DAMAGE EXPERIMENT WITH SUPERCONDUCTING SAMPLE COILS - EXPERIMENTAL SETUP AND OBSERVATIONS DURING BEAM IMPACT[*]

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Abstract

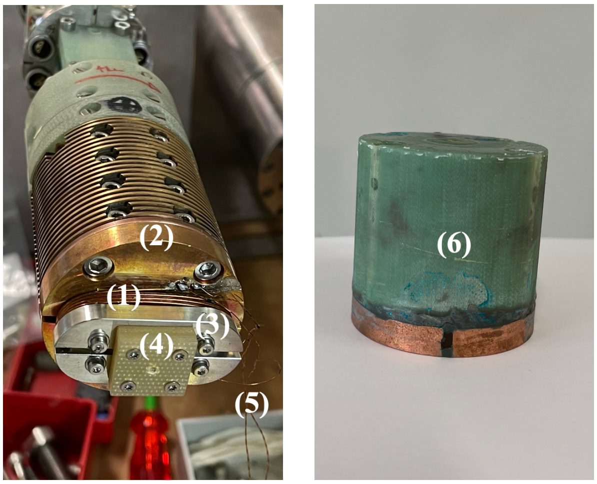
The damage mechanisms and limits of superconducting accelerator magnets due to the impact of high-intensity particle beams have been subject to extensive studies in the past years at CERN. Recently an experiment with dedicated sample coils made from Nb-Ti and Nb_3Sn strands was performed at CERN's HiRadMat facility. This paper describes the design and construction of the sample coils as well as the results of their qualification before the beam impact. In addition, the experimental setup will be discussed. Finally, measurements during the beam experiment like the beam-based alignment, the observations during the impact of 440 GeV protons on the sample coils and the achieved hot-spots and temperature gradients will be presented.

INTRODUCTION AND DESCRIPTION OF THE EXPERIMENTAL SETUP

To study the damage limits of superconducting coils due to proton beam impact, a multi-stage experimental campaign has been devised and carried out at the CERN HiRadMat experimental facility [1] over the past years. Prior experiments aimed at deriving the damage mechanisms and limits of superconducting strands made of Nb-Ti, Nb_3Sn, and high-temperature superconducting materials, both at room [2] and at cryogenic temperatures [3]. This latest experiment aims to study additional damage mechanisms in the coil as a whole, using sample coils wound with low-temperature superconducting strands that were impacted with 440 GeV/c proton beams at < 5.5 K. The experiment was carried out in October 2022 and is the focus of this paper.

Table 1: Properties of the Nb-Ti and Nb_3Sn Strands Used to Wind the Experimental Sample Coils (from [4] and [5])

Strand	Diameter	Cu-to-SC ratio	Filament size
Nb-Ti	0.825 mm	1.95	6 µm
Nb_3Sn	0.85 mm	1.2 ± 0.1	<55 µm



(a) (b)

Figure 1: (a) Nb-Ti coil mounted on the high-current probe at UniGe: (1) Nb-Ti winding (the shape is identical for the Nb_3Sn sample coil), (2) half-moon copper terminals, (3) wire-blocking part, (4) G10 holding piece, (5) voltage taps. (b) Nb_3Sn coil protected by (6) G10 clamp with diameter of 4.8 cm.

A set of small sample coils was wound at Karlsruhe Institute of Technology (KIT) using strands of polyimid insulated Nb-Ti, as used for the LHC dipole and quadrupole magnets and RRP® Nb_3Sn insulated with fibre-glass, which is used for the HL-LHC final focusing quadrupole magnets [5]. Table 1 shows the properties of the strands and filaments.

The strands with a length of about 1.7 m were wound around two half-moon-shaped copper pieces, as shown in Fig. 1, which are electrically insulated by a Macor® ceramics sheet. For the winding of the Nb-Ti coils a tension of 80 N was applied. For the Nb_3Sn coils a tension of 50 N was used. Stainless Steel wire-blocking parts were placed on the copper body to prevent the winding from shifting upwards. The finished structure was held together with a holding piece, made out of epoxy glass cloth laminated sheets (G10). The Nb-Ti coils were soldered to half-moon copper terminals along with two pairs of voltage taps for critical current measurements before and after beam impact. The Nb_3Sn coils were heat-treated at the University of Geneva (UniGe) using a standard temperature profile [5]. Then the leads and voltage taps were soldered to the copper terminals. Finally, the Nb_3Sn coils were impregnated with CDK101K epoxy at the CERN polymer lab and equipped with a G10 clamp to hold them in place during impregnation and prevent movement during powering.

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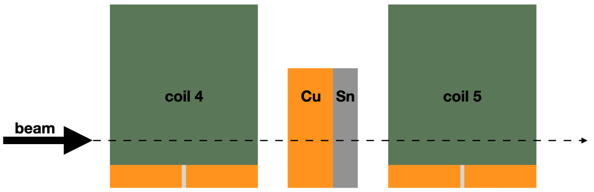

Figure 2: Schematic view of the arrangement of the different elements in a batch: the coils (green) are aligned along the beam axis and copper blocks (orange) are used to tune the hot-spot temperatures through the creation of additional secondary particle showers. Tin foils (silver) are used to record the beam impact with imprint marks. Note: this schematic only shows two out of the five coils contained in one batch.

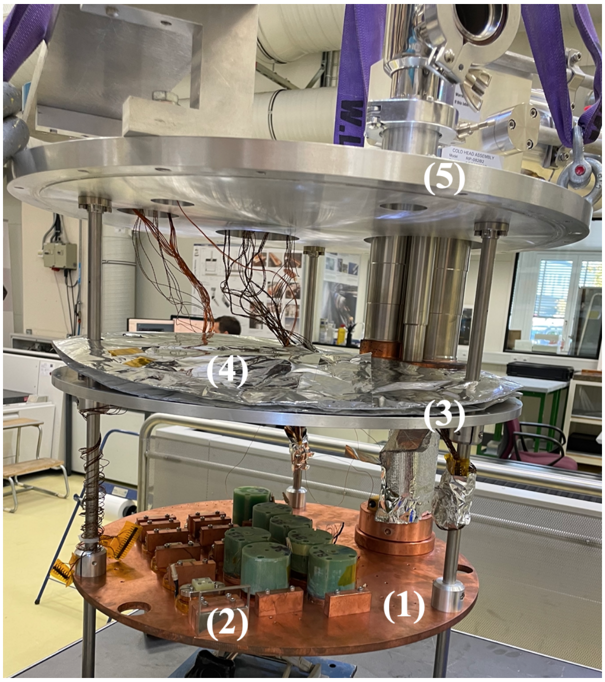

Figure 3: Internal view of the vacuum vessel: (1) second stage plate with the samples installed, (2) alignment piece, (3) first cooling stage, (4) multi-layer insulation, and (5) vacuum vessel lid. The radiation shield and the external vacuum tank are not shown.

Based on the damage limits derived in the previous beam impact experiment at 4 K [6] with Nb-Ti and Nb_3Sn superconducting strands, the hot-spot temperatures in the windings of the sample coils were chosen to reach between 200 and 750 K for Nb_3Sn and 300 to 900 K for Nb-Ti. Dedicated FLUKA [7] Monte Carlo simulations were conducted to define and optimize the experimental layout to reach these hot-spots. These simulations and results are discussed in detail in [8]. The final layout consists of three batches of five coils, aligned along the beam axis. The coils of each batch are separated by 1 cm thick copper blocks used to adjust the peak energy deposition along the batch by creating secondary particle showers. The first batch contains five Nb-Ti coils, the second batch two Nb_3Sn and three Nb-Ti coils and the third batch five Nb_3Sn coils. The 0.1 mm thick Sn foils were inserted downstream of the copper blocks to allow visualising the beam impact and beam size and also to benchmark the hot-spot temperature simulations. A schematic view of the arrangement of a batch is shown in Fig. 2.

For the beam impact, the coils were cooled down to 5.5 K using a cryogenic-free system [6], as shown in Fig. 3, mimicking the failure case of parts of the LHC beam impacting a superconducting magnet at cryogenic temperatures. The system comprises a vacuum vessel that houses a two-stage cryocooler (Sumitomo RP-082B2) and a radiation shield. The first stage cools the radiation shield, which surrounds the 50 cm wide second stage copper plate where the coils are installed. Each stage and the radiation shield are wrapped in multi-layer aluminium insulation to reduce radiative thermal losses. The vessel was placed on a horizontally and vertically movable stage to allow the precise alignment of the samples with beam for the impact of the three batches. Two diamond detectors [9] were installed outside the vessel to measure the particle showers during the Beam-Based Alignment (BBA) phase at the beginning of the experiment described below.

QUALIFICATION OF THE SAMPLES

For the pre-irradiation qualification process, the critical current of the sample coils was measured at UniGe in a dedicated cryostat in liquid helium. The Nb-Ti coils were measured in self field while the Nb_3Sn coils were qualified in an external field of 7 T. Finite Element Method simulations were performed to derive the relation between transport current and peak magnetic field and the load line of 2.44 T/kA ± 5 % [10]. The expected quench current was derived from critical current measurements performed on non-irradiated strand samples [6].

Figure 4 shows the measured critical currents of the Nb-Ti and Nb_3Sn samples coils, which were derived from fits on measured coil voltages, during the transition from the superconducting to the normal state. The number of training quenches for Nb_3Sn was up to three times higher compared to Nb-Ti. This could be caused by the fact, that the Nb_3Sn sample coils were measured in an external magnetic field of 7 T, whereas the Nb-Ti coils were measured in self field. The Nb-Ti coils reached critical currents between 976 and 1014 A (94-98% of the short-sample limit), while the critical current in the Nb_3Sn reached between 1027 and 1128 A (91-100% of the short-sample limit).

The position of each coil within the three batches was determined by the number of quenches and the critical current, such that the coils with fewer training quenches and higher critical currents were placed upstream of others as these coils are expected to be more sensitive to induced damage.

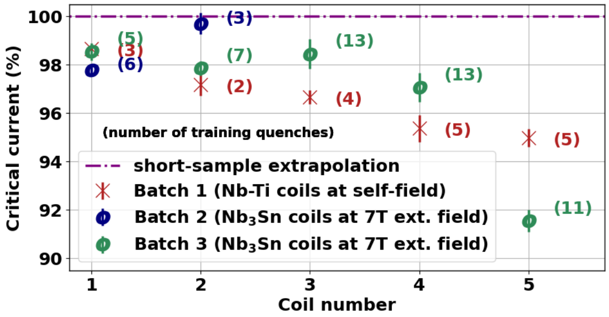

Figure 4: Critical current of the Nb-Ti and Nb_3Sn coils expressed as a fraction of the short-sample limit. The Nb-Ti coils (red crosses) were measured in self field. The Nb_3Sn coils (green and blue squares) were measured in an external field of 7 T. Note: the three last Nb-Ti coils in second batch haven't been qualified before the experiment and therefore the critical current is not shown here.

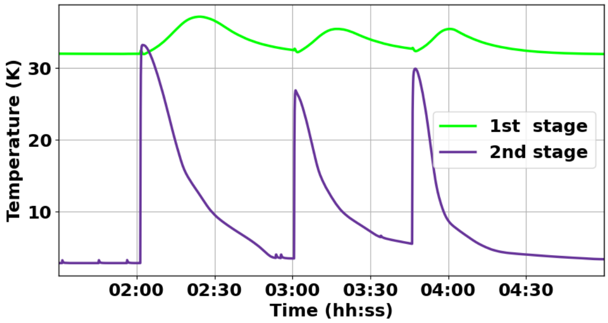

Figure 5: Measured temperature on the first stage (green) and on the second stage (purple) during the beam experiment. The temperature increase after each high-intensity shot is well visible.

BEAM TIME

The BBA in both transverse planes was performed by impacting the alignment piece, the base plate and the shower development copper blocks of batch one with low intensity beams. The losses were detected by a combination of the fixed installed ionisation chamber Beam Loss Monitors (BLMs) and the diamond detectors mounted on the experimental setup. The BBA confirmed the correct positioning and movement of the device, and the batches of samples were then successively irradiated with three high intensity beam shots. The beam impact positions were separated by 62.5 mm, so the device was moved after each high-intensity shot. The temperature of both stage plates was monitored during the experiment. After each shot the temperature of the second stage plate rose to values between 25 and 35 K and about 45 minutes were required to cool down back to < 5.5 K before the next shot (see Fig. 5).

The beam sizes and intensities for the three successive shots were measured using a beam screen (BTV) and fast beam current transformer (FBCT). The measured values are shown in Table 2. The intensities matched the target intensities within 8%, while the beam sizes where within 40% from the expected targets. These values were then used to recompute the achieved hot-spot temperatures from Monte Carlo energy deposition simulations. The hot-spot temperature in the Nb-Ti coils reached from 298 K to 863 K with gradients of up to 25 K/10μm. In the Nb_3Sn coils the hot-spots ranged from 206 K to 713 K with gradients of up to 18 K/10μm. More detailed results of the simulation are described in [8]. A subsequent visual inspection of the samples and partially melted tin witness foils finally confirmed the correct impact of the beam on each sample.

Table 2: Measured Parameters (Intensity, Pulse Length, and Transverse Beam Sizes) for the Three Beam Shots

	Batch	Intensity ($\times10^{12}$ p^+)	Pulse length	σ_x	σ_y
1	Nb-Ti	3.86	900 ns	1.4 mm	1.0 mm
2	Mixed	2.57	600 ns	1.4 mm	1.0 mm
3	Nb_3Sn	2.56	600 ns	1.4 mm	1.0 mm

SUMMARY AND OUTLOOK

For the first time, a damage experiment has been performed using Nb-Ti and Nb_3Sn sample coils at cryogenic temperature with 440 GeV/c proton beam at the CERN HiRadMat facility. A total of 15 samples grouped in three batches have been impacted by shots of up to 3.86×10^{12} protons, creating hot-spot temperatures in the coil windings between 206 K up to 863 K. The visual inspection of the irradiated samples and partially melted Sn witness foils confirmed the correct alignment of the sample plate for each beam shot and provided a further validation of the expected hot-spot temperatures. The post-irradiation critical current qualification measurements will be performed as soon as the activation levels have decayed sufficiently to evaluate the damage impact as a function of the hot-spot temperature and temperature gradients. Furthermore, thermomechanical simulations to calculated the stress in the coil windings caused by the beam impact will be performed.

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