IMPACT OF SUPERCONDUCTING MAGNET PROTECTION EQUIPMENT ON THE CIRCULATING BEAM IN HL-LHC*

M. Valette†, L. Bortot, A. Fernandez Navarro, B. Lindstrom, M. Mentink, E. Ravaioli, R. Schmidt, E. Stubberud, A. Verweij, D. Wollmann, CERN, Geneva, Switzerland

Abstract

The new superconducting quadrupole and dipole magnets for the High Luminosity LHC (HL-LHC) will rely on quench heaters or Coupling-Loss Induced Quench (CLIQ) units or a combination of both to protect the magnet coils in case of a quench. After the detection of a quench, the quench heater power supplies will discharge currents of several hundreds of amperes into the quench heater strips glued to the coils, and the CLIQ units will discharge an oscillating current in the order of 1 kA directly into the coils. These currents can have a significant effect on the circulating beam if the discharge occurs before the beam is dumped. In the HL-LHC inner triplet quadrupole magnets and 11 T dipole magnets, which will be installed in the collimation region dispersion suppressor, this effect will even be stronger due to the larger number of quench heaters and use of CLIQ units (triplet magnets only) as well as due to the greater value of beta function in comparison with the present LHC. In this paper, the expected effects of quench heater and CLIQ discharges on the circulating beam are summarized, and several mitigation methods are proposed and evaluated.

QUENCH PROTECTION OF SUPERCONDUCTING MAGNETS IN THE LHC AND HL-LHC

Due to the high energy stored in the HL-LHC magnets [1] (exceeding 7 MJ for some magnets), it is necessary to ensure that, in case of a quench, this stored energy is safely dissipated in the largest possible volume. Two main protection technologies are being considered for magnet protection.

1) the so-called quench heaters (QH), which are installed on the coil surface and are heated by a capacitive discharge [2].

2) the so-called Coupling-Loss Induced Quench (CLIQ) system, which is foreseen for the $\mathrm{Nb_3Sn}$ triplet. By discharging an oscillating current into the magnet, it causes inter-filament and inter-strand coupling losses in the copper matrix of the superconducting cables [3]. The current HL-LHC baseline includes both QHs and CLIQ for the protection of the triplet magnets.

During the operation of the LHC in 2016, a low amplitude, periodic particle-loss pattern was observed, just before beam dumps induced by quenches of an LHC dipole magnet. These losses were linked to a small, yet measurable, orbit oscillation of the beam in the vertical plane with very short timescales, in the order of three LHC turns (270 µs). This oscillation was associated with the magnetic flux induced by the current discharge into the QHs of the respective magnets [4].

MAGNETIC FIELD INDUCED BY QHS

The magnetic flux generated by a discharge of 80 A into the four quench heater strips of an LHC main dipole was simulated with COMSOL, a commercial finite element software [5]. An illustration of the magnetic flux density in the magnet is shown in Fig. 1.

The flux density along the beam axis created by the current discharge reaches 925 µT. While small compared with the nominal dipole field of 8 T, it leads to a kick of 49 µrad if integrated over the 14.3 meters magnetic length of a dipole magnet. Due to the connection scheme of the QH circuits the resulting field is that of a dipole in the horizontal plane, leading to a vertical orbit oscillation.

The QH parameters and magnetic flux induced along the beam axis by the discharge are detailed in Table 1 for a subset of magnets in the HL-LHC equipped with QHs. The values indicated for the main dipole and triplet were derived by magneto-static simulations with COMSOL. The others are based on analytical calculations, therefore, underestimating the contribution of the iron. The $\mathrm{Nb_3Sn}$ magnets will be equipped with up to 16 QH strips, hence higher flux distortions are induced in these magnets.

The estimations derived from simulations were confirmed during an LHC experiment [6] in which the QHs of selected dipole magnets were triggered with circulating beam at injection energy. The 500 µm orbit distortion measured from the beam position monitors matches the simulations done with MAD-X [7], the peak-to-peak error is within 100 µm which is in the range of the BPM resolution.

KICK ON THE BEAM

The kick (θ) due to the QH magnetic field was calculated first as an angle and then normalized ($\hat{\theta}$) to the beam size, which makes it dependent on the local optics:

$$\hat{\theta} = \frac{B_x L}{B\rho} \cdot \sqrt{\frac{\beta}{\epsilon}}. \tag{1}$$

where B_x is the magnetic flux density, L the magnet length, β the local Twiss parameter, ϵ the beam emittance and $B\rho$ the beam magnetic rigidity.

The two rightmost columns of Table 1 detail the results for the considered magnets. The beam will oscillate around a new closed orbit, which will be displaced with respect to the reference orbit by a number of transverse beam sizes (σ) as a function of the originating kick. This orbit offset leads

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* Work supported by the HL-LHC project

† Matthieu.Valette@cern.ch

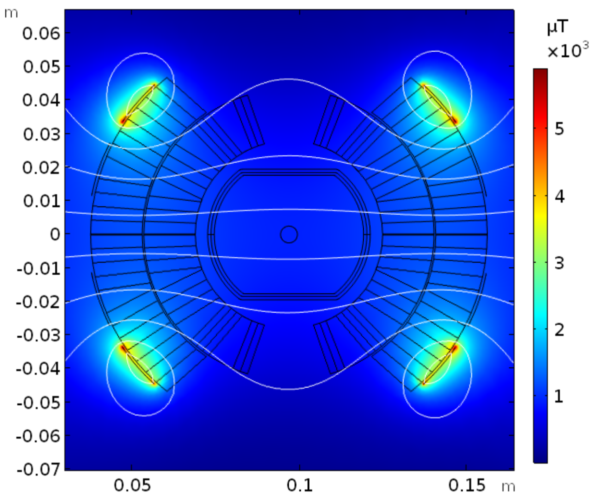

Figure 1: Norm of the magnetic flux density induced by the QHs of the main dipole magnet with flux lines in white. The top QH strips have an opposite polarity with respect to the bottom ones, leading to a horizontal dipole field. The beam area is marked with a circle in the middle of the aperture.

to increased beam losses when the beam passes through the LHC collimation system, which is the aperture bottleneck.

Such ultra-fast (sub-millisecond) orbit shifts with amplitudes below one σ are not a source of concern but some QH circuits would cause larger kicks and significant losses into the collimation system. For magnets such as the 11-T, separation and recombination dipoles, which will be protected by 8 QH strips per aperture it is possible to mitigate the large kicks. Connecting the QH in a quadrupole scheme allows nullifying the dipolar field created by a discharge and replacing it by a small quadrupolar field with negligible effect on the lattice (with an integrated gradient three orders of magnitude below one of the main quadrupoles).

For the triplet magnets, which will be protected by both QH and CLIQ, a quadrupole connection is not a viable solution due to considerations on voltage between the coil and the QH strips during a discharge of both protection systems. Therefore, the new quench detectors for the triplet magnets need to ensure that the beam dump is triggered before the discharge of either protection system. The main concern for the triplet QH is, thus, the spurious firing of an individual circuit. By connecting the QH circuits on two neighboring poles rather than across the magnet as illustrated in Fig. 2 it is possible to halve their kicks. The triplet magnet might also be equipped with inner layer quench heaters, located on the inner surface of the coil. These circuits would serve as back-up and, since they are much closer to the beam, will give a very large kick if connected, see Table 1.

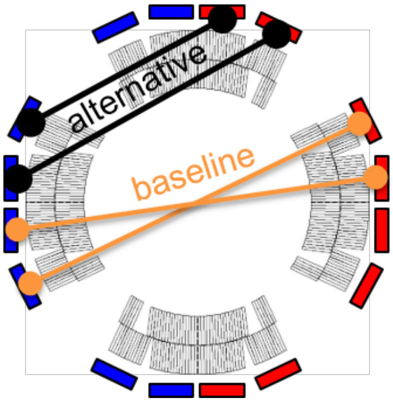

Figure 2: Schematics of the baseline and alternative connection scheme for the triplet QH.

CLIQ EFFECT ON THE BEAM

Implementing CLIQ to protect the $\mathrm{Nb_3Sn}$ triplet implies discharging currents in the order of a kilo-ampere in magnets with a nominal current of 18 kA, suggesting a large effect on the beam. The distortion of the magnetic field of a triplet quadrupole magnet during a normal CLIQ discharge was therefore simulated using the Simulation of Transient Effects in Accelerator Magnets (STEAM) framework [8].

During a normal discharge, the maximum distortion of the magnetic field is reached within tens of milliseconds [4]. It was shown that no dipole component is induced during such a discharge and that the main effect is a decrease of the quadrupole gradient by 0.2 %. The change of focusing strength in a quadrupole magnet will cause a β-beating with increasing amplitude as the gradient change increases.

Table 1: QH Parameters, Induced Fluxes and Kicks for a Subset of Magnets in the HL-LHC ($\mathrm{Nb_3Sn}$ are in bold font)

Magnet	**QH current (A)**	**flux (μT)**	**β function (m)**	**kick (μrad)**	**kick (σ)**
main dipole (14.3 m)	80	925	433	0.467	0.49
main quadrupole (3.1 m)	80	858	575	0.114	0.15
separation dipole (6.27 m)	168	1261	18’254	0.344	1.98
recombination dipole (7.78 m)	122	1623	5’789	0.540	2.43
11-T dipole (2×5.5 m)	150	1855	145	0.873	0.42
triplet (4×4.2 m & 2×7.15 m)	-	-	-	-	-
- 1 QH circuit, baseline	200	1420	21’642	1.08	3.4
- 1 QH circuit, alternative	200	991	21’642	0.754	2.35
- 1 QH circuit, inner layer	200	2128	21’642	1.61	5
- all 8 QH circuits for all 6 magnets	200	3539	4’100-21’642	4.71	28.8

The β-beating in case a CLIQ unit fires in Q2b (with the largest beta function) was simulated with MAD-X and the resulting β variations would reach up to 100 % within 12 ms (130 LHC turns) [9]. These changes in beam size will be kept sufficiently small by the foreseen interlocking on the discharge of a CLIQ unit. Furthermore, as they develop rather slow, the LHC's beam loss monitors will catch them before reaching dangerous levels.

BEAM SCREEN SHIELDING

It is expected that the copper beam screen [10] acts as a low-pass filter and damps any fast transient magnetic effect applied to the beam. However, it has been observed, during the discharge of the main dipole QH with beam in the LHC, that the kick can be applied to the beam much faster than anticipated.

These effects were studied using COMSOL simulations in time domain. Results from these simulations are illustrated in Fig. 3 and compared to magnetic flux densities from LHC dipole QH discharges reconstructed from orbit measurements. The magnet names are indicated. One can see that the rise of magnetic flux inside the beam screen does not follow the nominal case with a 30 K beam screen, but matches rather well the case of 200 K implying a resistivity of the copper beam screen of 8.5×10^{-9} Ω.m, allowing for the initial 2 T/s rise of the magnetic field.

The slower ramp rate of the magnetic field in the second part of the discharge (from 200 µs) is due to the shielding from the main coil of the magnet which is responsible for 30 % of the shielding and is taken into account in the simulation model. The small differences between discharges can be explained by differences in the resistance and capacitance of the QH strips and power supplies with the exception of C27R6 (gray). The slower ramp for the discharge in magnet B29L8 (yellow) could be explained by a delay between the firing of the QH circuits on both sides of the aperture.

Various effects could cause this (partial) transparency of the beam screen to QH discharges by increasing the resistivity of the copper layer on the inside of the screen, for example:

- magneto-resistivity due to the main field of the dipole operating at 8 T, which is responsible for 4×10^{-10} Ω.m
- higher temperatures of the beam screen material compared to the maximum operational value of 30 K,
- degradation of the copper's residual resistance ratio (RRR), e.g. due to radiation, which is specified to 100 for LHC magnets' beam screen.

Such a high resistivity would require a beam screen temperature of 200 K or a RRR of only 2 units, which would be way out of specifications. A combination of both effects, e.g. RRR=50 and a temperature of 100 K, could explain such a high resistivity and is more realistic. Simulations are ongoing to determine the beam screen heating due to the QH discharge.

A magnetic flux density of half the magneto-static value is therefore reachable within 270 µs (3 LHC turns), which is the time required to dump the LHC beam. This needs to be taken into account when designing the interlock of the QH discharge for the new HL-LHC magnets.

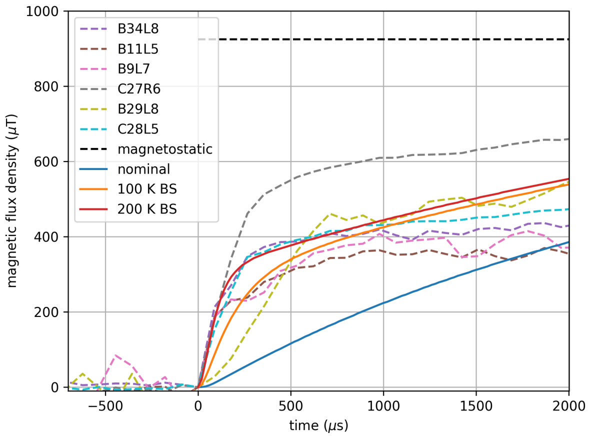

Figure 3: Simulated (solid lines) and reconstructed (dashed lines) magnetic flux density in the beam area for several scenarios of QH discharges. The reference scenario with nominal beam screen parameters is shown in blue. The orange and red lines show results for a beam screen at 100 and 200 K, respectively. The various observations from discharges in LHC magnets are colored according to the magnet which was affected. The magneto-static value of the flux mentioned in Table 1 is highlighted with a black dashed line.

CONCLUSIONS

Simulations have shown that the discharge of quench heaters and CLIQ can affect the circulating HL-LHC beam. These results were confirmed for QH discharges by dedicated beam experiments in the LHC. The QH connection schemes have been reviewed and alternative schemes with reduced effect on the beam were proposed. Furthermore, the new quench detectors for the HL-LHC magnets need to ensure that the beam dump is triggered before the discharge of either protection system. The spurious firing of a QH circuit or CLIQ system in the new HL-LHC triplets needs to be interlocked, the CLIQ discharge not being critical.

The expected shielding effect of the beam screen and the magnet coil has been studied in simulations in order to reproduce LHC observations. The beam screen reduces the maximum amplitude of the QH field along the beam axis, but allows for fast transients due to the QH discharge. This effect may allow to change the classification of a spurious QH discharge in the HL-LHC triplet from very critical to acceptable. Therefore, it is important to verify the shielding experimentally in a prototype triplet magnet with beam screen.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPAF062

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