterns obtained: note/paper in preparation
  - Initial steps performed with Ansys
  - ➢ Ready for detailed simulations (TECH Jannick L., September)
  - ➢ SC properties measurements at UNIGE (on-going)

Additional information and details

https://gitlab.cern.ch/***machine-protection-studies***/

https://gitlab.cern.ch/***machine-protection-studies***/**sc-damage-limits**

http://sc-damage-limits.web.cern.ch