CHANGE OF CRITICAL CURRENT DENSITY IN Nb-Ti AND Nb_3Sn STRANDS AFTER MILLISECOND HEATING

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Abstract

The damage mechanisms and limits of superconducting magnet components due to direct beam impact are not well understood. The energy deposition from beam losses can cause significant temperature rise and mechanical stress in the magnet coils, which can lead to a degradation of the insulation strength and critical current of the superconductor. An improved understanding of these mechanisms is not only important for the LHC in view of the planned increase in beam brightness, but also for other high energy accelerators using superconducting magnets. An experimental road map has been defined to study these damage mechanisms. Experiments have been performed with Nb-Ti and Nb_3Sn strands and cable stacks at room temperature. This contribution focuses on the experimental study on the effect of millisecond heating on superconducting strands.

INTRODUCTION

The energy stored in the particle beams of an accelerator such as CERN's Large Hadron Collider is substantial and requires a complex machine protection system to protect the equipment from damage. Losses of the beam can happen at very different time-scales, the most critical are so-called ultra-fast losses within less than 270 μs (~ 3 LHC turns). Protection against such losses relies on passive absorber elements [1]. The interaction between the LHC beam and these passive devices generates particle showers which might impact on the downstream elements such as superconducting magnets causing quenches or in the worst case damage.

In this paper the damage mechanisms of the superconducting magnet components and the experimental road map developed to study these mechanisms are presented. The experimental set-up to measure degradation of the critical current in Nb-Ti and Nb_3Sn strands due to millisecond heating is described. Using a fast capacitor discharge, superconducting strands were heated within a few milliseconds to peak temperatures ranging from 400 to 1000°C. The degradation of the superconducting properties of the strands were then studied with magnetization measurements.

DAMAGE MECHANISMS AND EXPERIMENTAL ROAD MAP

The absorption of high-energy particle pulses lasting several micro-seconds causes temperature increases of the same rise-time inside the intercepted material. During this short period, thermal expansion is prevented by mass inertia. This gives rise to dynamic stresses propagating through the material that could lead to permanent damage of the material, e.g. deformation or cracks.

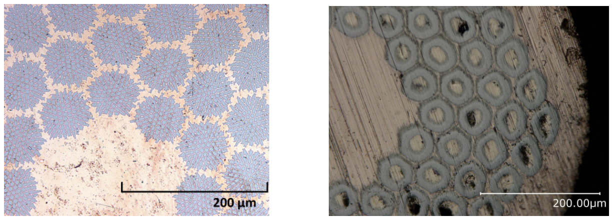
The most sensitive materials in the superconducting magnets of the LHC and its high luminosity upgrade are the superconducting cables and their insulation. Superconducting cables are classical Rutherford cables made of Nb-Ti/Cu [2] or Nb_3Sn/Cu wires insulated either by polyimide or E-glass tapes [3]. Three damage mechanisms were identified: degradation of the polyimide insulation when exposed to high temperatures, reduction of the critical current of the superconducting cable induced by high temperatures and reduction of the critical current induced by mechanical stress or deformation. An experimental road map was proposed and is being performed step by step to study the two first mechanisms for different time-scales.

The polyimide insulation degradation is studied for three time-scales: hours – heating with a furnace; milliseconds – capacitive discharge; micro-seconds – interaction with a proton beam at room and cryogenic temperature. The results for the first have been presented in [4]. Degradation of dielectric strength of the polyimide insulation was observed for exposure to temperatures above 400°C. The two other experiments are on going.

As part of the proposed experimental road map, the effect of heating on superconductors (Nb-Ti, Nb_3Sn) is being studied in the millisecond timescale, using capacitive discharges, and the micro-second timescale, irradiating strands with proton beams at room and cryogenic temperatures. The minute long timescale has already been studied earlier [5] and it has been measured that a 400°C heat treatment of Nb-Ti strands reduces the critical current by more than 20% at 3 T and 4.2 K . The experimental set up and results of the study on the effect of millisecond heating is presented in the next section.

MILLISECOND HEATING OF SUPERCONDUCTORS

For the experiment Nb-Ti sample strands from the LHC main dipole inner-layer cables and Nb_3Sn sample strands for the HL-LHC triplet [6] were used. The Nb-Ti strands and filaments have a diameter of 1.065 mm and 7 μm respectively [2]. The Nb_3Sn strand and filament diameter are 0.85 mm and 55 μm respectively. The copper to superconductor ratio of the Nb-Ti and Nb_3Sn strand is 1.65 and 1.2. The internal structure of the strands is shown in Fig. 1.



(a) Nb-Ti filament structure (b) Nb_3Sn filament structure

Figure 1: Microscopic picture of Nb-Ti (a) and Nb_3Sn (b) strands internal structure. The copper matrix and the superconducting filaments are clearly visible.

Experimental Setup

The discharge setup (see Fig. 2) consists of a circuit powered by a capacitor bank, including two resistances: a Nb-Ti or Nb_3Sn strand with a resistance of 3 mΩ and a connection cable with a resistance of 35 mΩ . The 10-centimeter-long strand was fixed with copper plates on a fiber glass plate. The voltage drop over the strand was measured between two sets of plates and used to estimate the achieved peak temperature in the strand. The experiment was performed at room temperature in air.

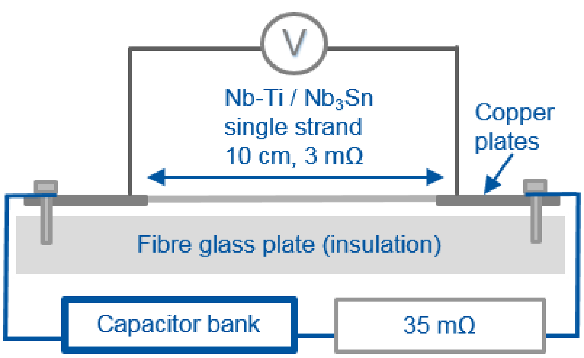


Figure 2: Schematic picture of the setup for the capacitive discharge experiment.

The samples were heated up to 1000^oC by a capacitive discharge. Samples were individually treated with increasing discharge voltage from sample to sample. The temperature rise to the peak value lasted ~ 9 ms. The cooling time constant was estimated from infrared camera recordings to ~ 7 s.

For every sample the voltage $U(t)$ over the strand and the circuit current $I(t)$ were measured. From this, the change of the strand's enthalpy (ΔH) was calculated for each discharge as:

$$\Delta H = \int_0^{t_{end}} I(t) \cdot U(t)\, \mathrm{d}t, \tag{1}$$

with t_{end} being the time, when $I(t)$ and $U(t)$ reached zero. Assuming an adiabatic process, the peak temperature ($T_{peak} = RT + \Delta T$) reached in each strand was then derived from the known relationship between the change of the strand enthalpy ΔH and the increase of the strand temperature ΔT starting from room temperature (RT):

$$\Delta H(\Delta T) = \int_{RT}^{RT+\Delta T} c_p(T)\, \mathrm{d}T, \tag{2}$$

where $c_p(T)$ is the heat capacitance of the strand as a function of the absolute temperature T derived from [7].

Magnetization measurements

The critical current of a superconducting strand is proportional to its irreversible magnetization [8]:

$$J_c \sim \frac{\Delta M}{d_f}, \tag{3}$$

where J_c is the critical current density, ΔM is the irreversible magnetization and d_f is the filament diameter of the strand. Magnetization measurements were performed on the strands' central parts of 5 mm length where the temperature profile was assumed to be homogeneous.

The measurements were performed using a SQUID Vibrating Sample Magnetometer (MPMS SQUID VSM) with a magnetic field sweep rate of 0.3 $\frac{T}{min}$ reaching a maximum of 7 T [9]. The measurements were performed at 2 K, 4 K and 6 K for Nb-Ti and 2 K, 4 K, 10 K and 15 K for Nb_3Sn.

Results

Fig. 3 shows the irreversible magnetization of the samples at 6 K and 10 K for different peak temperatures reached in Nb-Ti and Nb_3Sn respectively.

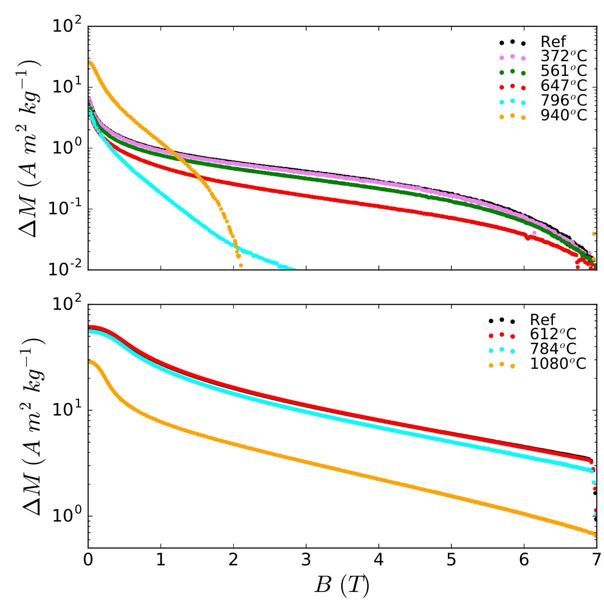


Figure 3: Irreversible magnetization (ΔM) of Nb-Ti strands at 6 K (upper) and Nb_3Sn strands at 10 K (lower) as a function of the external magnetic field up to 7 T.

The normalized pinning force F_p/F_{pmax} versus the reduced field b is shown in Fig. 4. The reduced field is defined

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as $b = B/B_{c2}(T)$, where B is the applied magnetic field, $B_{c2}(T)$ is the critical field of the sample and T the absolute temperature at which the magnetization measurement was performed. The magnitude of the pinning force is given by $F_p = J_c \cdot B$. The normalized pinning force is obtained as

$$\frac{F_p}{F_{pmax}} = \frac{\Delta M \cdot B}{(\Delta M \cdot B)_{max}} . \tag{4}$$

For each sample, the following temperature scaling law [10] was fitted to the data to obtain $B_{c2}(T)$ and thus b.

$$F_p/F_{pmax} = C(T)b^p(1-b)^q, \tag{5}$$

where p, q and $C(T)$ are fitting parameters.

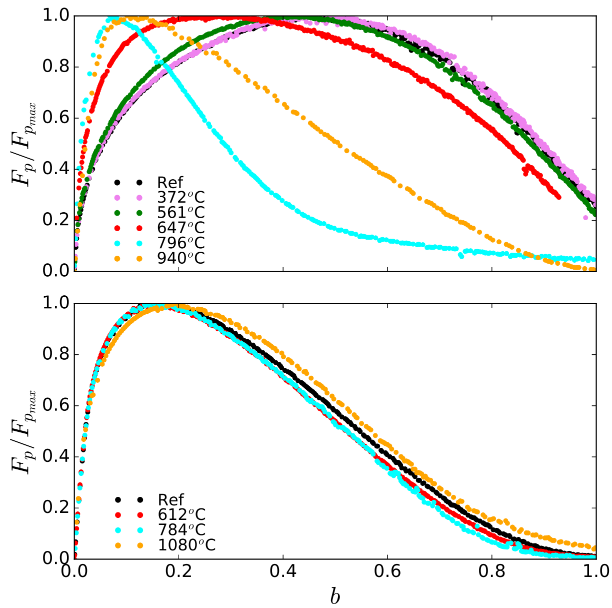

Figure 4: Normalized pinning force versus reduced field b after heat treatment with different peak temperatures for strands of Nb-Ti at 6 K (upper) and Nb_3Sn at 15 K (lower).

In Table 1, the maximum of the pinning forces for the different samples after heat treatment normalized to a reference sample are summarized.

Table 1: Maximum pinning force ($F_{p_{max}}$) after heat treatment with different peak temperatures (T_{peak}), normalized to the maximum of the reference sample ($F_{p_{max}ref}$) for strands of Nb-Ti at 6 K and Nb_3Sn at 15 K.

Nb-Ti		Nb_3Sn	
T_{peak} (°C)	$\frac{F_{pmax}}{F_{pmaxref}}$	T_{peak} (°C)	$\frac{F_{pmax}}{F_{pmaxref}}$
376	0.69	612	0.95
561	0.77	784	0.75
647	0.42	1080	0.16

Discussion

For Nb-Ti, Figure 3 indicates a degradation of ΔM and, thus, of J_c for peak temperatures above 372°C. From Figure 4, it can be seen that the maximum of the pinning force shifts from 0.5 b to 0.1 b with increasing peak temperature, indicating a change in the pinning behavior. Moreover, the magnitude of the pinning force is reduced by the heat treatment as shown in Table 1. As discussed in [5,10], this might be explained by a variation of the $\alpha - Ti$ precipitate size and spacing inside the Nb-Ti filaments. For peak temperatures above 647°C, another process causes an increase of ΔM at external fields below 2 T. This could be explained by an increase of the effective filament diameter or the creation of inter-filament loops. To confirm these hypotheses, transport current measurements and microscopic analysis of the samples are planned.

For Nb_3Sn, degradation of ΔM is only visible for peak temperatures above 612°C. The shape of the curves F_p/F_{pmax} versus b does not change during the degradation indicating that the pinning behavior was not modified by the heat treatment. However, as shown in Table 1, the pinning force of the Nb_3Sn samples is reduced by more than 25% for temperature above 784°C. This might indicate a growth of the grain size. In [11–13], it has been demonstrated that the flux pinning force is roughly proportional to the inverse of the grain size.

CONCLUSION

An improved understanding of the damage mechanisms and limits of superconducting magnet components is required, in particular in view of the planned increase of beam brightness in the LHC and its future High Luminosity upgrade. An experimental road map has been defined and studies are performed accordingly.

The degradation of the critical current density of Nb-Ti and Nb_3Sn strands after millisecond heating due to a capacitive discharge has been determined via magnetization measurements. Degradation of the critical current density has been observed in Nb-Ti strands for peak temperatures above 372°C and for Nb_3Sn strands above 612°C. For Nb-Ti strands reaching a peak temperature of 561°C, the critical current density is reduced by 30% at an applied magnetic field of 3 T and a temperature of 4 K. For the same magnetic field and temperature, Nb_3Sn strands show a degradation of 10% after reaching 784°C. For temperatures above 796°C, an additional mechanism causes a sudden increase of ΔM in external fields below 2 T. The identification of the source of this behavior is ongoing.

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