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Experimental study of high-temperature superconductor damage mechanisms from fast failure scenarios in high energy hadron colliders

Mémoire présenté en vue de l'obtention du diplôme
d'Ingénieur Civil Physicien à finalité Radiophysique Médicale

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Abstract

The discovery of the Higgs boson by the ATLAS and CMS experiments at CERN from proton-proton collisions produced by the Large Hadron Collider (LHC) completed the experimental validation of the so-called "Standard Model" (SM). However, experimental observations require the Standard Model to be extended and future facilities aim at discovering Beyond Standard Model (BSM) mechanisms. The Future Circular Collider at CERN (FCC-hh) is such a proposed infrastructure which would push forward the "energy frontier" by an order of magnitude by colliding proton beams at centre-of-mass energy of 100 TeV and provide a state-of-art high-energy physics instrument until the end of the century.

Such a collider will require novel superconducting magnets. The use of high-temperature superconductors (HTS) is considered in order to provide centre-of-mass energies even beyond 100 TeV and to achieve energy efficiency goals. Magnets based on Nb₃Sn coils featuring HTS inserts are being considered to achieve magnetic fields in excess of 16 T. Research and development is a key element to the widespread use of HTS conducting tapes based on Rare-earth Barium Copper Oxide (ReBCO).

In parallel with the technological challenges posed by the development of high-field magnets, future colliders will also face tremendous challenges due to the stored beam energy, as the loss of only a minute fraction of the beam can cause damage to the machine components, and in particular to the superconducting materials. Dedicated machine protection systems must therefore be devised to prevent such accidents. At this stage, however, the damage limits of the novel superconducting materials considered for FCC-hh are still unknown and represent an essential information for the viability of the machine operation. This thesis is dedicated to the experimental characterisation of the so-called "damage limits", i.e. the limits in terms of energy density deposition beyond which the superconducting material would be permanently damaged.

The experimental procedure follows the one of the experiments which were carried out to devise the damage limits of superconducting materials used at the Large Hadron Collider (LHC), namely Nb-Ti, and at the High-Luminosity Large Hadron Collider (HL-LHC), namely Nb₃Sn. Samples of superconducting materials, including HTS tapes, were impacted at cryogenic temperatures with 440 GeV proton beams at the "High-Radiation to Materials" (HiRadMat) facility, a dedicated test facility which is part of the CERN Accelerator Complex. This beam impact experiment aims at reproducing the conditions of a typical fast failure scenario involving beam losses in the magnet apertures. The damage limits are drawn from the correlation between the energy deposited during the beam impact experiment and the difference in critical current density pre- and post-irradiation. In addition, to probe energy density deposition over longer time-scales, another experiment was carried out at room temperature where a current from a capacitive discharge in the HTS conductor was used to induce a fast temperature increase.

This thesis analyses in detail the results obtained for the HTS tapes. To determine the amount of energy deposited in the samples during these experiments, new numerical simulations are performed

using input parameter values measured during the experiment. For the beam-impact experiment, Geant4-based Monte Carlo simulations are performed using Beam Delivery Simulation (BDSIM). For the current discharge experiment, a detailed study of the experiment is provided. The presented model is developed to determine the fraction of the generated heat which caused the tape damage. The results on the energy density deposited in the tapes based on the best experimental model are presented and discussed in detail. The damage limits are then derived based on critical current measurements performed by collaborators at the University of Geneva. This study of the correlation between the samples damage level and their critical current degradation draws first conclusions on the damage limits of ReBCO tapes. This thesis features for the first time a complete analysis of the damage limits of HTS sample tapes based on the unique experimental campaign performed at CERN.

Keywords : damage limits, HTS, ReBCO, HiRadMat, beam impact, FCC-hh

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Acronyms

BBA	Beam-Based Alignment
BCS	Bardeen-Cooper-Schrieffer theory
BDSIM	Beam Delivery Simulation
BLM	Beam Loss Monitor
CERN	European Organisation for Nuclear Research
CLIQ	Coupling-Loss Induced Quench
FCC	Future Circular Collider
FCC-hh	Hadron-Hadron Future Circular CoLLider
HiRadMat	High-Radiation to Materials
HL-LHC	High-Luminosity Large Hadron Collider
HTS	High Temperature Supraconductor
LHC	Large Hadron Collider
Linac	Linear Accelerator
LTS	Low Temperature Supraconductor
MLI	MultiLayer Insulator
PS	Proton Synchrotron
ReBCO	Rare-earth Barium Copper Oxide
RF	Radiofrequency
SPS	Super Proton Synchrotron
YBCO	Yttrium Barium Copper Oxide

At the European Organization for Nuclear Research (CERN), the world's largest proton collider, the Large Hadron Collider (LHC), collides 6.8 TeV protons for high-energy physics research. Indeed, the discovery of the Higgs boson by the ATLAS and CMS experiments from proton-proton collisions produced by the LHC completed the experimental validation of the so-called "Standard Model" (SM). To maintain the trajectory of the accelerated particles along its 26.7 km circumference, superconducting dipoles bend the beam by producing strong magnetic fields. Operating accelerators as the LHC represents a major technical challenge. At high energies, the beam itself constitutes a danger for the equipment, and protective systems are therefore implemented. Different types of failures can occur in an accelerator leading to energy deposition in the surrounding equipment that can damage them. In the LHC, one of the critical equipment is the superconducting magnets; if the superconducting materials are exposed to too-high energy deposition, they can lose their properties temporarily (quench) or definitely. This leads to the shut down of the accelerator with a more or less complex recovery. To optimise the machine protection systems, it is essential to assess the "damage limits" of the superconductors, i.e. the limits in terms of energy deposition beyond which the superconducting material would be permanently damaged. For the low temperature superconducting material (LTS) used in the LHC, the Nb-Ti actually and the Nb₃Sn for the next upgrade, experimental studies have already been conducted and these limits have been drawn [1, 2].

However, experimental observations require the Standard Model to be extended and future facilities aim at discovering Beyond Standard Model (BSM) mechanisms. The Future Circular Collider (FCC) in its hadron-hadron collision mode (FCC-hh) is such a proposed infrastructure which would push forward the "energy frontier" by an order of magnitude by colliding proton beams at centre-of-mass energy of 100 TeV [3]. Such a collider will require new technologies, including for novel superconducting magnets. With its construction due to start around 2060, the CERN community has high research objectives and they consider to use high-temperature superconductors (HTS) as inserts on Nb₃Sn coils to achieve magnetic fields in excess of 16 T. Research and development is a key element to the widespread use of HTS conducting tapes based on Rare-earth Barium Copper Oxide (ReBCO).

In this context, the machine protection group at CERN find essential to determine the damage limits of this novel superconducting material as they are required to design of the machine protection systems of this new collider. The methodology used for this study consists in experimentally reproducing the damages generated in case of failure. HTS samples have been damaged in two experiments: a beam-impact experiment to reproduce fast-failure scenarios, and a current discharge experiment in which the energy generated by Joule effect mimics a longer time-scale failure. These experiments were designed to create different damage on the samples. After being damaged, the samples are qualified to characterise their new superconducting properties.

The first aim of this thesis is to determine the energy density deposited inside the HTS samples. This quantity cannot be calculated directly from the values measured during the experiments and is obtained via numerical simulations. For each studied sample, the energy density deposition is used to define a single value representative of its damage level, allowing an easy comparison between the different samples.

The second goal is to determine the degradation of the superconducting properties of the HTS samples using critical current measurements made by collaborators at the University of Geneva. The damage level is correlated with the critical current degradation of each sample in order to highlight any relation between these quantities. With these results, the damage limits of the HTS material could be drawn and then be taken into consideration for the FCC-hh machine protection systems design.

The structure of this thesis is as follows. In Chapter 2, the context of the study is detailed. The fundamentals of accelerator physics are presented and used to describe the operation of high-energy hadron colliders. The structure of their superconducting magnets are exposed to show the localisation of the superconductors relatively to the beam. Different failure scenarios and the beam-matter interaction mechanisms are detailed to highlight how these superconductors are damaged in case of failure. Knowing these elements, the procedure of the research campaign on the damage limits of superconducting materials is described, including results from previous research on other materials. Chapter 3 is dedicated to superconductivity with a theoretical overview and a description of the characterisation of superconductors via critical current measurements. The HTS samples studied in this thesis are also presented. In Chapter 4 and 5, the results of the current discharge experiment and the beam-impact experiment are respectively analysed. For both experiments, the setup is described to justify the modelling used in the numerical simulations. The results on the damage level determination of the samples are detailed. In Chapter 6, the characterisation of the samples superconducting properties is made. They are compared with the damage level of the samples in order to highlight any relation between them. Finally, the conclusions of this work are drawn in Chapter 7 as well as the perspectives for this research.

Primer on accelerator technologies and machine protection

2.1 Context

Since 1932 and the build of the Cockcroft-Walton accelerator [4], which accelerated charged particles up to an energy of 600 keV, large advances have been made in accelerator technology. Those have enabled scientists to considerably improve accelerator performances, from higher energy, increased beam density and total stored energy, to more compact accelerators for medical applications. Accelerators are employed for many different applications depending on the accelerated particles and their energy [5, 6]. They are used for industrial applications (material treatment, semiconductor industry, food disinfection, etc.), for medical applications (radiotherapy, radionuclide production, etc.) and for research (fixed-target accelerators for studying the properties of materials, high-energy particle collisions, etc.).

The repartition per sector of applications of 35000 accelerators surveyed in 2020 [6] is shown in Figure 2.1. It highlights that high-energy accelerators, which are the focus of most research and interest, account for only 1% of accelerator applications. However, the technologies developed to make them work have spin-offs in a number of areas. Recent examples include the ultra-high-resolution brain images from the 11.7 T MRI in CEA Paris-Saclay [7]. The construction and commissioning of its main magnet made of Nb-Ti took 20 years and would not have been possible without the expertise developed by the companies that built LHC magnets [8].

A good example of technological improvement required for high-energy accelerator development concerns the machine protection systems. Indeed, the total energy stored inside these accelerators grows exponentially over the years [9] as illustrated in Figure 2.2 for the current and future colliders. The beams become increasingly dangerous for the installation and any uncontrolled failure can lead to severe damage.

2.2 The CERN accelerator complex

The European Organisation for Nuclear Research (CERN) is operating a large accelerator complex located at the Franco-Swiss border near Geneva. This accelerator complex, schematically shown in Figure 2.3, fulfils two distinct functions.

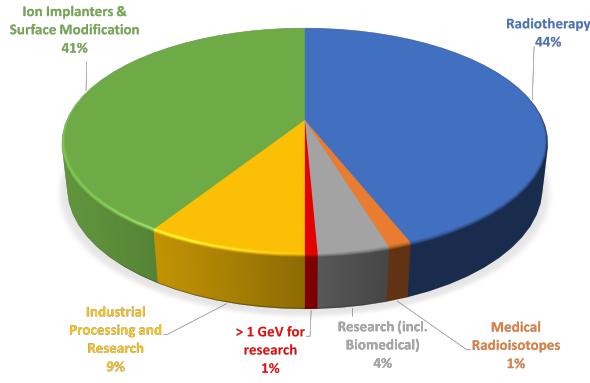


Figure 2.1: Repartition of the sector of applications of the accelerators in the world. High energy accelerators represent only 1% of accelerator applications. Data collected in 2020 for 35000 surveyed accelerators. Adapted from Ref. [6].

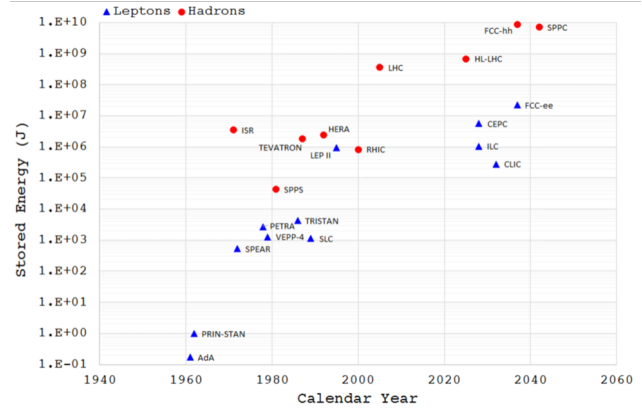


Figure 2.2: Increase over time in the energy stored in current and future accelerators. Both lepton and hadron colliders from all around the world are shown. Reproduced from Ref. [9].

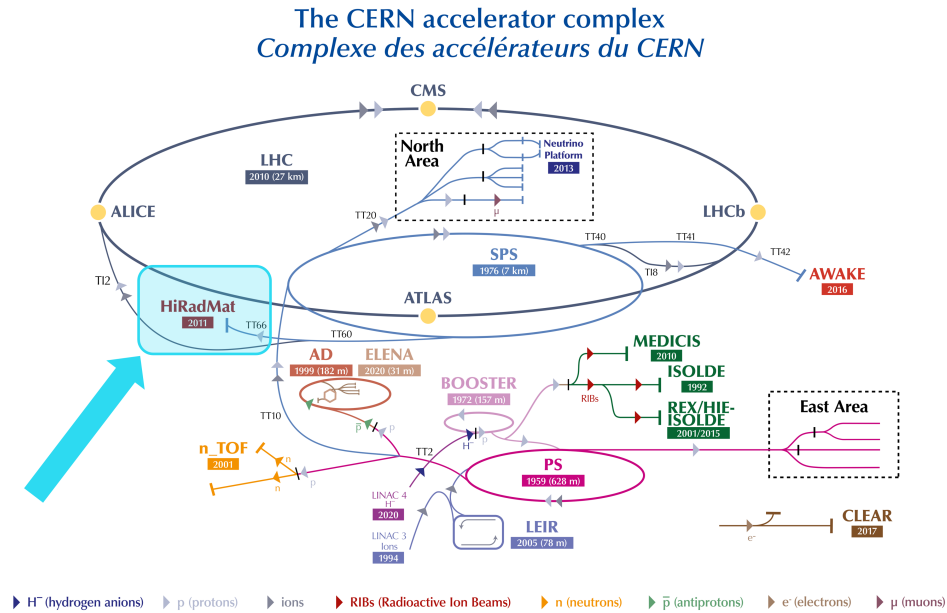


Figure 2.3: Schematic representation of the CERN accelerator complex. The protons are accelerated through the chain of injectors (LINAC4, PS Booster, PS and SPS) to reach the LHC at 450 GeV. The HiRadMat facility (highlighted in blue) which provides proton beams extracted from the SPS for beam-impact experiments constitute a unique facility to carry out damage study. Adapted from Ref. [10].

It is employed to prepare the beams that fill the *Large Hadron Collider* (LHC), the world's largest superconducting accelerator. The LHC is a hadron collider in which collisions at centre-of-mass energy of 13.6 TeV are realised. To reach this energy, the particles are accelerated through an entire chain of accelerators, called in this case injectors. When the LHC is in proton collision mode, negative hydrogen ions are accelerated in the *LINAC 4* before passing through a thin carbon foil to be stripped of their two electrons. Only the protons remain and pass through the different circular accelerators, the *Proton Synchrotron Booster* (PS Booster), the *Proton Synchrotron* (PS) and the *Super Proton Synchrotron* (SPS) before finally reaching the LHC with an energy of 450 GeV.

Besides filling the LHC, the beams produced by the different injectors are provided for a large number of other facilities, covering a wide range of research. For example, the PS provides proton beams to the antimatter factory which study the anti-hydrogen atom but also to the neutron time-of-flight (n-TOF) facility which study the neutron reactions. The "High-Radiation to Materials" (HiRadMat) facility, which provides beams from the SPS for beam-impact experiments, is highlighted in Figure 2.3. No LHC beam is used for external experiments and the beam provided by this facility is the highest energy beam that can be used for damage study. More detailed about the HiRadMat facility are given in Section 2.7.1.

2.3 High energy hadron colliders

All accelerators are based on the same key elements [5]. The charged particles are extracted from a source and collected to be accelerated. The bunches of particles are then conducted by different magnetic fields that focus or bend the beam to force it to remain in the vacuum chamber. The kinetic energy is given to the particles by an oscillating electric field provided by a radiofrequency (RF) cavity. Various diagnostic systems to control and monitor the beam ensure the operation of the accelerator. Once the particles reached their maximum energy, they are extracted towards other accelerators or used in dedicated experiments.

These main components are combined to create a wide variety of accelerators, including linear accelerators (LINAC), circular accelerators (cyclotrons, synchrotrons, etc.) and colliders. In this thesis, we focus on high-energy hadron colliders.

A collider is a circular accelerator in which two beams circulate in the opposite direction and can collide in dedicated areas. In the case of hadron colliders, the beams coming from previous accelerators are injected in separated but adjacent vacuum chambers. The RF cavities are disposed in a limited length of the trajectory and the particles recirculate several times to reach their maximal energy. In order to allow the collision of the bunches of particles, the two vacuum chambers are brought together at different points of the circumference, called collision points. It is around those points that the large detectors are placed to catch the results of the collisions.

The current larger hadron collider is the LHC. An even larger hadron collider is currently under a feasibility study at CERN, the Future Circular Collider (FCC). In its hadron-hadron configuration (FCC-hh), which is currently scheduled to go into operation around 2070, the energy reached by the proton would be 50 TeV. Some details about these colliders are given in the following.

2.3.1 A brief description of the LHC

The LHC, currently doing its third physics run, accelerates protons within its approximately 26.7 km circumference since 2008. A schematic layout of this superconducting large collider [11] is shown in Figure 2.4. The LHC, which is not perfectly circular, is divided into 8 sectors, each consisting of an arc and long straight sections. The arcs are composed mainly of alternating dipoles and quadrupoles to bend the beam

and maintain its stability inside the vacuum chamber, respectively. The straight sections (P1 to P8) are dedicated to more precise functions [12].

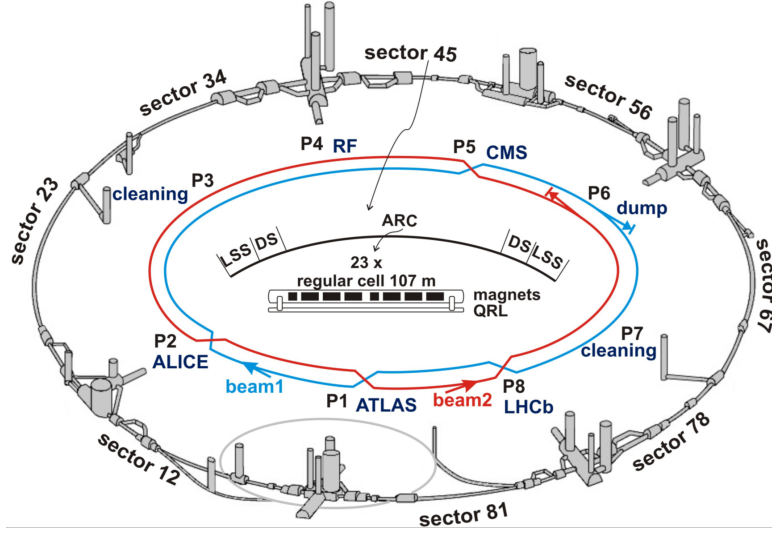


Figure 2.4: Schematic representation of the LHC. The LHC is divided in 8 sectors that are composed of an arc and straight sections. The geometry of the 8 access points is shown, including the four main experiments: ATLAS, ALICE, CMS and LHCb. Reproduced from Ref.[11].

The four straight sections corresponding to the intersection points of the beams are occupied by the large detectors of the main experiments: ATLAS in P1, ALICE in P2, CMS in P5 and LHCb in P8. They measure data from the collisions for the particle physics research. The physicists' requirements concern the collision energy but also the number of events in order to improve the statistics of their results. Each event has a probability to occur described by its cross-section. In colliders, this cross-section can be linked to the probability to observe an event through a proportionality factor depending of the beam parameters called the "Luminosity" [13]. To maximise the luminosity at the collision points, triplets quadrupoles are placed around them to manipulate the beam parameters. They reduce the beam emittance, i.e. the area of position-and-momentum phase space occupied by the charged particles of the beam. Indeed, a decrease in emittance induces an increase in luminosity. These triplets quadrupoles are then a key element of the High-Luminosity upgrade of the LHC (HL-LHC) [14].

Sections P3 and P7 are "cleaning zones" where collimators are placed close to the beam to remove the halo, i.e. the part of the beam with too-large momentum offset or too large transversal oscillations. It helps to improve the beam quality for the experiments.

The accelerating RF cavities are located in section P4. The target energy for the protons was 7 TeV in the design of the LHC. In reality, the highest energy reached is 6.8 TeV in 2023. The performances of the LHC are continuously improved to increase this maximum energy. The number of bunches inside the machine also evolved over the years to reach 2556 bunches in 2023. The stored energy inside one beam is given by Eq.(2.1) with the initial value of particles per bunches, $N_{p+/bunch} = 1.8 \cdot 10^{11} p^+$ for the third LHC run.

$$E_{beam} = E_{p+} \cdot N_{p+/bunch} \cdot N_{bunches/beam} \quad (2.1)$$

The two beam dumps located in section P6 consist into an extraction line that brings the beam directly into a large block of graphite. It is the most activated place at CERN and also the only one able to collect the total energy stored in one beam. The beam is extracted from the LHC voluntarily when it no longer has the qualities required for the experiments or when the protection system is triggered. Indeed, the beam and all the devices are permanently monitored to avoid failure and device damage.

To reach the level of energy required by the physicists inside the LHC, the magnets have to be superconducting (see Section 2.4) and so the equipment have to be maintained at cryogenic temperature. All the devices (the vacuum chambers, the alimentation cables, the superconducting electromagnets, certain monitoring systems, etc.) are placed together in cryomodules that are then assembled, taking into account the thermal expansion of the materials. The proximity of the different elements is visible in Figure 2.5 that shows the section of a LHC dipole cryomodule.

More details about the LHC design can be found in Ref.[12] but the key values of the LHC (HL-LHC) that are of interest to this thesis are given in Table 2.1. The mean beam parameters have evolved for the different runs. The detailed evolution over the years can be seen in Figure A.1 in the Appendix.

Table 2.1: Key values of the LHC and FCC-hh design.

	LHC					FCC-hh
	Geometry					
Circumference (m)	26 658.883					~ 91 000
Bending radius (m)	2803.95					10 660
	Beam parameters					
	Design	Run 1	Run 2	Run 3	HL	Design
Injection energy (GeV)	450					3300
Collision energy (TeV)	7	4	6.5	6.8	7	50
$N_{bunches/beam}$	2808	1380	2556	2556	2760	10 400
$N_{p+/bunch}$ ($10^{11} p^+$)	1.15	1.7*	1.25	1.8	2.2	1.0
Stored energy _{/beam} (MJ)	362	≈ 150	≈ 330	≈ 500	680	8300

* This value have been reached for a different bunch spacing in the machine: 50 ns compared to 25 ns in the next runs.

2.3.2 Values from the current FCC-hh design

The Future Circular Collider (FCC) will be approximately 91 km circumference and will be positioned next to the current CERN complex. In FCC-hh, the target centre of mass energy collision is 100 TeV. It is still under design but the main parameters are already approximately known [3] as they correspond to the physicist requirements. The exact values will possibly change until the final feasibility report. The values for FCC-hh from the 2019 design report are given in Table 2.1. A comparison of the energy stored per beam in the FCC-hh (8.3 GJ) and in the LHC (362 MJ at design) highlights the need for reliable protection systems.

2.4 Superconducting accelerator magnets

In very high-energy accelerators as the LHC, the magnetic field needed to bend the particles beam is very large. The relation between the momentum (p) of the particles, the arc radius (ρ) and the bending magnetic field (B) is the rigidity of an accelerator (Eq.(2.2)) [13].

$$\frac{p}{q} = (B\rho) \xrightarrow{\text{"Natural" Units}} \frac{p[\text{GeV}/c]}{q[e]} \approx 0.3 B[\text{T}] \rho[\text{m}] \quad (2.2)$$

When a new accelerator is designed, the momentum is fixed by the needs of the physicists. Multi-parameters optimisation calculations are then made to find the right values for the magnetic field and the radius. As the accelerator cannot be as large as we want, the best technology possible is used for the magnetic field generation. Using the design data of Table 2.1 in Eq.(2.2), the LHC bending magnetic field is found to be $B_{LHC} = 8.321$ T at collision energy.

To reach this type of magnetic field, superconducting magnets are required as iron dominated resistive magnets are limited to 2 T magnetic field [15]. The magnets used in the LHC are made of Niobium-Titanium (Nb-Ti) cables, a Low-Temperature Superconducting material (LTS). They are cooled by superfluid helium and operated at 1.9 K. The LHC dipoles deliver a magnetic field of 8.33 T. Their section is schematised in Figure 2.5 [16]. The main LHC quadrupoles are made with a similar structure and the magnetic field at the centre is 7.5 T.

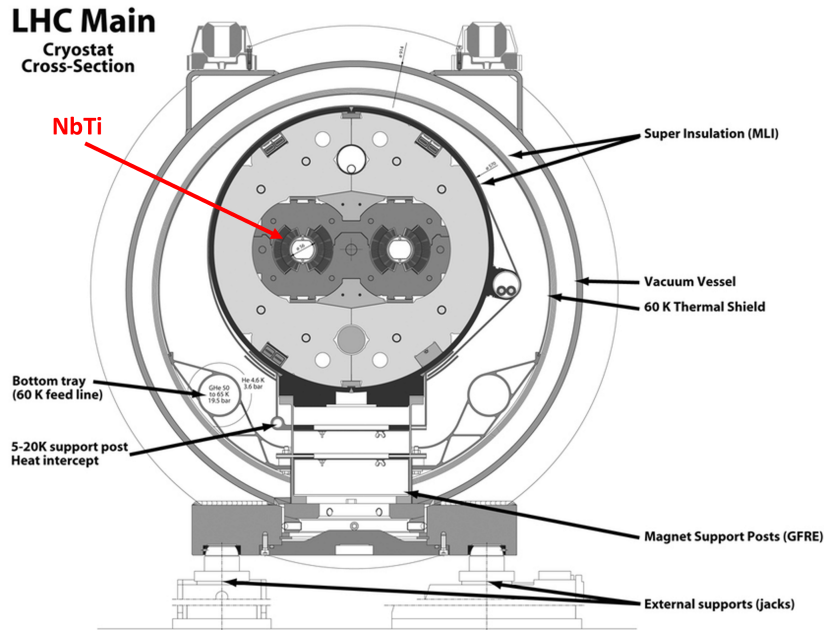


Figure 2.5: Schematic representation of an LHC superconducting dipole section. The Nb-Ti cables are visible around the two vacuum chambers. Adapted from Ref.[16].

The future accelerators will need even stronger magnetic field for their operation. For FCC-hh, the required magnetic field is double compared to the LHC. Using values from Table 2.1 in Eq.(2.2) the bending magnetic field B_{FCC-hh} has to worth 15.63 T.

It is a key challenge for the design and different options are explored. Nb-Ti does not meet the required properties for these new magnets and other superconducting materials have to be used (see Figure 2.7). The main candidate is Nb₃Sn, a LTS material used for the new triplet quadrupoles for HL-LHC. Studies are also made on High-Temperature Superconductor (HTS) to make an insertion in addition to the Nb₃Sn to produce 20 T magnetic field [17]. An example of the section of these types of magnet is shown in Figure 2.6. As part of the EuCARD2 project, a 5 T HTS insertion magnet, Feather-M2, has been designed and constructed to study HTS in detail [17].

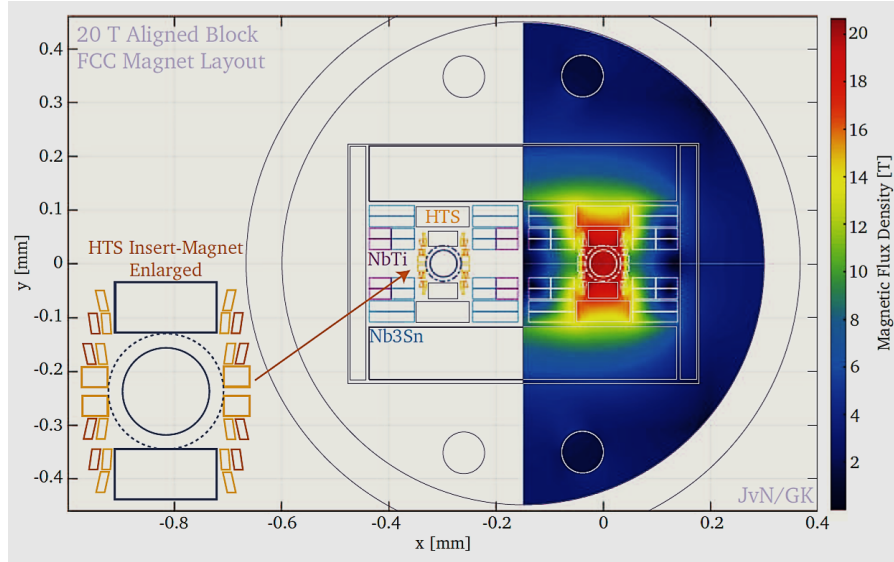


Figure 2.6: Design of a 20 T HTS insertion magnet made as part of the EuCARD2 project. The magnetic field is represented in the right side of the figure. Reproduced from Ref.[17].

The evolution of the utilisation of the different superconducting material and their limitation [18] are illustrated in Figure 2.7. It is important to notice that stronger magnetic fields already exist but the field has to be of really high quality and the FCC-hh will require thousands of magnets all along the 91 km of its circumference.

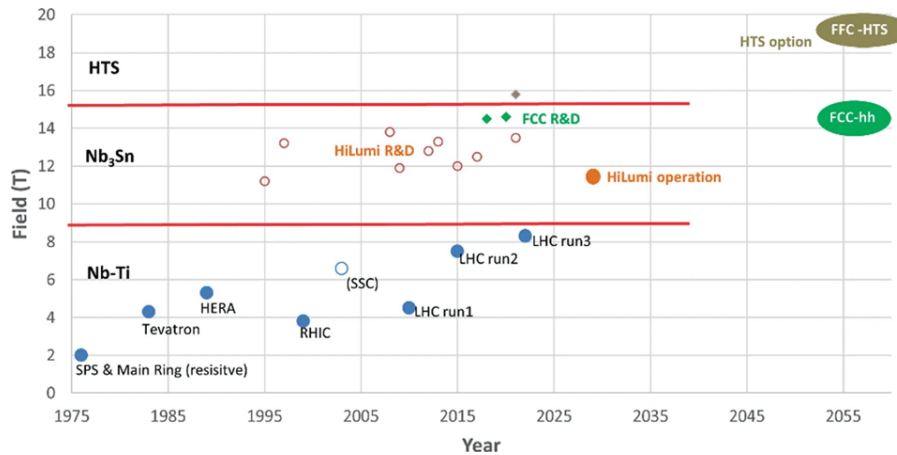


Figure 2.7: Illustration of the evolution of the superconducting magnet technologies. Year after year the magnetic field reached is higher. The material limitations are clearly visible and justify the large research made on novel superconducting materials for future accelerators. Reproduced from Ref.[18].

2.5 Operation failure and machine protection systems

During the operation of an accelerator, particle losses always occur. These steady beam losses are taken into account for the accelerator design. Failure scenarios also lead to particle losses and energy deposition. The failure that can occur in the LHC have been studied and different machine protection systems are used to prevent them or their consequences. Details of this study can be found in Ref.[19]. The different type of failures (detailed in the following) are classified according to the time constant of the loss in Table 2.2.

Table 2.2: Classification of the different beam loss failure in the LHC according to their duration [19].

	One-turn failure	Multiturn failure		
Type of losses	Ultra-fast	Very fast	Fast	Slow or Steady
Constant of time	89 μ s	< 5 ms	> 5 ms	≥ 1 s

To prevent harmful consequences of steady beam losses, one solution used is to select materials that are resistant to activation. The slow losses can be detected observing the heat load on the collimators and can lead to beam dump if a too-high level is observed for a long time. These slow losses can be dangerous if they are just below the beam dump threshold and can induce superconducting magnets quench or damage in the worst case.

The fast failures are monitored by the beam loss monitors (BLM) and they are long enough to protect the machine by dumping the beam. They may be due to the loss of hardware systems. For the very fast failure, protection systems (collimators, absorbers, etc.) [20] are used to prevent the damage and the beam dump is due to BLM triggering around those systems.

The ultra-fast losses are due to misfiring of fast-kicker magnets. It can happen at the injection, at the extraction or for all other fast kicker magnets. To prevent it, the beam quality is closely monitored at the extraction from the SPS. The consequences could be destructive as the stored energy in one LHC beam, 362 MJ at the design, can melt 540 kg of copper. Passive protection systems are used to counterbalance the consequences in case of such an accident. Nevertheless, energy deposition in surrounding magnets may happen as detailed in the example below.

2.5.1 LHC injection failures

The two LHC vacuum chambers are filled with protons coming from the SPS. Two injection lines visible in Figure 2.3 are used for the transfer. Large kicker magnets deviate the beams for the extraction from the SPS and the injection inside the LHC. Those magnets are electromagnets that have to be fired at the right moment with the right voltage to create the appropriate deviation. In case of wrong actuation, the beam is deviating out of the reference trajectory.

A study carried out during the design of the LHC showed that 450 GeV protons have an energy ten times greater than that needed to melt the surrounding materials [21]. In consequence, different machine protection systems have been implemented to protect the devices from a direct interaction with the beam.

For the protection of the superconducting magnets, absorbers are placed after the kicker magnet to absorb the potential deviated beam. The actual situation is schematically shown in Figure 2.8. In case of failure, the protons that hit the absorbers will induce secondary particle showers. Those particles can reach the upstream superconducting magnets. The energy deposition can lead to a quench of the superconducting magnet or to irreversible damage.

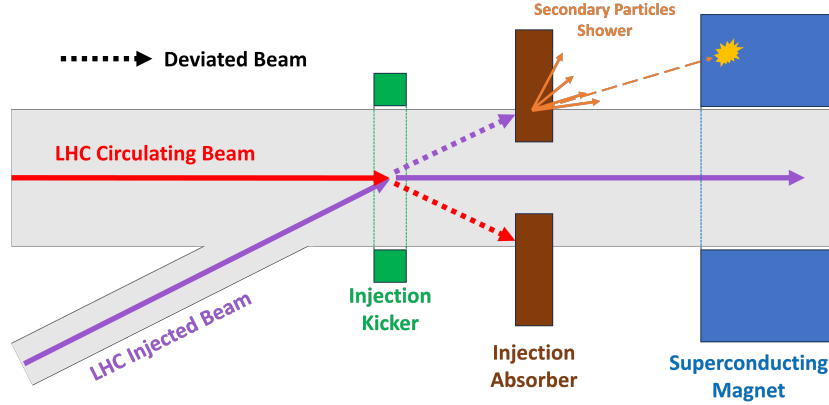


Figure 2.8: Schematic representation of the failure in the injection zone due to misfiring of the kicker magnet. Either the circulating beam is deflected, or the injected beam is not kicked or is badly kicked. In both cases, it hits the absorbers. A shower of particles is induced and the secondary particles reach the superconducting magnets, leading to quenching or damage. Adapted from Ref. [22].

2.6 Beam-matter interactions and energy deposition mechanisms

The interaction of particles with matter which can lead to energy deposition is a complex phenomenon because it depends on several parameters: the nature of the incident particles and their energy, the nature of the crossed material, the type of interaction, etc. There are many books on the study of particle-matter interaction, but reading A. Lechner's work (Ref. [23]) allows to concentrate on a part of the theory that concerns accelerator context. The part of his work that is relevant to this thesis is taken up in the following.

2.6.1 Cross-section and mean free path

Two key elements, the cross-section and the mean free path, related to particle-matter interactions are needed for the comprehension of the high-energy phenomena. The microscopic cross-section, $\sigma = \sigma(E, Z, A)$, describes the probability of the incident particles of energy E to interact with an atom with atomic number Z and a mass number A . It is often expressed in barn ($1b = 10^{-24} \text{cm}^2$) and interpreted as the effective area of a collision. Each mechanism of interaction has a different cross-section. The occurrence of the different mechanisms is determined by comparing their cross-section values. The mean free path λ is the mean distance between two interactions characterised by the cross-section σ on a material with a density of atoms N and is described by Eq. (2.3).

$$\lambda = \frac{1}{N\sigma} \quad (2.3)$$

2.6.2 High-energy particles shower

The Coulomb interaction of charged particles with matter is the main mechanism leading to energy deposition. For particles with an energy regime of the order of a GeV or more, as in high-energy colliders, their interactions with matter are described by the creation of a cascade of secondary particles, known as a "particle shower".

Electromagnetic shower

If the incident particles are high-energy electrons (positrons) or high-energy photons, the created showers are electromagnetic. These showers are characterised by an alternation between the creation of electron-positron pairs due to the interaction of high-energy photons with matter, and the production of photons via bremsstrahlung, which is the dominant mechanism for high-energy electrons (positrons). A schematic representation of the electromagnetic shower is shown in Figure 2.9a.

The energy of the particles decreases after each interaction and the cascade stops when the energy of the particle is too small ($E < E_c$). Below the critical energy E_c , the dominant phenomena are ionisation or excitation.

The longitudinal development of an electromagnetic shower X is the depth reached inside the material at the moment particles reach their critical energy. In the simplified model from Heitler, it is characterised by the energy of the incident particle E_0 , the critical energy E_c and by the radiation length X_0 , according to Eq.(2.4).

$$X = X_0 \cdot \log_2 \left(\frac{E_0}{E_c} \right) \quad (2.4)$$

The radiation length X_0 depends of the material and is expressed in g/cm^2 . It is the average distance required to reduce the energy of high-energy electrons (positrons) by a factor $1/e$. It can be approximated by Eq.(2.5) in which Z is the atomic number of the material, A the mass number and ρ the material density.

$$X_0 \cdot \rho = 716.4 g/cm^2 \cdot \frac{A}{Z(Z+1) \ln(287/\sqrt{Z})} \quad (2.5)$$

The radiation length also characterises the penetration of high-energy photons in matter. In high-energy regime, the pair production cross-section can be expressed as Eq.(2.6) [24]. The radiation length corresponds approximately to 7/9 of the mean free path of high-energy photons in the material.

$$\sigma_{pair} \approx \frac{7}{9} \frac{M}{\rho N_A X_0} \Rightarrow X_0 \approx \frac{7}{9} \lambda_{pair} \quad (2.6)$$

The transverse development of an electromagnetic shower is described by the Molière radius R_M which corresponds to the average radial deviation travelled by a particle while it moves of a radiation length X_0 . The value of R_M is given by Eq.(2.7) in which α is the Sommerfeld constant ($\alpha \approx 1/137$) and $m_e c^2$ is the electron mass.

$$R_M = \frac{\sqrt{4\pi\alpha m_e c^2}}{E_c} X_0 \approx \frac{21 \text{ MeV}}{E_c} X_0 \quad (2.7)$$

It is a good approximation to consider that 90% of the energy is deposited in a cylinder of radius R_M around the beam if the beam size is significantly smaller than R_M .

Hadronic shower

If the incident particles are high-energy hadrons, the most probable mechanism of particle-matter interaction is inelastic nuclear collision. These collisions lead to the creation of new particles as neutrons, protons and charged or neutral pions. A non-negligible part of the energy of the incident particle is lost in the breakdown of the binding energy, the recoil energy or through the emission of neutrinos which are not detected. The rest of the energy is given to the new particles. Created hadrons that are sufficiently energetic will induce new steps to the shower. A schematic representation of the hadronic shower is shown in Figure 2.9b.

Each particle interacts with matter following its own type of interaction but always losing a part of their energy. It is important to notice that neutral pion π^0 will decay in two photons that can induce electromagnetic showers. It means that in hadronic showers, a part of the energy is deposited via electromagnetic shower mechanisms. Higher is the incident particle energy, larger is the fraction of the energy that is deposited via electromagnetic shower.

The hadronic shower longitudinal development is described by the inelastic scattering length λ , the mean free path of the inelastic nuclear scattering. For a higher energy incident particle, the position of the shower maximum increases logarithmically and the transverse distribution remains the same.

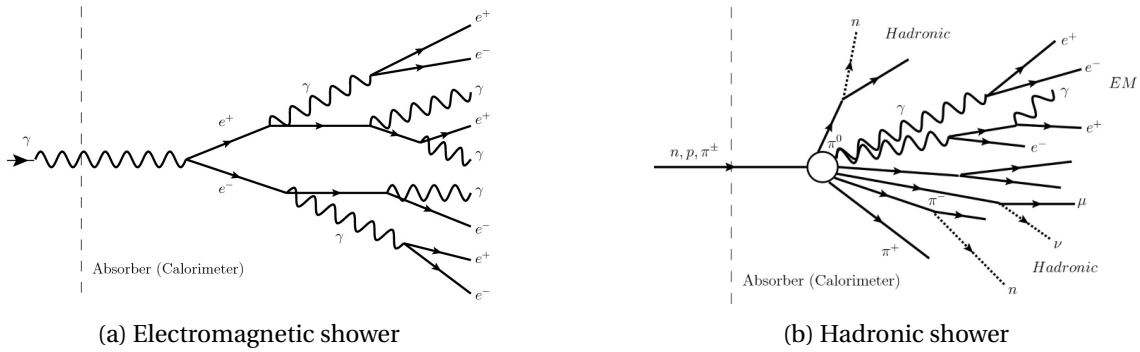


Figure 2.9: Schematic representation of the secondary particles shower induced by the interaction of a high-energy particle with matter. The electromagnetic shower (a) can be induced by high energy photons or high energy electrons (positrons). The hadronic shower (b) is induced by high energy hadrons (p , n , $\pi^\pm$). Reproduced from Ref.[25].

2.6.3 Simulation of the energy deposition

Monte Carlo simulations are used among others to study the interaction of high-energy particles with matter. For this particular application of Monte Carlo simulations, pseudo-random number generators are used to determine the probability of a given interaction. For each incident particle, a history is conducted

including the generation of secondary particles. Physical quantities as deposited energy or dose can be estimated by taking the average over histories of a significant number of incident particles. The statistical aspect of the simulation has to be taken into account and the error associated to the histories has to be minimised to guaranty reliable physical quantities.

Different Monte Carlo codes have been developed to simulate beam-matter interactions, e.g. FLUKA [26] or BDSIM [27]. Beam Delivery SIMulation (BDSIM) is the only code that allows to do particles tracking and particle-matter interactions simulations. The simulations can be done using beamline and classic accelerator components but also non-standard components as used in this thesis. For the particle-matter interaction, the particle trajectories inside matter are computed considering the interaction process through the C++ libraries Geant4 [28]. Complex geometry design can be provided through GDML (Geometry Description Markup Language) file and the results are given in ROOT format [29].

2.6.4 Comparison of energy deposition for different incident particles energy

The study of the energy profile deposited inside a copper block for different incident proton energies is an example of a study that can be carried out using Monte Carlo methods. It has been made by Y. Nie in Ref.[30]. FLUKA simulations have been performed for incident protons of 50 MeV and 50 TeV that target a cylinder of copper of radius around 1 cm and a length of a meter order of magnitude depending on the energy and the beam size. The 2D energy distribution obtained for a rms beam size of $\sigma = 0.2$ mm and incident energies of 50 MeV (a) and 50 TeV (b) are shown in Figure 2.10. For low-energy protons, the Bragg peak characteristic of their interaction with matter is clearly visible. In contrast, it no longer appears for high-energy protons and the deposited energy after the maximum is significant.

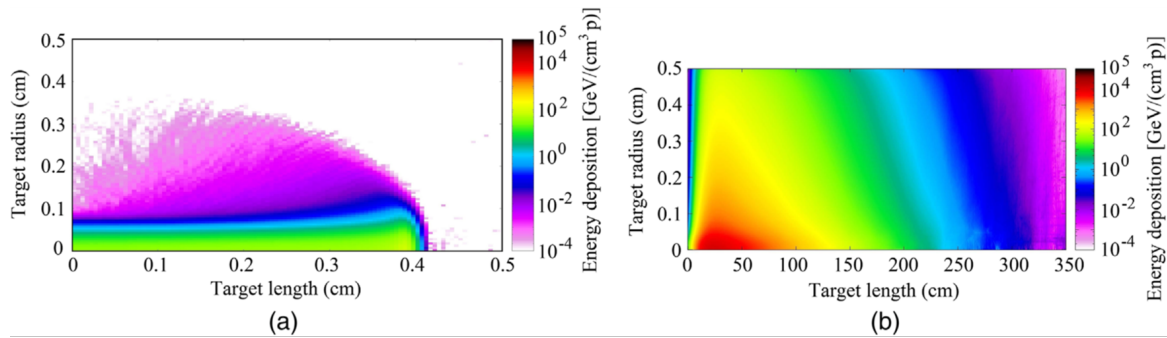


Figure 2.10: 2D representation of the energy deposited in a copper cylinder by a proton beam of size $\sigma = 0.2$ mm. For 50 MeV protons (a), the Bragg peak characteristic of their interaction matter is visible. For 50 TeV protons (b), it is no longer visible and there is a significant energy deposition after the maximum. The target length and the energy scaling are different in (a) and (b). Reproduced from Ref.[30].

The 2D representation (Fig.2.11) from Ref.[23] illustrates the difference of longitudinal and radial development as a function of the inelastic scattering length of the hadronic shower induced by 70 GeV and 7 TeV protons in copper. This representation shows clearly that the energy is deposited in similar development for the different incident energies.

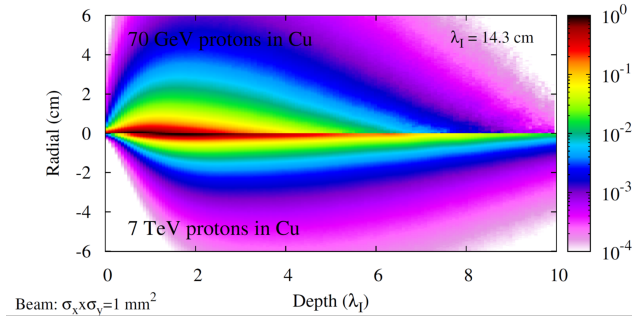


Figure 2.11: 2D representation of the longitudinal and radial development of hadronic shower for 70 GeV and 7 TeV incident proton beams in copper. The energy is normalised by the maximum deposited energy. Reproduced from Ref.[23].

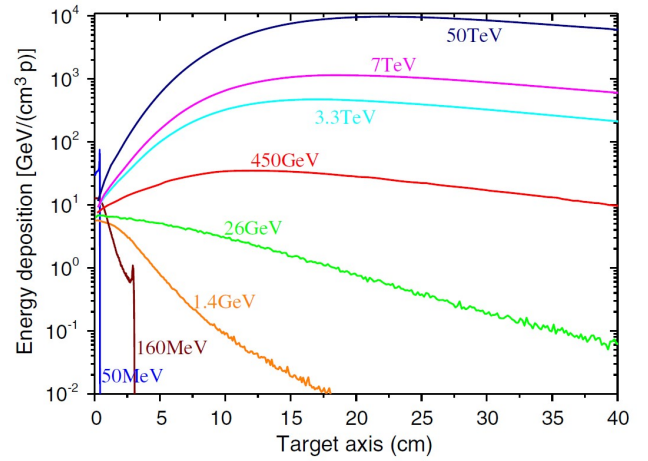


Figure 2.12: Representation of the deposited energy as a function of the depth on a copper cylinder. The incident proton beams have different energies and a fixed beam size of $\sigma = 0.2$ mm. Reproduced from Ref.[30].

In Ref.[30], Y. Nie also compares the energy deposition profile along the beam trajectory for more different incident energies in the same condition as for the 2D representation of Figure 2.10. Figure 2.12 shows that the values of energy deposition inside the material for incident particles which the energy is higher than 450 GeV behave the same. Already for energy above 1.4 GeV, the Bragg peak is not present anymore and the amount of deposited energy depends mainly of the quantity of crossed material.

These different studies make it possible to determine the energy deposition profile inside a material for different proton beams. For higher energies, at least above 450 GeV, it shows that the mechanisms and energy deposition profile remain the same. This means that the damage studies carried out with the SPS proton beam at 440 GeV can be used to study the energy deposition profile for higher-energy beams such as those from the LHC or the FCC-hh. The absolute values simply need to be scaled to the energy of the incident particles. Knowing that, experimental damage studies can be done with SPS beam to conclude about damage mechanisms that occur in high-energy colliders.

2.7 Damage studies campaign

In order to protect the accelerator, it is important to understand the mechanisms that occur when the beam interacts with matter whether intentionally or accidentally. Different studies are made at CERN to improve the knowledge on damage mechanisms that can occur in case of energy deposition. Some studies are made on the hydrodynamic tunnelling effect which appears in the graphite of the dump if all the beam is sent to the same place [31, 32]. A lot of research is made on the collimators that interact directly at the proximity of the beam [9]. This thesis is part of a large study made on superconducting material in order to have a better prediction of the superconducting magnets quench and to protect them from irreversible damage due to energy deposition.

The use or non-use of equipment after a failure can be determined if the damage limits are known. It can save time for post-failure actions and ensure the safe operation of the accelerator. These damage limits are also essential for the design of machine protection systems. CERN therefore decided to dedicate a budget for materials and damage studies and different facilities have been built to study the effect of particle-matter interaction, including the HiRadMat facility.

2.7.1 The HiRadMat facility

The "High-Radiation to Materials" (HiRadMat) facility is a CERN experimental area dedicated to beam-matter interaction studies. It opened in 2011 with the idea to carry out experiments for research linked to HL-LHC research [33]. This unique facility provides proton or heavy ion beams extracted from the SPS for high-energy beam impact experiments (see Figure 2.3). The beams normally produced to fill the LHC are deliberately lost for the purpose of these studies.

The idea is to have a flexible installation that allows different experimental devices to be placed inside the tunnel to be impacted by the beam. The beam energy is fixed at 440 GeV for protons but the number of bunches and their intensity can be defined according to the objective of the experiment. For more details on HiRadMat, see Ref.[33, 34].

2.7.2 The main stages in the superconducting materials damage studies campaign

The machine protection group at CERN is responsible for the campaign to study damage to superconducting materials, which began in 2015 and is still ongoing. The goal is to damage the materials using different energy sources and then study the level of degradation of their superconducting properties and the mechanisms behind this degradation.

The study focusses on three superconducting materials, two LTS (Nb-Ti and Nb₃Sn) and one HTS (ReBCO) which are used in actual accelerator magnets or will potentially be used in the next generation of magnets. The main information about those materials are compiled in Table 2.3. Inside the magnets, Nb-Ti is protected by an insulator (polyimide tape) which it is also studied in an experiment of the campaign.

Table 2.3: List of the superconducting material used in the damage study campaign. The basic information concerning the material, their uses in accelerator or potential uses are given. The format in which they have been studied is specified.

	Name	Type	Use (<i>under study</i>)	Studied form
Nb-Ti	Niobium-Titanium	LTS	LHC magnets	Insulated cables Strands Coils
Nb₃Sn	Niobium-Tin	LTS	HL-LHC quadrupole triplets <i>FCC-hh magnets</i>	Strands Coils
ReBCO	Rare-earth Barium Copper Oxide	HTS	<i>Insertion on FCC-hh magnets</i>	Tape

The different experiments that have been conducted on the materials are presented on Table 2.4. The type of experiment, the source of the deposited energy, the time-scale and the aim of the experiment, the studied material and the main conclusions are given. The timeline of the different experiments and the current status are shown in Figure 2.13.

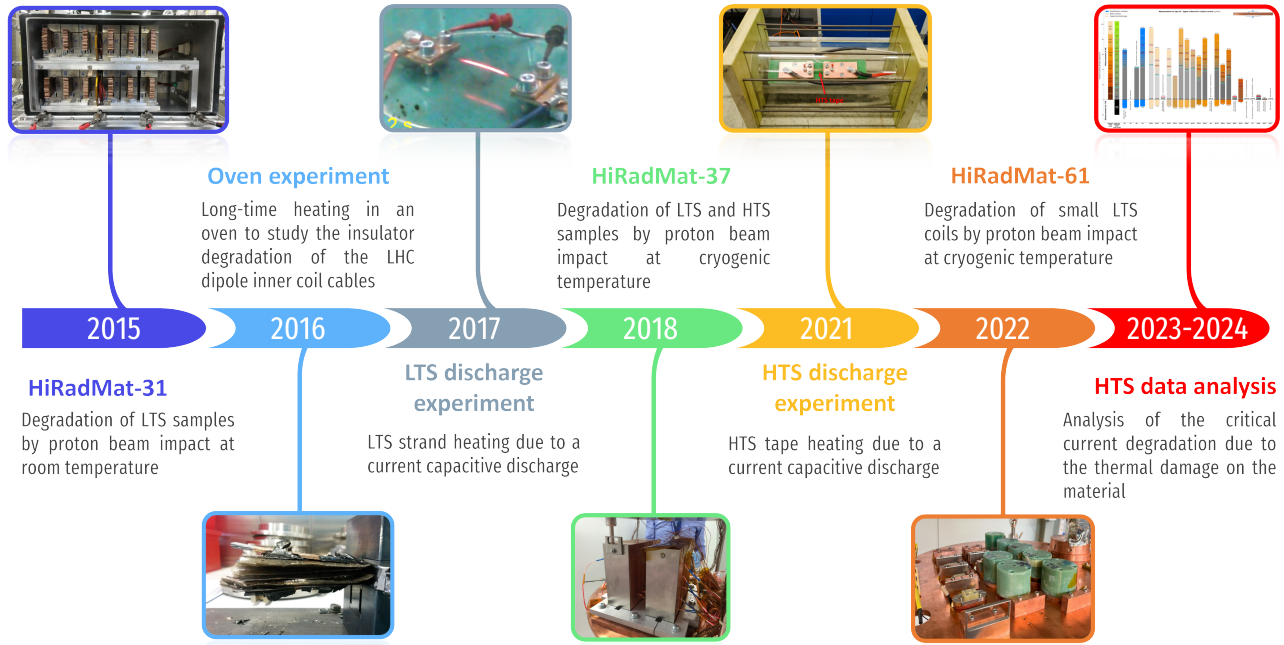


Figure 2.13: Timeline of the experiments of the superconducting material damage study campaign. The experiments made on HTS samples and studied in this thesis are the HiRadMat-37 experiment done in 2018 and the discharge experiment done in 2021. The other experiments concerns the study of other superconducting materials and their results can be found in Ref. [1, 2, 42, 43].

2.8 Damage experiments on High-Temperature Superconducting material

In this thesis, the two experiments carried out on HTS samples, the HiRadMat-37 experiment and the discharge experiment, are analysed. These experiments are designed to induce different energy depositions on HTS samples in order to reproduce realistic failure scenarios. The damage limits are then drawn from the critical current degradation post-damage as detailed in Chapter 6.

2.8.1 HiRadMat-37, the beam-impact experiment

The beam-impact experiment called HiRadMat-37 reproduces the consequences of a fast failure scenario involving beam losses in magnet aperture. To simulate real superconducting magnet configuration during the experiment, the HTS samples are arranged inside a copper sample holder placed inside a cryostat to maintain cryogenic temperatures.

After the beam impact itself, to be able to study the results of this experiment, the exact conditions of the experiment as the beam trajectory have been analysed. In Chapter 5, a brief overview is made of

the design of the experiment and the post beam-impact analysis. From these data, BDSIM simulations are computed to calculate the energy density deposition inside the samples. Then the damage level is translated into a "hotspot temperature" representative of the thermal damage on the samples.

2.8.2 The discharge experiment

To analyse the effect of a longer time-scale energy deposition (a few hundred milliseconds) and a different energy deposition mechanism, another type of experiment is required. The solution is to use the heat generated by Joule effect of a resistive material. At ambient temperature, the HTS samples are indeed resistive. To have a relatively high heat generation during a limited period of time, a current discharge is made in presence of an inductance to control the duration.

The design and the experimental procedure of this discharge experiment are described in Chapter 4. In order to analyse the thermal damage on the studied samples, the details of the experiment modelling are exposed.

Table 2.4: Description of the experiments in the CERN machine protection group campaign to study damage to superconducting materials.

	Type	Time-scale	Studied material	Detail of the experiment	Publication
HiRadMat-31	Beam-impact experiment at the HiRadMat facility	Several hundreds of nanoseconds	Stacks of insulated Nb-Ti cables under pressure, Nb-Ti and Nb ₃ Sn strands	It studies the damages made by the impact of 440 GeV proton beams while the materials are at room temperature.	[1, 35]
Oven experiment	Heating inside an oven filled with Argon	Several hours	Stacks of insulated Nb-Ti cables under pressure	It studies the degradation of the dielectric strength of the insulator and its lost of weight.	[1, 36]
Discharge experiment	Resistive heating by current discharge	Seconds	Nb-Ti and Nb ₃ Sn strands, ReBCO tapes	It damages the samples by resistive heating to allow a comparison of the results of the HiRadMat experiments. The experiments are conducted at room temperature.	[1, 37] for LTS samples
HiRadMat-37	Beam-impact experiment at the HiRadMat facility	Several hundreds of nanoseconds	Nb-Ti and Nb ₃ Sn strands, ReBCO tapes placed inside a copper block	It studies the damages made by the impact of 440 GeV proton beams while the samples are maintained at cryogenic temperature inside a cryostat. It reproduces with more fidelity the conditions met in case of fast failure scenarios in the accelerator.	[2, 38–40] for LTS samples
HiRadMat-61	Beam-impact experiment at the HiRadMat facility	Several hundreds of nanoseconds	Nb-Ti and Nb ₃ Sn small coils	It studies the coils in conditions equivalent to those of HiRadMat-37 to identify a possible influence on the results of a different geometry and of the winding required to make the coils.	[41, 42]

High-Temperature Superconductors (HTS)

3.1 General overview of superconductivity

The superconductivity, discovered in 1911 by H. K. Onnes [44], is a particular state of matter in which a material presents zero electrical resistance and expulsion of magnetic fields below a critical temperature. It was first observed when, during a study of ultra-pure mercury resistance at very low temperatures, the electrical resistance rapidly dropped to zero when the temperature was just below 4.2 K. This newly discovered state of matter was then studied in detail and several superconductors have been identified including alloys and compounds. Studies have also shown that the superconductivity is preserved only if the material remains under limits of temperature, external magnetic field and flowing current, respectively named the critical temperature (T_c), the critical magnetic field (B_c) and the critical current (I_c). Detailed overview of superconductivity phenomena can be found in Ref.[45] and with an approach oriented towards accelerator magnet applications in Ref.[46]. Key elements about superconductivity are detailed in the following.

3.1.1 Classification of superconductors

By its discovery, H. K. Onnes highlights the superconductor dependency in temperature: the material enters in its superconducting state below a critical temperature T_c [44]. Soon after that, the dependency in the magnetic field has been identified [45]. This led to the classification of the superconducting materials in two groups: type I, mainly for pure metals and type II for a few pure metals (e.g. Niobium or Vanadium), alloys and compounds.

As illustrated in Figure 3.1a, starting from the state A, the material can lose its superconducting state both by increasing the temperature ($T > T_c$) or the magnetic field ($B > B_c$). This behaviour corresponds to a type-I superconductor. Below B_c , it is in a superconducting state described by the Meissner effect, i.e. the expelling of the magnetic field out of the material. Above B_c , the material is back in its normal state. The behaviour of a type-II superconductor is more complex as shown in Figure 3.1b. Two critical magnetic fields are used to qualify the material, B_{c1} and B_{c2} . Below B_{c1} , the dominant effect is the Meissner effect as for type-I superconductors. Between B_{c1} and B_{c2} , the material is in a mixed state but is still superconducting. A higher magnetic field ($B > B_{c2}$) induces a return to normal state.

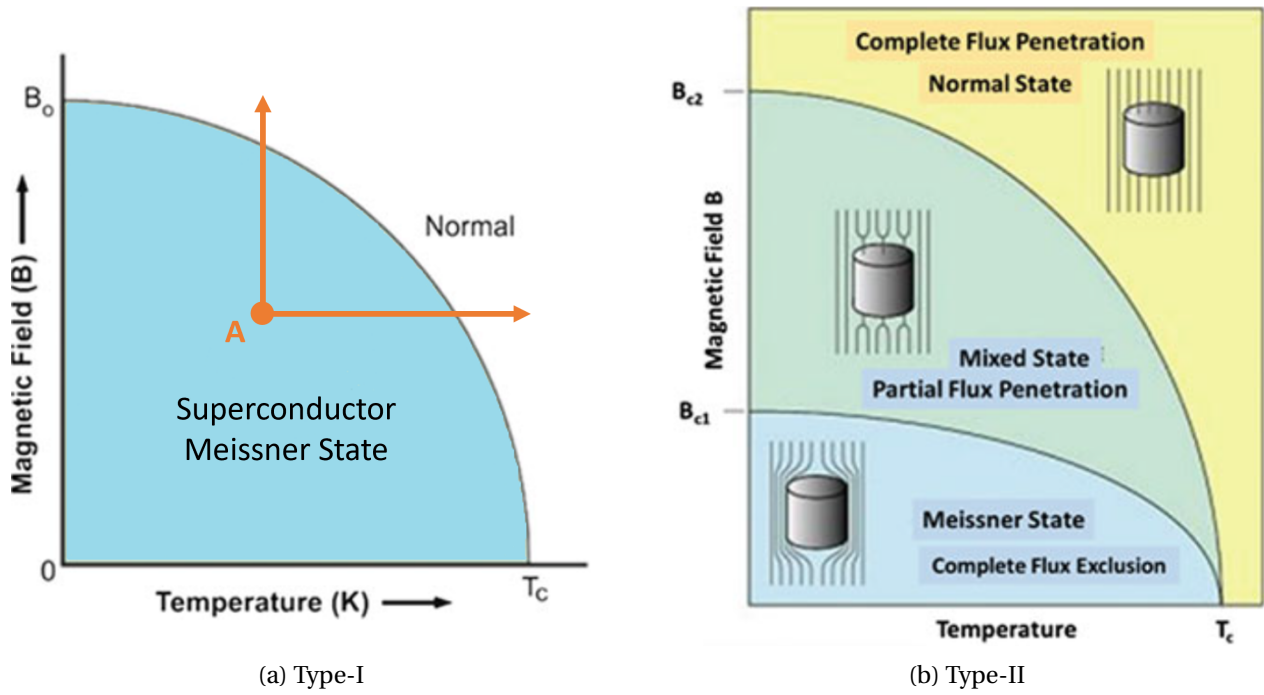


Figure 3.1: Magnetic phase diagram of type-I and type-II superconductors. Type-I is characterised by the Meissner effect. Too large increase in magnetic field or in temperature from a superconducting state, e.g. state A, results in a return to normal state. For type-II, under B_{c1} , the material is in Meissner state. Between B_{c1} and B_{c2} , the material is in a mixed state. Above B_{c2} , the material loses its superconductivity. Adapted from Ref.[45].

Another classification of the superconducting material can be done considering their critical temperature [45]. The superconductors that have to be cooled down with liquid helium (4.2 K) are called Low-Temperature Superconductors (LTS). The ones that can be cooled down with liquid nitrogen (77 K) are called High-Temperature Superconductors (HTS).

3.1.2 Properties of superconducting materials

The Meissner effect

The Meissner effect [47] corresponds to the transition of a metal from paramagnetic material behaviour in normal state into a perfect diamagnetic material behaviour in superconducting state. Below the critical temperature T_c , for limited values of the magnetic field, the magnetic flux is expelled out of the material as illustrated in Figure 3.1b for a small cylinder.

To respect the Faraday's law of electromagnetic induction (Eq. (3.1)), a surface current appears at the surface of the superconducting cylinder. Indeed, when the material in presence of a magnetic field is cooled down and goes from its normal state to the superconducting state, the expel of the internal magnetic field creates a time variation of the magnetic field which is always linked to the induction of an electric field and so a current.

$$\nabla \times \mathbf{E} = -\frac{\partial}{\partial t} \mathbf{B} \quad (3.1)$$

This effect also appears if the material is cooled down before being exposed to the magnetic field. And the origin can be explained by quantum theory.

The Cooper pairs

Inside a superconducting material, the electrons are attracted together due to the lattice vibrations leading to the creation of electron pairs called Cooper pairs. The formation of Cooper pairs is explained by the Bardeen-Cooper-Schrieffer (BCS) theory [48].

These electron pairs behave as bosons and are then not subject to the Pauli exclusion principle. All the pairs can be represented by a single wave function. Due to these differences with single electrons, the Cooper pairs are able to move without resistance inside the material. They are then responsible of the surface current of the Meissner effect as this current requires no energy to be maintained.

The characteristic lengths

The diamagnetism that occurs in the Meissner state is not perfect and the magnetic field enters the surface of the superconductor. The magnetic field decays exponentially inside the superconductor with a characteristic length, the London penetration depth λ_L [49]. This length is given by formula (3.2) in which n_s is the Cooper pairs density, $q_s = 2e$ their charge, $m_s = 2m_e$ their mass and μ_0 the free space permeability.

$$\lambda_L = \sqrt{\frac{m_s}{\mu_0 n_s q_s^2}} \quad (3.2)$$

Another characteristic length is the coherence length ξ [50]. This length is related to the non-abrupt decay of the number of Cooper pairs at the interface of a superconducting material with a normal material. The coherence length depends of the temperature and the quality of the material. Both the coherence length and the London penetration depth are shown in Figure 3.2.

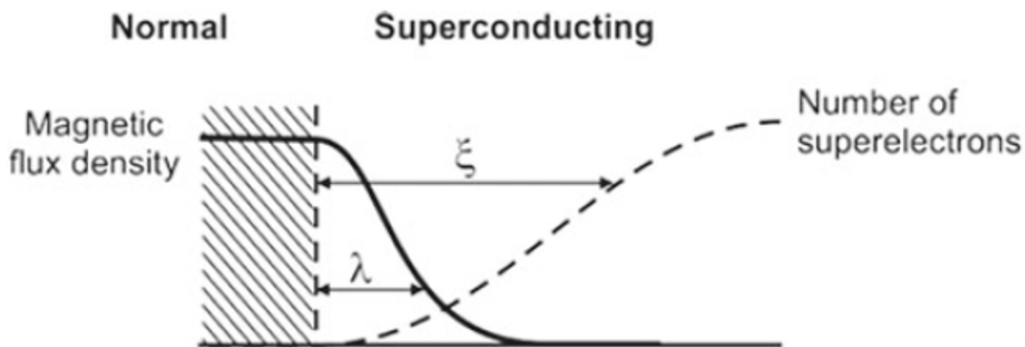


Figure 3.2: Representation of the characteristic lengths of superconductivity. The London penetration depth λ_L (λ in the Figure) characterises the exponential decay of the magnetic flux density inside the superconductor. The coherence length ξ characterises the decay of the number of Cooper pairs (superelectrons in the Figure) at the interface between normal state and superconducting state. Reproduced from Ref.[45].

The Ginzburg-Landau parameter, $\kappa = \lambda_L/\xi$, gives a criterion to distinguish the type-I and type-II superconductors [50].

$$\begin{cases} \text{type-I} : \kappa < 1/\sqrt{2} \\ \text{type-II} : \kappa > 1/\sqrt{2} \end{cases} \quad (3.3)$$

Mixed state

The mixed state of type-II superconductors that appears when the magnetic field is between B_{c1} and B_{c2} can be explained by a negative free energy at the interface between the normal and the superconducting state. This free energy is the result of two contributions: the energy linked to the electrons arrangement at the surface qualified by the coherence length ξ and the free energy linked to the expelled magnetic field qualified by the London penetration length λ_L . Inside the material, the two contributions cancel each other but at the surface, if $\xi \ll \lambda_L$, it results into a negative free energy.

In this case, it is energetically beneficial for the material to create interfaces between normal and superconducting states, leading to the creation of small vortexes, i.e. normal state insertion, inside the superconducting material [45]. Through each vortex goes a magnetic flux quanta $\Phi_0 (= h/2e)$ inducing a permanent current at its surface as illustrated in Figure 3.3. The size of the vortexes increases with the magnetic field until the upper critical value B_{c2} and the loss of the superconductivity.

Pinning forces

Type-II superconducting materials are known to carry out large currents. Nevertheless, a too large current induces the loss of the superconductivity. Indeed, while the current flows in the material, the vortexes that carry on their magnetic flux quanta Φ_0 experience a Lorentz force F_L perpendicular to the magnetic flux and to the current. This force will cause the flux lines to move, inducing a voltage and a resistance in the material. However, the crystal lattice also applies a reciprocal force to hold back the vortexes, called the pinning force F_p [45].

While F_L remains smaller than F_p , the flux lines are stationary. If the Lorentz force is too large ($F_L > F_p$), i.e. when a current density larger than the critical current density J_c flows inside the material, the flux lines move inducing resistance that finally brings back the material to normal state. This is the case in a material without any defect as the vortexes are free to move in the lattice. If the material has impurities and defects, the flux lines can accumulate and create pinning sites.

3.1.3 Hard superconductor for accelerator magnets

Type-II superconducting materials doped with impurities and defects are called hard superconductors. As they can carry on larger current density than other superconductors, they are used in high-field magnets [46]. Their condition of operation can be described by a critical surface as illustrate in Figure 3.4. This

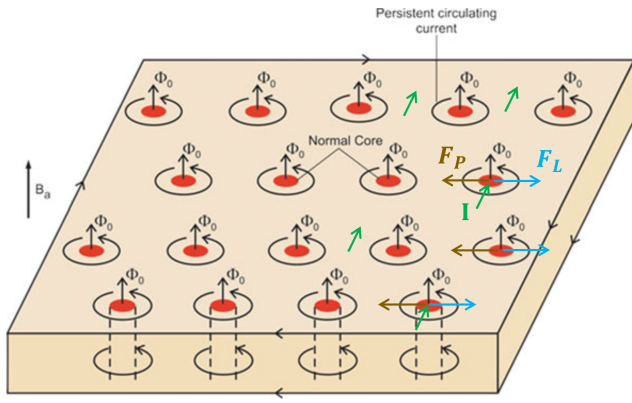


Figure 3.3: Representation of the mixed state on a type-II superconducting material. Small vortices carry on quanta flux line Φ_0 and persistent current are created around them. The current of the Meissner effect is still present due to the external magnetic field. The transport current I flowing inside the material induces Lorentz forces F_L . The lattice holds the vortices with pinning force F_p . Adapted from Ref.[45].

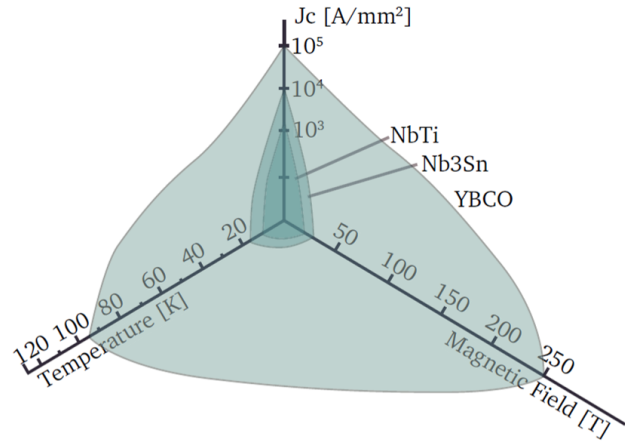


Figure 3.4: Critical surface of different superconducting materials (Nb-Ti, Nb₃Sn and YBCO). The three critical values are the critical temperature T_c , the critical magnetic field B_c and the critical current density J_c . Reproduced from Ref.[17].

surface can be mathematically described by a relation between the different critical values, i.e. a relation $I_c(B_c, T_c)$ or $J_c(B_c, T_c)$ with J_c the critical current density. This relation is unique for each material and depends of its exact manufacturing [51]. Studies are made to optimise the qualification process of the material by defining the minimum number of measurements required to qualify the critical surface and using scaling laws [52].

This qualification is more complicated for HTS materials because another parameter influences their superconducting properties. Indeed, HTS structure is highly anisotropic, which introduces an angular dependence of the orientation of the external magnetic field into the expression of the critical current density. In addition, the classical superconductivity theory as BCS cannot explain the HTS properties and different theories are currently considered [45]. Recent results for the characterisation of the critical current as a function of the magnetic field, the temperature and the angular orientation of the external magnetic field can be found in Ref.[53].

3.2 Qualification of superconducting materials by critical current measurement

In case of accelerator magnets, the critical current is the most important parameter about a superconducting material as it defines the maximum magnetic field they can produce. The critical current is then measured in an experimental setup as a function of the other critical values.

The methods used to measure the critical current are standardised and can be found for example in Ref.[54]. The method used to qualify the samples studied in this thesis is the transport method. The

principle is to measure the voltage through the material while a progressively increased current flows inside it. Indeed, when the current increases above I_c , an internal resistance R_{int} appears as a result of the flux lines motion due to too-high Lorentz force. The value of R_{int} is given by Eq.(3.4) in which R_c is the critical resistance (often defined by $R_c = \rho_c \cdot \frac{l}{A}$ with the critical resistivity $\rho_c = 10^{-14} \Omega m$), J the current density, J_c the critical current density and n that represents the abruptness of the transition. Details about this equation can be found in Ref.[46]. Once this internal resistance appears, the voltage which was initially zero starts to increase. This fast voltage variation is used to determine the critical current density J_c (or the critical current I_c).

$$R_{int} = R_c \left(\frac{J}{J_c} \right)^n \quad (3.4)$$

3.2.1 Setup for the critical current measurement

The measurements have been done in collaboration with the Applied Superconductivity laboratory of the University of Geneva [55]. Their experimental setup schematised in Figure 3.5 is typical for transport measurement of the critical current. The sample held by a sample holder is fixed at the extremity of a long device (image on the left top of Fig.3.5) placed inside a cryostat cooled with liquid helium and an electromagnet delivers the external magnetic field. The setup allows to do measurement at different temperatures and different magnetic fields depending of the study requirement. The temperature is controlled by sensors during the measurement. As the temperature naturally increases due to imperfect insulation, new liquid helium is introduced to keep the temperature at its target value. A similar setup is also cooled with liquid nitrogen for the measurements at higher temperatures. For HTSqualification, the measurements are often done at 4 K and 77 K as it corresponds to the temperatures encountered in practical applications with cooling using liquid helium or liquid nitrogen.

The current provided by a generator flows through the sample and the voltage is measured via different voltage taps. The sample holder used for the ReBCO tapes measurement studied in this thesis is shown in the bottom left image of Figure 3.5. Two pairs of taps have been used: tap-AB with an approximate length of 20 mm and tap-CD approximately 15 mm.

3.2.2 Determination of the critical current value

For each measurement done for a fixed temperature and fixed magnetic field, a voltage-current curve is obtained. Often the results are presented in terms of electric field E instead of voltage as they are proportional relatively to the distance between the voltage taps. An example of obtained E-I curve is shown in Figure 3.6. This curve can be described by Eq.(3.5) [54].

$$E = E_0 + k \cdot J + E_c \left(\frac{J}{J_c} \right)^n \quad (3.5)$$

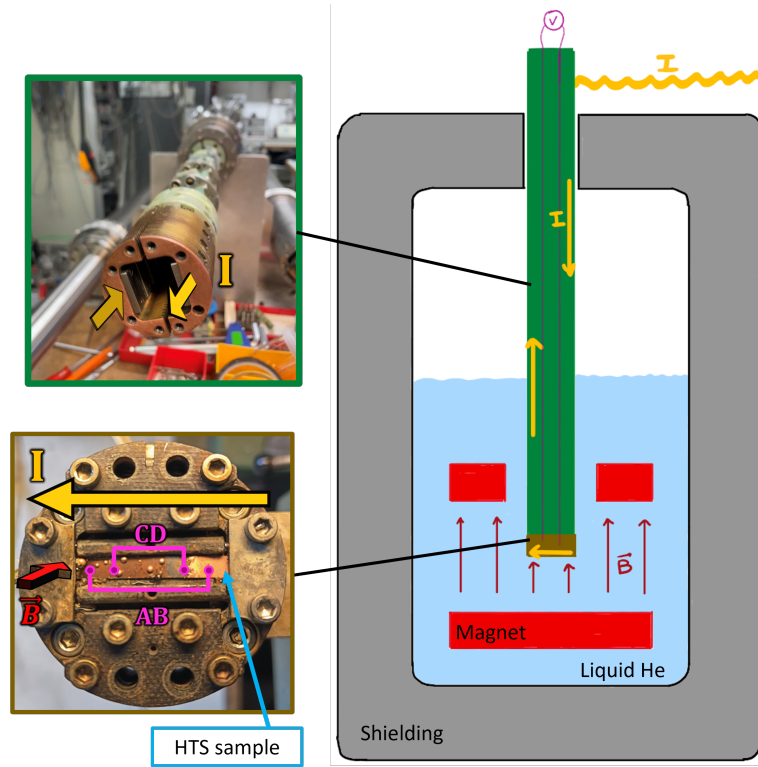


Figure 3.5: Overview of the experimental setup for the critical current measurement. The setup of the University of Geneva is schematised (right part). The cryostat is filled with liquid helium and an electromagnet provides a magnetic field. A long device connected to the current source and that carries on the different cables for the measurement (left top part) holds the sample holder (left bottom part) and is placed inside the cryostat. The current flows through the HTS tape and the voltage is measured by two pairs of voltage taps (tap-AB $\approx 20\text{ mm}$ and tap-CD $\approx 15\text{ mm}$).

The three contributions for the electric field E are respectively an offset due to the experimental setup (E_0), a resistive offset due to the resistance at the interface with the voltage taps ($k \cdot J$) and finally the contribution from the internal resistance ($E_c(J/J_c)^n$). The E-I curve clearly shows the behaviour of the material. For low current, it is perfectly superconducting and R_{int} is zero. When the current increases above I_c , the Pinning force is lower than the Lorentz force and the internal resistance appears leading to a rapid voltage rise. To avoid to damage the sample during the qualification, the current flow stops just after the quench of the superconductor. If the current had continued to increase, the slope of the E-I curve would have changed to follow an ohmic regime as the material would no longer be superconducting.

Different criteria exist to fix the value of the critical current from E-I curve [56]. Nevertheless, due to the thermal effect for measurement at 77 K, a simple voltage criterion is used. For the coherence between the different measurements, this criterion is also used for the measurement at 4 K. The critical current I_c is defined to be the current corresponding to an electric field of 10^{-6} V/cm for the upper criteria and 10^{-7} V/cm for the lower criteria [45]. The critical current density J_c is obtained from the current value considering only the section of the superconducting layer of the ReBCO tape. The engineering critical current density J_e , which is used when the results are applications oriented, is obtained by dividing the critical current I_c by the total section of the composite material [54].

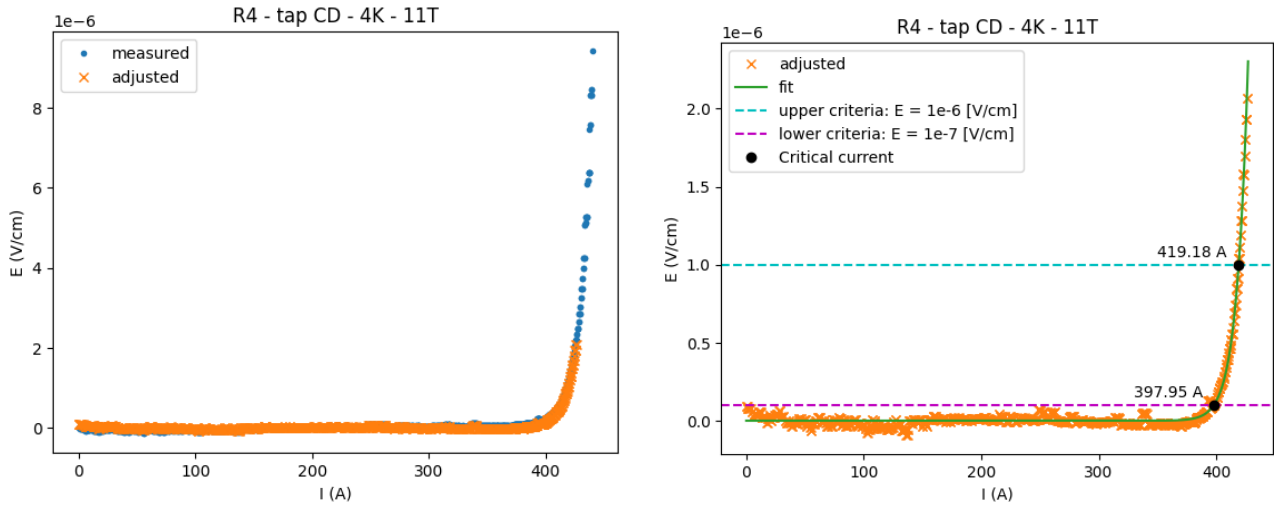


Figure 3.6: E-I characteristic of a critical current measurement. The left graph shows the measured values for the electric field with all the terms of Eq.(3.5) and the adjusted values which correspond to the internal resistance contribution. The right graph shows the fitted E-I characteristic and the two critical current criteria.

3.2.3 Procedure for the samples qualification

The measurements to qualify the HTS samples (described in detail in the next section) have been made at 77 K in self-field and at 4 K with an external magnetic field varying up to 19 T. Critical current measurements are always done in a way that the current flowing inside the tape increases to avoid to damage it by reaching too-high values. Measurements are taken first at 77 K, then at 4 K, starting with the highest external magnetic field and then decreasing.

For each measurement, the collaborators of the University of Geneva provide raw and analysed data. I decided to reanalyse the data to be confident on their meaning and to know how the values have been obtained. From that, the critical current values are determined using the voltage criteria for the different measurement conditions and voltage taps. Some samples have been qualified before any damage and are called reference samples. Their qualification is described in Section 3.3.2. The results of the qualification of the samples post-damage are detailed in Chapter 6.

Before detailing the results of the sample qualification, the studied HTS samples are described.

3.3 High Temperature Superconducting samples

The novel HTS material considered for FCC-hh magnets is the Yttrium Barium Copper Oxide (YBCO) of the ReBCO superconductor family. The discovery of superconductivity in YBCO or $Y_1Ba_2Cu_3O_{7-x}$ have been a revolution for the research in the domain [45]. Indeed, with a critical temperature of 93K, it leads to the possibility of cooling superconductor with liquid nitrogen instead of liquid helium. YBCO is part of the family of cuprate materials as BiSCCO, LBCO, etc. These materials are highly anisotropic which induces the magnetic field orientation critical current dependency. The first result of cuprate study indicates bad results

for current transport under magnetic field, due for example to the granularity of the materials. Research has been made and good results have been obtained for films and mono crystal structure.

This leads to the creation of HTS wires and ReBCO tapes that have been developed by different industries to meet the application requirements. The one studied in this thesis is a doubled-disordered YBCO (DD-YBCO) tape made by Bruker [57]. This multilayer tape (Fig.3.7) is based on a substrate layer made of Hastelloy (CrNi stainless steel), 50 μm to 100 μm thick and 4 mm or 12 mm wide. Then the substrate is coated with two layers, the YSZ layer and the CeO_2 layer. YBCO is then deposited via Pulsed Laser Deposition (PLD) to form the DD-YBCO layer. A silver layer is then deposited and the entire structure is plated with copper. Different modifications of the structure and fabrication technics are considered in Ref.[58] to improve the engineering critical current of the tapes for the magnet accelerator applications. Different tape compositions, as Roebel cables or round cables, are considered to create cables that can be used in the magnet design [17]. The performances of the Bruker tapes have been studied in detail and their critical current values under different conditions can be found in Ref.[52, 57, 58].

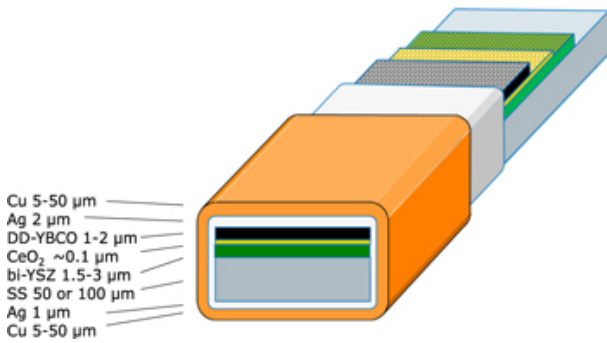


Figure 3.7: Schematic representation of the composition of the ReBCO tape provided by Bruker. Reproduced from Ref.[58].

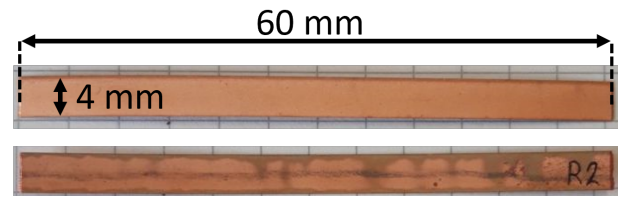


Figure 3.8: Overview of the HTS sample dimension. The bottom picture illustrates how the Hastelloy layer is marked by a black line.

3.3.1 Details about the studied samples

Bruker delivered a 3m long piece of tape labelled #Q037-18 based on a 95 μm Hastelloy substrate and 4 mm (with ± 0.1 mm tolerance) wide which was then cut into 6 cm long samples. The substrate side of the tape is marked to know the orientation of the superconducting layer (Fig.3.8). At delivery, the tape was qualified of good homogeneity in terms of critical current as the I_c distribution inside the tape has a deviation below 5%. Another piece from the same set has been qualified and the critical current at 4.2 K with an external magnetic field $B//c$ of 5 T worths 730 A.

The thickness of each material inside the tape is not exactly known. The values given by Bruker are in the first column of Table 3.1. During the analysis of an experiment, it has been required to know more confidently the total thickness of the tape. To do so, I measured some samples in collaboration with the CERN metrology service. It appears that the thickness varies depending on whether the measurement is taken over the full width of the tape or only partially. The values vary from 0.19 mm to 0.22 mm with a precision of a few micrometres.

For the simulation and the study of the material, fixed values have been taken for each material (second column of Table 3.1). For the simplicity of the simulation, the copper and silver layers on the side of the tape are ignored. The percentage indicates the proportion of the thickness of each material relatively to the total thickness. The tape volumic mass is calculated using a weighted sum of the volumic mass of the different materials.

Table 3.1: Details about the ReBCO tape thickness. Values given by Bruker at the delivery are used to define fixed values for the simulation. The percentage of each material in the total composition of the tape is computed and used to calculate the tape equivalent volumic mass.

Material	Thickness			Volumic mass (g/cm^3)
	Bruker	Simulation	Fraction of total	
	(μm)	(μm)	(%)	
Hastelloy	95	95	52.495	8.90
YSZ	~2	2	1.105	2.05
CeO2	0.05-0.1	0.07	0.039	7.65
DD_YBCO	1.5-1.9	1.7	0.939	6.30
Silver	Hastelloy side	0.7	1.216	10.50
	YBCO side	1.5		
Copper	both sides	2*40	44.206	8.96
Tape	~200	180.97	100	8.84

3.3.2 Qualification of the reference samples

Four samples have been set apart from the beam-impact experiment and considered as reference samples. They are named R1, R2, R3 and R4. They have been qualified in order to have pre-irradiation values for the comparison after the experiment. As the measurements made on R1 and R4 gave almost the same results, sample R2 have not been measured and considered equivalent to the others. Sample R3 that has quenched during the measurement at 4 K and 17 T is considered broken. The critical currents at 4 K are shown in Figure 3.9 and the values from measurement at 77 K in self-field are in Table 3.2. The results for sample R1 are the same for tap AB and tap CD because only one tap with intermediate length has been used.

Table 3.2: Critical current values at 77 K in self-field for the reference samples. Different voltage taps have been used during the measurement. The critical currents corresponding to the upper and lower criteria are given.

	tap AB		tap CD	
	lower criteria	upper criteria	lower criteria	upper criteria
R1	67.65 A	74.1 A	67.65 A	74.1 A
R3	60.91 A	65.77 A	60.94 A	66.6 A
R4	53.75 A	60.27 A	54.17 A	60.35 A

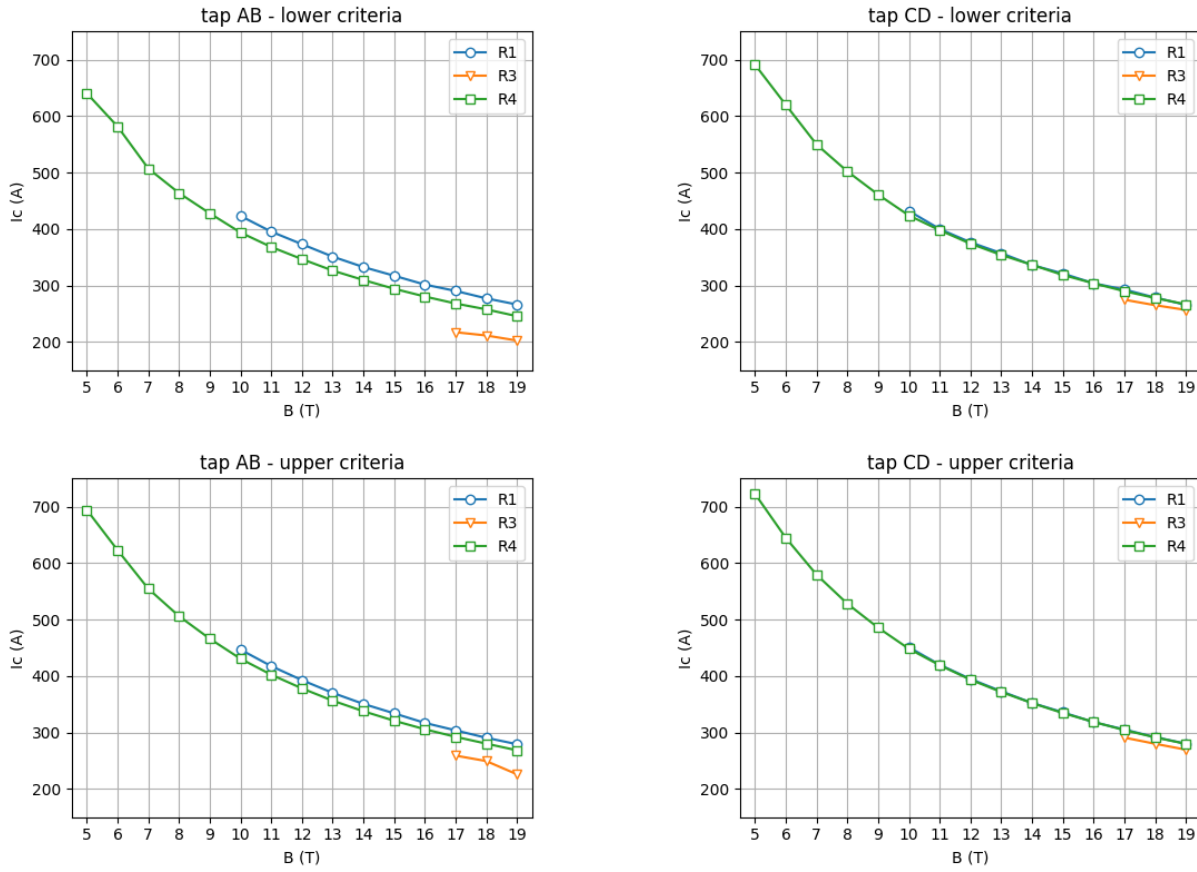


Figure 3.9: Critical current at 4 K for the reference samples as a function of the external magnetic field. Different voltage taps have been used during the measurement. The curves corresponding to the upper and lower criteria are given.

The accordance between the critical current of the different samples is better for the measurement with tap CD. The experience gained from previous experiments demonstrated it is indeed more precise. For the simplicity of the results analysis, only tap CD will be considered in Chapter 6. An arbitrary choice is also made to use the upper criteria for the analysis.

Results from the current discharge heating experiment

This chapter presents the results of the discharge experiment made on some of the HTS samples described in Section 3.3. This experiment has been done in 2021 but the results are analysed for the first time here. The aim of this experiment and its design are described. The experimental setup and all the modelling steps needed for the interpretation of the results are detailed. Using the measurements of current and voltage made during the discharge, the heat generated inside the tapes is calculated. The result is the qualification of the damage to the HTS tapes by the highest temperature reached inside them.

4.1 Design of the discharge experiment

The goal of this experiment is to damage the HTS samples by depositing energy for hundreds of milliseconds to get values representative of failure cases. The corresponding range of temperature reached inside the material is between 400 K and 1000 K. To meet the requirement of the experiment, a large amount of current must flow in the tape, leading to a resistive heat generation by Joule effect. To have a high current during a limited period of time, the solution is to use the current flow induced by a capacitor discharge. The duration of the discharge is controlled with an inductor.

4.1.1 Description of the experimental setup

A HTS tape is maintained and connected to the circuit with two copper clamps fixed on an insulator (Figure 4.1). Inside an "airtight" chamber, implemented to ensure safety and support the nitrogen airflow required to prevent the combustion of the tape, the current discharge is realised using CLIQ-2 system. CLIQ stands for "Coupling-Loss Induced Quench", it is a device developed at CERN to protect high-field superconducting magnets in case of quenching [59]. For this experiment, the CLIQ unit is used not for its primary function, but because it allows a large quantity of electrical energy to be stored in a capacitor and released by a discharge.

The system is linked to the sample holder via large cable connected to the clamps (red and black cables in Figure 4.1). The electrical circuit of the experimental setup is schematically shown in Figure 4.2. Inside the CLIQ unit, a capacitor and an inductor are in series with the circuit. A resistance, called "current

limiter", is added in series to limit the circulating current, maximum 6 kA tolerated by the CLIQ-2 system, in case of a short circuit of the tape.

Different devices are added for the measurement. A small inductor is present to induce a small-time delay for the quality of the measurement. The current could have been measured by the built-in current transformer of the CLIQ unit but to have a better control on the measurement another current transformer is placed in the circuit. The voltage measurement is done by the oscilloscope through two voltage taps placed on the clamps near the extremities of the HTS tape. A voltage divider (not visible on Figure 4.2) is used to protect the oscilloscope from a too-high voltage.

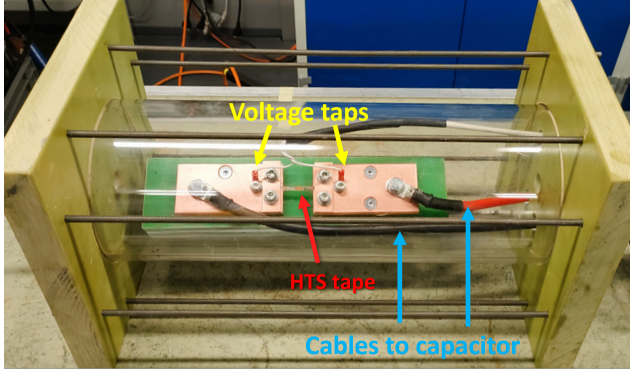


Figure 4.1: Overview of the experimental setup. The HTS tape is held by two copper clamps connected to the cables that provide the current during the discharge. The voltage across the tape is measured through two voltage taps fixed on the clamps on both sides of the tape.

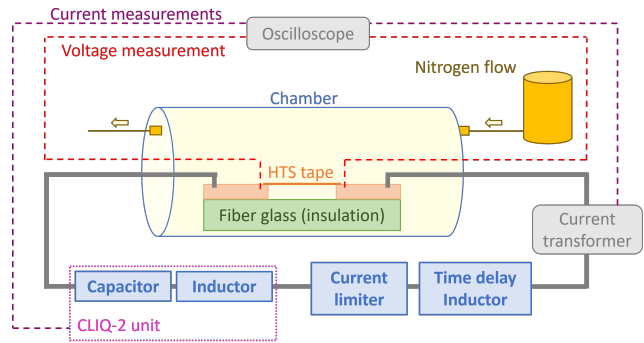


Figure 4.2: Schematic representation of the experimental setup. The HTS tape and the copper clamps are placed inside the chamber filled of nitrogen. The full line represents the electric circuit. The dashed lines represent the measurements.

The circuit inductance is known by design. The circuit resistance which takes into account both the cables and the current limiter has been measured using a digital micro-ohmmeter. The resistance of the tape has been measured at room temperature for a 5 cm tape length. The different values are compiled in Table 4.1. The CLIQ voltage and capacitance are fixed for each sample. The capacitance can vary from 10 mF to 50 mF in steps of 10 mF. The voltage can vary from 100 V to 1000 V in steps of 100 V. However, with the measured value of 102.9 mΩ for the circuit resistance the voltage is limited to 617 V to respect the current limitation of the CLIQ unit.

4.1.2 Resolution of the electrical circuit

To determine the values for the initial CLIQ voltage and for the capacitor, the circuit is approximated by an RLC circuit (Figure 4.3) in which the time-delay inductance is neglected. The derivative equation of an RLC circuit is given by Eq.(4.1). The initial conditions of the circuit are known and the equation can then be solved. The initial current is null as the circuit is open and the first derivative in $t = 0$ s worths $\frac{-V_0}{L}$ (Eq.(4.2)).

$$L \cdot \frac{d^2 i(t)}{dt^2} + R \cdot \frac{di(t)}{dt} + \frac{1}{C} \cdot i(t) = 0 \quad (4.1)$$

Table 4.1: Parameters of the electric circuit of the experimental setup.

Fixed parameters		
Circuit Resistance	$R_{circuit}$	$102.9\text{ m}\Omega$
Tape Resistance	R_{tape}	$\approx 2.788\text{ m}\Omega$
CLIQ Inductance	L	2.25 mH
Time-delay Inductance	L_{time}	$1\mu\text{H}$
Variable parameters		
CLIQ Voltage	V_C	$100 - 600\text{ V}$
CLIQ Capacitance	C	$10 - 50\text{ mF}$

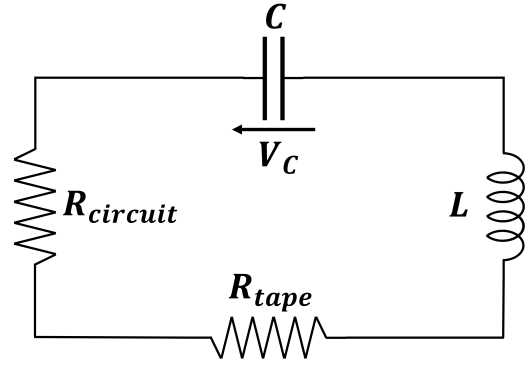


Figure 4.3: Schematic representation of the equivalent RLC circuit equivalent.

$$\begin{cases} i(0) = 0 \\ L \cdot \frac{di(t)}{dt} \Big|_{t=0} + R \cdot i(0) + V_C(0) = 0 \Rightarrow \frac{di(t)}{dt} \Big|_{t=0} = \frac{-V_0}{L} \quad \text{with} \quad V_0 = V_C(0) \end{cases} \quad (4.2)$$

As the tape resistivity (ρ_{tape}) vary significantly with the temperature, the total resistance $R = R_{circuit} + R_{tape}$ is time dependent. It is then required to solve iteratively the system using the numerical expression of the equations. Details about the numerical expression and the equation resolution are in Appendix B.1.

The heat generated inside the tape by Joule effect during a finite time Δt depends on the resistance of the tape and the current (Eq.(4.3)). From the generated heat, the temperature reached inside the tape $T(t)$ can be calculated with Eq.(4.4), using the specific heat capacity of the material which varies as a function of the temperature.

$$Q(t+1) = R_{tape}(t) * I(t)^2 * \Delta t \quad (4.3)$$

$$T(t+1) = T(t) + \frac{Q(t+1)}{m_{tape} \cdot c_{tape}(t+1)} \quad (4.4)$$

The equivalent specific heat capacity of the tape, c_{tape} , is calculated (Eq.(4.5)) only considering the three main components of the tape, i.e. the Hastelloy, the copper and the silver, by taking the weighted sum of the specific heat capacity of the materials. Considering only these three materials, the Hastelloy represents 53.6% of the tape volume, the copper 45.1% and the silver 1.3%. The temperature dependence of the specific heat capacity is given for the different materials in Eq.(4.6) [60].

$$c_{tape}(T) = 53.6\% \cdot c_{Hast}(T) + 45.1\% \cdot c_{Cu}(T) + 1.3\% \cdot c_{Ag}(T) \quad (4.5)$$

$$\begin{cases} c_{Hast}(T) = 0.1009 \cdot T(t) + 469.759 \text{ [J/kgK]} \\ c_{Cu}(T) = 0.1009 \cdot T(t) + 358.4 \text{ [J/kgK]} \\ c_{Ag}(T) = 0.066 \cdot T(t) + 211.13 \text{ [J/kgK]} \end{cases} \quad (4.6)$$

The resistance of the tape is calculated considering the three main materials seen in parallel for the current flow (Eq.(4.7)). The resistivity of each material depends of the temperature following Eq.(4.8) [60].

$$\begin{cases} R_{tape}(t+1) = \rho_{tape}(t+1) * \frac{l_{tape}}{A_{tape}} \\ \frac{1}{\rho_{tape}(t+1)} = \frac{53.6\%}{\rho_{Hast}(t+1)} + \frac{45.1\%}{\rho_{Cu}(t+1)} + \frac{1.3\%}{\rho_{Ag}(t+1)} \end{cases} \quad (4.7)$$

$$\begin{cases} \rho_{Hast}(t+1) = 6.9 \cdot 10^{-7} \cdot (1 + 0.00094 \cdot (T(t+1) - 293.15)) \text{ } [\Omega m] \\ \rho_{Cu}(t+1) = 1.68 \cdot 10^{-8} \cdot (1 + 0.00393 \cdot (T(t+1) - 293.15)) \text{ } [\Omega m] \\ \rho_{Ag}(t+1) = 1.59 \cdot 10^{-8} \cdot (1 + 0.0038 \cdot (T(t+1) - 293.15)) \text{ } [\Omega m] \end{cases} \quad (4.8)$$

These equations have been used in the numerical model computed to design the experiment. The study has been made by trial and error looking at the reached temperature and varying the initial CLIQ voltage V_C and capacitance C . The values retained to achieve the target temperatures are compiled in Table 4.2. The corresponding current and short current are recalled to check the CLIQ unit limitation. In total seven samples are studied with each a precise target temperature.

Table 4.2: Values of the design of the discharge experiment. The CLIQ voltage and capacitance values are chosen to reach the target temperatures. The values of current and short current are compiled to check the current restriction for the CLIQ-unit.

Samples	Target	CLIQ Parameters		Simulated maximum values		
	Temperature (K)	V_C (V)	C (mF)	Temperature (K)	Current (A)	Short current(A)
R1	420	200	30	415.7	549.5	552.6
B1S1	500	300	20	494.4	706.9	710.3
B1S2	600	500	10	603.1	890.9	894.1
B2S1	640	300	30	638.8	824.2	828.9
B2S2	740	400	20	732.7	942.4	947
R4	820	300	40	816.5	914.4	920.3
R2	1040	300	50	1037.1	988	995

For this experiment, each sample has a different background. Indeed, ReBCO is an expensive material and it was not possible to buy new tapes for this experiment. On the seven studied samples, three of them are the reference samples of the HiRadMat-37 experiment and four of them are tapes from Batch 1 and Batch 2 of the HiRadMat-37 experiment and have been impacted (see Chapter 5). As detailed in Section 5.3, they received a small amount of energy and they are only slightly damaged. To simplify the analysis, the sample names are kept from the HiRadMat experiment.

4.1.3 Experimental procedure

The experimental procedure, identical for all samples, is as following. The tape is fixed to the clamps, held by the screwed copper plates. The connections are secured before placing the assembly in the sealed chamber. The CLIQ unit is charged with the required parameter previously set up while the nitrogen flow

is started. Once the capacitor has been charged, the discharge can occur. The measurements are automatically taken during the discharge. At the end, the nitrogen flow is maintained until the sample return to ambient temperature. It is replaced by the next one until all seven discharges have been completed.

4.2 Modelling of the experimental setup

During the design of the experiment, a lot of simplification (simplified material composition, neglect of the heat transfer, perfect contact between the tape and the clamps, etc.) has been made to model the system and calculate the reached temperature at the end of the discharge. However, no justification was given to motivate these hypotheses.

The exact numerical model used for the design has been lost through the years but I managed to find back the equations and the process used. With these equations, the numerical model has been redone and when I tried to compare this model to the results of the experiment large deviation has been observed up to 20%. As the only parameters of the model were the tape composition and the tape dimension, I made an optimisation study on all the results to see if the modification of one parameter gave significantly better agreement between the simulations and the measurements. The best parameter to change was the thickness of the tape that has to be 0.15 mm. Nevertheless, measurements have been done at the metrology service and they confirm that the tape thickness is between 0.19 mm and 0.22 mm.

This leads to the conclusion that other simplifications made for the modelling of the experiment were at the origin of the bad agreement. Then two factors are studied in detail to improve the experiment modelling: the heat transfer and the contact resistance. A small study on the sensitivity to the simplification of the tape composition is also made to confirm that it has not a large impact on the simulations.

4.2.1 Heat transfer analysis

The first hypothesis used during the design phase of the discharge experiment was that the heat generated inside the tape stayed inside it ignoring heat transfers. However, the clamps represent a large volume of copper (25 cm^3), three orders of magnitude larger than the volume of a tape (48 mm^3) and the copper being a good thermal conducting material, large heat transfer could take place.

The simplified situation considering only the two main materials of tape (Copper and Hastelloy) is represented in Figure 4.4. In first approximation, no distinction is made between copper and Hastelloy concerning the heat produced by Joule effect due to the circulating current. To determine whether the heat remains inside the sample or flows completely to the clamps, the thermal conductivity of the materials is compared.

Copper is a good thermal conductor and its thermal conductivity worth approximately $400\text{ W/m}\cdot\text{K}$ at 300 K and $340\text{ W/m}\cdot\text{K}$ at 1200 K varying linearly between these two values [60]. In comparison, Hastelloy has a thermal conductivity of $12\text{ W/m}\cdot\text{K}$ at ambient temperature [60].

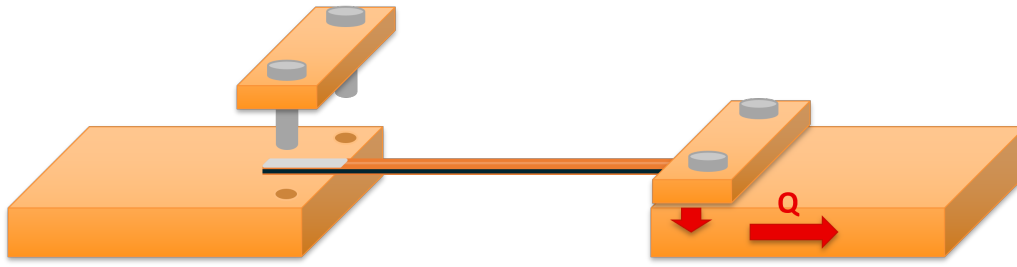


Figure 4.4: Schematic representation of the tape and the clamps to support the heat transfer study. The Copper is in orange and the Hastelloy inside the tape is dark. The surface contact between the tape and the clamp is highlighted in gray. The heat transfer from this contact surface to the copper clamp is simulated by the red arrow.

The heat flux density $\bar{q}$ [W/m^2] is described by the Fourier's law (Eq.(4.9)) in which k [$W/m \cdot K$] is the thermal conductivity of the material and $\bar{\nabla} T$ [K/m] is the temperature gradient. The heat diffuses always from the highest temperature to the lowest in order to reach a thermal equilibrium.

$$\bar{q} = -k \cdot \bar{\nabla} T \quad (4.9)$$

In the studied situation, the heat generated inside the tape at the contact area will directly flow to the copper clamps that represent a large volume of metal at lower temperature and with a good thermal conductivity. Nevertheless, the Hastelloy inside the tape acts like a "heat sponge" and will keep the heat in the tape long enough to reach a high temperature. The heat generated in the central part of the tape, the part qualified during the critical current measurements, contributes then to the damage of the tape. The heat produced at the contact between the tape and the clamps must therefore be removed from the total generated heat calculated from the voltage and current measured during the discharge experiment. To calculate the fraction of the heat to be removed, we need to know the corresponding resistance.

4.2.2 Estimation of the impact of the contact resistance

The tape is fixed to the clamps by a piece of copper that is screwed to the copper block to compress to tape while having a good contact for the current circulation. However, at the contact between two conductors, a contact resistance is always induced. This contact resistance depends of a lot of parameters and is a key problem in electrical circuits.

In the considered case, different elements can impact the contact resistance. The material at the contact varies as some samples have already been qualified at the University of Geneva, which required a tin deposition at the extremities of the samples. It changes the resistivity of the material at the contact but also its microscopic granularity that has an impact on the type of contact. The strength of compression with which the tape is fixed to the clamp is another factor physically translating into the torque apply to the screws to fix the sample. The cleanliness of the contact zone (presence of dust, moisture, etc.) but also its total surface can influence the resistance. The oxidation state of the material can change the resistance too.

For example, the most common copper oxide produced in ambient air (Cu_2O) has an electric resistivity of $37 \, \Omega \cdot m$, nine orders of magnitude higher than the electric resistivity of the copper ($1.68 \cdot 10^{-8} \, \Omega \cdot m$).

As these elements were not taken into consideration during the design phase, no attention was paid to this during the experiment. In order to verify the negligible impact of the variation of these parameters on the contact resistance, measurements have been made reproducing variable conditions.

Contact resistance qualification

For the contact resistance measurement, the sample holder of the discharge experiment has been reused and connected to an electric circuit. The idea is to have a significative current going through the tape to measure the voltage across different parts of the tape placing voltage taps as shown in Figure 4.5. The current produced by the power supply follows a pyramidal distribution of values to allow the suppression of a possible offset. The current is measured by an external device to have a more precise value for the resistance calculation. Three voltages are measured during the experiment following the disposition of the four voltage taps on Figure 4.5: the positive contact resistance from the centre of the screw to the sample tap ($V_{\text{contact}+}$), the sample resistance between the two sample taps (V_{sample}) and the negative contact resistance from the sample tap to the middle of the screw ($V_{\text{contact}-}$). The voltage taps on the sample are placed as closed as possible to the clamps avoiding any direct contact that would have modified the value. A computational program directly calculates the slope of the voltage-current characteristics and gives the different resistance values.

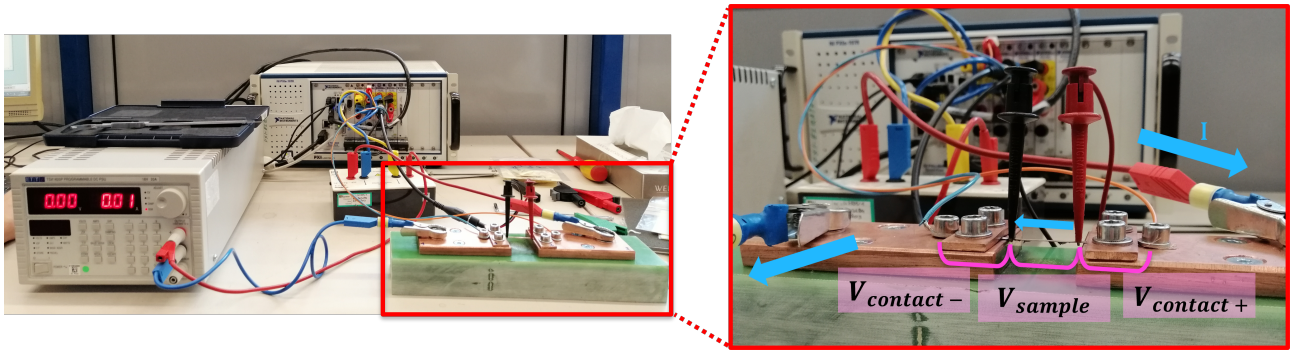


Figure 4.5: Overview of the experimental setup of the contact resistance measurement. The current provided by a power supply goes through the clamps and the HTS sample. The voltages are measured through different taps.

The measurement is done for some samples of the discharge experiment (R1, B1S1, B1S2, B2S1 and B2S2) and for sample B1S7 of the HiRadMat experiment to analyse the influence of tin contact and reproduce the condition of sample R2 which has been destroyed during the discharge experiment. Several parameters, that could impact the contact resistance, are varied independently during the different measurements. These parameters and their possible values are compiled in Table 4.3.

Using these parameters, it requires 6 to 9 measurements per sample. For each measurement, four resistances are calculated, the three partial resistances and a total resistance. The detailed results are in the

Table 4.3: Overview of the varied parameters of the contact resistance measurement experiment. The possible values and impact on the contact resistance are given.

Parameter	Possible values	Explanation
Torque value	1.75 Nm - (2.5 Nm) - 4 Nm	The strength, applied to screw the copper plate in order to maintained the sample and make a good contact, is controlled with a torque key.
Cleaning	Yes - No	The contact area of the tape and of the clamp are cleaned with a bit of alcohol and dry before placing the tape.
Tape positioning	Up - Down	The tape is placed with the superconducting layer up or down. The idea is to impose a complete removal of the tape and so a modification of its positioning.
Tin contact	Yes - No	For one reference tape with no tin layer at the contact area, the measurement has been done without it and then a small layer of tin have been soldered to compare the direct influence.

Appendix B.2. For each sample, the mean and the variance over the measured resistances are calculated to observe the impact or not of the variable parameters.

For all the samples, the variance on the values is below $3\text{E-}07$ except for sample B1S1 for which the positive contact resistance has significantly larger resistance than the others. It leads to a variance of $2.56\text{E-}06$. For this sample, the contact resistance represents a more significative part of the total resistance. It might be due to a smaller surface of contact as the tape is shorter than the other. Despite this small variation, it is clearly shown that the tested parameters do not influence the contact resistance. Looking at all the samples together, the variance on the resistance values is below $8.87\text{E-}07$. The mean over the values can be then used to determine the percentage of the resistance that is part of the contact (Table 4.4). The mean value of the sample resistance ($1.44\text{ m}\Omega$ for 2.6 cm long tape) is also consistent with the value measured for the reference tape ($2.788\text{ m}\Omega$ for a 5 cm long tape). The mean values, the variances and the contribution to the total resistance are compiled in Table 4.4. We can conclude that the contact resistance corresponds to the half of the total measured resistance and take this value to calculate the fraction of the generated heat that flows on the clamps and does not contribute to the tape damage.

Table 4.4: Global results of the contact resistance measurements. The mean value of resistance over all the samples in the different configurations is given for different voltage taps pairs. The value is representative as the variance is small. The contribution of each part to the total resistance is calculated.

	Positive contact	Sample	Negative contact	Total
Mean resistance [Ω]	$7.71\text{E-}04$	$1.44\text{E-}03$	$6.59\text{E-}04$	$2.86\text{E-}03$
Variance	$8.87\text{E-}07$	$8.43\text{E-}09$	$5.28\text{E-}08$	$8.42\text{E-}07$
Contribution	27%	50%	23%	-

4.2.3 Sensitivity of simulations to variations in HTS tape composition

During the design phase, the simulations have been made using the three main components of the tapes. To verify this hypothesis, a sensitivity study is made to analyse the impact of the considered composition on the results of the simulation. The study is made both for the specific heat capacity and the tape resistance. The results for three components (53.6% Hastelloy, 45.1% copper and 1.3% silver) and two components (54.2% Hastelloy and 45.8% copper) are compared. The percentage of each component is calculated as a function of their thickness considering the total thickness as their sum only. The total tape thickness is considered to be 0.2 mm as it corresponds to the measurement made on the tape used for the discharge.

For the specific heat capacity, the obtained values for simulations with fixed voltage and capacitance are illustrated on Figure 4.6. The contribution of each material to the equivalent specific heat capacity is shown. The silver contribution leads to an increase of 3 J/kgK of the value, corresponding to 2.6% of the total value which is negligible for the precision required for the final results.

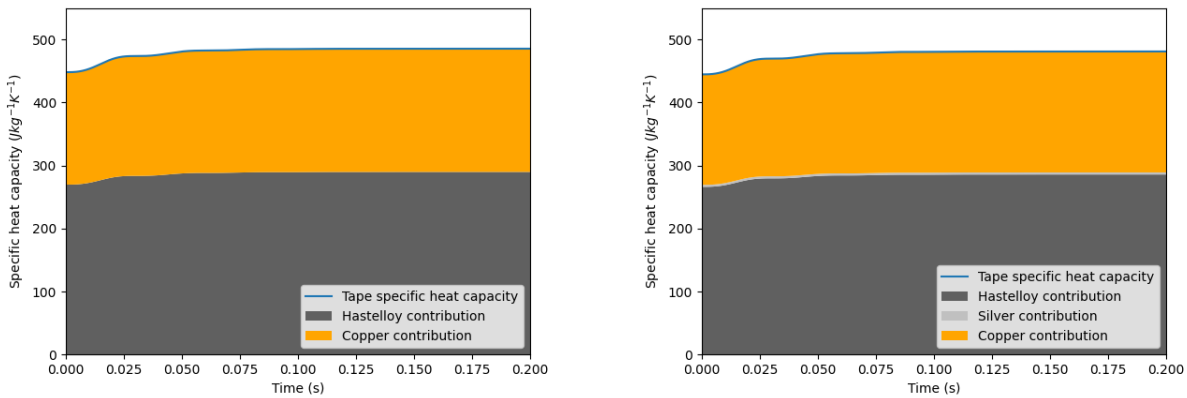


Figure 4.6: Illustration of the contribution of each material to the equivalent specific heat capacity of the HTS tape. The silver contribution is negligible compared to the one of Hastelloy and copper.

For the equivalent resistance, the contribution of each material to the conductivity of the sample is given in Table 4.5. The copper is clearly dominant which is relevant with the main purpose of this layer to conduct the current when the tape loses its superconductivity. Silver contributes to less than 5% of the conductivity of the tape and can then be neglected for the modelling.

Table 4.5: Contribution of each material to the HTS tape conductivity.

	Contribution to tape conductivity	
	2 materials	3 materials
Hastelloy	6.2%	5.9%
Copper	93.8%	91.2%
Silver	-	2.9%

4.2.4 Conclusion on the experiment modelling

The heat transfer study shows that only the heat generated inside the tape, out of the contact, contributes to the rise of temperature inside the tape leading to damage. At the contact, the generated heat flows too quickly on the copper clamps and does not contribute to the damage at the centre of the tape.

With the additional measurements made, we can conclude that the contact resistance worth half of the total resistance. So with Eq.(4.3), only half of the heat calculated from the measurements made during the discharge has to be considered to determine the damage on the samples.

The simulations are not too sensitive to the composition of the tape. The impact of the silver layer is below 5% both for the equivalent specific heat capacity and for the equivalent resistance. For the simulation simplicity, only the Hastelloy and the Copper are considered for the final results studied in the next section.

4.3 Deposited energy and damage qualification

Seven samples have been damaged by the discharge following the experimental procedure described in Section 4.1.3 and using the circuit parameters determined during the design phase (Table 4.2).

The measured voltage and current are shown in Figure 4.7 for samples B1S1 and R2. The results for the other samples (similar to B1S1) are in Appendix B.3. The normal behaviour of the capacitor discharge is observed. The current increases quickly when the circuit is closed and then oscillates due to the presence of the inductor. It finally reaches zero when the capacitor is fully discharged. The voltage follows the same behaviour. The experiment went well for all the samples except for sample R2 which have been heated too much at the contact with the clamps and broke. This is clearly visible in the results as the voltage dropped instantaneously.

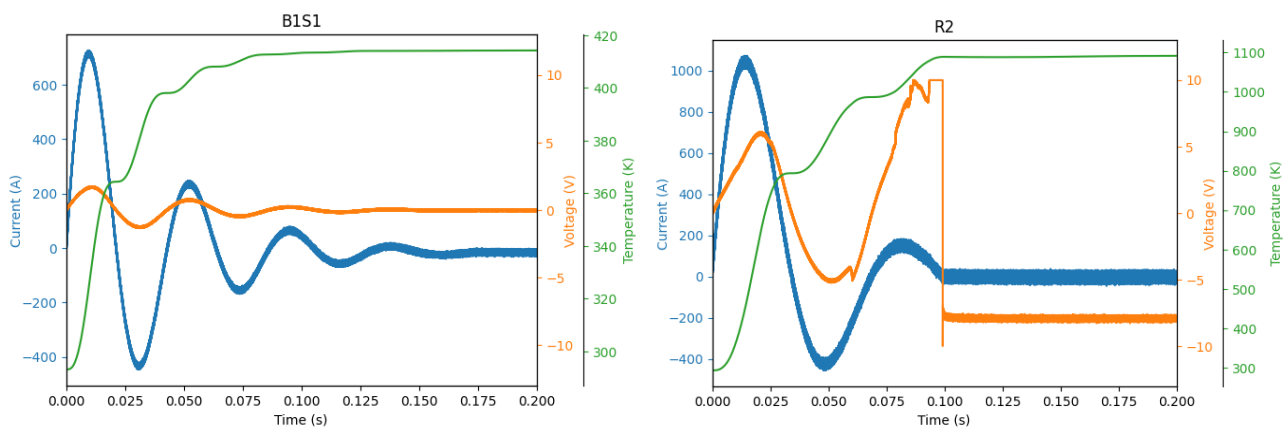


Figure 4.7: Results from the discharge experiment for sample B1S1 and R2. The voltage and the current measured during the experiment clearly follow the normal behaviour of a capacitor discharge in an RLC circuit. The temperature inside the tape which is proportional to the heat generated is represented over the time. The break of sample R2 happened at the moment the voltage has dropped.

The heat generated by Joule effect is given by Eq.(4.10) for discrete measurement. Q_{Joule} is calculated from the current and the voltage measured during the experiment. Nevertheless, with the conclusion drawn

from the modelling analysis, half of the heat flows directly on the copper clamps. The heat that really induces damage on the sample, Q_{sample} , worths only half of Q_{Joule} . The values of Q_{sample} are given in Table 4.6.

$$\begin{cases} Q_{Joule} = \sum_{\Delta t} V(\Delta t) \cdot I(\Delta t) \cdot \Delta t \\ Q_{sample} = \frac{Q_{Joule}}{2} \end{cases} \quad (4.10)$$

To transform the heat into the temperature reached inside the tape, Eq.(4.4) is used considering the value of the heat for each time step. The specific heat capacity of the tape is given by Eq.(4.5) but considering 54.2% of Hastelloy and 45.8% of copper. The mass of the tape is determined considering only the length of the central part from the contact resistance measurement, i.e. 27 mm. The variation of the temperature over the time is calculated for each sample (see Figure 4.7 for samples B1S1 and R2 and Appendix B.3 for other samples). The increase in temperature follows directly on the current and voltage oscillations.

The hotspot temperatures (compiled in Table 4.6) are defined to qualify the damage level and correspond to the temperature reached inside the tape when the discharge is complete. For sample R2, it corresponds to the higher value measured before the break of the tape. The values are lower than the target temperature but remains in the scope of the study. It is clearly linked with the simplification hypothesis made during the design as detailed on the modelling study.

Table 4.6: Hotspot temperature of the samples damaged on the discharge experiment. The target temperature and the parameters of the circuit are reminded. The specific heat generated inside the sample that leads to damage is also given.

Samples	Target	CLIQ Parameters		Results of the experiment	
	Temperature (K)	V_C (V)	C (mF)	Q_{Sample} (kJ/kg)	Hotspot Temperature (K)
R1	420	200	30	32.32	364
B1S1	500	300	20	54.99	414
B1S2	600	500	10	87.43	484
B2S1	640	300	30	115.65	544
B2S2	740	400	20	145.14	606
R4	820	300	40	184.00	686
R2	1040	300	50	388.60	1089

4.4 Conclusion

Seven samples (R1, R2, R4, B1S1, B1S2, B2S1 and B2S2) have been damaged by a current capacitive discharge with different initial voltages and capacitances. The detailed modelling of the experiment confirms that the heat transfer that occurs at the contact between the tape and the copper clamps cannot be neglected. Indeed, the calculation of the contact resistance shows that 50% of the heat generated during the experiment flows on the clamps and does not induce damage on the centre of the samples. The damage made on the HTS tapes are represented by the highest reached temperature which lies between 364 K and 1089 K as detailed in Table 4.6.

Results from the HiRadMat-37 cryogenic beam-impact experiment

This section is dedicated to the HiRadMat-37 experiment, of which key elements of the design, the experimental procedure and the post beam-impact analysis are described. This thesis focuses only on the HTS samples irradiated during the experiment and one can read Ref.[2] for LTS samples results. The energy deposition inside the HTS samples and the sample holder is calculated through BDSIM simulations performed using input parameter values measured during the experiment. The final result is the qualification of the samples damage by a representative temperature calculated from the deposited energy.

5.1 Design and preparation of the HiRadMat-37 experiment

5.1.1 The design of the sample holder

The aim of this experiment is to reproduce fast failure that can occur in accelerators. The design of the FCC-hh magnet is not yet complete, but as shown in Figure 2.6, it will probably be similar to that of the LHC. The superconducting wires are placed very close to the vacuum chamber and the amount of crossed material in the event of a failure can be considered to be of the order of a few centimetres to a few tens of centimetres. To recreate these conditions, the impacted ReBCO tapes are placed in a sample holder made of copper.

As described in Section 2.6, the energy deposited by high-energy proton beams depends mainly on the amount of material traversed. The energy deposition will be higher at the exit of the beam from the sample holder than at the entrance. Using this property, tapes are placed in different depths inside the sample holder to reproduce different levels of energy deposition. BDSIM simulations have been made to determine the dimensions of the sample holder and the disposition of the tapes with the condition that the temperature remains below the melting point of copper, i.e. 1358 K.

As illustrated in Figure 5.1, 42 ReBCO tapes are placed inside the sample holder divided in 6 batches with 7 samples each and with two different orientations. Batches B1, B2, B3 and B4 correspond to horizontal orientation; the beam impacts the tape perpendicular to its thickness (Fig.5.1a) with the YBCO layer on the top of the sample. The two other batches, B5 and B6, are in vertical orientation; the beam impacts the tape

perpendicular to its broader surface (Fig.5.1b) with the YBCO layer impacted first. The samples are labelled according to their batch and position in the sample holder, with the sample number increasing following the beam direction. The first sample of the first batch is then called B1S1, the second B1S2 and so forth.

The sample holder is not made of a large block of copper but of several layers fixed together to be able to place the HTS tapes inside it. In addition to the thick copper layers containing the samples, thin copper layers are interleaved at various positions (e.g. between S1 and S2), housing foils made of aluminium or tin. The foils are placed on the beam path and are used in the post-impact analysis to check the exact trajectory observing impact and melting sign of the material. A more detailed description of the sample holder is done in Ref.[43].

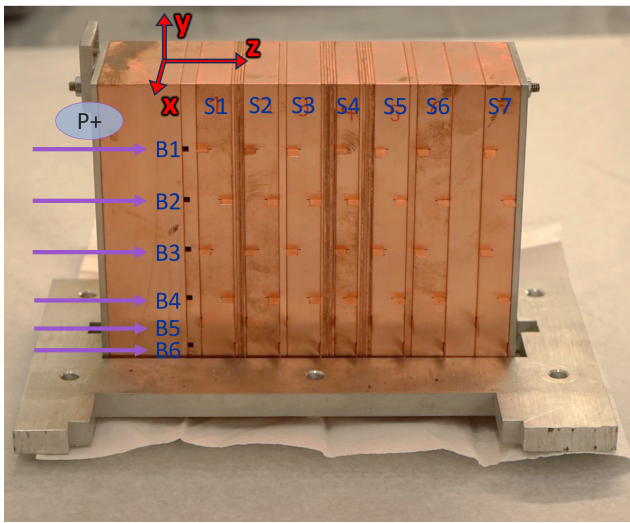


Figure 5.1: Overview of the HTS sample holder. The samples are labelled according to their position in the sample holder, e.g. B1S1 for the first sample of the first batch. The arrows in front of each batch represent the beam trajectory during the impact. The beam is along the z-direction according to the reference frame.

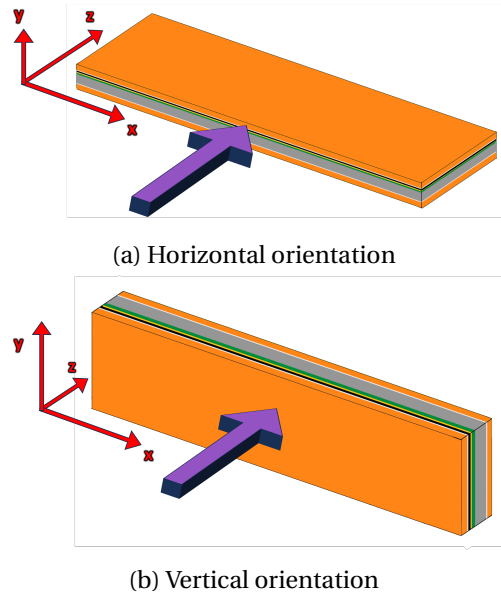


Figure 5.2: Representation of the two tape orientations met inside the sample holder. The reference frame is identical to the sample holder reference frame and the beam represented by the purple arrow is in the z-direction. The YBCO layer, important for the final orientation in the sample holder is in black inside the tape.

5.1.2 Description of the experimental setup

To reproduce superconducting magnet operation conditions, the experiment is conducted at cryogenic temperature by placing the sample holder is then placed inside a cryostat cooled with liquid helium. The sample holder is fixed to a copper plate directly connected to the cold head of the cryostat as highlighted in Figure 5.3. The many cables visible on Figure 5.3 are connected to sensors placed in different locations to monitor the temperature during the experiment. On the top of the HTS sample holder, a fixed metallic window is present. This window is used for the Beam-Based Alignment (BBA) of the cryostat, an alignment method detailed in the following.

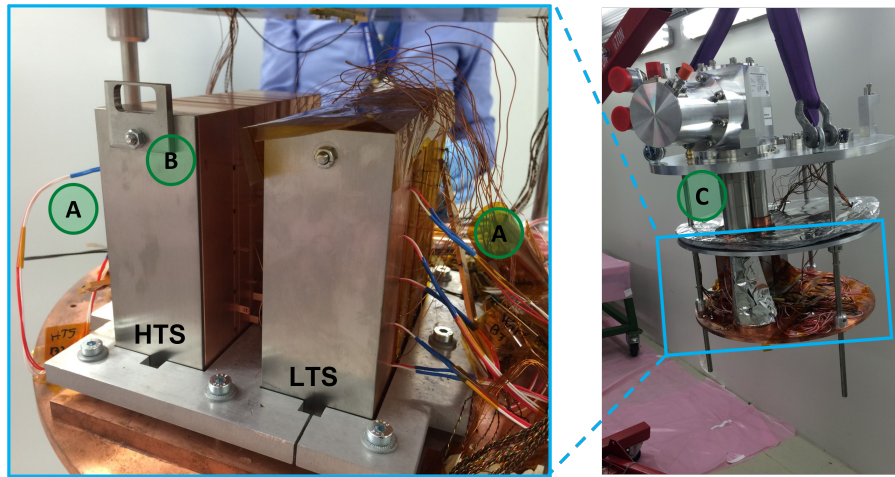


Figure 5.3: Overview of the sample holder inside the cryostat. The sample holder is fixed to a copper plate connected to the cold head (C) filled with liquid helium for the cooling. The temperature sensors (A) are placed to follow the temperature evolution at different strategic points inside the cryostat during the beam time. The metallic window (B) is used for the BBA of the cryostat.

To reach a temperature of 4K inside the cryostat, several layers of insulation are required. Thermal aluminium multilayer insulators (MLI) are used in addition to the two primary tanks. Initially, the sample holders and the nearest equipment are enveloped with MLI and then enclosed within the first tank (see Figure 5.4). The first tank itself is enveloped and placed in a second one (see Figure 5.4). Inside the cryostat, vacuum is sustained by a compressor. More detailed about the cryostat can be found in Ref.[43].

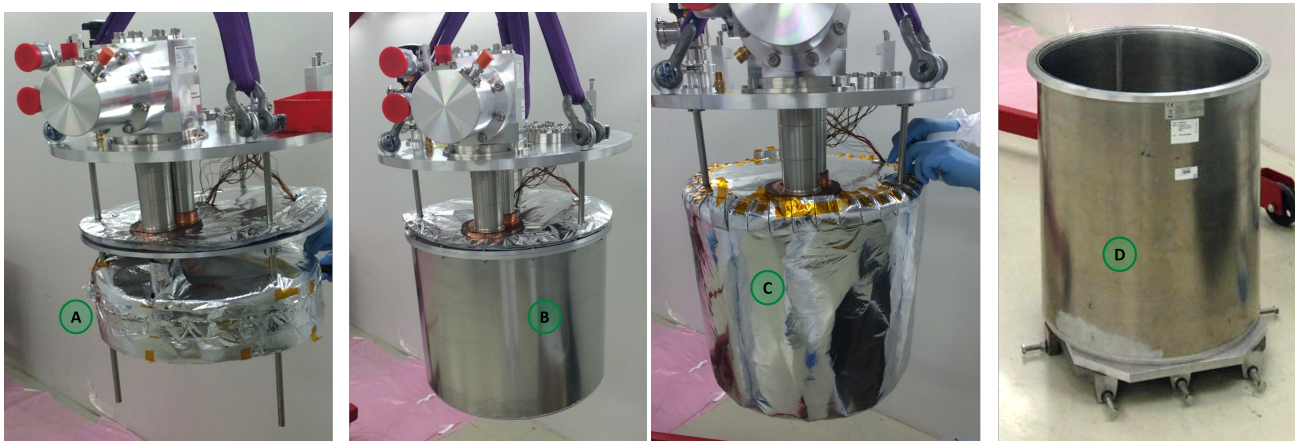


Figure 5.4: Pictures of the open cryostat. The different layers that ensure the thermal insulation are visible. The more internal layer (A) is a thermal aluminium multilayer insulator (MLI). It covers the cold head and the sample holders. A first tank (B) is fixed around it and then covered again by a MLI (C). The final layer is a larger tank (D) which is screwed on the top part of the cryostat.

Inside the HiRadMat tunnel (Fig. 5.5), the cryostat is fixed to a moveable structure. The motion along the x and y directions is required to align the different batches of the sample holder to the beam trajectory. The proper alignment of the cryostat is essential for the experiment success and the metrology service is in charge of it. The motors used to move the table are also calibrated and the exact position of the sample holder relatively to the beam is determined using the following Beam-Based Alignment (BBA) technic.

The cryostat is first approximately placed to have the beam close to the metallic window (labelled (B) in Figure 5.3). Two diamond detectors fixed outside the cryostat measure the surrounding radiation. When the beam impacts the window, the level of radiation increases. When the beam is outside the window, the absence of secondary particle showers leads to a change in the signal recorded by the detectors. By manipulating the table position, the exact shape of the window can be observed. As its position is perfectly known relatively to the cryostat and so to the sample holder, an origin position can be determined. The movements applied to the table to reconstruct the window shape provide the correlation between the motor command and the displacement.

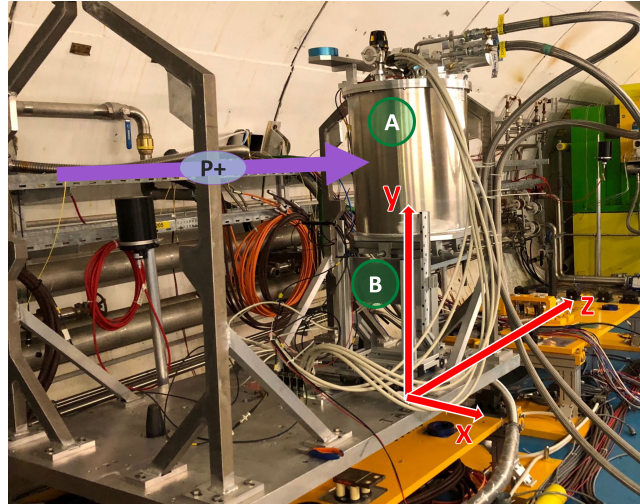


Figure 5.5: Overview of the HiRadMat tunnel. The cryostat (A) fixed on the moveable table (B) is placed inside the tunnel of the HiRadMat facility. The purple arrow represents an incoming protons beam, along the z-direction. The reference frame in red is the one attached to the table which is moveable along the x and y directions.

5.2 Experimental procedure and measurements

Any experiment at CERN has to be planned in advance as it required the beam production by the chain of accelerators. As the beam characteristics are chosen for the needs of the experiment, their production is dedicated. At the defined moment, the experimental setup must be ready (cryostat cooled at 4K, motors of the moveable table calibrated, etc.) and all the monitoring systems installed and connected. The first beams are then used for the BBA of the cryostat and when the alignment is complete, the samples can be impacted.

In total six beams are needed for the HTS part of the experiment, one per batch. To reach the required number of incident protons, the duration of one impact is fixed to 600 ns corresponding to 24 bunches of particles 25 ns apart. Between successive impacts, the cryostat is repositioned to align the next batch with the beam. There is a waiting period until the temperature inside the cryostat returns to a level close to 4 K. As discussed in the previous section, temperature sensors positioned inside the cryostat measure the temperature evolution. Detailed results regarding temperature monitoring are in Ref. [43].

Despite the precaution taken by the metrology service for the alignment of the cryostat and the calibration of the table, slight deviations remain possible. After the BBA, a deviation of approximately -1.5 mm along the x-direction and no significant deviation along the y-direction have been detected. As the samples have constant composition along the x-direction, a deviation of 1.5 mm compared to the 60 mm length is not problematic and no correction has been done for this offset.

Quantifying the exact energy deposition inside the samples during the experiment is not possible but it is calculated via Monte Carlo simulations as detailed in Section 2.6.3. The difference with the design simulation for the sample holder concerns the parameters that have been updated with inputs from the experiment as the beam intensity, its transverse size and its precise position relatively to the samples.

5.2.1 Beam parameters during the experiment

The beam parameters determination, done just after the experiment, is complex and only the results useful for the simulations are given here. The details can be found in Ref.[43].

The beam intensity is measured directly at the extraction from the SPS and recorded. This intensity is expressed as the number of incident protons of energy 440 GeV. The value for each beam is presented in Table 5.1. The transverse beam size is calculated from a beam profile measurement done by a Beam Television monitor (BTV) placed at the end of the beam trajectory. The measurement is done for the first beam and considered constant during the experiment. The obtained values for the transverse beam size are $\sigma_x = 1.1$ mm and $\sigma_y = 1.1$ mm.

To determine the real trajectory of the beam and so the exact impact position, different measurements and calculations have been done. The final values used for the BDSIM simulation consist on an offset in the y-direction (values in Table 5.1). The x-offset measured with the BBA is not taken into account in the simulations.

Table 5.1: Parameters of the beams that impacted the HTS tapes during the HiRadMat-37 experiment.

	Intensity ($\times 10^{12}$ p+)	y-offset (mm)
B1	3.15	-0.4
B2	3.06	-0.8
B3	3.08	-0.6
B4	3.10	-1.4
B5	3.16	+1.5
B6	3.05	+2.5

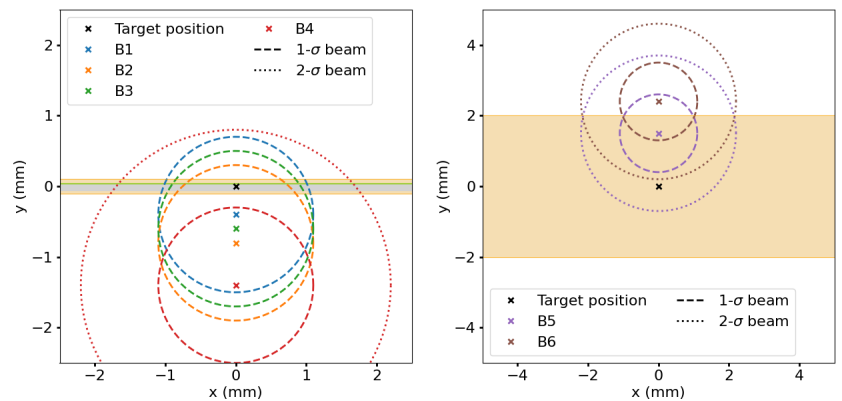


Figure 5.6: Representation of the impact position relatively to the tape dimensions. The offset along the y-direction is taken into account for the BDSIM simulations. The gaussian beam is represented by its 1- σ and 2- σ dimensions knowing that $\sigma_x = \sigma_y = 1.1$ mm.

The impact position relative to the tape dimensions can be visualised in Figure 5.6. The offset for batch B4 is quite big and only a less intense part of the beam impacts the tape. It results in a lower energy deposition compared to the other batches, confirmed by analysing the results of energy deposition (Figure C.2 in the Appendix). For batches B5 and B6, it is evident that only a located part of the tape is impacted by the centre of the beam. Nevertheless, the superconducting layer, being perpendicular to the beam (Fig. 5.1b), has been indeed damaged. Figure 5.7 shows a picture of the sample holder after the experiment. The position of the impacts are clearly visible and the deformation of the material indicates where the energy has been deposited.

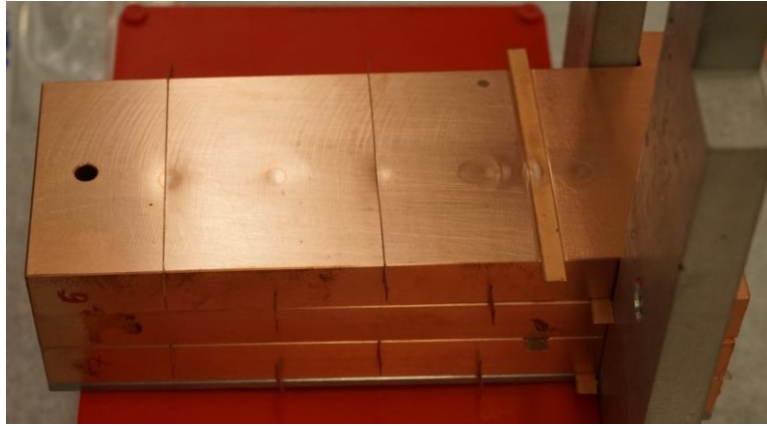


Figure 5.7: Picture of a part of the sample holder with some HTS samples after the beam impact. The deposited energy induces deformation of the material.

5.3 Post-experiment BDSIM simulations of energy deposition and thermal analysis

5.3.1 Energy deposition

With the parameters of the beam, the post-irradiation BDSIM simulations of the energy deposition inside the tapes and the sample holder can be performed. The geometry files from the final design of the sample holder are used. Six simulations (one per beam) with different y-offset are required to calculate the deposited energy. For these simulations, some people worked previously on it without going to the end of the analysis. The simulation code made in 2018 was no longer compatible with the current python package and an update of this code has to be made. Some part of the code was not given physical results first and a deep analysis highlighted different errors including on the mesh positioning.

Indeed, for Monte Carlo simulations, the geometry studied is divided into small volumes called "bins", the size of which is determined by a mesh. A larger mesh is used for the sample holder to obtain a general understanding of the energy deposition within it. A thinner mesh is used for the samples themselves and a tape has 120 divisions along its length, 10 divisions along its thickness and 40 divisions along its width, resulting in bins with a volume of $9.045 \cdot 10^{-4} \text{ mm}^3$.

Figure 5.8 which represents all simulations together provides a first qualitative interpretation of the results. As expected, the amount of deposited energy increases from the entrance in the sample holder to the exit. The Gaussian shape of the beam is also clearly visible. The same representation with different points of view can be found in Appendix C.1.

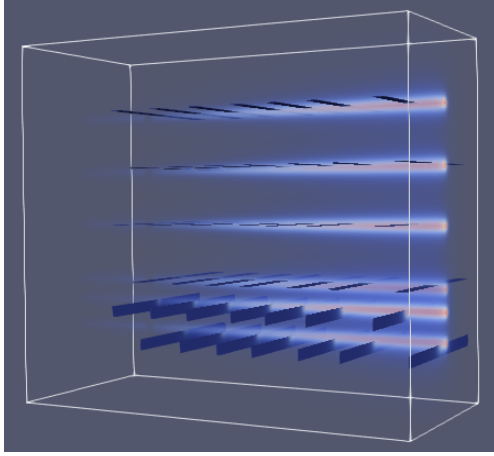


Figure 5.8: 3D representation of the sample holder with the beams impacting the tapes of the different batches. This qualitative representation shows the energy deposition through the material. The beams come from the left part of the figure.

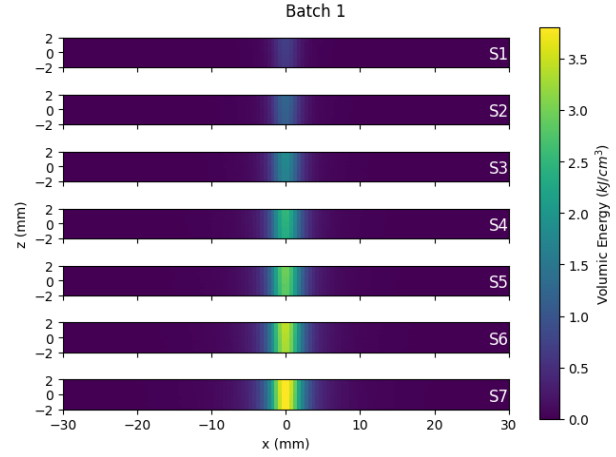


Figure 5.9: 2D representation of the energy deposition for batch B1. The volumic energy deposited inside the tape is represented by taking the mean over the thickness of the tape.

The results of the Monte Carlo simulations give the energy deposition per bin and these values can be easily normalised by the bin volume. The volumic energy deposited in each tape of batch B1 is illustrated in Figure 5.9. The results for the other batches can be found in Figure C.2 in the Appendix. For these 2D representations, as the energy over the tape thickness is relatively constant, the mean over the 10 bins is considered. The impact position and the variation of energy across the samples are distinctly visible in the representation.

5.3.2 Statistical analysis

The statistical nature of a Monte Carlo simulation leads to uncertainties on the obtained values. They are quantified during the simulations and the error values are determined per bin. The error in one bin ϵ_{bin} is given by Eq.(5.1) in which σ is the variance on the results and n the number of incident particles. The Monte Carlo simulations are conducted with one million incident protons at an energy of 440 GeV and then normalised by the real beam intensity.

$$\epsilon_{bin} = \frac{\sigma}{\sqrt{n}} \quad (5.1)$$

The simulations are considered accurate if the relative error (ϵ_{rel}) is below 5% in more than 80% of the part of interest. A better precision is not required as the uncertainties on the beam position and beam intensity are $\sim 10\%$ as detailed in Ref. [43]. The obtained relative errors for the tapes of batch B1 are shown in

Figure 5.10. The left graph (a) shows the results for the entire tape and the right graph (b) shows the values obtained in the region of interest, i.e. where the tape receives the most energy. For the analysis, this region is defined as a cut of one tenth of the tape length around its centre. Similar results are found for the other batches and the graphs are in Appendix C.2.

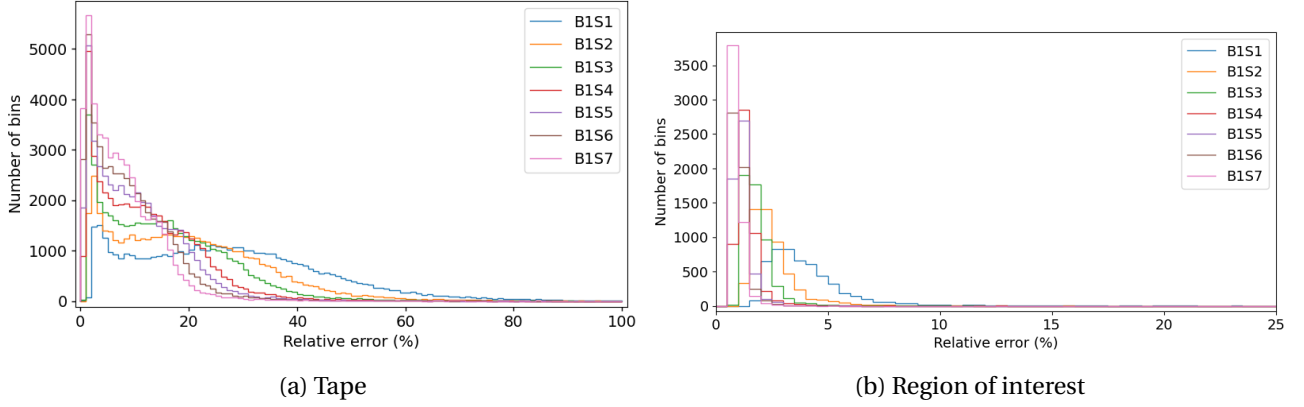


Figure 5.10: Relative error on the energy deposition values for BDSIM simulations with 10^6 incident particles for the HTS tapes of batch B1. The values are given for the entire tape (a) and for the region of interest (a cut of one tenth of the tape length around its centre) (b).

These graphs show that the values obtained for the first tape of each batch are slightly less accurate, which makes sense considering the beam-matter interaction mechanisms described in Section 2.6. Indeed, at the start of the secondary particles shower, fewer particles interact with the matter and the energy deposition is then based on fewer events which increase the variance of the results. Nevertheless, the numerical results of Table 5.2 confirm that the simulations are still below the limit of 5% in more than 80% of the region of interest.

Table 5.2: Percentage of bins with $\epsilon_{rel} < 5\%$ in the region of interest (a cut of one tenth of the tape length around its centre) for the BDSIM simulation made with 10^6 incident protons.

	S1	S2	S3	S4	S5	S6	S7
B1	84.85%	97.10%	99.25%	99.85%	99.94%	100%	100%
B2	92.85%	98.25%	99.60%	99.88%	100%	100%	99.98%
B3	82.35%	97.60%	99.46%	99.75%	99.88%	99.98%	100%
B4	91.98%	98.15%	99.37%	99.83%	99.96%	99.98%	99.98%
B5	81.77%	96.33%	98.54%	99.75%	99.94%	99.96%	99.98%
B6	88.77%	97.65%	99.13%	99.56%	99.85%	99.90%	99.98%

5.3.3 Determination of the hotspot temperature inside the material

To characterise the damage and facilitate comparisons between samples, the deposited energy is converted into a reached temperature. The relation between the specific energy e [J/kg] and the temperature T [K] is given by Eq. (5.2).

$$e = \int_T c_p(T) dT \quad (5.2)$$

The factor c_p is the specific heat capacity expressed in J/kgK . It quantifies the heat deposition required to increase the temperature of the material by 1K. The value of c_p varies with the temperature of the material. The specific heat capacity of the Hastelloy is used for the calculation as it has the dominant contribution. As the experiment starts with tapes at cryogenic temperature, Eq.(4.5) used in the analysis of the discharge experiment cannot be used. The values for the specific heat capacity at cryogenic temperature are studied in Ref.[61]. The obtained relation between the energy deposited and the temperature is illustrated in Figure 5.11.

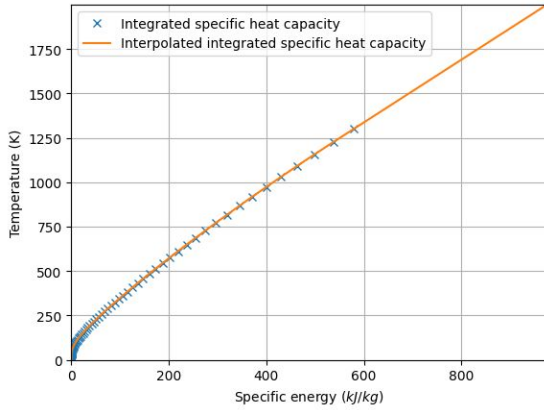


Figure 5.11: Temperature evolution as a function of specific energy, taking into account the temperature-dependent specific heat capacity of Hastelloy from Ref.[61].

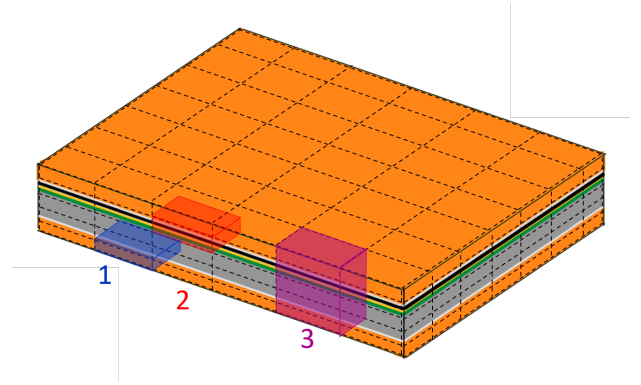


Figure 5.12: Simplified representation of the mesh on ReBCO tape. The bins theoretically considered for the different definition of the hotspot temperatures are shown.

The temperature repartition inside the tape looks similar to the energy repartition and the highest temperatures are reached inside the region of interest. To qualify the damage with a single representative value, a "hotspot temperature" must be defined and three potential definitions have been studied.

First, we assumed that the degradation made on the volume of one bin is significant enough to consider an impact on the superconducting properties of the material. The maximum temperature reached is then considered to be the hotspot value and is directly determined for all samples. The obtained values with the corresponding energy deposition are compiled in Table C.1 in the Appendix. The relative error on the energy for the bin, considering the statistical uncertainties of BDSIM simulation and the corresponding maximal temperature deviation are also given. Nevertheless, when the position of the corresponding bin is analysed, it is neither inside nor close to the superconducting layer. It corresponds for example to the position of bin 1 of Figure 5.12, the superconducting layer being in green. For the horizontally oriented tapes, this is in agreement with the y-offset, which moves the most intense part of the beam away from this superconducting layer, as shown in Figure 5.6. For the vertically oriented tapes, the superconducting layer is impacted first and the amount of deposited energy increases while the material is crossed, leading to the same conclusion about the bin position. Knowing this, the considered approach might not be the best to study the damage on the superconductor.

That's why, in a second time, only the bins containing YBCO layer are considered. As this layer is $1.7 \mu\text{m}$ thick, it corresponds to a layer of one bin as shown for bin 2 of Figure 5.12. The values obtained in this case are in Table C.2 in the Appendix. The hotspot temperatures are significantly smaller than the one obtained before. The temperature differences range from approximately 50 K for the first samples of the batches to 200 K for the last samples. Even if an underestimation of this value is more in line with the objectives of this research, the variation is significant. In addition, the studied results correspond to the instantaneous temperature repartition after the beam impact neglecting any heat transport within the material. In reality, transport will occur leading to a homogenisation of the temperature.

The solution to take into account the homogenisation is to consider the mean over the ten bins of the tape thickness. It creates a new mesh composed of large bins equivalent to bin 3 of Figure 5.12. This mean is computed for the deposited energy and then converted into temperature as calculating it directly with temperatures would have given other values due to the non-linearity of the relation. The hotspot temperature is the maximal temperature reached considering a unique value for each large bin. The values obtained are compiled in Table C.3 in the Appendix. They lie between the values from the previous approaches and they are then chosen to be the "hotspot temperature" used to qualify the damage of the samples.

To more precisely qualify the damage, the temperature gradient inside the tapes is studied. Starting from the hotspot temperature position, the gradient in temperature along the length and the width of the tape can be studied. The profile for batches B1 and B5 are shown in Figure 5.13. Along the length of the tape, the gradient is large around the impact position while the temperature remains low in the extremities of the tape. The profile over the width is different for the horizontal and vertical orientation. For the horizontal tapes as for B1, the temperature increases slightly as it corresponds to the beam direction. For the vertical tapes as for B5, the Gaussian shape corresponds to the beam profile with a positive y-offset corresponding to the beam impact position.

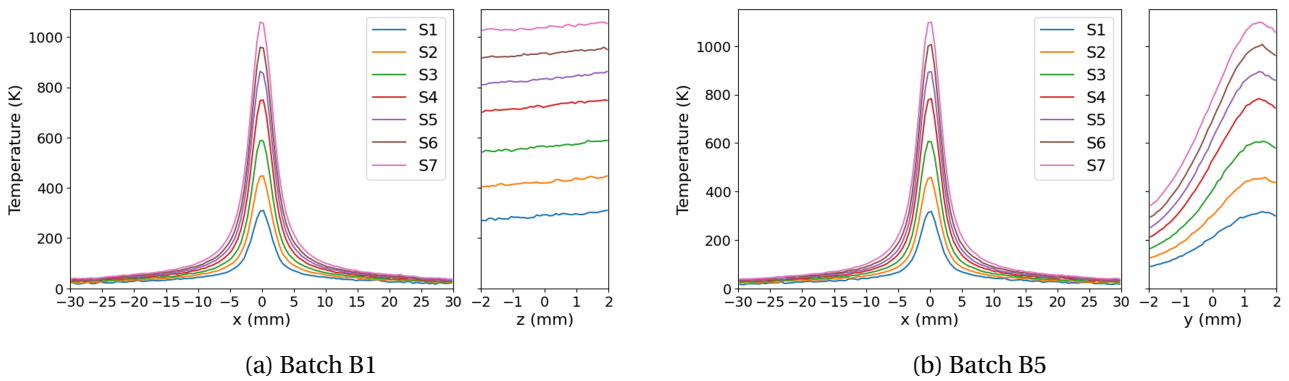


Figure 5.13: Distribution in temperature along the length and the width of the tape. The gradient is taken for the bin layer that corresponds to the position of the hotspot temperature for each sample.

The hotspot temperature that will be used for the damage analysis in Chapter 6 (for batches B1 and B2) are shown in Figure 5.14 with the error bar indicating the maximal deviation relatively to the statistical errors of the BDSIM simulations only.

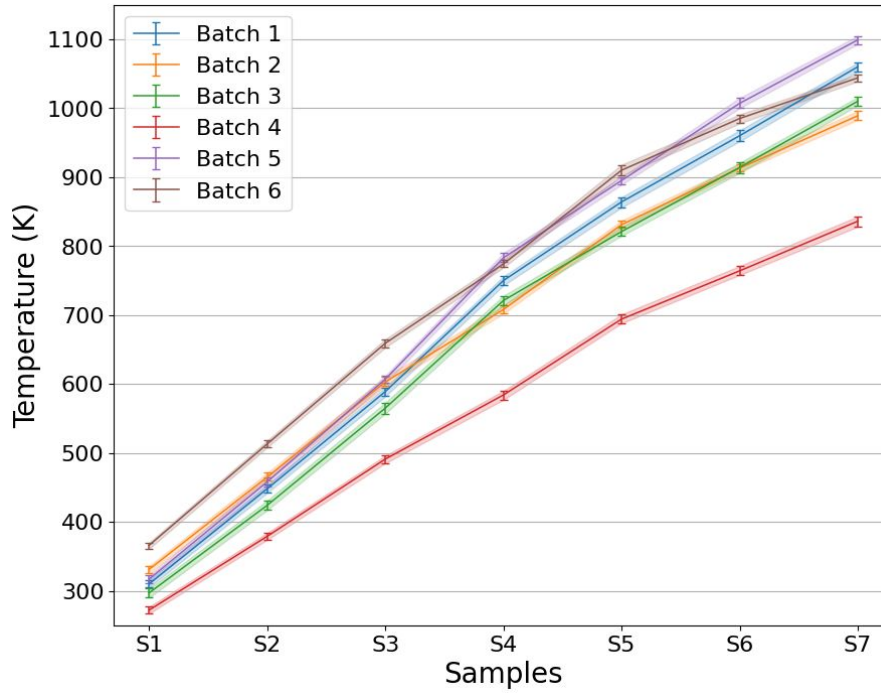


Figure 5.14: Hotspot temperature of the samples. The error bars show the maximal deviation relatively to the statistical errors of the BDSIM simulations.

5.4 Conclusion

The results of the Monte Carlo simulations performed using BDSIM based on the updated beam parameters show that the 42 tapes have been impacted during the experiment. The deposited energy profiles obtained from the simulation are in agreement with the beam trajectory and the beam-matter interaction mechanisms as the deposited energy increases along the beam trajectory. We conclude from the energy deposition profile that the hotspot temperature (maximal temperature reached inside a small volume that covers the entire tape thickness) can be used as a single numerical quantity to encapsulate the details of the induce damages. For brevity, these hotspot values are not repeated here but the reader can consult Table 6.1 which summarises the final results relevant to the analysed samples.

Damage qualification and quantification on HTS samples

6.1 Overview of the samples qualification

Damaged samples have been brought to the University of Geneva to measure their critical current following the technic described in Chapter 3. These measurements are expensive and time consuming and only twelve samples have been qualified after the HiRadMat-37 experiment (from batches B1 and B2) and seven after the discharge experiment.

Table 6.1 provides an overview of these samples history. Reading it from left to right, allows to know which damage and critical current measurement they have experienced. The information that concerns the HiradMat-37 experiment is in green with T_H the HiRadMat hotspot temperature and in dark green the I_c measurements post-irradiation except for the reference samples (in yellow) that have not been impacted. The information that concerns the discharge experiment is in blue with T_D the discharge hotspot temperature and in dark blue the I_c measurement after the discharge. For the critical current measurements, only the conditions (temperature and magnetic field) for which a I_c value is determined are given.

The results of the critical current measurement after the discharge experiment cannot be trusted. Indeed, during their shipping to the University of Geneva, the samples were not enough protected and may have been degraded. Any damage can then be caused by the discharge experiment itself or by the transport. Even if no conclusions can be drawn, the analysis is carried out to get an idea of the degradation of the properties of the samples.

As justified before (see Section 3.3.2), only the results for the voltage tap CD and for the upper critical current criteria ($V = 1\mu V/cm$) are detailed here for the analysis but the other configurations lead to the same conclusions.

Table 6.1: Overview of the history of some HTS samples. The different damaged experiments and critical current measurements, they have experienced, are given. The temperatures represent the damage level of a sample after the experiment. The given conditions for the critical current measurements are the one that leads to a I_c value. The information that concerns HiRadMat experiment is in green and the discharge experiment in blue. The reference samples are in yellow to highlight that they have been qualified without being impacted.

	HiRadMat-37		I_c Measurement		Discharge		I_c Measurement	
		T_H (K)	77K	4K		T_D (K)	77K	4K
R1	X	X	V	19T-10T	V	364	X	19T-1T
R2	X	X	X	X	V	1089	X	X
R3	X	X	V	19T-17T	X	X	X	X
R4	X	X	V	19T-5T	V	686	X	X
B1S1	V	310	V	19T-6T	V	414	V	18T-3T
B1S2	V	448	V	18T-6T	V	484	V	12T-11T
B1S3	V	589	V	19T-6T	X	X	X	X
B1S4	V	750	V	19T-4T	X	X	X	X
B1S5	V	864	V	11T, 8T-4T	X	X	X	X
B1S6	V	960	X	19T-0T	X	X	X	X
B1S7	V	1060	X	X	X	X	X	X
B2S1	V	331	V	19T-5T	V	544	V	19T, 17T-15T, 10T-9T
B2S2	V	465	V	19T-4T	V	606	V	19T-16T, 14T-12T, 8T-4T
B2S3	V	603	V	19T-4T	X	X	X	X
B2S4	V	708	V	19T-2T	X	X	X	X
B2S5	V	831	V	19T, 14T-12T, 9T-0T	X	X	X	X
B2S6	V	913	X	X	X	X	X	X
B2S7	V	989	X	8T-0T	X	X	X	X

6.2 Results of the critical current measurement

The critical current values obtained from the analysis of the measurements made by collaborators at the University of Geneva are shown for the different samples in Appendix D. Figure D.1 shows the results of the measurement at 4 K for batch B1 of the HiRadMat experiment, Figure D.2 for batch B2 and Figure D.3 for the discharge experiment. The critical current values at 77 K are compiled for all the studied samples in Figure D.4.

To be able to look at all the values at once, I developed an alternative representation of the results shown in Figure 6.1. The samples are represented along the x-axis with the reference samples in blue and the samples post-damage in different shades of orange. The shade of orange indicates the level of damage of the sample considering the scale on the top right of the figure. The plain colours correspond to the measurement after the HiRadMat-37 experiment. The hatched colours correspond to the measurement after the discharge experiment. The samples are classified by increasing hotspot temperature which value

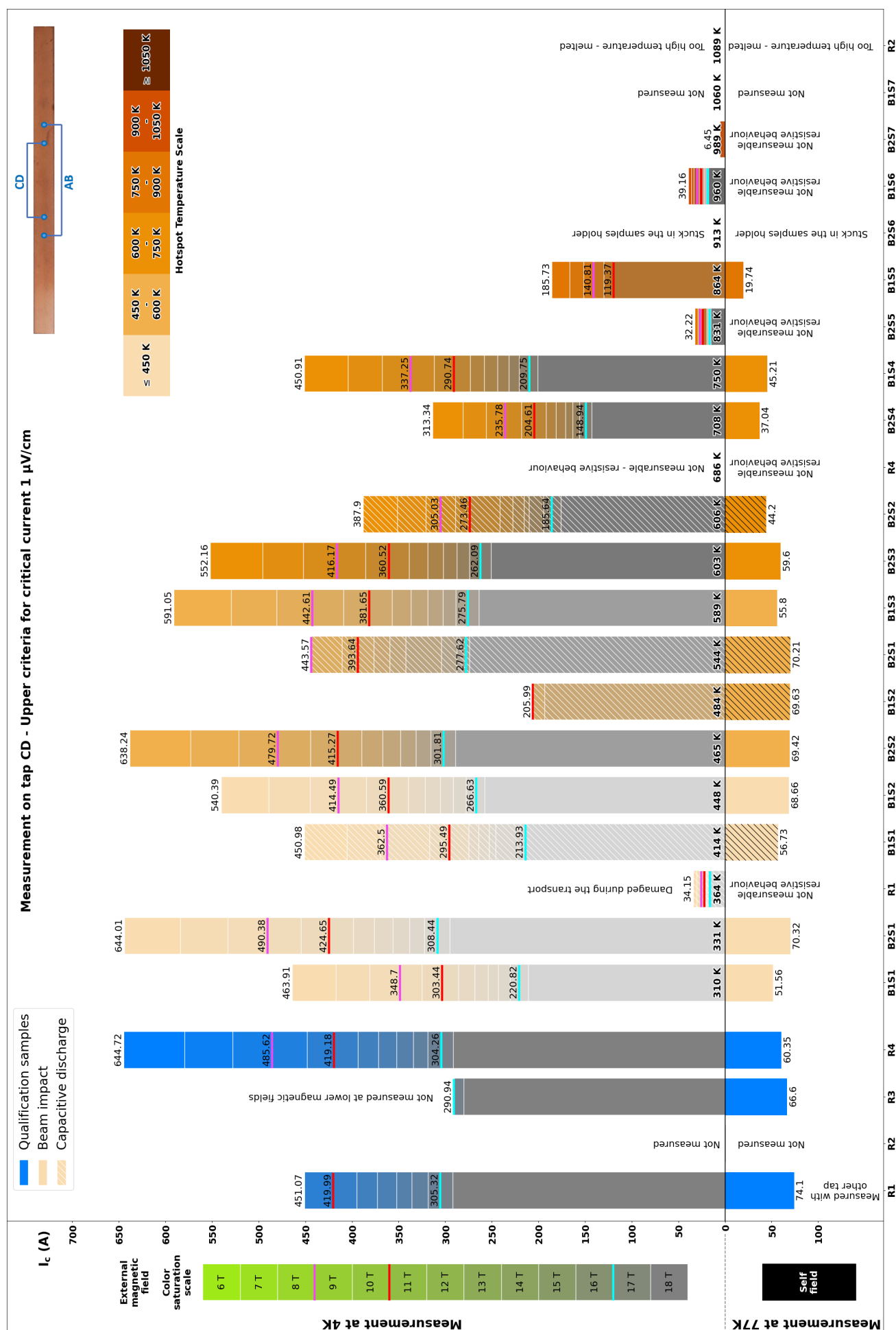


Figure 6.1: Overview of the critical currents for the studied HTS tapes pre- and post-damage.

is recalled above the x-axis. Looking at the larger deviation on the hotspot temperature given in Table C.3, the order remains the same even if the extreme values are taken.

For each sample, the critical current (y-axis) is given for all measurement configurations, one per level of the bar plot. The value corresponding to the measurement at 77 K in self-field is below the x-axis. The values corresponding to the measurements at 4 K are above the x-axis. The external magnetic field variation is indicated by the colour saturation following the green scale at the left of the figure. The external magnetic field varies from 18 T to 6 T. The coloured line added for some magnetic field values (17 T, 11 T and 9 T) are used to ease the identification of the different magnetic fields. Taken sample B1S1 as an example, the critical current at 77 K in self-field worths 51.56 A. Its critical current at 4 K and 18 T is approximately 210 A, at 4 K and 17 T it is 220.82 A as indicated above the turquoise line, etc.

For some samples, the measurements have not been done with all configurations. If a missing value is intermediate, it is calculated via interpolation from the values at higher and lower external magnetic fields. If there is no value at lower or higher magnetic field, the missing value is omitted and one has to pay attention to the saturation of the first colour and the last one to identify correctly the magnetic field value.

On Figure 6.1, comments are also given to explain the reason of missing values for some samples or to recall information important for the analysis. Often when there is no value, the measurement has been done but no critical current values have been calculated due to resistive behaviour of the samples, which corresponds to a fully damaged sample.

The first important conclusion drawn by looking at the graph without comparing the samples is that the damage induced by the experiments have an impact on the superconducting properties of the ReBCO tapes. For the most damaged samples, the degradation is very significative. For the least damaged samples, an in-depth analysis has to be done to interpret the results.

6.2.1 Comparison between the different samples

By comparing the critical current values of the characterised samples, a possible relation between the damage level and the degradation of the superconducting properties can be detected. To do this comparison, it is important to choose the parameters of the measurement (temperature and magnetic field) and to compare the critical current value of the different samples for the same conditions.

For instance, choosing the values at 4 K and 11 T (red lines on Figure 6.1) and focusing on HiRadMat samples (plain colour on Figure 6.1), a first look allows to see that they are not following any logical behaviour. Inversions are visible and less damaged samples show larger I_c degradation than the other one, e.g. B1S1 compared to B2S1, B1S2 compared to B2S2 or B2S4 compared to B1S4. Looking at more damaged samples (B2S5, B1S5, B1S6, B2S7), they show a clear reduction in critical current or they are fully broken. These behaviours are more or less the same for the other measurement conditions (tap AB).

Looking at the critical current values of the samples post-discharge experiment (R1, R2, R4, B1S1, B1S2, B2S1 and B2S2), one can directly notice that sample R1, R2 and R4 are totally broken. For R1, it is

clearly more probable that this damage has been caused by the transport as mentioned earlier. For R2, the I_c degradation can totally be explained by the temperature reached during the discharge as this sample melted during the experiment and any additional damage caused by the transport do no change anything. For R4, the situation is intermediate and it is not possible to prefer one origin of damage to the other. For the other samples (B1S1, B1S2, B2S1 and B2S2), the I_c degradation is consistent with the results obtained for similar hotspot temperature of the HiRadMat-37 experiment. For these samples, it is important to keep in mind that the degradation has to be considered from the most recent measurement done on the sample and not necessarily from the reference value.

6.2.2 Analysis of the degradation of the critical current

To be able to go further in the analysis and really compare the degradation before and after each damage, the degradation factor, $I_c/I_{c,0}$, is determined. The critical current values before damage $I_{c,0}$ are:

- for the HiRadMat samples: the mean of the reference samples critical current,
- for the discharge samples: the I_c value from the last measurement done on the sample.

This degradation factor is calculated for all critical current measurement configurations. It appears that the factors are relatively constant for the different configurations and the mean as well as the standard deviation for all measurements are calculated. The mean degradation factor is represented as a function of the hotspot temperature for the samples of the HiRadMat experiment in Figure 6.2. The error bars correspond to the standard deviation of the degradation factor.

The analysis is first made considering only the HiRadMat samples. It seems that the samples with a hotspot temperature below 500-600 K are not really damaged. One can imagine that the variation observed for sample B1S1 is due to the quality of the sample before the experiment. Above 500-600 K, the samples experience a critical current degradation proportional to the hotspot temperature. Above 900-1000 K, the degradation factor is closed to 0 and the tapes are completely damaged.

Using optimisation function, the data can be approached by two different fitting functions. The first one is a function linear by part described by Eq.(6.1). The least square optimisation of this function on the HiRadMat samples data gives $T_0 = 553.29 \text{ K}$ and $T_1 = 931.61 \text{ K}$ with a deviation compared to the exact values of 14.39%. This fit is represented by the green curve in Figure 6.2. A degradation factor equal to zero for hotspot temperature higher than T_1 is justified as other samples no present in Figure 6.2 (B2S6 and B1S7) can be considered broken and have hotspot temperature close to T_1 .

$$f_L(T) = 1 - \frac{\left[\left(|T - T_0| + (T - T_0) \right) - \left(|T - T_1| + (T - T_1) \right) \right]}{2(T_1 - T_0)} = \begin{cases} 1 & \text{if } T \leq T_0 \\ 1 - \frac{T - T_0}{T_1 - T_0} & \text{if } T_0 < T \leq T_1 \\ 0 & \text{if } T_1 < T \end{cases} \quad (6.1)$$

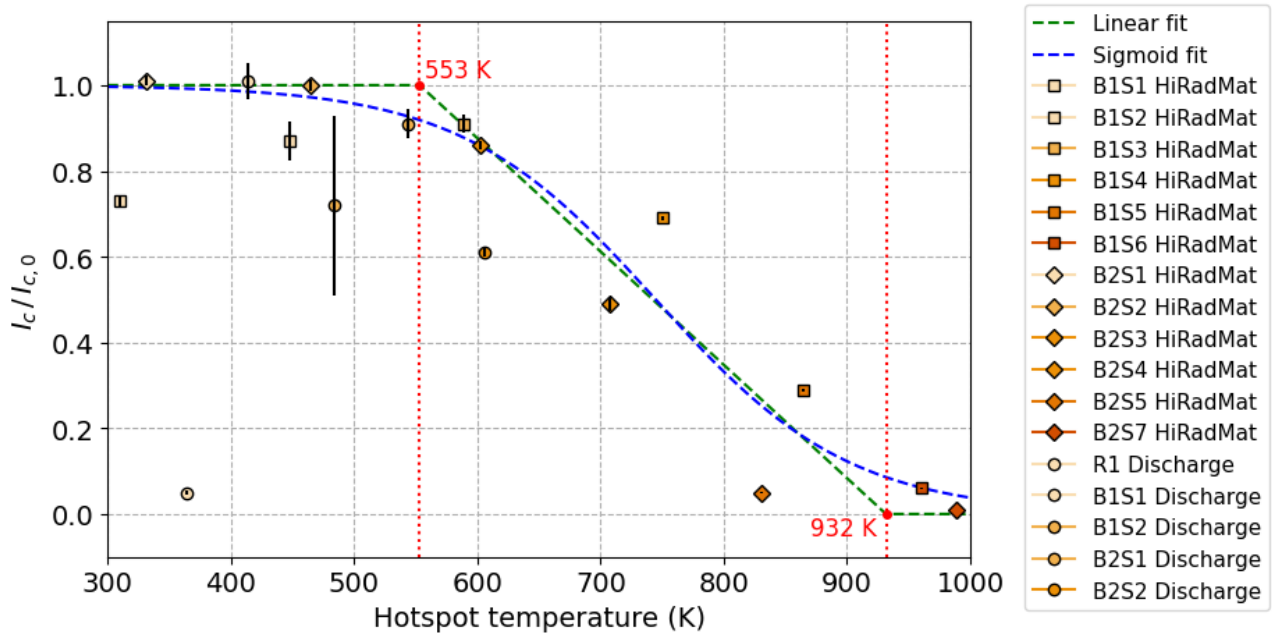


Figure 6.2: Graphical representation of the critical current degradation factor as a function of the hotspot temperature of the different damage experiments. The degradation factor is the mean over the different critical current measurement configurations. The standard deviation of this degradation is represented by the black error bars. The fit functions are calculated using only the HiRadMat samples.

A sigmoid function can also be used to fit the data. This function is considered as it is used to model a lot of thermomechanical phenomena. The sigmoid function of Eq.(6.2) gives the blue curve on Figure 6.2 for $a = 1.266 \cdot 10^{-2}$ and $T_k = 744.8$ determined by a least square optimisation. The deviation compared to the exact values is 14%.

$$f_S(T) = \frac{1}{1 - e^{a(T-T_k)}} \quad (6.2)$$

The results for the discharge samples are represented by the small circle on the same graph (Fig.6.2). Sample R1 again show a total degradation and can be ignored for the analysis. Sample B2S1 shows a very large error on the degradation factor which can be explained by the quality of the measurement for this particular sample. Indeed, a comment of the University of Geneva mentioned a resistive slope on the E-I curve due probably to a bad contact inducing variation between the different measurements. The other samples show a relatively good agreement with the fit functions. Ignoring sample R1, the linear fit has a deviation of 27.33% compared to the exact values and the sigmoid fit a deviation of 24.46%.

To choose one or the other fit and to conclude with strong certainty on the damage limits, the qualification of more samples is required as the critical current of the other batch of the HiRadMat experiment could reinforce the statistics of the results.

6.2.3 Interpretation of the variation between similar samples

In addition to increase the number of studied samples to confirm the damage limits, some other aspects could help to have a better understanding of the results post-irradiation.

Indeed, only the thermal aspect has been considered to qualify the damage of the tapes but other things clearly influences it. First, any thermal modification inside a material lead to internal strains. In case of multilayered material as ReBCO tape, the strain can be different for the materials leading even larger effects. These strains could break or modify the structure of the superconducting layer, which has a direct impact on the properties of the material. Thermomechanical studies has to be done using for example ANSYS simulation tools which allows to use the energy deposition results of the BDSIM simulations to do transient thermal-mechanical simulations.

In addition to the internal stress and strain, the tapes are also subject to constraints from the sample holder. The samples are indeed stuck in the large block of copper which experiences mechanical deformation due to the beam impact as shown in Figure 5.7. The way the sample holder influences the HTS tapes damage is different for the different batches. Indeed, the sample holder is not symmetrical as visible in Figure 5.1 and some samples are next to a large copper plate or multiple thin copper plates which can change the behaviour of the material. Analysing the results for the samples of batches B5 and B6 can give more information as due to their vertical orientation, they have experienced different mechanical constraints. Only looking to the position of batch B1 and B2, it could help to explain the variation seen on Figure 6.2 between similar samples of different batches (B1S4 vs B2S4 and B1S5 vs B2S5).

6.3 Conclusion

In conclusion, this analysis highlights that the samples damage induce degradation on their critical current values. There is a relation between the damage level of the sample and the decrease of the critical current. The fit function highlights three ranges of damage level. For hotspot temperatures below 553 K, the critical current is not degraded. For hotspot temperatures above 932 K, the samples show no more superconducting state. For intermediate hotspot temperatures, the critical current degradation is inversely proportional to the hotspot temperature. These values constitute the first results on the damage limits of ReBCO tapes but the qualification of more samples of the HiRadMat experiment is required to confirm them.

A deeper analysis of the damage induced to the samples during the HiRadMat-37 experiment, including mechanical studies, are needed to explain the variation between the samples for similar hotspot temperature. This further analysis could help to define a more precise mathematical relation between the damage level and the critical current degradation.

The work carried out for this master's thesis is part of a challenging context in which superconducting magnet technology is being improved. For the FCC-hh at CERN, HTS insertion dipole magnets are considered to conduct the beam along its 91 km circumference. In high-energy collider, machine protection systems are required to protect the equipment of the energy deposition induced by particles-matter interaction that occurs in case of failures. For the superconducting magnets, it is essential to know the damage limits of the superconductor to optimise the design of their protection. In this thesis, the results of damage experiments made on ReBCO tapes are studied to highlight the damage limits of this novel superconducting material.

The current capacitive discharge made on seven samples have reproduced damages that can occur in a hundred-millisecond time-scale failure. A detailed analysis of the experiment allowed to model the heat generation and the damage induced to the tapes. Considering the heat transfer and the contact resistance between the samples and the large copper clamps, we conclude that only 50% of the heat calculated from the current and voltage measurements contributed to the damages. Each current discharge is made with different initial voltages and capacitances, leading to different damage levels which are represented by the higher temperature reached inside the sample during the experiment. For the seven ReBCO tapes studied, these temperature lies between 364 K and 1089 K.

The beam impact realised with 440 GeV protons at cryogenic temperature during the HiRadMat-37 experiment induced damage on the HTS samples reproducing the scenario of a fast failure. Forty-two samples have been impacted receiving different amounts of energy due to their disposition on the sample holder. Using the beam parameters from the experiment, the energy deposited inside the tapes is determined via Monte Carlo simulations made using BDSIM. The energy profiles obtained correspond to the behaviour expected from particles-matter interactions mechanisms. To characterise the different damage level of the samples, a hotspot temperature is determined for each sample considering the maximal energy density deposited in a volume that covers the entire thickness of the tape. The hotspot temperatures vary from 270 K to 1100 K, increasing from the first sample impacted to the last one for each batch.

The critical current degradations are studied and compared according to the damage level of the samples. The HTS samples of two batches of the HiRadMat-37 experiment and five HTS samples of the discharge experiment have been qualified at the University of Geneva leading to the determination of their critical current post-damage. The analysis of the post-HiRadMat experiment measurement allows to highlight some information about the damage limits of ReBCO tape. For a hotspot temperature below 553 K, the tapes seem to keep their initial superconducting properties. For a hotspot temperature above 932 K, the tapes can be considered fully broken and they are not superconducting anymore. Between these values, the critical current degrades as the hotspot temperature increases. The samples of the discharge experiments show a relatively good agreement with these limits.

These results constitute the first information about the damage limits of ReBCO tapes. Even if the qualification of other samples of the HiRadMat-37 experiment has to be done in addition to a thermomechanical analysis, these damage limits give essential information for the FCC-hh design as they govern the viability of the machine operation.

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Appendix

LHC beam parameters evolution

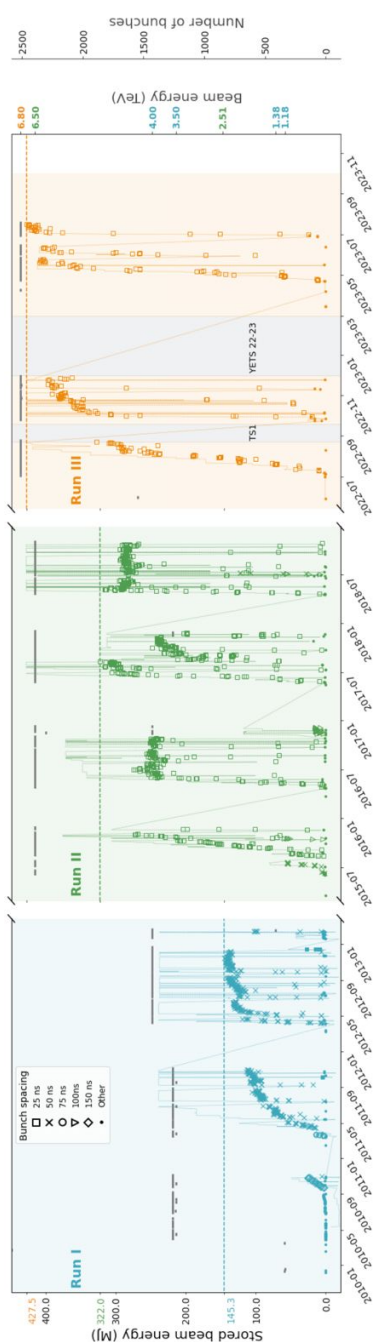


Figure A.1: Representation of the LHC performances for its three runs. The evolution of the maximal energy reached by the protons is shown. The total energy stored in one beam is calculated for the different run. The different dot shapes on the graphic indicate the time spacing between two bunches, which influences directly the amount of energy stored in the beam. Courtesy: C. Hernalsteens

Complement for discharge experiment results analysis

B.1 RLC equation

The RLC circuit equations are derived using the Kirchoff's voltage law (Eq.(B.1)). The simplest RLC circuit is considered as illustrated in Figure B.1 in which V_R is the voltage across the resistance R , V_L the voltage across the inductance L and V_C the voltage across the capacitance C .

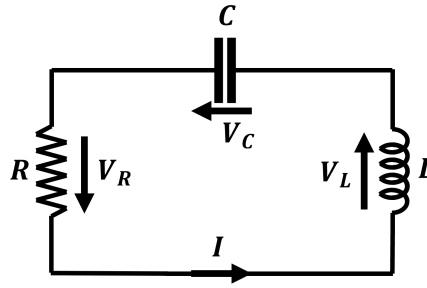


Figure B.1: Schematic representation of an RLC circuit. The current and voltage across the different components are represented and used to solve the Kirchoff's law.

$$V_R + V_L + V_C = 0 \quad (\text{B.1})$$

The voltage can be express in terms of the variable current $i(t)$.

$$\begin{cases} V_R(t) = R \cdot i(t) \\ V_L(t) = L \cdot \frac{di(t)}{dt} \\ V_C(t) = V_0 + \frac{1}{C} \int_0^t i(\tau) d\tau \end{cases} \quad (\text{B.2})$$

Substituting (B.2) in (B.1):

$$L \cdot \frac{di(t)}{dt} + R \cdot i(t) + (V_0 + \frac{1}{C} \int_0^t i(\tau) d\tau) = 0 \quad (\text{B.3})$$

Taking the derivative with respect to t :

$$L \cdot \frac{d^2 i(t)}{dt^2} + R \cdot \frac{di(t)}{dt} + \frac{1}{C} \cdot i(t) = 0 \quad (\text{B.4})$$

This second-order derivative equation can be solved using the initial conditions of the problem (see Eq.(B.5)). The initial current is null as the circuit is open at the time $t = 0$ s. The first derivative of the current is determined using (B.3) evaluated in $t = 0$ s.

$$\begin{cases} i(0) = 0 \\ L \cdot \frac{di(t)}{dt} \Big|_{t=0} + R \cdot i(0) + V_C(0) = 0 \Rightarrow \frac{di(t)}{dt} \Big|_{t=0} = \frac{-V_0}{L} \quad \text{with} \quad V_0 = V_C(0) \end{cases} \quad (\text{B.5})$$

In the studied case, the resistance is time dependent as the resistivity vary with the temperature.

$$R(t) = \frac{\rho(t) \cdot l}{A} \quad \text{with} \quad \rho(t) = \rho_0 \cdot (1 + \text{coef} \cdot (T(t) - T_0)) \quad (\text{B.6})$$

The system is then solved iteratively using numerical expression of the equations. In numerical expression, the derivation has to be converted in their discrete expression:

$$\begin{cases} \frac{di(t)}{dt} \rightarrow \frac{I(t) - I(t-1)}{\Delta t} \\ \frac{d^2 i(t)}{dt^2} \rightarrow \frac{I(t+1) - 2I(t) + I(t-1)}{\Delta t^2} \end{cases} \quad (\text{B.7})$$

Using (B.7) for (B.4), the numerical expression is:

$$L \cdot \frac{I(t+1) - 2I(t) + I(t-1)}{\Delta t^2} + R \cdot \frac{I(t) - I(t-1)}{\Delta t} + \frac{1}{C} \cdot I(t) = 0 \quad (\text{B.8})$$

$$\Leftrightarrow I(t+1) = \frac{\Delta t^2}{L} \cdot \left(I(t) \cdot \left[\frac{2L}{\Delta t^2} - \frac{R}{\Delta t} - \frac{1}{C} \right] + I(t-1) \cdot \left[\frac{R}{\Delta t} - \frac{L}{\Delta t^2} \right] \right) \quad (\text{B.9})$$

Equation (B.9) can be solved as $I(0)$ and $I(1)$ are determined from the initial conditions (B.5).

$$\begin{cases} I(0) = 0 \\ I(1) = \frac{V_0}{L} \cdot \Delta t \cdot \left(\frac{R \cdot \Delta t}{L} - 1 \right) \end{cases} \quad (\text{B.10})$$

Indeed:

$$I(1) = I(t+1)|_{t=0} \quad (\text{B.11})$$

$$= \frac{\Delta t^2}{L} \cdot \left(I(t)|_{t=0} \cdot \left[\frac{L}{\Delta t^2} - \frac{1}{C} \right] + (I(t) - I(t-1))|_{t=0} \cdot \left[\frac{L}{\Delta t^2} - \frac{R}{\Delta t} \right] \right) \quad (\text{B.12})$$

With (B.7) and (B.5):

$$(I(t) - I(t-1))|_{t=0} = \left. \frac{di(t)}{dt} \right|_{t=0} \cdot \Delta t = \frac{-V_0}{L} \cdot \Delta t \quad (\text{B.13})$$

$$\Rightarrow I(1) = \frac{\Delta t^2}{L} \cdot \left(0 \cdot \left[\frac{L}{\Delta t^2} - \frac{1}{C} \right] + \frac{-V_0}{L} \cdot \Delta t \cdot \left[\frac{L}{\Delta t^2} - \frac{R}{\Delta t} \right] \right) \quad (\text{B.14})$$

$$= \frac{\Delta t^2}{L} \cdot \left(\frac{V_0 \cdot R}{L} - \frac{V_0}{\Delta t} \right) \quad (\text{B.15})$$

$$= \frac{V_0}{L} \cdot \Delta t \cdot \left(\frac{R \cdot \Delta t}{L} - 1 \right) \quad (\text{B.16})$$

B.2 Contact resistance measurements

In order to study the sensitivity of the contact resistance of a HTS tape placed on the sample holder of the discharge experiment, measurements have been conducted while different parameters were varied. The measurements have been done for six samples for every composition of the parameters of Table B.1 (identical to Table 4.3).

Table B.1: Overview of the varied parameters of the contact resistance measurement experiment. The possible values and the incidence of the contact resistance are given.

Parameter	Possible values	Explanation
Torque value	1.75 Nm - (2.5 Nm) - 4 Nm	The strength, applied to screw the copper plate in order to maintained the sample and make a good contact, is controlled with a torque key.
Cleaning	Yes - No	The contact area of the tape and of the clamp is cleaned with a bit of alcohol and dry before placing the tape.
Tape positioning	Up - Down	The tape is placed with the superconducting layer up or down. The idea is to impose a complete removal of the tape and so a modification of its positioning.
Tin contact	Yes - No	For one reference tape with no tin layer at the contact area, the measurement has been done without it and then a small layer of tin have been soldered to compare the direct influence.

The results obtained for the different samples are compiled in the following tables.

Sample R1											
Tape length: 49 mm											
Meas. ID	Experimental condition								Resistance (Ω)		
	Torque (Nm)	Cleaning Yes/No	Position Up/Down	Tin contact Yes/No	Voltage tap position (mm)		Sample	Contact +	Contact -	Sample	Total
1	1.75	No	Up	Yes	25	26	23	2.87E-04	1.42E-03	3.39E-04	2.05E-03
2	2.5	No	Up	Yes	24	27	23	6.68E-04	1.44E-03	4.84E-04	2.59E-03
3	1.75	No	Up	Yes	24	27	23	9.68E-04	1.45E-03	4.71E-04	2.89E-03
4	2.5	No	Up	Yes	24	27	23	1.21E-03	1.35E-03	4.59E-04	3.02E-03
5	1.75	No	Down	Yes	25	26	24	4.02E-04	1.34E-03	9.41E-04	2.68E-03
6	2.5	No	Down	Yes	25	26	24	3.32E-04	1.41E-03	1.13E-03	2.87E-03
7	1.75	Yes	Up	Yes	24	27	24	3.86E-04	1.45E-03	9.02E-04	2.74E-03
8	2.5	Yes	Up	Yes	24	27	24	3.79E-04	1.46E-03	7.60E-04	2.60E-03
9	4	Yes	Up	Yes	24	27	24	3.68E-04	1.47E-03	6.99E-04	2.54E-03
Average								5.56E-04	1.42E-03	6.87E-04	2.66E-03
Variance								9.46E-08	1.97E-09	6.37E-08	7.04E-08

Sample B1S1											
Tape length: 46 mm											
Meas. ID	Experimental condition							Resistance (Ω)			
	Torque (Nm)	Cleaning Yes/No	Position Up/Down	Tin contact Yes/No	Voltage tap position (mm)		Sample	Contact +	Contact -	Sample	Total
1	1.75	No	Up	Yes	23	27	23	2.80E-03	1.39E-03	6.10E-04	4.80E-03
2	4	No	Up	Yes	23	27	23	1.60E-03	1.38E-03	5.21E-04	3.50E-03
3	1.75	No	Down	Yes	24	27	24	5.06E-03	1.34E-03	6.26E-04	7.03E-03
4	4	No	Down	Yes	24	27	24	3.51E-03	1.33E-03	5.71E-04	5.41E-03
5	1.75	No	Up	Yes	24	27	24	7.44E-04	1.33E-03	1.19E-03	3.26E-03
6	4	No	Up	Yes	24	27	24	5.21E-04	1.31E-03	8.97E-04	2.73E-03
Average								2.37E-03	1.35E-03	7.36E-04	4.46E-03
Variance								2.56E-06	8.22E-10	5.56E-08	2.16E-06

Sample B1S2											
Tape length: 48 mm											
Meas. ID	Experimental condition								Resistance (Ω)		
	Torque (Nm)	Cleaning Yes/No	Position Up/Down	Tin contact Yes/No	Voltage tap position (mm)			Contact -	Contact +	Sample	Total
					Contact +	Sample	Contact -				
1	1.75	No	Up	Yes	24	26	23	7.60E-04	1.41E-03	5.81E-04	2.75E-03
2	4	No	Up	Yes	24	26	23	6.31E-04	1.40E-03	5.78E-04	2.61E-03
3	1.75	No	Down	Yes	24	27	23	1.77E-03	1.48E-03	6.67E-04	3.92E-03
4	4	No	Down	Yes	24	27	23	1.24E-03	1.48E-03	5.86E-04	3.31E-03
5	1.75	Yes	Up	Yes	24	26	23	3.25E-04	1.48E-03	5.76E-04	2.38E-03
6	4	Yes	Up	Yes	24	26	23	3.34E-04	1.46E-03	5.45E-04	2.34E-03
Average								8.43E-04	1.45E-03	5.89E-04	2.88E-03
Variance								2.66E-07	1.15E-09	1.40E-09	3.15E-07

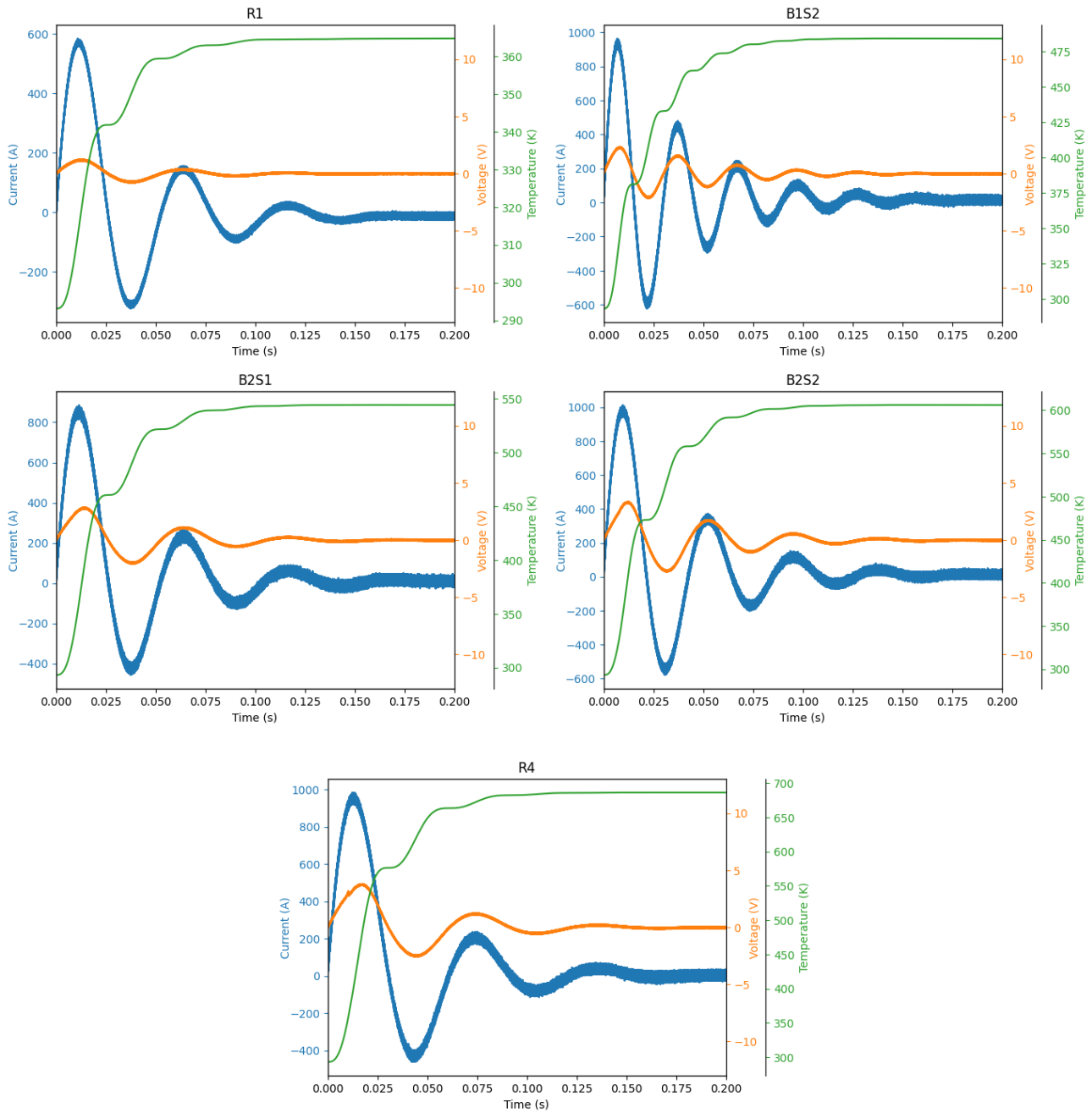
Sample B2S1											
Tape length: 48 mm											
Meas. ID	Experimental condition								Resistance (Ω)		
	Torque (Nm)	Cleaning Yes/No	Position Up/Down	Tin contact Yes/No	Voltage tap position (mm)			Contact -	Contact +	Sample	Total
					Contact +	Sample	Contact -				
1	1.75	No	Up	Yes	24	27	24	2.68E-04	1.48E-03	1.76E-04	1.92E-03
2	4	No	Up	Yes	24	27	24	2.65E-04	1.48E-03	4.65E-04	2.21E-03
3	1.75	No	Down	Yes	23	27	23	2.70E-04	1.50E-03	5.17E-04	2.29E-03
4	4	No	Down	Yes	23	27	23	2.50E-04	1.37E-03	5.35E-04	2.16E-03
5	1.75	Yes	Up	Yes	24	27	24	2.72E-04	1.49E-03	4.50E-04	2.21E-03
6	4	Yes	Up	Yes	24	27	24	2.40E-04	1.49E-03	4.38E-04	2.17E-03
Average								2.61E-04	1.47E-03	4.30E-04	2.16E-03
Variance								1.38E-10	1.98E-09	1.41E-08	1.29E-08

Sample B2S2											
Tape length: 48 mm											
Meas. ID	Experimental condition							Resistance (Ω)			
	Torque (Nm)	Cleaning Yes/No	Position Up/Down	Tin contact Yes/No	Voltage tap position (mm)			Contact +	Sample	Contact -	Total
					Contact +	Sample	Contact -				
1	1.75	No	Up	Yes	24	27	23	2.65E-04	1.43E-03	9.94E-04	2.69E-03
2	4	No	Up	Yes	24	27	23	2.54E-04	1.44E-03	8.51E-04	2.55E-03
3	1.75	No	Down	Yes	24	27	24	8.42E-04	1.02E-03	1.03E-03	2.89E-03
4	4	No	Down	Yes	24	27	24	3.39E-04	1.37E-03	6.74E-04	2.38E-03
5	1.75	Yes	Up	Yes	23	27	24	2.97E-04	1.43E-03	1.28E-03	3.01E-03
6	4	Yes	Up	Yes	23	27	24	2.63E-04	1.44E-03	9.37E-04	2.64E-03
Average								3.77E-04	1.36E-03	9.61E-04	2.69E-03
Variance								4.41E-08	2.30E-08	3.38E-08	4.32E-08

Sample B1S7											
Tape length: 61 mm											
Meas. ID	Experimental condition							Resistance (Ω)			
	Torque (Nm)	Cleaning Yes/No	Position Up/Down	Tin contact Yes/No	Voltage tap position (mm)			Contact +	Sample	Contact -	Total
					Contact +	Sample	Contact -				
1	1.75	No	Up	No	24	28	24	4.79E-04	1.54E-03	6.32E-04	2.65E-03
2	4	No	Up	No	24	28	24	6.75E-04	1.55E-03	5.94E-04	2.82E-03
3	1.75	No	Down	No	24	28	23	4.07E-04	1.54E-03	5.34E-04	2.48E-03
4	4	No	Down	No	24	28	23	4.97E-04	1.54E-03	5.70E-04	2.61E-03
5	1.75	Yes	Up	No	24	27	24	4.51E-04	1.51E-03	6.55E-04	2.62E-03
6	4	Yes	Up	No	24	27	24	5.31E-04	1.52E-03	5.86E-04	2.64E-03
7	1.75	No	Up	Yes	25	27	23	4.20E-04	1.52E-03	5.48E-04	2.49E-03
8	4	No	Up	Yes	25	27	23	3.98E-04	1.52E-03	5.18E-04	2.44E-03
9	4	No	Up	Yes	24	27	24	4.16E-04	1.51E-03	5.40E-04	2.47E-03
Average								4.75E-04	1.53E-03	5.75E-04	2.58E-03
Variance								6.81E-09	1.95E-10	1.89E-09	1.33E-08

B.3 Discharge measurements and results

The current and voltage measured during the discharge experiment and the evolution of the temperature reached inside the tape are plotted on the graphs for the different samples. The results for sample B1S1 and R2 are in Section 4.3 with the analysis. The results for sample R1, B1S2, B2S1, B2S2 and R4 are compiled here. Their analysis is the same as for sample B1S1.



C.1 Visualisation of the energy deposition

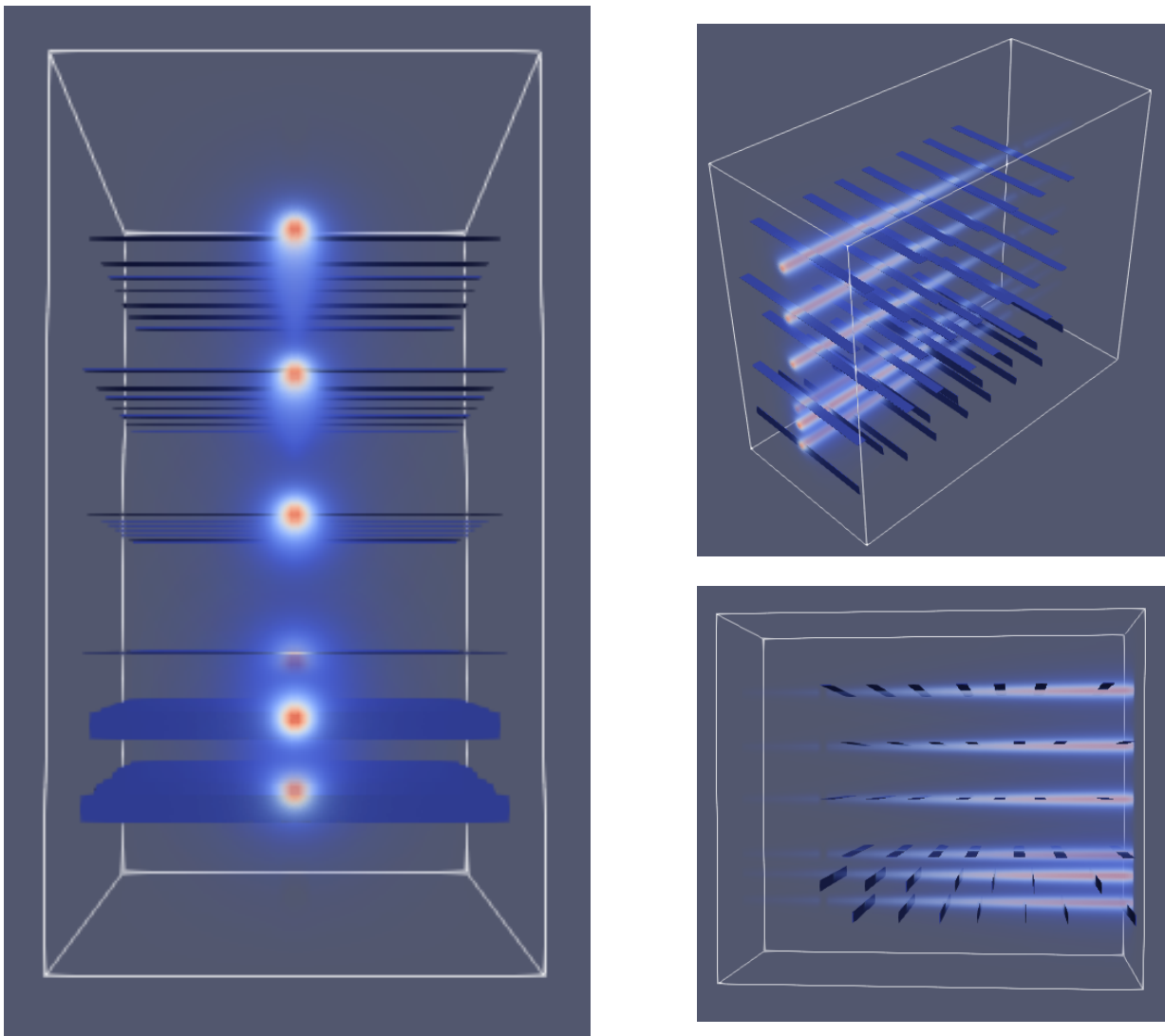


Figure C.1: 3D representation of energy deposition from different orientations.

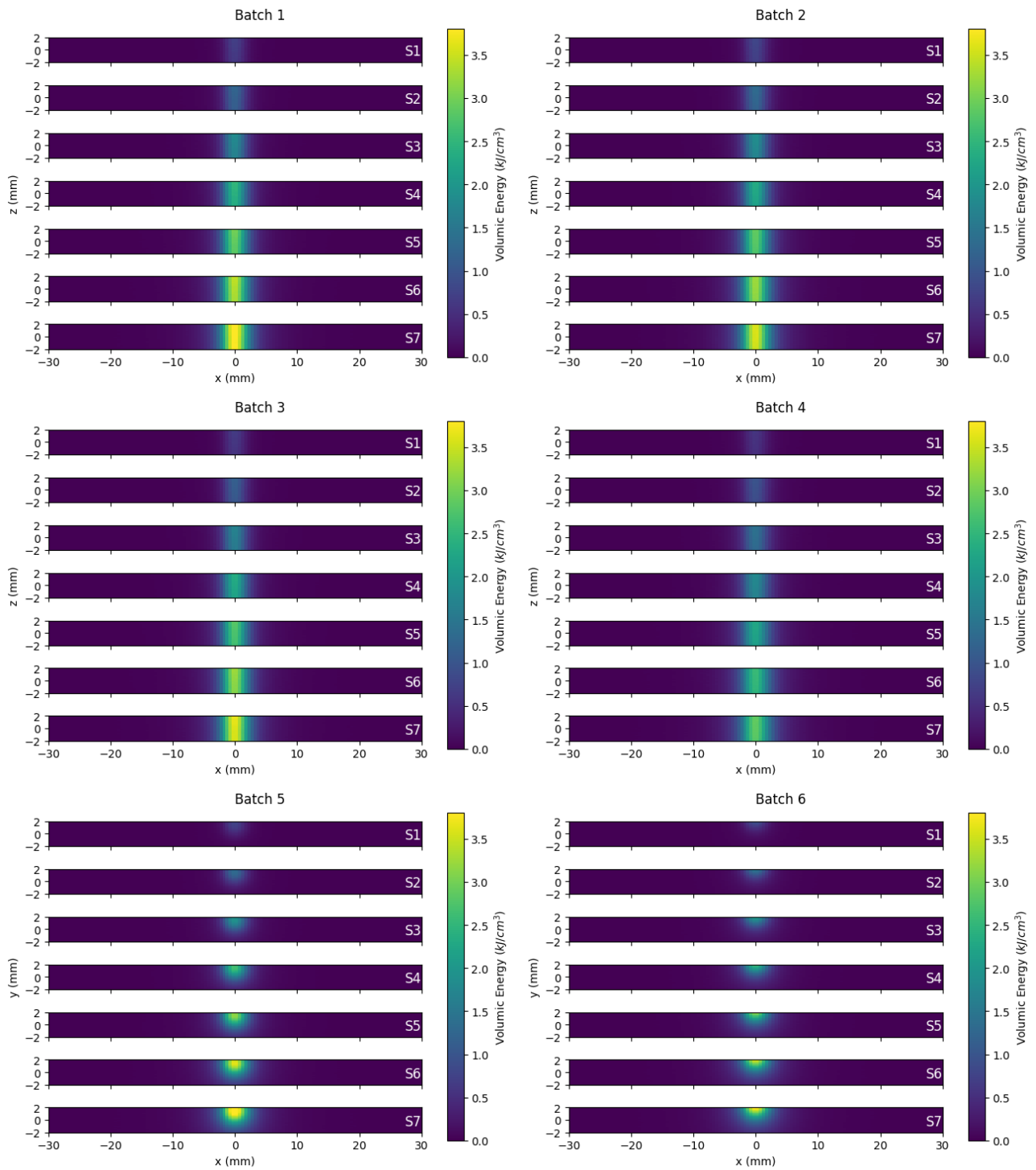


Figure C.2: 2D representation of the energy deposition. The volumic energy deposited inside the tape is shown in 2D by taking the mean over the thickness of the tape. These graphs show clearly the impact position and a corresponding energy deposition profile. It is clear that B4 received less energy than the other batches.

C.2 Monte Carlo simulation statistical study

Entire tape

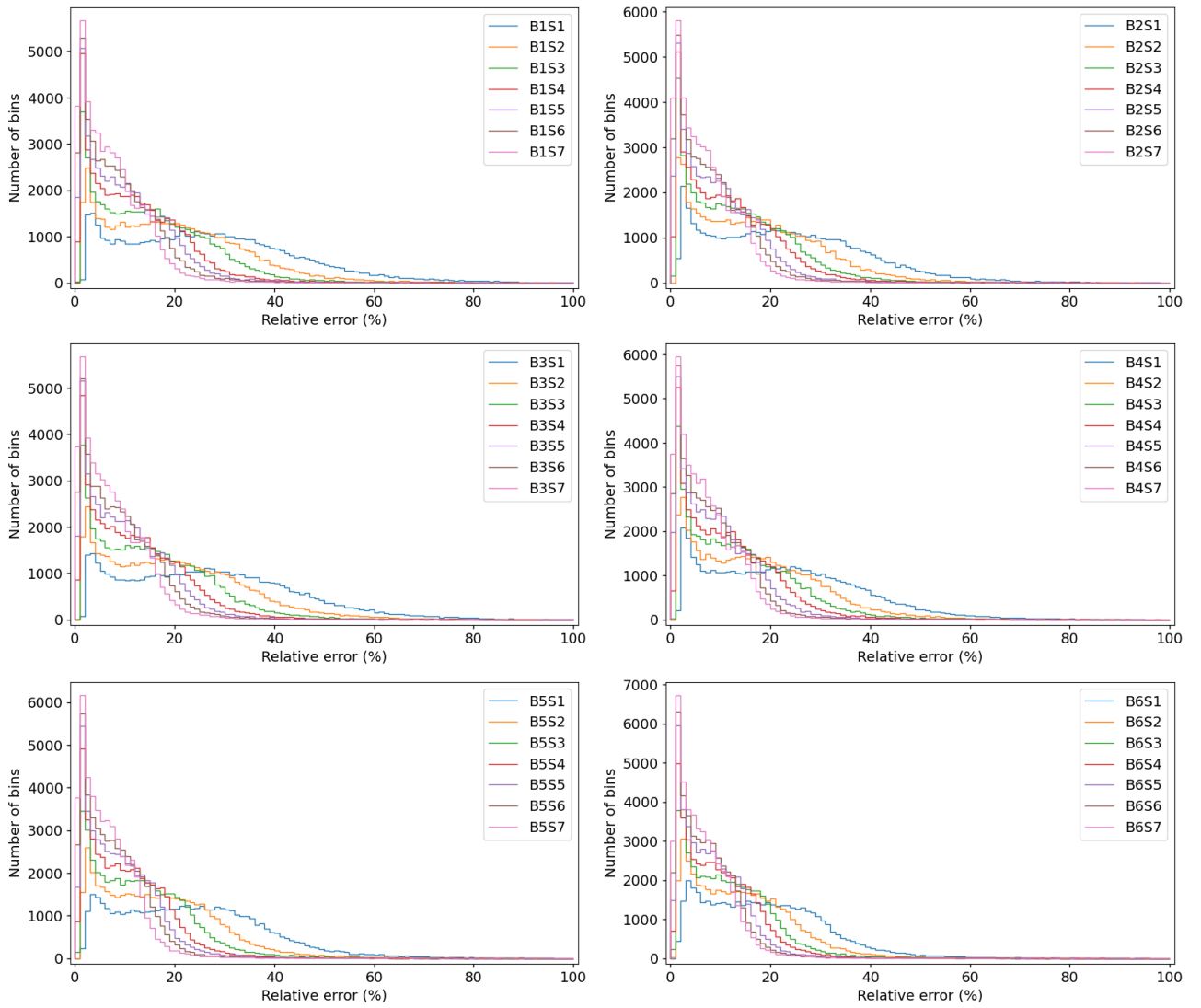


Figure C.3: The relative error in terms of deposited energy per bin is shown for all tapes of all batches. The histograms are similar for the different batches and we see that the relative error is smaller in the tapes that received the more energy: better statistics in S7 compare to S6, etc.

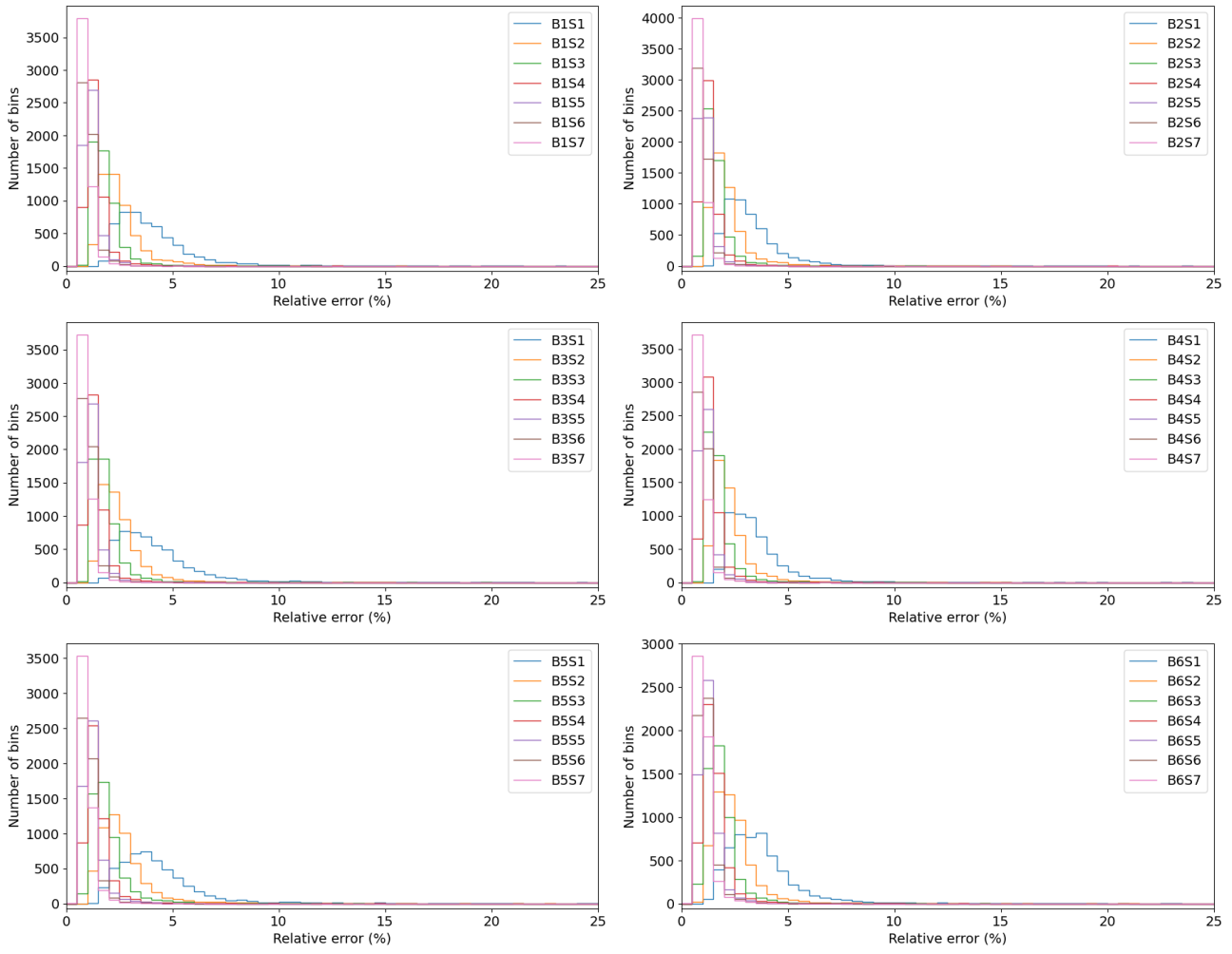
Part of interest

Figure C.4: The relative error in terms of deposited energy per bin is shown for all tapes of all batches in the region of interest (a cut of one tenth of the tape length around its centre). The relative error is significantly smaller in the part of interest and the criteria that 80 % of the part of interest has a relative error below 5% is respected.

C.3 Values from the hotspot temperature determination

Table C.1: The hotspot values determined considering the highest temperature reached in one bin of the tape. The corresponding energy deposition and its associate relative error are given. The largest temperature deviation corresponding to this error is also given.

Batch 1	B1S1	B1S2	B1S3	B1S4	B1S5	B1S6	B1S7
$T_{max}(K)$	333	489	635	809	934	1045	1145
$E_{max}(\frac{kJ}{kg})$	92.92	161.48	229.47	315.23	378.88	438.01	492.35
r (%)	4.09	4.3	1.61	0.99	1.0	1.06	0.73
$\Delta T(K)$	[323, 341]	[473, 504]	[627, 642]	[803, 815]	[926, 940]	[1036, 1054]	[1138, 1151]
Batch 2	B2S1	B2S2	B2S3	B2S4	B2S5	B2S6	B2S7
$T_{max}(K)$	362	509	662	786	919	1005	1087
$E_{max}(\frac{kJ}{kg})$	105.35	170.6	242.51	303.41	371.3	416.62	460.49
r (%)	3.53	2.1	1.32	1.7	0.76	1.39	1.03
$\Delta T(K)$	[353, 370]	[501, 516]	[655, 668]	[775, 796]	[913, 924]	[994, 1016]	[1078, 1095]
Batch 3	B3S1	B3S2	B3S3	B3S4	B3S5	B3S6	B3S7
$T_{max}(K)$	321	473	626	789	907	1001	1103
$E_{max}(\frac{kJ}{kg})$	88.14	154.13	225.15	305.11	364.94	414.16	469.15
r (%)	4.44	5.07	2.12	1.48	1.72	1.18	1.81
$\Delta T(K)$	[311, 330]	[455, 489]	[615, 635]	[780, 798]	[894, 919]	[991, 1009]	[1087, 1118]
Batch 4	B4S1	B4S2	B4S3	B4S4	B4S5	B4S6	B4S7
$T_{max}(K)$	303	421	550	665	781	857	931
$E_{max}(\frac{kJ}{kg})$	80.58	130.96	189.63	243.8	301.17	339.26	377.25
r (%)	3.52	6.37	1.64	2.1	2.59	1.14	0.79
$\Delta T(K)$	[296, 309]	[401, 439]	[543, 556]	[653, 675]	[765, 797]	[849, 864]	[924, 936]
Batch 5	B5S1	B5S2	B5S3	B5S4	B5S5	B5S6	B5S7
$T_{max}(K)$	343	501	656	846	966	1083	1190
$E_{max}(\frac{kJ}{kg})$	97.22	167.0	239.46	333.76	395.79	458.17	517.07
r (%)	3.26	2.37	5.55	0.98	0.69	0.95	0.84
$\Delta T(K)$	[335, 350]	[492, 509]	[627, 683]	[839, 852]	[960, 971]	[1074, 1090]	[1182, 1197]
Batch 6	B6S1	B6S2	B6S3	B6S4	B6S5	B6S6	B6S7
$T_{max}(K)$	385	552	720	850	998	1087	1167
$E_{max}(\frac{kJ}{kg})$	115.11	190.49	270.78	335.87	412.78	460.24	504.2
r (%)	1.86	1.92	0.84	0.71	1.08	0.93	0.72
$\Delta T(K)$	[379, 389]	[544, 559]	[715, 724]	[845, 854]	[989, 1006]	[1078, 1094]	[1160, 1173]

Table C.2: The hotspot values determined considering the highest temperature reached in one bin on the superconducting layer of the tape. The corresponding energy deposition and its associate relative error are given. The largest temperature deviation corresponding to this error is also given.

Batch 1	B1S1	B1S2	B1S3	B1S4	B1S5	B1S6	B1S7
$T_{max}(K)$	297	418	544	697	795	888	981
$E_{max}(\frac{kJ}{kg})$	78.35	129.69	186.92	259.69	307.78	355.04	403.51
r (%)	6.7	4.58	1.5	1.45	0.85	0.91	1.07
$\Delta T(K)$	[284, 310]	[404, 431]	[538, 550]	[689, 705]	[789, 799]	[881, 893]	[972, 988]
Batch 2	B2S1	B2S2	B2S3	B2S4	B2S5	B2S6	B2S7
$T_{max}(K)$	305	438	553	653	772	845	914
$E_{max}(\frac{kJ}{kg})$	81.47	138.71	191.07	238.27	296.21	333.24	368.75
r (%)	7.25	3.13	1.7	1.43	2.9	2.07	1.33
$\Delta T(K)$	[290, 319]	[428, 448]	[546, 560]	[646, 660]	[754, 788]	[831, 858]	[904, 923]
Batch 3	B3S1	B3S2	B3S3	B3S4	B3S5	B3S6	B3S7
$T_{max}(K)$	278	392	528	654	753	847	935
$E_{max}(\frac{kJ}{kg})$	70.55	118.41	179.53	238.75	287.09	334.49	379.76
r (%)	5.3	4.65	5.09	1.78	1.67	2.37	1.04
$\Delta T(K)$	[269, 287]	[379, 404]	[508, 548]	[645, 662]	[743, 762]	[831, 863]	[927, 942]
Batch 4	B4S1	B4S2	B4S3	B4S4	B4S5	B4S6	B4S7
$T_{max}(K)$	256	348	467	533	631	693	758
$E_{max}(\frac{kJ}{kg})$	61.44	99.53	151.56	181.59	227.51	257.39	289.75
r (%)	5.69	2.66	4.17	1.18	1.21	0.89	1.35
$\Delta T(K)$	[246, 264]	[341, 354]	[452, 480]	[528, 537]	[624, 636]	[687, 697]	[750, 766]
Batch 5	B5S1	B5S2	B5S3	B5S4	B5S5	B5S6	B5S7
$T_{max}(K)$	299	427	569	727	825	931	1021
$E_{max}(\frac{kJ}{kg})$	79.16	133.84	198.32	274.31	323.3	377.71	425.18
r (%)	3.71	3.12	4.6	1.85	1.02	2.27	1.47
$\Delta T(K)$	[292, 306]	[417, 436]	[549, 588]	[716, 737]	[818, 831]	[914, 947]	[1009, 1033]
Batch 6	B6S1	B6S2	B6S3	B6S4	B6S5	B6S6	B6S7
$T_{max}(K)$	339	479	609	714	843	905	968
$E_{max}(\frac{kJ}{kg})$	95.52	156.81	217.17	267.59	332.09	363.83	397.0
r (%)	2.12	2.21	0.92	0.76	1.04	0.74	0.75
$\Delta T(K)$	[333, 343]	[470, 486]	[604, 613]	[709, 717]	[835, 849]	[899, 909]	[962, 973]

Table C.3: The hotspot temperature is the maximum temperature reached inside the tapes while considering the mean energy over the thickness. The corresponding specific energy value and the relative error on this value are given. The largest deviation in temperature gives values ΔT . These values are the one used for the damage limits determination.

Batch 1	B1S1	B1S2	B1S3	B1S4	B1S5	B1S6	B1S7
$T_{max}(K)$	310	448	589	750	864	960	1060
$E_{max}(\frac{kJ}{kg})$	83.64	142.95	207.69	285.39	342.78	392.64	445.74
r (%)	2.87	1.92	1.44	1.16	1.13	1.09	0.80
$\Delta T(K)$	[305, 316]	[442, 454]	[582, 595]	[743, 756]	[856, 871]	[952, 968]	[1053, 1066]
Batch 2	B2S1	B2S2	B2S3	B2S4	B2S5	B2S6	B2S7
$T_{max}(K)$	331	465	603	708	831	913	989
$E_{max}(\frac{kJ}{kg})$	92.14	150.87	214.43	264.92	326.25	368.33	408.22
r (%)	2.59	1.73	1.42	1.17	0.86	0.82	0.79
$\Delta T(K)$	[325, 336]	[460, 471]	[597, 610]	[702, 714]	[826, 837]	[908, 919]	[983, 996]
Batch 3	B3S1	B3S2	B3S3	B3S4	B3S5	B3S6	B3S7
$T_{max}(K)$	297	424	565	721	821	914	1010
$E_{max}(\frac{kJ}{kg})$	78.04	132.31	196.66	271.36	321.25	368.43	419.06
r (%)	3.29	2.32	1.87	1.24	1.00	0.99	0.80
$\Delta T(K)$	[290, 303]	[417, 431]	[557, 573]	[714, 728]	[815, 828]	[906, 921]	[1004, 1016]
Batch 4	B4S1	B4S2	B4S3	B4S4	B4S5	B4S6	B4S7
$T_{max}(K)$	272	379	491	584	694	764	836
$E_{max}(\frac{kJ}{kg})$	68.05	112.91	162.20	205.21	258.24	292.63	328.46
r (%)	3.12	1.89	1.52	1.45	1.25	1.05	1.15
$\Delta T(K)$	[267, 277]	[374, 384]	[485, 496]	[577, 590]	[688, 701]	[758, 771]	[828, 843]
Batch 5	B5S1	B5S2	B5S3	B5S4	B5S5	B5S6	B5S7
$T_{max}(K)$	317	458	607	783	895	1007	1099
$E_{max}(\frac{kJ}{kg})$	86.21	147.56	216.14	302.16	358.73	417.62	466.94
r (%)	2.81	2.16	1.22	1.12	0.81	0.93	0.74
$\Delta T(K)$	[311, 322]	[451, 465]	[601, 612]	[777, 790]	[889, 900]	[1000, 1015]	[1093, 1105]
Batch 6	B6S1	B6S2	B6S3	B6S4	B6S5	B6S6	B6S7
$T_{max}(K)$	366	513	659	774	910	985	1044
$E_{max}(\frac{kJ}{kg})$	106.92	172.47	241.00	297.53	366.37	405.61	437.28
r (%)	1.98	1.42	1.22	0.93	1.13	0.84	0.59
$\Delta T(K)$	[361, 370]	[508, 518]	[653, 665]	[769, 780]	[902, 918]	[978, 991]	[1039, 1049]

Complement for the critical current results

Results of the critical current measurement analysis for the analysed HTS samples. The values presented here correspond to the measurement done with the voltage tap CD and for the upper criteria for the critical current values. They are equivalent to the data presented in Figure 6.1.

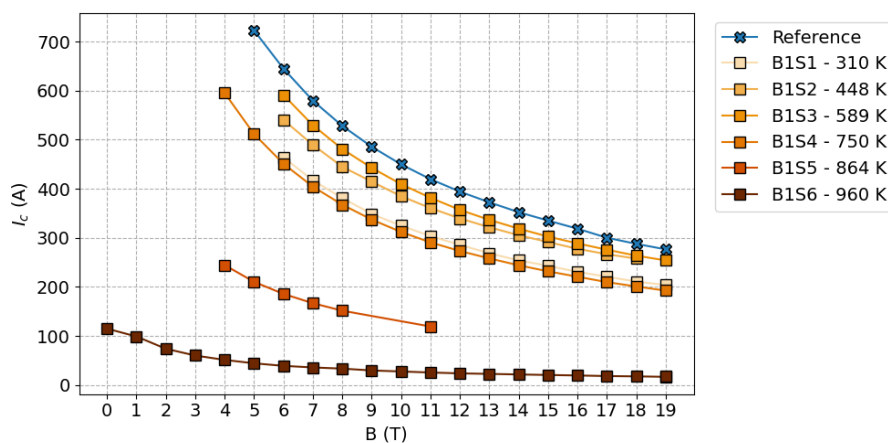


Figure D.1: Critical current at 4 K for different magnetic fields for the Batch B1 samples of the HiRadMat-37 experiment.

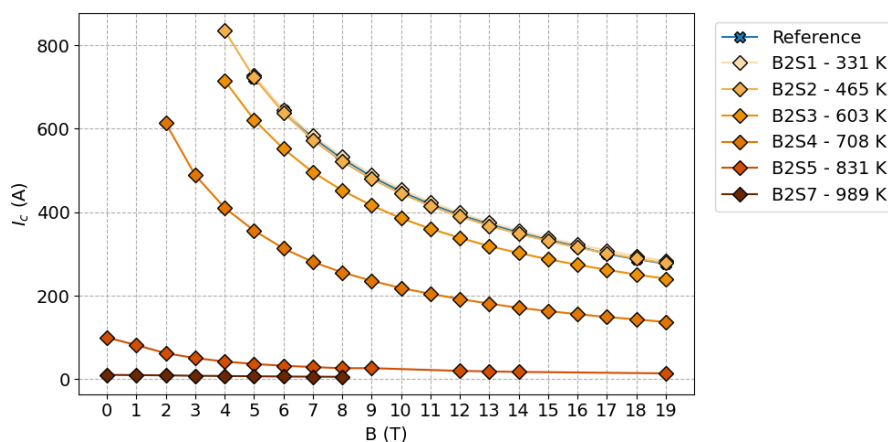


Figure D.2: Critical current at 4 K for different magnetic fields for the Batch B2 samples of the HiRadMat-37 experiment.

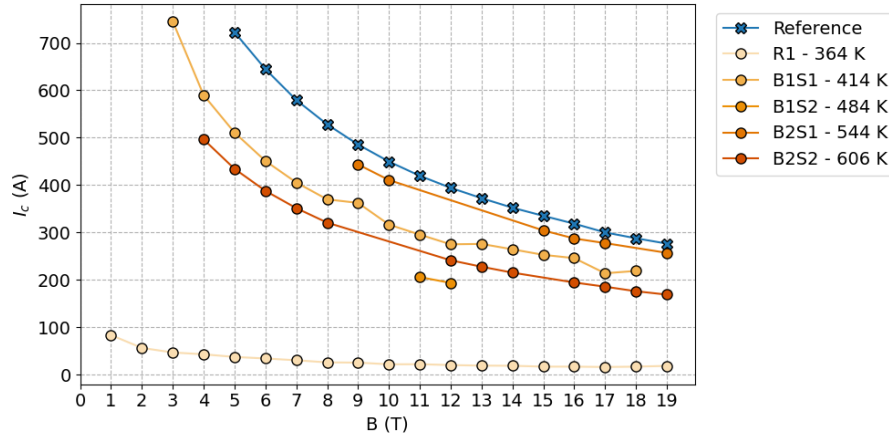


Figure D.3: Critical current at 4 K for different magnetic fields for the samples of the Discharge experiment.

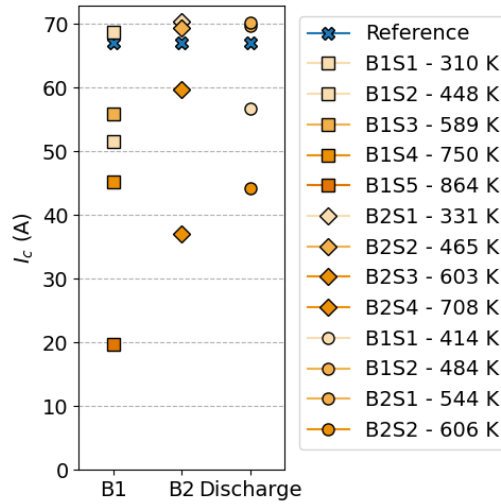


Figure D.4: Critical current at 77 K for all samples.