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ENERGY DEPOSITION SIMULATIONS FOR A DAMAGE EXPERIMENT WITH SUPERCONDUCTING SAMPLE COILS*

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Abstract

An experiment to study damage caused by the impact of 440 GeV/c protons on sample superconducting racetrack coils made from Nb-Ti and Nb_3Sn strands was recently carried out at CERN's HiRadMat facility. This paper reports on the detailed Monte Carlo simulations performed with FLUKA and Geant4 to evaluate the energy deposition of the 440 GeV/c proton beam on the sample coils positioned in the experimental setup, using the measured beam parameters during the experiment. The measured hot-spot temperatures and temperature gradients reached in the sample coils are presented and compared with the simulations. In addition, comparisons between the simulation results from FLUKA and Geant4 are discussed in detail.

INTRODUCTION

The use of Nb_3Sn technology for superconducting magnets is an integral part of the upcoming High-Luminosity upgrade of the Large Hadron Collider (HL-LHC). Different failure scenarios lead to beam losses and subsequent energy deposition on the superconducting magnets coils. To study the damage limits from beam impact on superconducting materials such as Nb_3Sn and Nb-Ti, a series of tests, following a multi-stage experimental campaign, were conducted. The latest experiment was carried out at CERN's HiRadMat facility [1] in October 2022 to study the damage limits of superconducting coils from proton beam impact at 440 GeV. Prior experiments shed light on the damage limits in different scenarios. The degradation of cables insulation from heating over long timescales was first studied [2]. The degradation of individual strands from millisecond heating (using a capacitive discharge) and from direct beam impact on strands at room temperature was investigated in dedicated experiments [3] and the corresponding damage limits were obtained. In addition, a beam impact experiment was carried out at cryogenics temperature [4]. The latest experiment aims to highlight and characterize damage mechanisms in coils as a whole, using sample coils wound with low-temperature superconducting strands impacted at temperatures below 5.5 K. During the experiment, both the Nb-Ti and Nb_3Sn samples were impacted with the beam. This paper focuses on simulating the temperature profile in the Nb_3Sn coils.

A total of 5 Nb_3Sn coils were grouped as one batch and placed along the beam axis on a copper plate in a vacuum vessel equipped with cryogenic device (see Fig. 1). This arrangement of the coils ensured that downstream samples reached higher peak hot-spot temperatures. To adjust the hot-spot temperature profile along the batch, a 1 cm-thick copper shower block was placed in front of the first and the fifth coil. The experimental setup is described in more detail in [5].

This paper focuses on the detailed Monte Carlo simulations performed with the FLUKA Monte Carlo code [6] using the FLAIR graphical interface [7] and Geant4 [8] to evaluate the energy deposition of the proton beam on the sample coils, using measured beam parameters. The hot-spot temperatures were then computed from the deposited energy using the integral of the product of the material density and specific heat (data taken from [9] and [10]) as shown in Fig. 2 and based on the relative fractions of materials as indicated in Tab. 1. The targeted temperature profile and the one obtained based on beam measurements are compared and discussed.

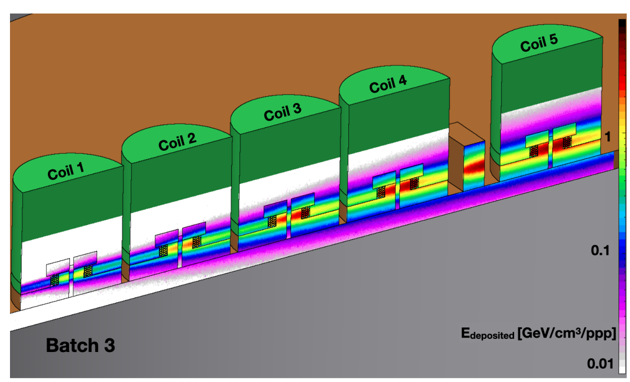

Figure 1: FLUKA model and energy deposition result overlay of the experimental setup for Nb_3Sn batch. The five sample coils are located on top of the copper base plate (brown), with G10 clamps (green) in place. The detailed geometry of the windings is visible from the structure of the energy deposition overlay (central part of each coil). The shower development from the copper block in front of coil 5 is clearly visible.

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Table 1: Materials used for the FLUKA and Geant4 models. The definition of the compounds and material densities are also provided.

Component	Compound (relative fraction)	Density (g/cm^3)
Nb_3Sn strand	Cu(0.55), Nb_3Sn(0.45)	8.96
G10 clamp	O(0.53), Si(0.27), Ca(0.19), H(0.01)	2.52
Epoxy (CTD101K)	H(0.55), C(0.36), O(0.08), N(0.01)	1.03
Nb_3Sn strand insulation	SiO_2(0.55), CaO(0.2), Al_2O_3(0.15), B_2O(0.1)	2.20
Macor ceramic	SiO_2(0.46), MgO(0.17), Al_2O_3(0.16), K_2O(0.1), B_2O_3(0.07), F(0.04)	2.52

The goal of the simulations prior to the experiment was to design the layout, *i.e.* define the coils positions, beam intensities and thicknesses of the copper blocks. Based on the damage limits derived in the previous beam impact experiment at 4 K for Nb_3Sn strand samples, the hot-spot temperatures in the windings of the sample coils were chosen to reach between 200 and 750 K.

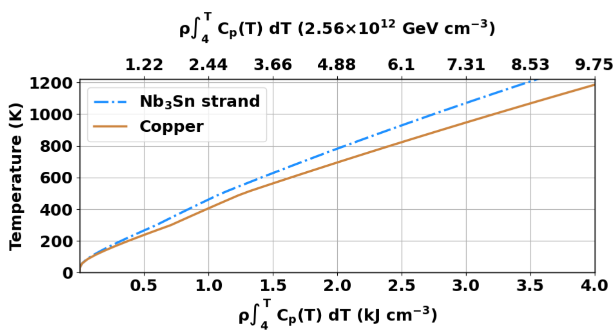

Figure 2: Hot-spot temperature as a function of the energy deposited per unit volume. The horizontal axis represents the energy deposited during beam impacting on the Nb_3Sn batch with the measured intensity of 2.56×10^{12} protons.

MODEL

The FLUKA model contains the copper base plate on which the samples were placed. Each sample coil consists of two half-moon-shaped copper electrodes and a Macor® ceramic sheet which electrically separates the two halves. Stainless Steel wire-blocking grooves are screwed on the copper body to stabilise the winding. The coils are equipped with a G10 clamp surrounding the windings and the top part of the coil assembly. The base of the coil has a circular shape with a diameter of 4.8 cm. The height of the coils is 2.2 cm without and 4.2 cm with the G10 clamp installed.

The windings are modeled with a high level of detail as they are crucial to properly compute the energy deposition. The strands are modeled as nested cylinders, the inner one representing the superconducting material (with a diameter of 0.85 mm [11]), the outer one with a diameter of 0.95 mm representing the insulation. They are placed parallel to each other to represent the windings and this region is then embedded in an epoxy box. The winding consist of 18 turns divided into four layers (5|4|5|4). The properties of the materials used in the model are described in Tab. 1.

To allow a direct comparison with FLUKA, the drawings of the model have been converted into a Geometry Description Markup Language (GDML) file using the Pyg4ometry Python library [12]. This GDML file was then imported into BDSIM [13], a Geant4-based particle tracking code that simulates the transport and the interaction of particles, where the beam parameters of the experiment were also specified. The results were stored in a scorer mesh with the exact dimensions used in the FLUKA simulation, and the histograms are analyzed through the Python library pybdsim.

SIMULATION RESULTS

The simulations were performed for the design values before and with the measured beam parameters after the experiment. The design values were optimized during the design stage to obtain the desired temperature profile. The intensity of 2.4×10^{12} protons and a beam size equal to σ_x=σ_y=1.0 mm was identified to produce the desired temperature profile. During the experiment the intensity was 6 % higher (2.56×10^{12} protons) and the horizontal beam size 40% bigger (σ_x=1.4 mm) as compared to design values while the vertical beam size was similar to the design value. A statistical sample of 1.5 million primary particles was used and the results from both codes are shown in Fig. 3. A very good agreement between the two codes can be seen in the shower blocks and in the copper cores inside the coils. Discrepancies are visible within the winding regions due to differences in material contribution due to an offset between the different binning. Geant4 simulations with refined scoring meshes are on-going.

The energy deposition was also scored in the volume of the strands, with a 10 μm bin width along the length of the strands in FLUKA. That scoring region thus contains only the superconducting compound and the energy deposition-temperature relation mentioned earlier (Fig. 2) was used to asses the hot-spot temperature profile of each individual strand. For each coil the temperature profile for the strand with the highest energy deposition of the winding is shown in Fig. 4, as it is believed that this will be dominating the coils performance after the beam impact. The downstream coils experienced increasing hot-spot temperatures and temperature gradients as the number of secondary particles increases along the beam path. The first sample experienced a hot-spot of 205 K after which the temperature increases in steps

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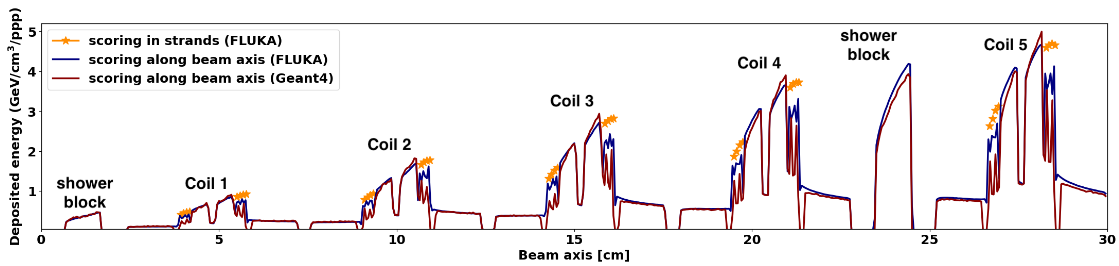

Figure 3: Simulated energy deposition per primary proton using the measured beam size along the beam axis for the batch. FLUKA (blue) and Geant4 (red) scoring along the beam axis and inside the most impacted strand in each layer (orange stars) is shown. The locations of the sample coils and shower blocks are indicated. .

of approximately 130 K up to 713 K in the last coil. The maximum value of the temperature gradient varies between 4.4 K/10μm in the first and 14.1 K/10μm in the fifth coil. In Fig. 5 the hot-spot temperatures in the most irradiated strand of each coil are shown. The results with the design and measured beam parameters are compared. The hot-spot temperatures expected during the experiment reach between 91 % to 95 % of the designed values, which is a very good result. During the experiment the beams were larger and had a slightly higher intensity, than foreseen. Therefore, secondary showers were produced in a broader region, causing less energy deposition and a lower hot-spot temperature. The error bars that are shown were obtained by the uncertainty in the beam size of 10% and intensity of 5% .

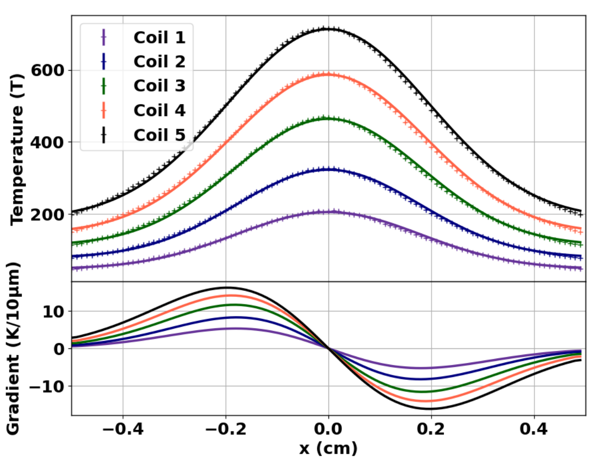

Figure 4: Hot-spot temperature and temperature gradient computed from energy deposition using the FLUKA model. The results are shown for the individual strands reaching the highest temperature in each coil.

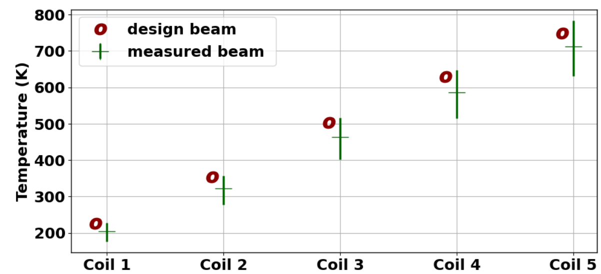

Figure 5: Comparison of temperature profiles from FLUKA with design and measured beam parameters. The designed temperatures (red circles) are between 5 and 9 % higher than the ones expected to be obtained with the measured beam paramters (green crosses), as the beam size was bigger than foreseen. The error bars indicate the effect of the uncertainty in the measured beam size (10%) and intensity (5%).

CONCLUSION AND OUTLOOK

The first-ever experiment, studying damage limits of superconducting sample coils from direct beam impact, was conducted in late 2022. The achieved hot-spot temperatures were simulated with FLUKA and Geant4 and compared to the targeted values. FLUKA and Geant4 show a very good agreement in terms of energy deposition along the beam axis, with discrepancies in the winding regions. These discrepancies can be attributed to a difference in the contributions of materials in the particular bin due to non-identical scoring meshes between two codes.

The simulations show that the expected hot-spot temperature varies from 205 K for the first coil to 713 K for the fifth one. The designed hot-spot temperatures were between 5 and 9 % higher than the expected values in the beam experiment due to differences in the beam parameters. The discrepancy between results from both codes will be further studied and then simulations will be performed for the two remaining coil batches. A visual inspection of the irradiated samples will be performed and will allow estimating the exact position of the beam impact for each batch. In addition, the it is planned to measure the critical current of the sample coils after the beam impact. The measured values will be correlated to the achieved hot-spot temperatures.

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