LHC MAGNET QUENCH TEST WITH BEAM LOSS GENERATED BY WIRE SCAN

M. Sapinski, F. Cerutti, K. Dahlerup-Petersen, B. Dehning, J. Emery, A. Ferrari, A. Guerrero, E.B. Holzer, M. Koujili, A. Lechner, E. Nebot, M. Scheubel, J. Steckert, A. Verweij, J. Wenninger
CERN, Geneva, Switzerland

Abstract

Beam losses with millisecond duration have been observed in the LHC in 2010 and 2011. They are thought to be provoked by dust particles falling into the beam. These losses could compromise the LHC availability if they provoke quenches of superconducting magnets. In order to investigate the quench limits for this loss mechanism, a quench test using a wire scanner has been performed, with the wire movement through the beam mimicking a loss with similar spatial and temporal distribution as in the case of dust particles. This paper will show the conclusions reached for millisecond-duration dust-provoked quench limits. It will include details on the maximum energy deposited in the coil as estimated using FLUKA code, showing a reasonable agreement with quench limit estimated from the heat transfer code QP3. In addition, information on the damage limit for carbon wires in proton beams will be presented, following electron microscope analysis which revealed strong wire sublimation.

INTRODUCTION

The maximum amount of energy which can be deposited in a superconducting cable without provoking the transition to a normal-conducting state is called the quench limit. It depends, among other parameters, on the duration of the energy perturbation, in this case the beam loss [1]. For very fast beam losses, shorter than $100\ \mu\mathrm{s}$, the quench limit is calculated from the change of the enthalpy of the cable components. For steady state losses, the quench limit is an overall measure of the heat evacuation efficiency and can be estimated from experiments and calculations. The quench limits for intermediate duration losses are more speculative because the time constants of the various cooling processes are not well known [2, 3].

The LHC operation in 2010 and 2011 has been affected by the phenomenon of millisecond-duration beam losses, observed by the Beam Loss Monitoring (BLM) system. These losses are suspected to be provoked by dust particles falling into the beams. They are called Unidentified Falling Objects (UFO) [4].

The UFO losses caused beam dumps as the BLM beam abort thresholds are conservative because of a poor knowledge of the quench limits for millisecond losses and because they are set for a direct beam loss scenario [5]. So far, UFOs have not provoked quenches of the superconducting magnets, although this could be an issue when the beam energy and intensity increase.

The main goal of the following experiment was to determine the quench limit in case of millisecond beam losses and validate the QP3 code. The only way to generate millisecond losses in a controlled way in the LHC is to use the wire scanner as a source of the loss. A particle shower simulation is done afterwards to estimate the energy deposition in the magnet coil.

EXPERIMENT

The experiment was performed on November 1, 2010 using the wire scanner installed on beam 2 of LHC. This beam was chosen due to the fact that the collimation region downstream of the wire scanner prevents propagation of the losses around the ring.

The beam intensity was $1.53 \cdot 10^{13}$ protons contained in 144 bunches and the energy was 3.5 TeV per proton. The LHC wire scanners are linear devices with a nominal speed of the carbon fiber of 1 m/s. They always perform two scans: IN, moving the fork with the wire from parking position through the beam, and after a delay scan OUT, back to the parking position.

The most affected magnet is a separation dipole called MBRB placed about 33 meters downstream of the wire scanner. The magnet operates at 4.5 K and its current at 3.5 TeV is 3075 A. Further downstream, in the same cryostat, there is a quadrupole magnet MQY, which has also been a potential candidate for quenching. There are 8 BLMs installed on these magnets.

The IN wire scans were always performed with a nominal wire speed of 1 m/s, while the speed during the scan OUT was gradually decreased with the sequence: $1,\ 0.75,\ 0.5,\ 0.37,\ 0.3,\ 0.25,\ 0.2,\ 0.15$ and $0.05\ \mathrm{m/s}$, when the magnet quenched. During these tests technical problems with the wire scanner electronics were encountered which led to delays of the procedure and to the loss of beam profile data for slow scans. The quench of the magnet triggered an acquisition of post-mortem buffers with high-precision data which are presented in Figure 1. The blue points show the BLM data and the red ones the voltage measured on the magnet coil by the Quench Protection System (QPS) probes.

DAMAGE TO THE WIRE

During the winter technical stop the wire scanner was opened and the wire recovered. It was inspected using a scanning electron microscope [6] with magnifications reaching 1500. At the location of the beam impact the wire

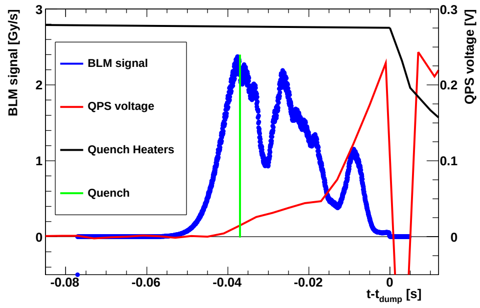

Figure 1: BLM post-mortem signals (blue) overlaid with QPS voltage readout (red) during the wire scan which led to quench of MBRB magnet. In the moment when quench heaters fire (black line, arbitrary units) the QPS reading is suffering from interference (gap in the data). The green line marks the time at which the QPS voltage indicates the presence of the resistive zone.

material sublimated reducing its diameter by almost 50%, from the initial $34\ \mu\mathrm{m}$ down to about $18\ \mu\mathrm{m}$. The image of the central part of the fiber is shown in Figure 2. The linear energy density during the last scan was about 4 times larger than during the wire breaking in SPS [7], which needs further investigation.

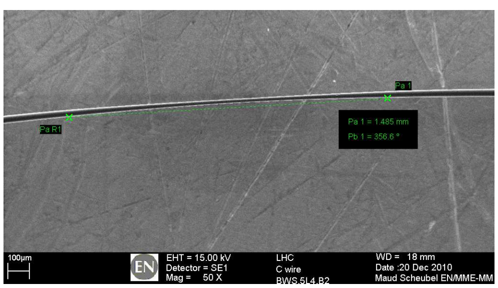

Figure 2: The carbon fiber after the experiment pictured using scanning electron microscope with magnification 50.

DISCUSSION OF LOSS PROFILE

The loss profile from the wire scanner scintillators was not recorded, but the same profile, observed by the BLMs, is shown in Figure 1. This profile, for regular scans, reproduces the near gaussian transverse shape of the beam. About $1.1 \cdot 10^{14}$ protons are expected to pass through the wire in such a case. The irregular shape observed is due to vibrations of the fiber during the scan, when its temperature reaches sublimation. Similar behaviour has already been observed during previous wire-damaging scans [7].

The vibrations of the wire, as well as the sublimation process taking place during the last scan, make it difficult to estimate the actual number of protons which passed through the wire ($\mathrm{N_p}$). This information can be recovered using data from previous scans, performed with higher speeds, and assuming that the product $\mathrm{N_p} \cdot \mathrm{v_w}$ is invariant for those scans. The total dose in the BLMs ($\mathrm{D_{BLM}}$) is proportional to $\mathrm{N_p}$ and therefore:

$$\mathrm{D_{BLM}} \cdot \mathrm{v_w} = \mathrm{const.} \qquad (1)$$

This invariant is illustrated in Figure 3 for scans performed during the test.

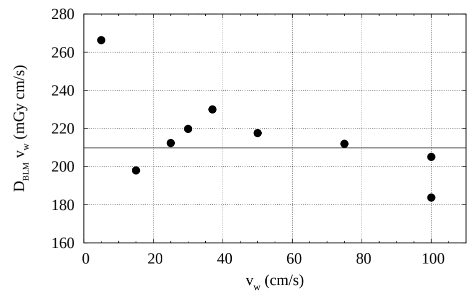

Figure 3: The behaviour of invariant $\mathrm{D_{BLM}} \cdot \mathrm{v_w}$ during the quench test.

It is observed that, during the last scan with $5\ \mathrm{cm/s}$, the invariant is not preserved anymore, and about 27% more protons (i.e. $1.4 \cdot 10^{14}$) pass through the wire than it is expected from the scan speed. There is no way to find exactly what has happened with the wire during this scan, but one can speculate that it started to vibrate, passing through the beam more than once (three peaks are observed in the time pattern of the BLM signal).

FLUKA SIMULATIONS

The results of FLUKA [8, 9] simulations are discussed in detail in [10]. A precise geometry was implemented, including the BLMs on the two magnets downstream of the wire scanner. The Figure 4, normalized to $1.4 \cdot 10^{14}$ protons passing the wire, shows a good agreement, within 30%, between the simulated and observed BLM signals. This agreement supports the results for the energy deposition in the coil.

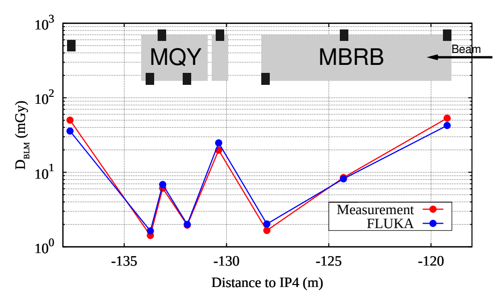

Figure 4: Comparison of simulated (blue) and measured (red) BLM signals for the scan with $\mathrm{v_w} = 5\ \mathrm{cm/s}$.

A longitudinal peak distribution of the energy density along the coils is shown in Figure 5. The maximum is narrow and located, as intuitively expected, in the front part of MBRB magnet coil.

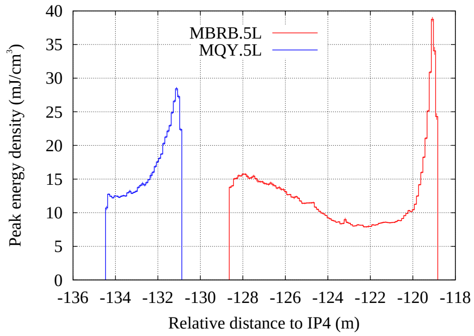

Figure 5: Distribution of the peak energy density deposited, averaged over cable radius, along the magnets coils. The beam is coming from the right.

The radial distribution of energy density in the most exposed longitudinal location is shown in Figure 6. The maximum value, at the inner surface of the coil, is $62.5\ \mathrm{mJ/cm^3}$ and the average over the cable radius is $38.8\ \mathrm{mJ/cm^3}$, as already seen in Figure 5.

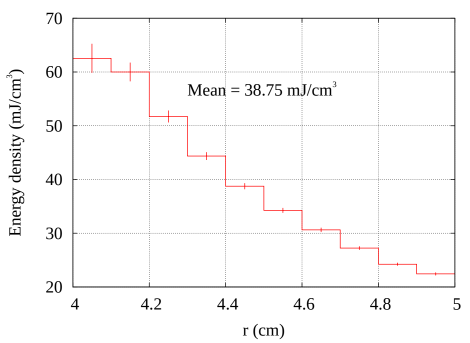

Figure 6: Radial distribution of the energy density deposit for the most impacted azimuth and longitudinal position of the MBRB magnet. The errors are statistical.

QP3 QUENCH LEVEL

The QP3 code [3] has been used to estimate the quench limit for the loss generated by the wire scanner, with the input being the radial loss profile obtained from FLUKA simulations (Figure 6). The calculated quench limit corresponds to the creation of any resistive zone, therefore it takes place for the time $t_Q = -0.037\ \mathrm{s}$ in Figure 1 (green line). Such a definition of the quench cannot exclude that it could have appeared already with the $15\ \mathrm{cm/s}$ scan and disappeared due to cooling. The quench limit, averaged over the cable, is calculated to be between $15.6\ \mathrm{mJ/cm^3}$ if no liquid helium is present in the cable and $20.5\ \mathrm{mJ/cm^3}$, if the liquid helium fills all the volume in-between the strands (4% of volume). This value must be compared with only 30% fraction of FLUKA results which correspond to the fraction of the loss before t_Q. The quench limit values, summarized in Table 1, show a good agreement.

Table 1: Comparison FLUKA and QP3 quench levels

energy density	**FLUKA** $[\mathrm{mJ/cm^3}]$	**QP3 4%He** $[\mathrm{mJ/cm^3}]$	**QP3 no He** $[\mathrm{mJ/cm^3}]$
cable average	11.6	20.5	15.6
maximum	18.8	31.8	24.2

CONCLUSIONS

An experiment was performed in which an LHC magnet quench was provoked by a loss generated by a wire scan. The main goal of the experiment was to validate a code predicting the time-dependence of quench limits on millisecond time scale. This timescale is characteristic for UFO events - unexpected losses observed during LHC operation in the 2010 and 2011 runs. In the end, the loss which led to a magnet quench turned out to be longer than initially planned (quench occured after 10 ms instead of 1 ms). The carbon fiber, which is used as a moving target in the wire scanner, was found sublimated to almost 50% of its initial diameter. The FLUKA simulations, together with experiment results, have shown that the quench took place for an energy density averaged over the cable radius of about $10\ \mathrm{mJ/cm^3}$. Calculation with QP3 code give results about two times higher. This agreement between both approaches is encouraging, considering various unknowns affecting the measurements and the calculations, for instance the actual amount of liquid helium in the voids between strands or the steepness of the longitudinal energy density distribution in the coil. Another test of this type is planned in 2011.

REFERENCES

[1] J.B. Jeanneret et al., “Quench levels and transient beam losses in LHC magnets”. LHC Project Report 044.

[2] A. Priebe et al.,”Beam-induced quench test of LHC main quadrupole”, this proceedings.

[3] A. Verweij,“QP3: Users Manual”, CERN/EDMS 1150045

[4] T. Baer et al.,”Dust Particles in LHC”, this proceedings, E. Nebot et al.,”Analysis of fast losses in the LHC with the BLM system”, this proceedings.

[5] M. Sapinski et al.,”Simulation of Beam Loss in LHC MB Magnet and Quench threshold test”, LHC-Project-Note-422

[6] M. Scheubel, “SEM observations of a Carbon wire”, CERN/EDMS 1110058

[7] M. Sapinski et al.,”Carbon fiber damage in particle beam”, proceedings of 46th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams.

[8] A. Fassò, A. Ferrari, J. Ranft and P.R. Sala, “FLUKA: a multi-particle transport code”, CERN-2005-10, INFN/TC-05/11, SLAC-R-773

[9] G. Battistoni et al., “The FLUKA code: Description and benchmarking”, AIP Conference Proceeding 896, 31-49, (2007)

[10] A. Lechner et al., paper in preparation