EXPERIMENTS ON THE MARGIN OF BEAM INDUCED QUENCHES FOR A SUPERCONDUCTING QUADRUPOLE MAGNET IN THE LHC

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Abstract

Protection of LHC equipment relies on a complex system of collimators to capture injected and circulating beam in case of LHC kicker magnet failures. However, for specific failures of the injection kickers, the beam can graze the injection protection collimators and induce quenches of downstream superconducting magnets. This occurred twice during 2011 operation and cannot be excluded during future operation. Tests were performed during Machine Development periods of the LHC to assess the quench margin of the quadrupole located just downstream of the last injection protection collimator in point 8. In addition to the existing Quench Protection System, a special monitoring instrumentation was installed at this magnet to detect any resistance increase below the quench limit. The correlation between the magnet and Beam Loss Monitor signals was analysed for different beam intensities and magnet currents. The results of the experiments are presented.

INTRODUCTION

Proton beams are injected, through the TI 2 and TI 8 transfer lines, into the LHC straight sections in point 2 (IR 2) and 8 (IR 8), respectively. The injection system, in each IR, consists of 5 horizontally deflecting septum magnets (MSI) and 4 vertically deflecting kickers (MKI). An absorber (TDI) is installed at a phase advance of 90° with respect to the MKI to intercept mis-kicked beams. Further protection in case of phase errors is provided by two auxiliary collimators (TCLIA and TCLIB) located at 180° ± 20° from the TDI. The design half-aperture of all the injection protection collimators corresponds to 6.8 σ, where σ is the RMS beam size.

Injections of 4 batches of 36 bunches of up to $1.5 \cdot 10^{10}$ protons per bunch and a transverse emittance $\varepsilon = 2$ μm are currently used during standard LHC operation.

INJECTION FAILURE AND FOLLOW-UP

A breakdown in one of the Beam 2 MKIs occurred during the injection of two batches of 36 bunches in April 2011, as a consequence of vacuum degradation in the kicker region. The second injected batch was over-kicked (110-125% nominal deflection) and the proton bunches grazed the TDI and the TCLIB; the scattered protons and the showers of secondary particles induced the quench of 11 downstream superconducting magnets.

As a follow-up a number of improvements were applied to the hardware and the diagnostics, and more severe limits were defined for the MKI interlocks [1]. Moreover, the TCLIB opening was relaxed by 1.5 σ (new setting: 8.3 σ) in order to minimize the number of primary protons intercepted at this collimator and thus the load on the downstream superconducting quadrupole Q6.L8.

Machine Development (MD) time was dedicated to quantify the loss rate at the Q6.L8, as a function of different TCLIB settings, and to define the quench margin of this magnet. Special monitoring equipment was installed in the injection region of Beam 2 for the test.

TEST SETUP

An additional Beam Loss Monitor (BLM), with an RC delay filter (R = 150 kOhm, C = 47 nF) in front of the readout electronics, was installed close to the already existing ionization chambers at the TCLIB. This was done in order to overcome saturation problems and to be able to correlate the BLM reading with the number of protons lost at the collimator.

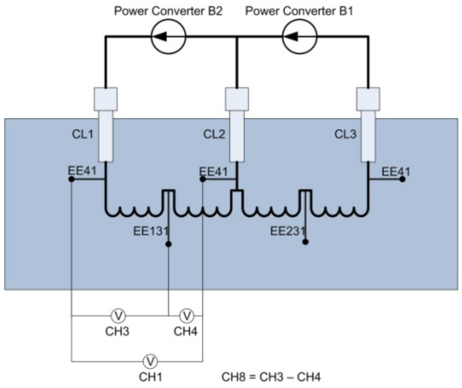

Figure 1: Measurement diagram: electrical connection of B2 magnet aperture.

A dedicated measurement system was installed close to the Quench Protection System (QPS) [2] of the Q6.L8 rack (Fig.1) in the Underground Area. This system allows measurement of the voltage drop across the superconducting coils of the magnet in order to rapidly diagnose any quickly developing normal conducting zone. The electrical signal is picked up in parallel to the QPS system and is connected to the high impedance measuring device. A number of patches ensure that the QPS remains connected and can work normally to provide the standard level of protection.

Two types of devices are used to record the electrical signals:

- A 10 kHz Data Acquisition (DAQ) with an analog filter on the input
- A 20 MHz digital oscilloscope

The measurements were performed with a nominal pilot bunch (10^{10} protons) in inject-and-dump mode (first turn). The TCLIB jaws were closed, in steps, from 8.3 σ to 1.3 σ. This last aperture corresponds to a gap of ~1 mm, very close to the anti-collision mechanical limits. In order to intercept the full beam, an offset of up to -3 σ with respect to the beam centre was applied while keeping the gap at minimum. Several injections were performed for each setting while monitoring the QPS signal and the losses at the TCLIB and at the downstream magnet (Fig. 2).

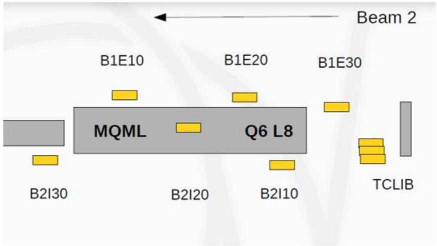

Figure 2: Schematic view of the position of the BLMs (yellow rectangles) at the location of the Q6.L8 magnet downstream of the TCLIB.

The same measurements were repeated with bunch intensity of $2 \cdot 10^{10}$ and $3 \cdot 10^{10}$ protons.

Measurements were also performed with the TCLIB intercepting the full beam, increasing the current in the magnet Q6.L8 in steps of 200 A until 2200 A, which is the operational current for 5 TeV.

MEASUREMENT OBSERVATIONS

Beam Loss Monitors

The filtered BLM at the TCLIB reached saturation for all injections performed with the TCLIB half-gap smaller than 2.3 σ. This BLM was expected to show a signal a factor of 180 smaller than the nearby ionization chamber without filter. In reality the linear correlation between the losses at these two monitors, when not in saturation, gave a reduction factor of 18.64 ± 0.72: one order of magnitude smaller than the theoretical one. It was therefore not possible to calibrate the TCLIB BLM. To define the load on the downstream magnet we assumed that the full injected intensity was impacting at the TCLIB when closed at 1.3 σ and with -3 σ offset. The load at the Q6.L8 was calculated taking into account the BLM in the middle position (B2I20 in Fig.2) and considering a calibration factor of $4.57 \cdot 10^{-13}$Gy/p$^+$ (factor of 3 uncertainty) [3]. The number n_p of protons which are lost at the magnet and correspond to a loss level L (in Gy/s) at the BLM can be defined as:

$$n_p = \frac{L \cdot T}{4.57 \cdot 10^{-13}}, \qquad (1)$$

where T is the BLM signal integration time (40 µs in this case).

The BLM B2I20 at the Q6.L8 did not saturate when injecting a nominal pilot bunch of $1 \cdot 10^{10}$ protons, while it was in saturation when increasing the bunch intensity. Detailed analysis showed a correlation between the unsaturated signal at this BLM and at the B1E10 on the same magnet (Fig.2). The B1E10 monitor never saturated; this signal was used to reconstruct the losses at the B2I20 ($L_{B2I20} = 2.5 \cdot L_{B1E10}$). The load on the Q6.L8 could be calculated for each injection and is estimated to be about 10 % - 20 % of the beam impacting on the TCLIB.

In Fig.3 the BLM signal at Q6.L8 is plotted for several injections performed while increasing the current in the magnet. Measurements identified with the numbers between 6 and 29 were carried out injecting a pilot of $3 \cdot 10^{10}$ protons. The BLM signals vary for these measurements by 10 % - 15 %, compatible with intensity fluctuations.

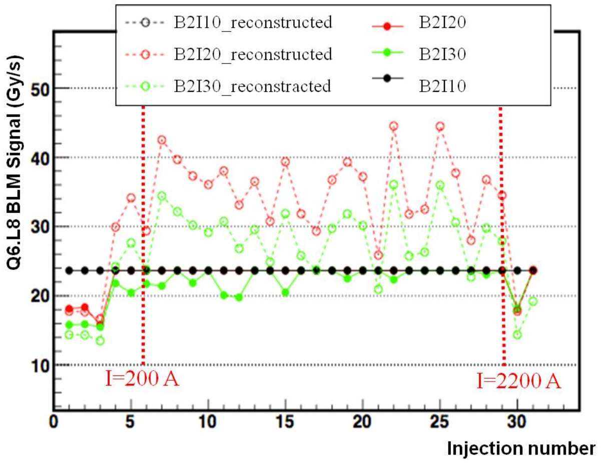

Figure 3: Signal of the BLMs at Q6.L8 for different injections with increasing magnet current. When saturated, the signals of these BLMs were reconstructed from the signal measured in the BLM B1E10.

The quench level of the Q6.L8 magnet is estimated to be 5.8 Gy/s at 450 GeV (200 A) and 0.46 Gy/s at 5 TeV (2200A) [4]. The reconstructed BLM signals exceed these values by a factor of ~8 at 450 GeV and ~40 at 5 TeV.

Quench Protection System

During each beam loss event an electrical signal was observed (Fig. 4) on the magnet aperture where the losses were provoked.

The short-lived voltage spike is followed by the response of the power converter which feeds the magnet coil. By analysing the power converter response one can indirectly obtain the current measurement from its Digital Current Current Transformer (DCCT). A direct measurement was not performed due to technical limitations. The indirect measurement indicates a current drop at the magnet of 0.1 A.

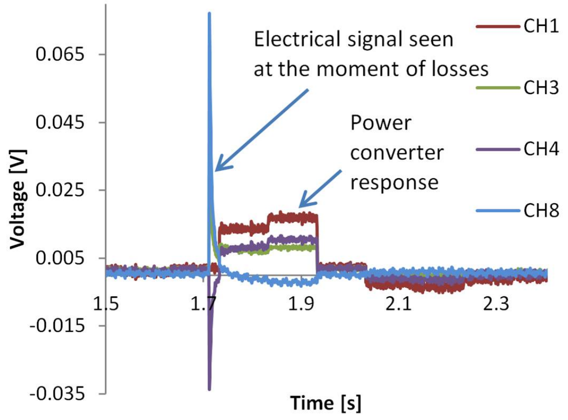

Figure 4: Typical signal resulting from the beam losses.

The 20 MHz acquisition oscilloscope was used to measure the actual time scale of the voltage signal. It was seen that the signal rises above 1 V and lasts for about 30 µs. By averaging the data points obtained by the scope it is possible to obtain results identical to those of the 10 kHz system. This agreement excludes measurement errors and proves that this signal really arrives at the QPS electronics.

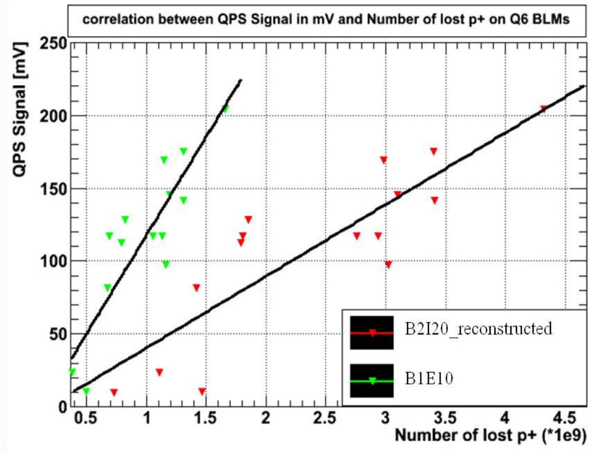

Figure 5: Correlation between the electrical signal seen on the level of the QPS electronics and the number of protons lost on Q6.L8.

The correlation between the QPS signal and the number of protons lost at the Q6.L8 has been investigated and is presented in Fig. 5. As a first approximation, the QPS signal can be considered as proportional to the number of lost protons.

No correlation was, however, observed between the measured signal and the current in the magnet. This practically excludes the possibility of a resistive zone appearing in the coil and disagrees with what was predicted in terms of losses with respect to the quench level. The reason could be that the TCLIB intercepts the full injected beam diluting the losses and the energy deposition into the Q6.L8. The quench limits were defined for a direct impact of the beam on the magnet aperture; this could explain why no quench was observed even if losses were much higher than the expected limits.

The signal which is recorded by the QPS varies as a function of the bunch intensity and could be induced by the interaction of the electromagnetic showers with the magnet coil.

CONCLUSIONS

Dedicated tests were performed during MD time in the LHC to assess the quench margin of the quadrupole magnet Q6.L8.

Single bunches, with increasing intensities, were dumped on the TCLIB and the correlation between the QPS and the BLM signals, at the Q6.L8, was analysed when increasing the magnet current.

The BLM signals exceeded the predicted quench limits by a factor of ~8 at 450 GeV and ~40 at 5 TeV. The QPS signal showed to be proportional to the number of lost protons but no correlation was observed with the current in the magnet, excluding the presence of a resistive zone in the coil.

The quench limits were originally defined in case of direct impact of the beam on the magnet aperture; the dilution provided by the TCLIB could explain why no transition was observed.

REFERENCES

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