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BEAM IMPACT EXPERIMENT OF 440 GeV/p PROTONS ON SUPERCONDUCTING WIRES AND TAPES IN A CRYOGENIC ENVIRONMENT*

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Abstract

The superconducting magnets used in high energy particle accelerators such as CERN's LHC can be impacted by the circulating beam in case of specific failure cases. This leads to interaction of the beam particles with the magnet components, like the superconducting coils, directly or via secondary particle showers. The interaction leads to energy deposition in the timescale of microseconds and induces large thermal gradients within the superconductors in the order of 100 K/mm. To investigate the effect on the superconductors, an experiment at CERN's HiRadMat facility was designed and executed, exposing short samples of Nb-Ti and Nb_3Sn strands as well as YBCO tape in a cryogenic environment to microsecond 440 GeV/p proton beams. The irradiated samples were extracted and are being analyzed for their superconducting properties, such as the critical transport current. This paper describes the experimental setup as well as the first results of the visual inspection of the samples.

INTRODUCTION

In order to understand the damage limits of superconducting accelerator magnets due to direct beam impact, an experimental road-map was set up, as described in [1, 2]. Within this road-map several experiments, with and without beam, have been launched to study the degradation of Nb-Ti and Nb_3Sn based superconducting strands due to ultra short and localized energy deposition. This paper describes the first direct beam impact experiment in cryogenic environment on Nb-Ti, Nb_3Sn and YBCO superconductors.

The low temperature superconductors (LTS) used in the magnets of CERN's LHC and its upgrade, the HL-LHC, are based on Nb-Ti and Nb_3Sn. Therefore, in the beam experiment 50 mm long samples of the LHC dipole type Nb-Ti strands with a diameter of 0.825 mm [3] and the HL-LHC type RRP® Nb_3Sn strand with a diameter of 0.85 mm [4] were used. The Nb_3Sn short strand samples were reacted in quartz glass tubes, to guarantee perfect strand straightness and ease the alignment in the sample holder. The cross section of both strand types are shown in Fig. 1. The copper matrix and the filaments are clearly visible. Furthermore, 60 mm long samples of high temperature superconductor (HTS) tape based on YBCO were used. This tape was provided by BRUKER and one sample is shown in Fig. 1.

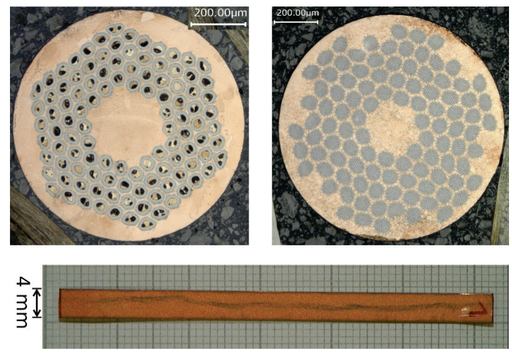

Figure 1: Nb3Sn* (top left) and Nb-Ti strand* (top right) as well as short sample of YBCO-tape (bottom), used in the experiment. *Image Courtesy M. Meyer, CERN.

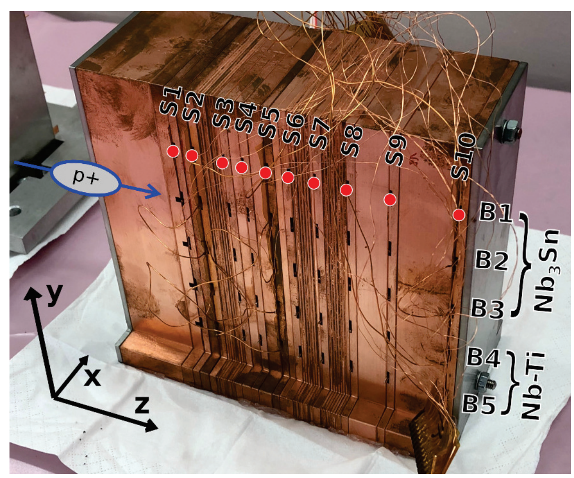

Figure 2: Side view of the assembled LTS tape sample holder. The setup from different blocks of copper is clearly visible. The blue arrow indicates the proton beam direction.

EXPERIMENTAL SETUP

Sample Holders

The two sample holders consist of blocks of copper, allowing easy sample mounting. The blocks of the first sample holder have slits adapted to the geometry of the HTS tapes.

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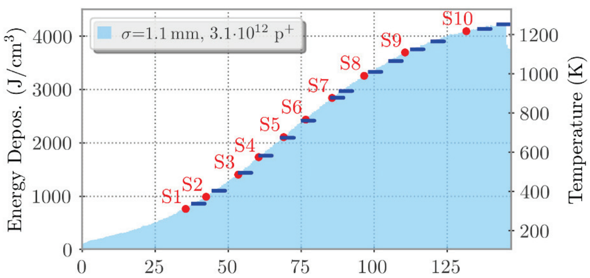

Figure 3: Energy deposition in the sample holders along the beam axis, calculated with FLUKA [5, 6]. The corresponding peak temperatures reached in copper are indicated on the right axis. The red dots indicate the position of the Nb-Ti and Nb_3Sn strand samples, the blue bars indicate the position of the YBCO tapes.

The blocks of the second sample holder have grooves designed to fix the Nb-Ti and Nb_3Sn strands. Figure 2 shows the fully assembled sample holder for the LTS strands. The LTS sample holder houses 50 short strand samples, split into five batches (B1-5 in Fig. 2) of 10 samples each. In total, three batches of Nb_3Sn strands and two batches of Nb-Ti strands were mounted in the LTS-sample holder. For each batch, the samples are installed along the beam axis. Therefore, they are impacted simultaneously by one beam pulse. The HTS sample holder houses six batches of seven HTS-tape samples, i.e. a total of 42.

The energy deposition in the sample holders and samples was calculated using FLUKA [5, 6] and is shown along the beam axis for one beam pulse in Fig. 3. The equivalent peak temperatures reached in the copper varied between 300 K and 1200 K with a spacing of about 100 K between the samples. This peak temperatures are calculated under the assumption of instantaneous energy deposition as the beam impact happens within 600 ns.

Cryostat

Figure 4 shows the open experimental cryostat without thermal shields and vacuum vessel. It is a cryogen-free system, based on a two-stage cryo-cooler with a large copper interface plate on the second stage, which can be cooled to 4 K. The two sample holders are bolted to this interface plate to ensure good thermalization. The first stage is used to cool a thermal shield that fully surrounds the second stage. The system is compact with a height of about 0.9 m, including the cold head, and a diameter of about 0.6 m. As the vacuum vessel consists of Aluminum, leading to a sufficiently low energy deposition of the 440 GeV proton beam into the vessel, beam windows are not required.

BEAM TIME

The experiment was carried out in HiRadMat [7], a facility at CERN, providing proton beam pulses of up to 288 bunches with 25 ns bunch spacing and an energy of 440 GeV/p towards fixed targets. The beam size at the sample position was chosen with a standard deviation of σ = 1.1 mm. For the experiment 11 beam pulses of 24 bunches with an intensity of $\sim 3.1 \times 10^{12}$ protons per pulse were used, resulting in the energy deposition to the samples as shown in Fig. 3. The cryostat was moved horizontally and vertically to change the impacted batch between the pulses. After each pulse a pause of 45 mins was required to allow the setup to cool down to the initial temperature of $\sim$ 4 K.

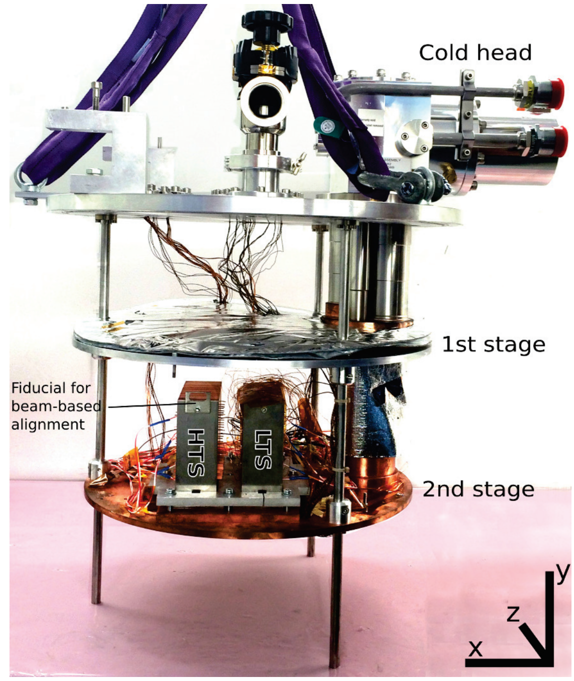

Figure 4: Open experimental cryo-cooler based cryostat without thermal shields. The sample holders are bolted to the second stage interface to ensure good thermalization.

The beam size and position in the facility as well as the beam intensity were reproducible during the $\sim$ 9 hours of the experiment. The beam parameters and the temperatures of the sample holders were monitored and recorded during the experiment.

SAMPLE EXTRACTION AND FIRST VISUAL INSPECTION

The impact positions of the beam were determined by visual inspection of the impact marks on various pieces of the sample holder, using a digital optical microscope and measuring the distance to the edges of the blocks. A systematic vertical offset of about one millimeter was observed for the LTS samples. The vertical beam offset from the expected impact positions for the HTS samples was observed to be around 0.5 mm for batches one to three. For batches four to six of the HTS samples, the beam offset was up to 2 mm due to an operator error in the vertical positioning during the experiment.

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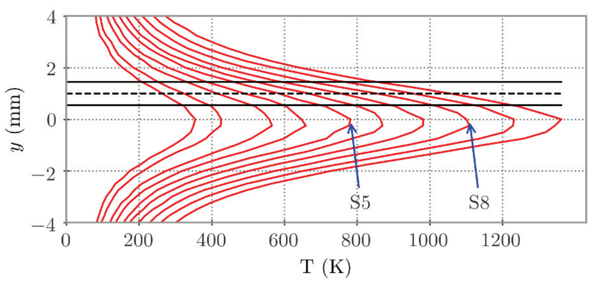

Figure 5: Calculated maximum temperature profiles perpendicular to the LTS strands, with the measured vertical beam offset taken into account, for a pulse with 3.1×10^{12} protons. The strands outline with respect to the beam center is indicated with a solid line, the center of the strand with a dashed line.

Temperature Profiles

According to the evaluated offsets and using the measured beam properties, refined FLUKA simulations were performed and the energy deposition for all samples and each shot individually was calculated. The reached peak temperature intervals are summarized in the Table 1 below. The simulated temperature profiles transverse to the strands are shown in Fig. 5.

Table 1: Lowest and highest peak temperatures reached in the strands and tapes

Superconductor	Min. Temp	Max Temp.
Nb-Ti	300 K	1190 K
Nb_3Sn	290 K	1200 K
YBCO	240 K	1357 K

Nb-Ti and Nb_3Sn

Being a ductile material, the Nb-Ti strands showed no visual degradation. The Nb_3Sn based strands however showed clear deformations starting from the fifth sample in the sample holder with a peak temperature of about 700 K. The deformation is prominent in the form of a central bending of the strands around the beam position of few degrees as can be seen in Fig. 6. This bending results from the offset of the beam impact in vertical (y-) direction which results in a transverse temperature gradient of up to 300 K. This large imbalance in thermal expansion then results in a bending and permanent deformation, when the stresses in the material become too large. Furthermore, the copper matrix of several samples showed partial cracks. For these samples, permanent degradation in the critical transport current is expected.

YBCO

Some of the YBCO-tapes have been welded to the sample holder by the beam impact, which complicated the removal

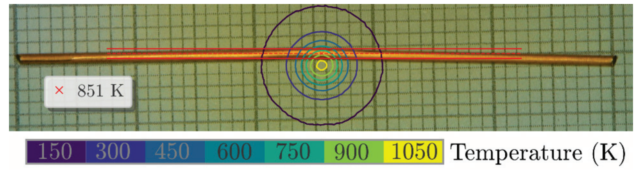

Figure 6: One of the samples at position S8 of the Nb_3Sn strands after beam impact. Clear deformation in form of a bending of the strand around the beam impact center is visible. The radial lines indicate the energy deposition.

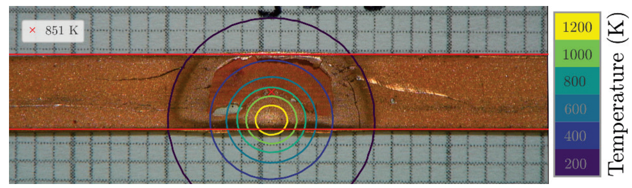

Figure 7: HTS tape which had seen a peak temperature of ~ 1200 K after removal from the sample holders. The red lines indicate the tape position according to the simulation with measured beam parameters and offsets. The circles indicate the temperature at different parts of the tape. A damage of the top copper layer is clearly visible.

of the samples after the experiment. Four HTS samples could not be removed from the sample holder and two samples were damaged during the removal. The welding occurred for samples in position S5 and higher (see Fig. 3), reaching peak temperatures of around 700 K and above. Figure 7 shows as an example the last sample of one of the batches, overlayed with the calculated peak temperatures, taking into account the measured beam parameters and offset. A damage of the top copper layer is clearly visible.

SUMMARY AND OUTLOOK

For the first time a damage experiment has been performed with superconducting Nb-Ti and Nb_3Sn strands, as well as YBCO tapes at 4.2 K using 440 GeV protons. In total 92 short samples were impacted by shots of 3.1×10^{12} protons. A visual inspection revealed clear mechanical deformation of Nb_3Sn samples, which experienced peak temperatures of ~ 700 K and above. At comparable peak temperatures also HTS tapes showed visual damage. No visual damage was observed in Nb-Ti samples. The measurement of the critical current density of the irradiated samples is currently ongoing in collaboration with the University of Geneva. In addition, thermo-mechanical transient stresses present in the Nb_3Sn strands during the experiment are currently studied with coupled simulations of FLUKA and FEM codes for transient structural analysis.

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