EXPERIMENTAL SETUPS TO DETERMINE THE DAMAGE LIMIT OF SUPERCONDUCTING MAGNETS FOR INSTANTANEOUS BEAM LOSSES

V. Raginel, B. Auchmann, R. Schmidt, D. Schoerling, A. Verweij, D. Wollmann
CERN-TE, 1211 Geneva 23, Switzerland

Abstract

The damage mechanisms of superconducting magnets due to the direct impact of high intensity particle beams are not well understood. Obvious candidates for upper bounds on the damage limit are overheating of insulation, and melting of the conductor. Lower bounds are obtained by the limits of elasticity in the conductor, taking into account dynamic effects (elastic stress waves). The plastic regime in between these two bounds will lead to differential thermal stress between the superconductor and stabilizer, which may lead to a permanent degradation of the magnet. An improved understanding of these mechanisms is required especially in view of the planned increase in brightness of the beams injected into the LHC [1] and of the future High Luminosity-LHC [2] and Future Circular Collider (FCC).

In this paper the plans for room temperature damage tests on critical parts of superconducting magnets and the strategy to test their damage levels at 4.3 K in the HiRadMat facility at CERN [3], using a 440 GeV proton beam generated by the Super Proton Synchrotron (SPS), is presented. Moreover the status of numerical simulations using FLUKA and multi-physics FEM code (ANSYS) to assess the different effect and the irradiation of the proposed experimental setup in preparation of the test is shown.

INTRODUCTION

Losses of the LHC beam can happen at very different time scales, the most critical are so-called ultrafast losses, less than 270 µs (~3 LHC turns). Protection against such losses depends on passive devices intercepting lost particles. The interaction between the LHC beam and these passive devices generates particle showers which can be intercepted by the downstream elements such as superconducting magnets causing quenches or in the worst case damage.

At several occasions the passive devices for injection protection demonstrated their efficiency: due to failures of the injection kickers the injected beam was partially intercepted by the injection absorbers thus preventing damage. However, one event is not understood, which lead to the damage of small corrector magnets. During LHC Run 1, three small corrector circuits in the LHC inner triplet left of IP2 (IT.L2) have been found open after a failure during injection. Several magnets including the main quadrupole magnet where these correctors are mounted on the front face quenched during this event [4].

In this paper the thermo-mechanical effects due to the interaction between high energetic particles and matter are described. Then potential damage of critical parts of a superconducting magnet and their consequences for the magnet are discussed. The roadmap to perform damage tests with and without proton beam is presented. A preliminary experimental setup for a test of superconducting coils and cable samples at 4.3 K at CERN HiRadMat facility with a 440 GeV proton beam is shown. Finally it is explained how the thermo-mechanical effect of beam impact on the proposed experimental setup will be assessed with numerical simulations.

THERMO-MECHANICAL EFFECTS

The absorption of intense high-energy proton pulses of several micro-seconds duration causes a considerable temperature increase of the same rise-time inside the intercepted material. During this short period, thermal expansion of the irradiated material is partly prevented by its mass inertia. This gives rise to dynamic stresses propagating through the material [5].

With increasing energy deposition in a material, dynamic stresses pass from the elastic, to the plastic and ultimately to the shock wave domain. No damage occurs if the material stays in the elastic domain but shock waves will lead to severe damage in the affected components.

For cryogenic copper, which is major part of superconducting cables, the limit of the elastic regime is reached with an energy deposition of < 50 J/cm3. For metal-based materials, like superconducting cables, it can be shown that shock waves do not appear before melting [6]. The energy deposition to melt copper is ~6 kJ/cm^3 [7]. It is not understood if energy deposition in the plastic regime between 50 J/cm^3 and 6 kJ/cm^3 will cause damage to NbTi filaments or a degradation of the polyimide tape insulation and therefore cause a permanent loss of performance of the magnet.

IDENTIFIED CRITICAL PARTS OF MAGNET

Superconducting cable, insulation, quench heater, copper wedges and end spacers were identified as the critical parts of the superconducting magnets of the LHC.

The LHC superconducting cables are classical Rutherford cables made out of NbTi/Cu wires (see Fig. 1). The breaking of some NbTi filaments due to high dynamic stresses could lead to a reduction of the critical current.

As shown in Fig. 2, cables are insulated with several layers of polyimide tapes. Damage on the insulation due to high temperature could cause a short circuit either to ground – fatal for the magnet – or inter-turn short – leading to a longer ramping time of the magnets and damage during a magnet quench.

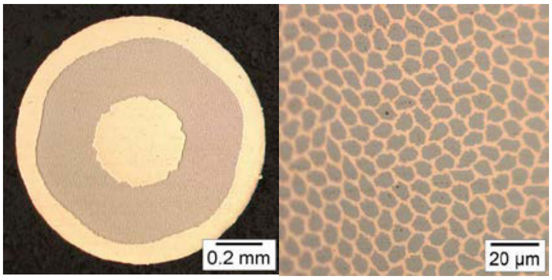

Figure 1: Transverse cross section of composite NbTi/Cu wire.

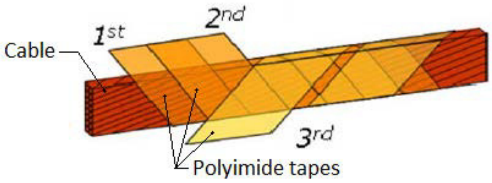

Figure 2: Superconducting cable insulation.

DAMAGE TESTS WITHOUT BEAM

It is planned to perform at least two types of damage tests without beam, on the insulation tape and on the superconducting strand and cable.

The first idea is to perform a heat-up test of the insulation tape within an inert atmosphere. As illustrated in Fig. 3, the insulation tape will be clamped between two plates that provide equivalent mechanical stress to the one experienced in an operating superconducting LHC dipole - 70 to 100 MPa [8]. The set-up will be heated up step by step until the polyimide tape fails. The electrical insulation of the tape will be tested between each step with high DC voltage e.g. 2 kV.

A second damage test will be done on the superconducting cable and strand. A fast current discharge (~10 ms) into NbTi and Nb_3Sn cables will be performed. Thermal gradients inducing damage in superconducting strand could be deduced from such an experiment. Mechanical limits of the cables and strands will be deduced from mechanical test. It is foreseen to run tensile, compressive and shear tests at room temperature and at cryogenic temperature (~70 K).

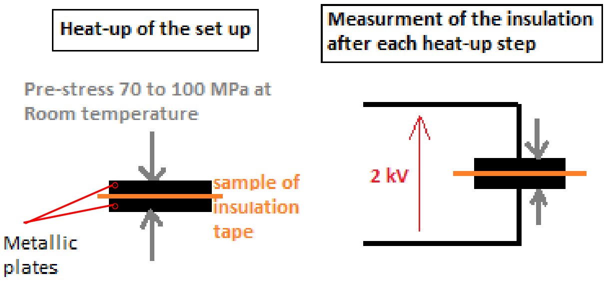

Figure 3: Sketch of the damage test on the insulation tape.

DAMAGE TESTS WITH BEAM

Proposed Experimental Setup

Ultimately the damage limit of superconducting magnets shall be measured with beam in cryogenic conditions at the CERN HiRadMat test facility with a 440 GeV proton beam delivered by the SPS. As shown in Fig 4, three sample coils (NbTi and Nb3Sn) and several superconducting cable samples will be tested at 4.3K in a cryostat with liquid helium. The beam will be shot on the samples and cause an instantaneous local heating. The impacting beam intensity will be increased in steps. After each shot, the electrical integrity of the coils will be measured with high voltage test and their superconducting properties of the coils will be tested by measuring the critical current.

The cable samples will be removed after the irradiation and post mortem analyses like critical current measurements and microscopic inspections will be performed.

To minimize heat losses and to simplify the setup, the cryostat will not have any beam windows, but the beam will be directly shot onto its walls. Therefore maximum beam intensity will be chosen as to rule out melting of the cryostat and of the samples. The peak energy deposition due to the beam impacts will be varied to achieve hot spot temperature in the samples from 50 K to 400 K. The experiment is aiming at determining the beam loss intensity limit when the superconducting samples fail.

During the irradiation, diamond particle detectors will monitor the particle showers outside of the cryostat, temperature sensors will monitor the coil temperatures.

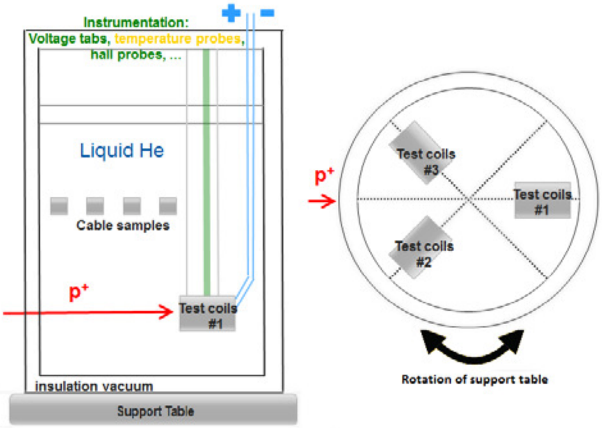

Figure 4: Sketch of the cryostat for the HiRadMat Experiment. Left: Cross section side view. Right: Cross section top view at right.

Numerical Simulations

In parallel to the design of the experimental setup numerical simulations are performed to study the thermo-mechanical stresses in bulk and composite materials due to interaction with high intensity proton beams. These studies will help to define the final design of the samples and the intensity steps during the irradiation.

The energy deposition in a given structure for specific beam parameters is calculated with FLUKA [9, 10]. The energy deposition distribution is imported into a standard Finite Element Model (FEM) code such as the ANSYS Transient module to calculate the dynamic stresses in the impacted sample. As this study focuses on the thermo-mechanical behaviour below melting temperature, ANSYS can reasonably treat this kind of thermally-induced dynamic phenomena [6, 11].

Extracted from literature and experiments, mechanical and thermal properties of Copper OFE and NbTi filaments at different temperatures will be used as input for the model of the superconducting cable and strands.

The superconducting strands are composed of several thousands of NbTi filaments embedded in a copper matrix. To optimize the computation time, the model of a strand has to be simplified. Thus as first approximation the NbTi filaments embedded in the copper matrix will be modelled as a bulk material. The model of the cable will have only one strand, the rest of the cable is modelled as a bulk (see Fig. 5).

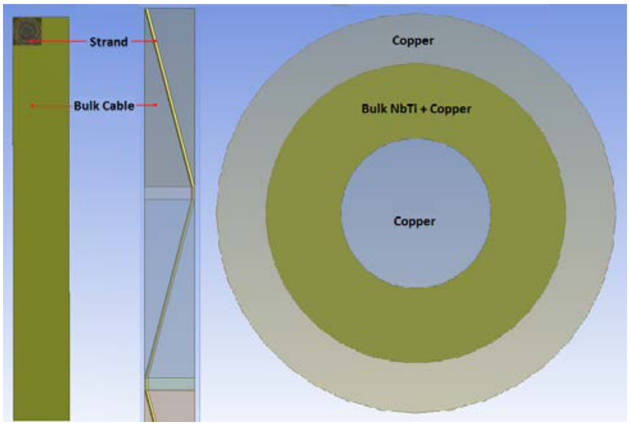

Figure 5: Sketch of ANSYS models for the Rutherford cable (left) and an NbTi superconducting strand (right).

CONCLUSION

The road map to determine the damage limit of superconducting magnets for instantaneous beam losses was presented. Setting up damage tests without beam at room temperature is ongoing. The insulating tape will be tested by heating it up under mechanical stress within an inert gas atmosphere. Tests on the superconducting cable and strand will be done by means of a fast current discharge to estimate the maximum thermal gradients before damage. In parallel, the design of an experiment in HiRadMat is progressing. A 440 GeV proton beam will be shot on several magnet coils and cable samples (NbTi and Nb_3Sn) in a cryostat with liquid helium. The electrical integrity and superconducting properties of the magnet coils will be controlled on-line, while the cable samples will undergo microscopic analysis and critical current measurements after the irradiation. In order to assess the temperature and the dynamic stress induced by the impacting beam on the materials, numerical models are under development.

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