EXPERIMENTAL SETUP TO MEASURE THE DAMAGE LIMITS OF SUPERCONDUCTING MAGNETS DUE TO BEAM IMPACT AT CERN'S HIRADMAT FACILITY

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Abstract

The future upgrade of CERN's injector chain for the Large Hadron Collider (LHC) will lead to an increase of the beam brightness in the LHC. Beam absorbers are capturing missteered beams, but some limited beam impact on superconducting magnets can hardly be avoided. Therefore, it is planned to measure the damage limits of superconducting magnet components due to beam impact at CERN's HiRadMat facility using the 440 GeV proton beam from the Super Proton Synchrotron. Two experiments are proposed. One at ambient and one at cryogenic temperatures, where several pre-stressed stacks of LHC main dipole Nb-Ti cables and some single strands will be irradiated with varying beam intensities. The electrical integrity and the degradation of critical current will be measured after the removal from the HiRadMat facility. In the cold experiment some sample magnets will be added and the degradation of performance will be monitored online.

In this contribution the experimental setup of the first experiment, including the sample container and cable stacks, is presented.

INTRODUCTION

Failures in the LHC can lead to beam losses at very different timescales. Ultrafast losses, happening within 3 LHC turns ($\approx$ 270 µs), are the most critical. Protection against such losses relies on passive absorber elements [1]. Beam interaction with the absorbing elements will create particle showers which may cause damage to downstream components.

Critical parts of the LHC magnets have earlier been identified and a roadmap to investigate the damage limits of LHC magnet components has been presented [2]. Potential mechanisms which may lead to loss of performance include degradation of cable insulation due to high temperatures, phase changes in the superconductor composition, thermally induced stresses etc.

An experiment where the degradation of dielectric strength of the insulation of LHC cables when exposed to temperatures above 400 °C at a long timescale has been performed [3]. Investigations of the insulation behaviour and the degradation of critical current due to heating within milliseconds are ongoing. As beam induced heating will lead to heating within the order of microseconds, it is important to study the same effects further at this timescale.

To explore the damage limits of LHC superconducting cables due to beam impact, two experiments in the HiRadMat facility at CERN are proposed [4]. First, an experiment at ambient temperature, where stacks of superconducting Nb-Ti cables and single strands will be irradiated with protons followed by an experiment at cryogenic temperatures where also sample magnets are included. The degradation of magnet performance will be monitored online after each exposure. Choosing a phased approach allows to derive first results with beam earlier and gain experience with a significantly simpler setup in preparation of the final experiment within liquid helium.

HEATING EXPERIMENTS

An experiment where LHC inner layer main dipole cables were heated in an oven shows that the polyimide insulation starts loosing its dielectric strength when exposed to temperatures above $\approx$ 400 °C [3]. Furthermore, previous experiments suggest that the degradation of polyimide insulation is thermally driven and the rate of degradation is highly temperature dependent [5, 6]. Thus, for shorter exposure times, higher reaction rates can be tolerated before degradation is observed.

The degradation of critical current in Nb-Ti wires when annealed at temperatures above 400 °C has previously been studied [7, 8]. A strong degradation after minutes of heating above 550 °C was observed because of formation of Cu-Ti intermetallic phases. This effect can potentially lead to loss of performance in LHC cables, but as the exposure time is significantly shorter it is expected that degradation will only be observed at higher temperatures.

The objective of the proposed experiments is to quantify how these mechanisms affect the performance of LHC magnet components when triggered by beam losses.

EXPERIMENT AT AMBIENT TEMPERATURE WITH BEAM

The setup for the experiment at room temperature consists of four stacks of Nb-Ti main dipole Rutherford cables placed in moulds of 10 cm length. The cables are 15.1 mm wide, 1.5 mm high and 20 cm long. The cables need to be longer than the moulds to allow for the measurement of dielectric strength. For sufficient statistics, the setup consists of two floors with identical layout as shown in Fig. 1. The setup is placed on a vertical moveable table such that different zones can be irradiated. To simulate the conditions in the LHC main dipole magnets, the stacks will be kept under approximately 100 MPa pressure by stainless steel moulds, comparable to the one shown Fig. 2. In addition single LHC Nb-Ti strands are placed parallel to the cables. This allows

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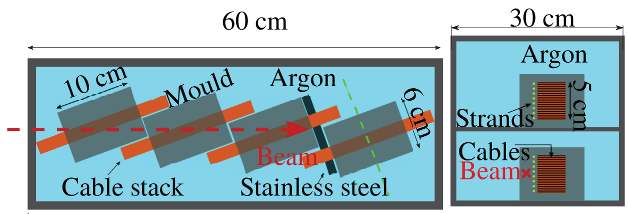
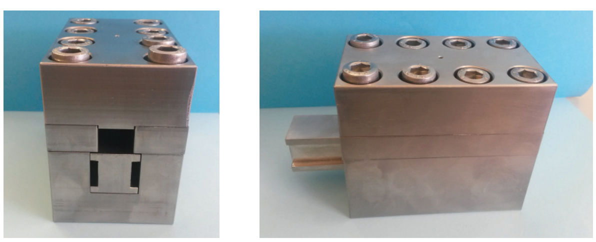


(a) Top view

(b) Cut along the green line.

Figure 1: Schematic drawing of the experimental setup for the experiment at ambient temperature. *Fig. a*: Container with moulds and cable stacks. The container is filled with argon. *Fig. b*: Front view of the setup. There are 30 cables with dimensions $1.51\,\mathrm{cm} \times 0.148\,\mathrm{cm} \times 20\,\mathrm{cm}$ in each mould.

to measure the decrease of critical current as a function of radiation exposure by either direct measurements or by magnetization measurements. The strands will be positioned at the sides of the mould, hence the moulds used in this experiment will differ slightly from the one shown in Fig. 2.



(a) Front view (b) Side view

Figure 2: Mould which is used to keep the cables under pressure. This mould was made for studying the degradation of insulation on long timescales (~ hour) [3].

It is known that the presence of oxygen will enhance the degradation of the polyimide insulation, hence the samples will be kept in an argon atmosphere inside an over pressurized aluminium container [9].

In preparation of the experiment within liquid helium, a stainless steel plate will be added between mould 3 and 4 from the left to verify the structural integrity of steel after being irradiated by 6, 12 and 24 bunches with the beam parameters given in Table 1. This is important, as the cryostat will be made from stainless steel and experience comparable thermal stresses.

ENERGY DEPOSITION SIMULATIONS

The energy deposition in the targets, shown in Figs. 3 and 4, was calculated using the FLUKA code with the beam parameters in Table 1 [10,11]. In Fig. 4 it can be seen that the energy depositon is approximately a factor 10 lower at 5 mm distance from the beam axis. Hence, cables ~ 5 mm away from the beam axis can be considered as unaffected by the previous shot. By moving the table 5 mm vertically between each shot, data from 9 shots per floor can be collected. This means that the samples can be irradiated with 6 trains for

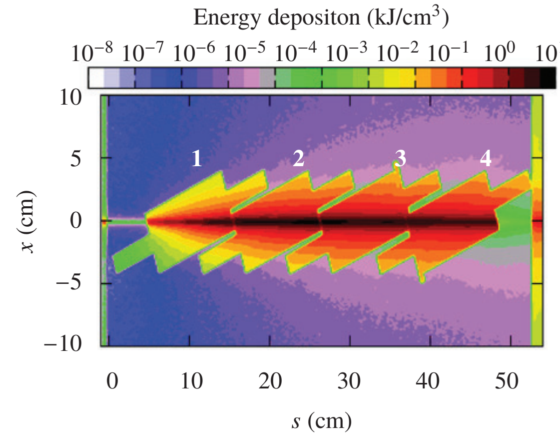


Figure 3: Energy deposition in the four moulds after being irradiated with 24 bunches . The beam penetrates the samples from the left.

each of the three intensities 6, 12 and 24 bunches. Fig. 4 also shows that the energy deposited in the aluminium container is significantly lower than in the samples.

Table 1: Proton Beam Parameters

Parameter	Value
Energy	440 GeV
Beam sigma	1 mm
Protons per bunch	1.15×10^{11}
Number of bunches	6,12,24

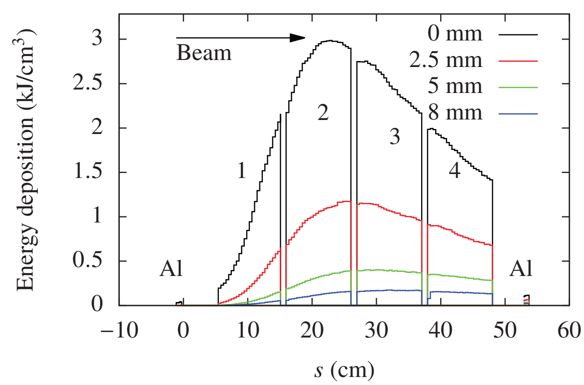


Figure 4: Energy deposition in the targets after irradiated with 24 bunches. The different colours refer to various radial distances from the beam axis. The different numbers refer to the mould numbering in Fig. 3 and Al refers to the aluminium box.

From Fig. 5 it is seen that with the planned bunch patterns peak temperature rises of 250 °C to 900 °C will be reached. It is seen in Fig. 5 that the four moulds experience different peak temperature rises when irradiated with a given number of bunches. As an example irradiation with 24 bunches gives peak temperature rises of approximately 300 °C, 550 °C, 750 °C and 900 °C in the four moulds respec-

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tively. In comparison, the temperature rise in the aluminium container is approximately 60 °C for 24 bunches.

Melting of the cable is not of interest in this experiment as this clearly leads to loss of performance. Hence, the peak temperature rise of the samples has been designed such that they stay well below melting. The melting temperatures of copper and aluminium is depicted in Fig. 5 by dotted lines, showing that both the aluminium container and the samples stays far below their respective melting temperature.

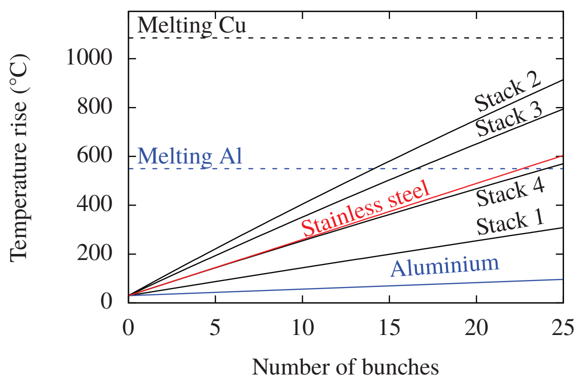

Figure 5: Peak temperature rises in different parts of the targets. The temperature rise in the stacks are labeled 1-4 as shown in Fig. 3. The red line refers to the stainless steel plate inserted between mould 3 and 4 and the blue referes to the aluminium container. The dotted lines correspond to the melting temperature of aluminium and copper respectively.

Structural Considerations of the Containers

Beam impact on copper, zinc and stainless steel has previously been studied [12]. No visible damage was observed in copper and stainless steel after irradiation with 24 bunches. However, microscopic investigations of the samples after the exposure were not performed. The simulations presented show that the energy deposition in the aluminium box is low compared to the moulds, which is made from stainless steel. Hence, no damage to the aluminium box is expected. Anyhow, as the aluminium container is not a pressure vessel, potential plastic deformation due to the temperature rise of 60 °C will not cause problems.

In the future experiment at cryogenic temperatures, a pressurized cryostat made from stainless steel will be used. Hence microscopic investigations of the stainless steel plate included in the experiment at ambient temperatures will be performed to verify the structural integrity after irradiation with 24 bunches.

CONCLUSION

The experimental plan for studying the damage limits of LHC superconducting cables due to ultrafast beam losses at ambient temperature has been presented. The experiment will give valuable information of potential damage due to ultrafast beam losses and in particular allow to compare the results to the ones obtained for long timescales and therefore help to understand how the timescale affects the results.

The cold experiment is still on a very early stage in the design process and the details and instrumentation of the setup will be topic of further work.

REFERENCES

[1] R. Schmidt *et al.*, "Protection of the CERN large hadron collider," *New Journal of Physics*, vol. 8, no. 11, p. 290, 2006.

[2] V. Raginel *et al.*, "Experimental setups to determine the damage limit of superconducting magnets for instantaneous beam losses," *In Proceedings of the IPAC15*, 2015.

[3] V. Raginel *et al.*, "Degradation of the insulation of the LHC main dipole cable when exposed to high temperatures," *In these Proceedings*, 2016.

[4] I. Efthymiopoulos *et al.*, "Hiradmat: a new irradiation facility for material testing at cern," CERN, Tech. Rep., 2011.

[5] N. Arnold and N. Bityurin, "Model for laser-induced thermal degradation and ablation of polymers," *Applied Physics A*, vol. 68, no. 6, pp. 615–625, 1999.

[6] N. Regnier and C. Guibe, "Methodology for multistage degradation of polyimide polymer," *Polymer degradation and stability*, vol. 55, no. 2, pp. 165–172, 1997.

[7] T. Schneider and P. Turowski, "Critical current degradation of a Nb-Ti-multifilament conductor due to heat treatment," *Magnetics, IEEE Transactions on*, vol. 30, no. 4, pp. 2391–2394, 1994.

[8] C. Scheuerlein *et al.*, "Temperature induced degradation of Nb-Ti/Cu composite superconductors," in *Journal of Physics: Conference Series*, vol. 234, no. 2. IOP Publishing, 2010, p. 022031.

[9] K. Pramoda *et al.*, "Characterization and thermal degradation of polyimide and polyamide liquid crystalline polymers," *Polymer degradation and stability*, vol. 67, no. 2, pp. 365–374, 2000.

[10] T. Böhlen *et al.*, "The FLUKA code: Developments and challenges for high energy and medical applications," *Nuclear Data Sheets*, vol. 120, pp. 211–214, 2014.

[11] A. Ferrari *et al.*, FLUKA: A multi-particle transport code (program version 2005). Geneva: CERN, 2005. [Online]. Available: https://cds.cern.ch/record/898301

[12] V. Kain, "Machine protection and beam quality during the LHC injection process," Ph.D. dissertation, Universität Wien, 2005.

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