DEGRADATION OF THE INSULATION OF THE LHC MAIN DIPOLE CABLE WHEN EXPOSED TO HIGH TEMPERATURES

V. Raginel[1,2], B. Auchmann[1], D. Kleiven[1,3], R. Schmidt[1], A. Verweij[1], D. Wollmann[1]
[1]CERN-TE, 1211 Geneva 23, Switzerland
[2]Vienna University of Technology, Vienna, Austria
[3]Norwegian University of Science and Technology, Trondheim, Norway

Abstract

The energy stored in the LHC beams is substantial and requires a complex machine protection system to protect the equipment. Despite efficient beam absorbers, several failure modes lead to some limited beam impact on superconducting magnets. Thus it is required to understand the damage mechanisms and limits of superconducting magnets due to instantaneous beam impact. This becomes even more important due to the future upgrade of CERNs injector chain for the LHC that will lead to an increase of the beam brightness. A roadmap to perform damage tests on magnet parts has been presented previously [1]. The polyimide insulation of the superconducting cable is identified as one of the critical elements of the magnet.

In this contribution, the experimental set-up to measure the insulation degradation of LHC main dipole cables due to exposure to high temperature is described. Compressed stacks of insulated Nb-Ti cables have been exposed to a heat treatment within an Argon atmosphere. After each heat treatment, the dielectric strength of the insulation is measured with high voltages. The results of this experiment provide an upper damage limit of superconducting magnets due to beam impact.

INTRODUCTION

The LHC main dipoles and quadrupole coils are wound from Nb-Ti Rutherford cable insulated by three layers of Polyimide tape (see Fig. 1). Reduction of its insulation strength could lead to critical failures. An inter-turn short would be fatal for the magnet in case of a quench whereas a short circuit to ground would prevent LHC operation and require most probably a replacement of the magnet. For these reasons, the degradation of magnet insulation when exposed to high temperatures has been studied.

Compressed stacks of LHC dipole type cable were exposed to heat treatment within an Argon atmosphere. After each heat treatment, the cable to cable dielectric strength was measured.

In parallel measurements of the weight loss of polyimide tapes due to heat treatment were performed. A weight loss model has been developed and compared to these measurements. Finally a model to correlate the weight loss with the degradation of the dielectric strength was derived.

DIELECTRIC STRENGTH DEGRADATION

Samples

LHC main dipole inner-layer cables are made out of 28 strands. The cables have a width of 15.1 mm, a mid-thickness of 1.9 mm and a keystone angle of 1.25°. They are insulated with three layers of polyimide tapes (see Fig. 1). The two inner layers with a thickness of 50.8 μm

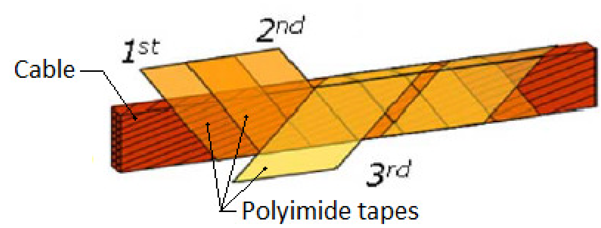

Figure 1: Superconducting cable insulation [2].

are wrapped around the cable with a 50 % overlap. The third layer, with a thickness of 68.6 μm, is wrapped in opposite direction with a spacing of 2 mm. The outer side of the third layer has a polyimide based adhesive coating. The adhesive coating is non-sticky at room temperature and bonds itself at a minimum temperature of 185°C and a moderate contact pressure. [3]

To measure the degradation of the dielectric strength of the insulation when exposed to high temperature, experiments were performed with stacks of six inner-layer cables with a length of 240 mm. The cables were alternately stacked to compensate for the keystone angle, thus forming a rectangular stack. The heat treatment of the stacks was performed under a compression of 100 MPa and in an inert atmosphere which is comparable to the situation in the LHC dipoles during operation. To achieve such a pressure, the stacks were placed in a stainless steel mould.

Heat Treatment

Heat treatments were performed on the samples up to 600°C in an oven filled with Argon. The temperature ramp rate of the oven was set to 150°C/h, with a flat top of 5 minutes. Two identical cable stacks were put in the oven during each heat treatment. The temperature profiles of the cable stacks were measured and recorded. In addition to the moulds with cable stacks, samples of polyimide tape were put into the oven to determine their weight loss. The different temperature profiles of the cable stacks are shown in Fig 2.

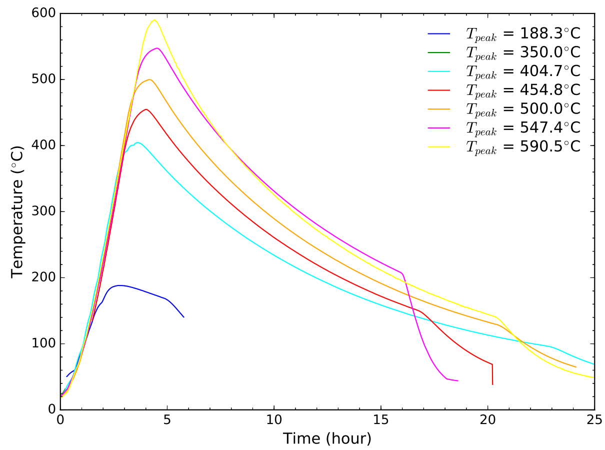

Figure 2: Temperature profiles of the cable stacks during the heat treatment.

Dielectric Strength Measurements

Dielectric strength measurements were performed after each heat treatment. Cable to cable measurements were done with voltages up to 20 kV, resulting in six measurements for each peak temperature - three per stack.

Experimental results

Fig. 3 shows the cable stacks after the heat treatment. The peak temperatures are indicated in the picture. For

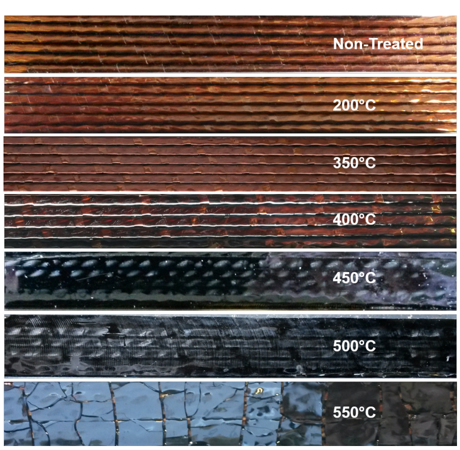

Figure 3: Cable stacks (side view) before and after the heat treatment with different peak temperatures

temperatures below 400°C, the cable looks the same after heat treatment. From the color of the polyimide it can be concluded that the changes appear above 400°C. From 400°C the adhesive film coated on insulation turns black. Above 450°C, all three insulation layers turn black and above 550°C cracks appear.

The results of the measurements of the dielectric strength after heat treatment of the cable stacks are shown in Fig. 4. Triangle markers indicate that no breakdown was achieved

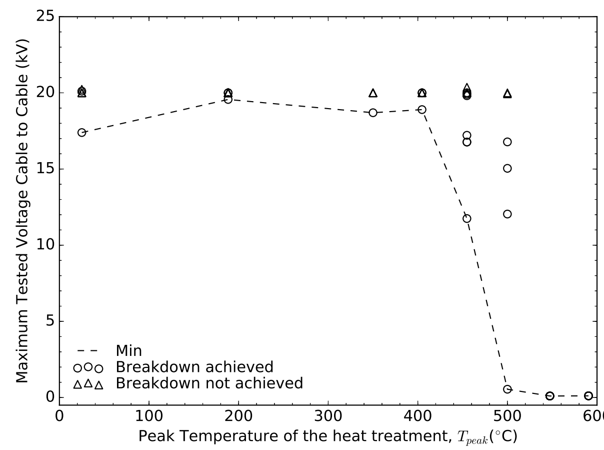

Figure 4: Results of the dielectric strength measurements after heat treatments at different peak temperature

with voltages up to 20 kV, round markers indicate that a breakdown was observed. The dashed line indicates minimum breakdown voltages as a function of temperature. The dielectric strength of the non-treated samples is between 17.4 and 20 kV, which is in agreement with previous measurements [2]. No degradation of the dielectric strength was measured on stacks after a heat treatment up to 400°C. Degradation of the insulation was first observed on samples exposed to a peak temperature of about 450°C with the lowest breakdown voltage is measured at 11.7 kV. After an exposure to temperatures above 500°C, the dielectric strength measurements have a large spread from 500 V to 20 kV. From 550°C, decisive signs of degradation were observed with resistance cable to cable ranging from 30 kΩ to 3 MΩ.

The degradation of the insulation when exposed to high temperature has several reasons. First, as the polyimide reacts, the insulation tapes become thinner and thinner. Second, it has been shown in [4] that the non-volatile product of the reaction is mostly solid carbon which is a conductor.

Variation of the measured breakdown voltages within each measurement set can probably be explained by inhomogeneities in the samples. These variations can also be expected in LHC magnets due to the significant length of the used cables. Thus, the lowest breakdown voltage defines the temperature limit below which no degradation of the insulation was observed to 400°C.

WEIGHT LOSS

In addition to the cable stacks, samples of polyimide tape with a thickness of 50 and 125 μm were heated. The weight of the tapes was measured before and after heat treatment

ISBN 978-3-95450-147-2

to deduce the weight loss.

Reaction rate of polyimide

A model of the reaction rate of polyimide exposed to high temperature was developed based on data provided by Dupont [5].

The reaction rate model from [6] was fitted to the data of Dupont. The temperature dependency of the reaction rate was derived as

$$\frac{1}{w_f}\frac{dw}{dt} = -k_0 \exp\left(-\frac{E_a}{RT}\right)\left(1-\frac{w}{w_f}\right)^n, \qquad (1)$$

where $\frac{dw}{dt}$ is the reaction rate, w is the actual weight loss and w_f is the weight loss after a full degradation of the polyimide set to 0.55, R is the ideal gas constant, T is the temperature in Kelvin and k_0, E_a and n are fitting parameters.The fit parameters obtained can be found in Table 1. The weight loss is defined as

$$w = \frac{(m_0 - m)}{m_0}, \qquad (2)$$

where m is the actual mass and m_0 is the initial mass.

Table 1: Fit parameters obtained by fitting (1) to data from [5]

k_0	$3.78 \times 10^{10}\ \mathrm{s^{-1}}$
E_a	$226\ \mathrm{kJmol^{-1}}$
n	3.71

Comparison of the Measurements and Model

By inserting the measured temperature profiles of the polyimide tapes in (1), the expected sample weight losses were calculated and compared to measurements (see Fig.5). The model fits the measurements well.

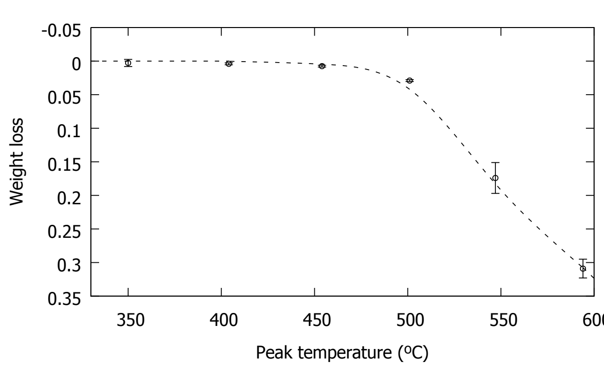

Figure 5: Weight loss of polyimide tape vs peak temperature. The dashed line is given by the model, the round markers are the average of the weight loss measured after the heat treatment with their standard deviation.

RELATION BETWEEN DIELECTRIC STRENGTH AND WEIGHT LOSS

Weight loss can be used as an indicator for the degradation of the dielectric strength of polyimide insulation. The lowest breakdown voltages in function of the average weight loss after heat treatment are plotted in Fig6. It can

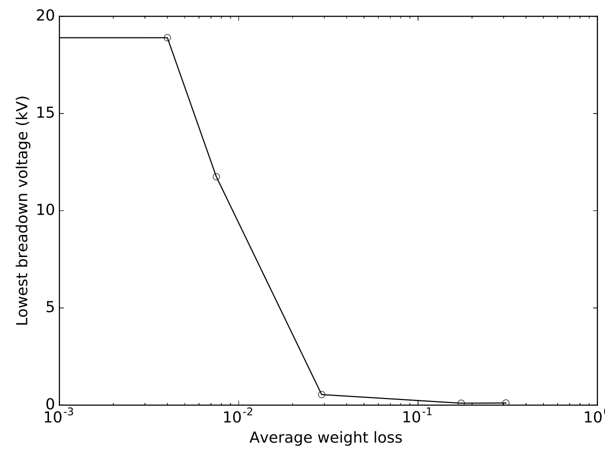

Figure 6: Lowest breakdown voltage measured on cable stacks vs average weight loss of polyimide tape measured after heat treatment.

be observed that for a weight loss below 0.4% no degradation of the dielectric strength is expected. A weight loss between 0.4% and 2.9% indicates a starting degradation of the dielectric strength. A total loss of the dielectric strength is expected for weight loss above 2.9%.

CONCLUSION

The degradation of the dielectric strength of the polyimide insulation of LHC superconducting magnet cables due to an exposure to high temperature has been measured.

In parallel a model was developed to predict the weight loss of the insulation when exposed to heat. Weight loss measurements were performed on samples of polyimide films. It has been shown that the weight loss model and measurements are in good agreement.

For temperatures below 400°C, with weight loss below 0.4%, no degradation was observed.

The developed weight loss model could become a way to predict degradation of the dielectric strength of polyimide for other temperature profiles and time-scales.

REFERENCES

[1] V. Raginel *et al.*, “Experimental Setups to Determine the Damage Limit of Superconducting Magnets for Instantaneous Beam Losses”, IPAC15, WEPHA016, pp. 3138-3140.

[2] P. Fessia *et al.*, “Electrical and Mechanical Performance of an Enhanced Cable Insulation Scheme for Superconducting Magnets”, *IEEE Trans. Appl. Supercond.*, Vol. 20, No. 3, 2010

[3] The LHC Design Report, tech. rep., CERN, 2004.

[4] R. Srinivasan *et al.*, "Chemical transformations of the polyimide Kapton brought about by ultraviolet laser radiation",*Journal of Applied Physics* 78, 4881 (1995); doi: 10.1063/1.359776.

[5] Summary of Properties for Kapton Polyimide Films. *Dupont TM, Kapton R.*

[6] N. Regnier, and C. Guibe, "Methodology for multistage degradation of polyimide polymer", *Polymer degradation and stability*, 55.2 (1997), pp. 165-172.

ISBN 978-3-95450-147-2