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BEAM IMPACT EXPERIMENT TO QUALIFY THE DAMAGE LIMITS OF Nb_3Sn SAMPLE COILS PRE-IRRADIATED TO 30 MGy*

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Abstract

The superconducting magnets of high-energy accelerators are exposed to two types of beam-induced effects: long-term exposition to a radiation field and instantaneous beam impact from fast failure cases. A series of experiments has been carried out at CERN to derive the damage limits of low-temperature superconductor strands and sample coils. The latest experiment characterised the damage limits of Nb_3Sn racetrack sample coils impacted by a 440 GeV/c proton beam at cryogenic temperature. The effect of a beam impact on superconducting coils aged by long-term radiation exposure, however, is currently unknown. This paper outlines the preparation of an experiment to be performed at CERN's HiRadMat facility to investigate the damage on sample coils which have been radiation-aged with γ-rays prior to the beam impact, to simulate the anticipated integral dose levels reached by the HL-LHC final focusing triplet magnets during their operational lifetime, of 25 to 30 MGy. The damage limits for these sample coils will be derived and compared with the results obtained in the previous experiment for non-aged coils. The design and fabrication of these sample coils, the details of the γ-ray irradiation and the results from their qualification tests before beam impact is discussed. The results of energy deposition simulations that define the optimal parameters for the proton beam to be used in the experiment to reach the envisaged energy deposition levels are presented. The experimental setup and the experimental procedure are discussed.

INTRODUCTION

The High-Luminosity Large Hadron Collider (HL-LHC) will be the first accelerator to operationally use magnets with Nb_3Sn coils [1]. The main advantage of the Nb_3Sn material compared to the Nb-Ti is the higher critical current density J_c and the higher upper critical field $B_{c,2}$, while its brittleness is the main disadvantage. Therefore, Nb_3Sn magnets are impregnated with CTD101k epoxy to prevent any strand movement.

Collisions in a high-energy collider induce intense radiation to the superconducting magnets on both sides of the interaction points. Depending on their polarity and the total integrated luminosity, the total dose expected in the HL-LHC final focusing quadrupoles will reach between 20 and 30 MGy [2, 3]. The mixed radiation field consists mainly of photons with a wide range of energies [4]. The effects of the radiation dose on the different parts of the magnets were studied experimentally. After a dose of 8 MGy (valid for both photons and protons), the electromagnetic shower component degrades the CTD101k by separating the radicals, which reduces its mechanical strength [5].

In addition to the long-term radiation damage, the Nb_3Sn magnets could be damaged by machine misconfiguration causing ultra-fast failures, which brings the beam on an incorrect trajectory, leading to the development of particle showers, eventually reaching the superconducting magnets [6, 7]. The energy deposited by the shower particles causes localised heating, leading to mechanical stresses [8–12]. The damage limits of Nb_3Sn coils impregnated with CTD101k due to the impact of high-brightness beams have been studied during the prior HiRadMat-61 experiment [13–15]. No degradation was found in racetrack coil samples damaged with hot spots up to 670 K and peak strains in the winding up to 0.5%. The damage limit from the instantaneous impact could be lower if the epoxy was aged by long-term radiation exposure.

To prepare the upcoming experiment, the sample Nb_3Sn coils were exposed to γ-rays at doses of 25 and 30 MGy. They will be subsequently irradiated with a high-intensity 440 GeV/c proton pulse at 4 K.

This paper discusses the fabrication of the sample and the pre-irradiation transport current measurements, which qualified the coils prior to both γ-ray irradiation and proton beam impact, to allow quantitative comparison after the induced damage. The γ-ray irradiation procedure is discussed along with the energy spectrum used during the radiation ageing and measurement of received dose and its spacial distribution. The beam intensity and size for the experiment were fixed and the resulting energy deposition was simulated using the radiation transport code FLUKA [16] with graphical interface FLAIR [17]. The conversion of the deposited energy into hot spot temperatures and temperature gradients was performed. The potential degradation of coils, resulting from the beam with the requested properties, in the terms of critical current is discussed.

Coil samples were wound using a tension of 50 N with ~1.7 m long 108/127 RRP® Nb_3Sn strand insulated with S2 glass fibre, identical to that used in the HL-LHC triplets

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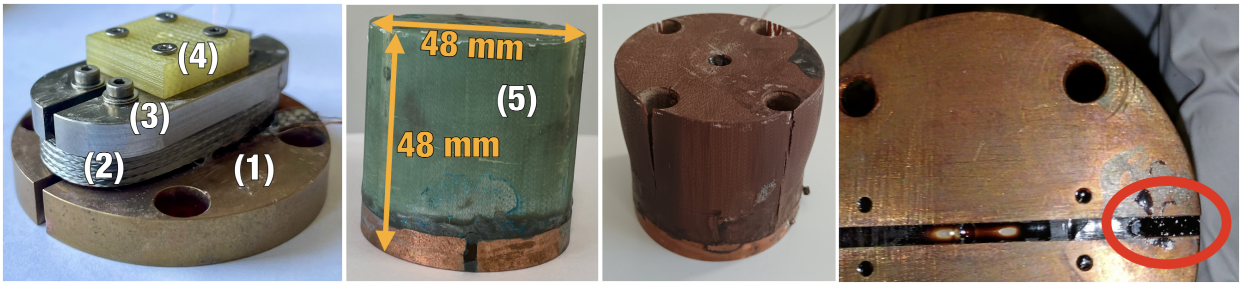

(a) (b) (c) (d)

Figure 1: (a) Photo of a Nb_3Sn sample coil: (1) semi-circular copper core piece, (2) winding consisting of the 108/127 RRP® Nb_3Sn strand insulated with S2 glass fibre, (3) stainless-steal blocks, (4) G10 support piece; (b) Sample coil with G10 protection clamp (5); (c) Deformed G10 clamp after exposure to a dose of 30 MGy. (d) Bottom view of the coil showing bubbles inside the CTD101k epoxy following exposure to a dose of 30 MGy.

[18]. There are four winding layers with a total of 18 turns. The non-magnetic core consists of two semicircular copper pieces electrically insulated by a sheet of Macor® ceramic. The core has a racetrack shape with straight sections of 25 mm and a bending radius of 5 mm. The two semi-circular copper pieces block the winding from below and the top is bounded by two stainless steel blocks held together by a G10 support piece. The assembled coil was heat treated with the HL-LHC temperature profile [18]. After heat treatment (see Fig. 1, item (a)), two sets of voltage taps were soldered to the strand to be used during critical current measurements. A G10 protection clamp was fitted to resist the Lorentz forces to the coil, which are maximal in the centre of the straight racetrack coil parts. The clamp also acts as a reaction mould for the CTD101k epoxy impregnation. The complete Nb_3Sn sample with a diameter and height of 48 mm is shown in Fig. 1, item (b).

SAMPLE SUPERCONDUCTING COILS

A total of ten coil samples were prepared and there are different subsets of them as shown in Table 1. Six of them were already impacted during the HiRadMat-61 experiment with a 440 GeV proton pulse at 4 K. Nevertheless, they are reused as their performance was not altered. The superconducting properties of these samples will be obtained by measuring the critical transport current in an external magnetic field of 7 T cooled down with liquid helium to 4.2 K. The experimental setup for the transport current measurements will be identical to the one used for the HiRadMat-61 experiment.

γ-RAY IRRADIATION

The γ irradiation was carried out by STERIS in Däniken, Switzerland. To prevent damage during handling and transport, each coil was enclosed in a cylindrical aluminium box (with a wall thickness of 0.4 mm). The five samples inside the boxes were glued to a Ethafoam holder and four alanine dosimeters were attached to each sample at equidistant angular positions of 90° around the circumference as shown in Fig. 2. The dose recorded by each dosimeter was used to assess the dose distribution on each side of the specimen. Based on this information, the boxes were periodically rotated to ensure a more uniform exposure. The dose rate ranged from 22-50 kGy h^{-1}. The total dose received by each sample is given in Table 1 where the uncertainly is the difference between minimum and maximum dose received by any side. The photon field was produced by bombarding a water cooled tantalum target with a 7 MeV/c electron beam. The energy spectrum in air simulated with FLUKA shows

Table 1: Overview of the sample coils for the scheduled experiment. The samples will be sorted in two batches A and B. The history of each sample is described by the maximum temperature, T_{61}, reached during the previous beam impact experiment (HRMT-61) and the dose, D, reached during the γ-irradiation. T_{70} and ∇T_{70} are the target hot-spot temperatures and temperature gradients for the upcoming beam impact experiment (HRMT-70).

#	T_{61} (K)	D (MGray)	T_{70} (K)	∇T_{70} (K/mm)
A1	300 ± 16	30±9%	310	67
A2	197 ± 10	25±4%	516	130
A3	197 ± 10	25±3%	701	193
A4	454 ± 22	0	927	194
A5	0	0	1030	207
B1	0	30±4%	310	67
B2	0	25±8%	516	130
B3	300 ± 16	0	701	193
B4	574 ± 21	0	927	194
B5	0	0	1030	207

Figure 2: The setup at the γ-irradiation facility at STERIS, showing five samples, each with four alanine dosimeters to characterise the spatial distribution of dose on each side of each sample. Photo courtesy of P. Reppert.

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a peak energy around 270 keV with the maximum reaching several MeVs.

Upon reception, the samples were visually inspected. A picture of a sample exposed to 30 MGy is shown in Fig. 1, item (c). The irradiation altered the colour of the G10 clamp (compare with Fig. 1, item (b)). There is a small area between the two copper half-moons at the bottom of the coil where the epoxy is still visible (see Fig. 1, item (d)). Besides a change in colour, it also shows traces of bubbles. This behaviour has been observed for other epoxy systems such as MY750 and Araldite F [5]. However, this is observed for the first time for CTD101k. Furthermore, the G10 clamps of sample A2 and B1 cracked and their clamps were deformed (see Fig. 1, item (c)). A detailed investigation of sample B1 was carried out with Computed Tomography (CT), as depicted in Fig. 3. The cracks and bubbles inside the clamp are clearly visible as well as the clamp deformation. Presumably there are also defects in the epoxy close to the winding, but the presence of dense materials inside the strands and core hampers the resolution of the CT scan for the epoxy around it. Critical current measurements will be performed with the aged samples coils to re-qualify there performance before being impacted by the proton beams.

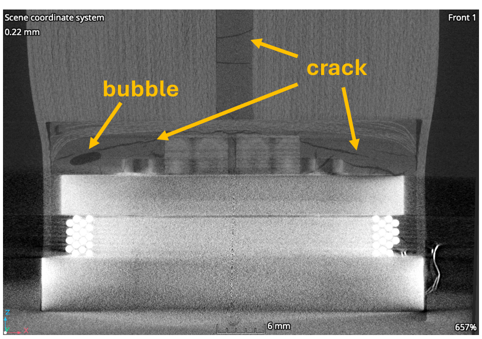

Figure 3: CT scan of sample B1 after exposure to 30 MGy. A large bubble and many cracks are visible in the upper part of the coil (yellow arrows) where no dense material is present [19].

EXPERIMENTAL SETUP DESIGN

The upcoming experiment, scheduled for late 2025, will be performed at the High-Radiation to Materials (HiRadMat) facility at CERN using proton beam pulses of 440 GeV/c [20]. For this experiment, pulses consisting of 24 bunches with 1.6×10^{11} protons (in total 3.84×10^{12} protons per batch of samples) and a transverse size of σ=1 mm will be used.

The experimental setup will be similar to the previous beam damage experiment with the sample coils [8–13, 21]. To mimic a real accelerator failure, the samples will be hit by the beam inside a dry cooled cryogenic vessel at 4 K. The vessel consists of two cooling stages which reach below ~ 4 K and 30 K respectively. The samples will be fixed to the second-stage plate in two batches, with each batch receiving a single pulse. Delivering a pulse to five samples ensures that each successive sample experiences increasing

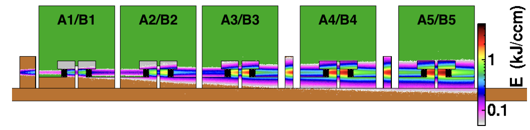

Figure 4: FLUKA model with energy deposition overlay for one batch. The five sample coils are placed on the copper base plate (brown) and held by G10 clamps (green). The detailed winding geometry is reflected in the energy deposition patterns at the coil centres. Shower development from the copper blocks is clearly visible.

hot-spot temperatures. The two batches consist of samples with a similar history in terms of dose received and hot-spot temperature, and thus, should exhibit similar degradation. The layout of the samples is shown in Fig. 4. The first sample in each batch is aged to 30 MGy, as it is expected to be the most sensitive to beam impact. This is followed by one or two samples exposed to 25 MGy to assess whether degradation is induced at a higher hot-spot temperature but a lower dose. Next, virgin samples will be positioned to experience higher energy depositions than the coils during the previous beam experiments, allowing to determine the onset of permanent degradation of the critical current. Finally, the previously impacted samples at the end of the batch will be exposed to the highest levels of energy deposition. Copper blocks will be placed along the beam path, one 1 cm-thick in front of the first coil and one 0.5 cm in front of the forth and the fifth, to modulate the target energy deposition in the sample coils.

A FLUKA model has been developed to simulate the energy deposition in each strand of the coil samples using the assumed beam properties. Figure 4 shows the Flair geometry view with the energy deposition map. Hotspot temperatures between ~300 and 1030 K will be reached.

CONCLUSION AND OUTLOOK

An unique experiment to study damage limits of radiation-aged superconducting sample coils from direct beam impact is being prepared. The samples were produced and a subset was irradiated up to 25 and 30 MGy. A CT scan investigation of sample B1 revealed defects in the epoxy following the γ-ray irradiation. This is the first observation of such defects in CTD101k epoxy. The samples will be qualified for critical transport current and subsequently impacted by a proton beam in CERN's HiRadMat facility. The hot-spot temperatures and temperature gradients to be achieved were simulated using the foreseen beam properties. The beam impact experiment will be carried out in October 2025.

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