EFFECT OF QUENCH HEATER AND CLIQ FIRING ON THE HL-LHC CIRCULATING BEAM

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Abstract

A small vertical orbit oscillation of the LHC beam was observed following a quench of a main dipole magnet. This effect was thought to be caused by the current discharged in the quench heater (QH) strips of the superconducting magnet and confirmed in dedicated experiments with beam in the LHC. Quench heater connection schemes with the largest effect have been identified for the LHC and its future HiLumi upgrade (HL-LHC). Furthermore, the impact on the beam following discharges of the Coupling-Loss Induced Quench (CLIQ) system, a novel technology to protect high current superconducting magnets in case of a quench, was studied to evaluate the possible failure cases.

SUPERCONDUCTING MAGNET PROTECTION IN THE LHC AND HL-LHC

Due to the high energy stored in the HL-LHC magnets (exceeding 7 MJ per magnet), it is necessary to ensure that, in case of a quench, this stored energy is dissipated in the largest possible volume, ideally the whole coil. In order to achieve this, two main protection technologies are being considered for magnet protection.

The first one relies on the so-called quench heaters (QH), which are installed on the coil surface and are heated by a capacitive discharge, in case a quench is detected [1].

The second protection system, which is foreseen for the Nb_3Sn triplet of the HL-LHC upgrade, is the so-called Coupling-Loss Induced Quench (CLIQ) system. The goal is to create inter filament and inter strand coupling losses in the copper matrix of superconducting cables by discharging an oscillating current into the magnet [2]. The current HL-LHC baseline includes both QHs and CLIQ for the protection of the triplet magnets.

During 2016 operation of the LHC, 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 but measurable orbit oscillation of the beam in the vertical plane. This oscillation was associated with the magnetic field induced by the current discharge into the QHs of the respective magnets.

QH MAGNETIC FIELD

The magnetic field generated by a discharge of 80 A into the quench heaters was simulated with COMSOL, a commercial finite element software [3]. An illustration of the magnetic flux density in the magnet is shown in Fig. 1. The field along the beam axis created by the current discharge reaches 0.688 mT. While small compared with the nominal dipole field, it leads to a kick of 47 µrad if integrated over the 15 meters of a dipole magnet. Due to the skew-dipole connection scheme of the QH circuits the resulting field is horizontal, leading to a vertical orbit oscillation with values matching the measured amplitudes.

For simplification purposes, the calculations of the magnetic field induced by QHs in other magnets was done analytically. Assuming the magnet's iron yoke is fully saturated and taking into account the symmetries of the QH layout, the skew dipole magnetic flux density is given by:

$$B_x = \frac{4\sin(\Phi)\mu_0\, I}{2\,\pi\, r},$$

where Φ is the angle of the QH strip to the horizontal axis, μ_0 the vacuum magnetic permittivity, I the current in the QH circuit, and r the distance of the QH strip to the beam. The error of this method compared to the simulations is less than 2% (for the main dipole magnet case).

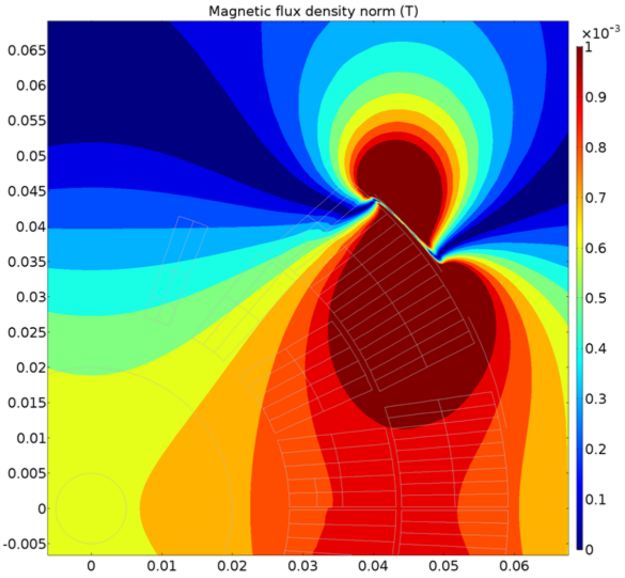

Figure 1: Norm of the magnetic flux density induced by the QHs of the main dipole magnet, at peak current 80 A.

The QH parameters and magnetic field induced by the discharge along the beam axis are detailed in Table 1 for a subset of the most relevant magnets in the LHC and the HL-LHC upgrades equipped with QHs. The Nb_3Sn magnets with higher current densities will be equipped with more QH circuits than the existing Nb-Ti ones, hence higher flux distortions are induced in these magnets.

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KICK ON THE BEAM

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

$$\hat{\theta} = \frac{B_x L}{\sigma_{x'} B\rho},$$

where B_x is the magnetic flux density, L the magnet length, $\sigma_{x'}$ the beam divergence and $B\rho$ the beam magnetic rigidity.

The right part of Table 1 details the results for the considered magnets. Since the current rise in the QH circuit lasts for only 40 µs, which is less than half an LHC turn (89 µs), it can be assumed to be instantaneous. The decay time of the QH current is however much longer (80 ms). The beam will, thus, 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 to increased beam losses when the beam passes through the LHC collimation system, which is the aperture bottleneck.

Amplitudes below 0.25 σ are not a source of concern with LHC intensities [4] but could cause significant losses into the collimation system with HL-LHC intensities as the beam intensity will be a factor two higher.

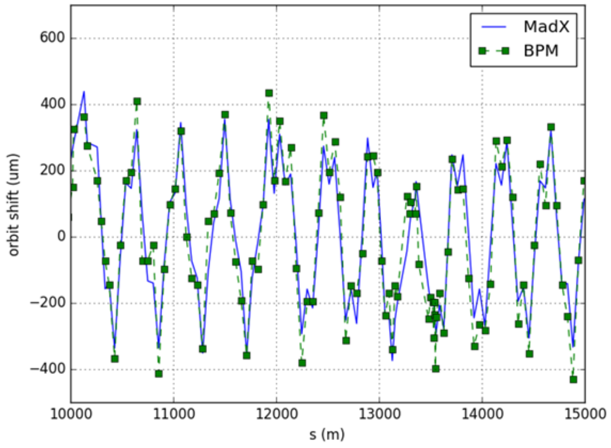

Figure 2: Measured and simulated orbit shift after firing the QHs in a dipole magnet, zoom around the magnet.

LHC Experiment

In order to confirm the estimations derived from the simulations, an LHC experiment was performed [5] in which the QHs of selected dipole magnets were triggered with circulating beam at injection energy. The orbit distortion measured from the beam position monitors matches the simulations done with MAD-X [6] with peak to peak errors below 150 µm and matching positions of all zero-crossings, as illustrated in Fig. 2. This confirms the QHs as the source of the oscillation. It was also evidenced that, due to some delays inherent to the triggering of the quench protection system, the beam was only dumped 30 to 35 turns after the QHs were fired. The reaction time is expected to be much shorter in case the quench heaters in the triplet magnets are fired, which will be experimentally confirmed during the 2017 run.

CLIQ EFFECT ON THE BEAM

Implementing CLIQ to protect the Nb_3Sn triplet implies discharging currents in the order of kilo-Amperes in a magnet powered with 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 [7,8]. The detailed connection scheme of the CLIQ units protecting the triplet circuit composed of the Q1, Q2a, Q2b and Q3 magnets is discussed in [9].

CLIQ Discharge in the 2nd Triplet Quadrupole

The maximum magnetic field, which is reached 12 ms after the beginning of a CLIQ discharge in the Q2b magnet, is shown in Fig. 3. After a multipole decomposition of this field, it was evidenced 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. The β-beating in case a CLIQ unit fires in Q2b while beam is circulating was simulated with MAD-X and the resulting β variation at the position of the collimators is illustrated in Fig. 4. One can see that a horizontal β variation of 10%, at which the cleaning efficiency of the collimation system cannot be guaranteed [10], is reached in less than 40 turns (3.5 ms).

CLIQ Discharge in the 3rd Triplet Quadrupole

A worst-case failure would be a spurious firing of one

Table 1: QH parameters, Induced Fluxes and Kicks for a Subset of Magnets in the LHC and HL-LHC

Magnet name	current (A)	flux (mT)	magnetic length (m)	kick (µrad)	kick (σ)
Main dipole	80	0.7	14.3	0.47	0.1
Separation dipole (D1)	168	0.81	6.27	0.23	0.013
Recombination dipole (D2)	122	1.24	7.78	0.45	0.07
Nb_3Sn 11 T-dipole	150	1.85	2×5.5	0.94	0.24
Nb-Ti Triplet	200	0.2**	2×5.5+2×6.37	0.24**	0.014**
Nb_3Sn Triplet	200	3.53	2×7.15+4×4.2	5.07	0.23
Nb_3Sn Triplet with Inner Layer Quench Heaters	200	6.37	2×7.15+4×4.2	9.15	0.41

** in x and in y due to an asymmetric QH layout of the CLIQ units protecting the Q3 magnets. If only one of them were to fire with circulating beam, the discharge into the magnet will be asymmetric. Such a discharge was simulated with STEAM and the magnetic field at the first current peak of the discharge (20 ms) is presented in Fig. 5. The field generated by such a discharge has dipole and skew dipole components in the order of 50 mT in the beam aperture area.

A tracking simulation with MAD-X was performed to evaluate the effects of such a discharge. The displacement of the beam orbit until the peak of the discharge (20 ms) is shown in Fig. 6. The maximum beam displacement of $0.7\ \sigma$ is reached after ~ 200 turns and lower than the $1\ \sigma$, which could have been expected from two 4.2 m long magnets with a 50 mT magnetic flux. This smaller impact can be explained with the partial compensation of this perturbation from one of the Q3 magnets to the next, which is a direct result of the CLIQ connection scheme [9].

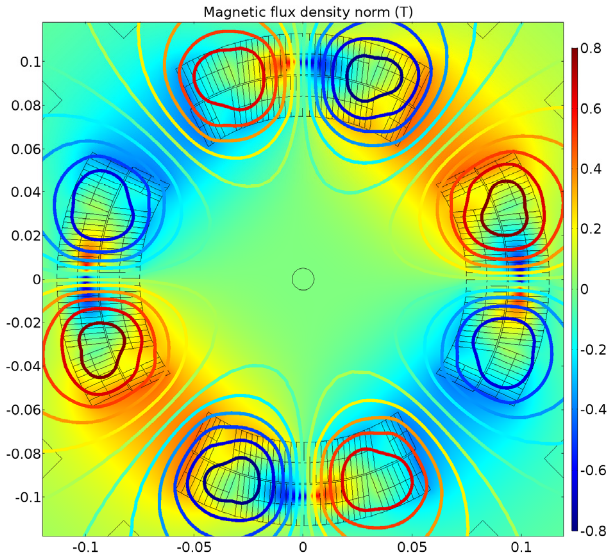

Figure 3: Magnetic flux density and flux lines at the first current peak (12 ms) of a CLIQ discharge in a Q2b magnet.

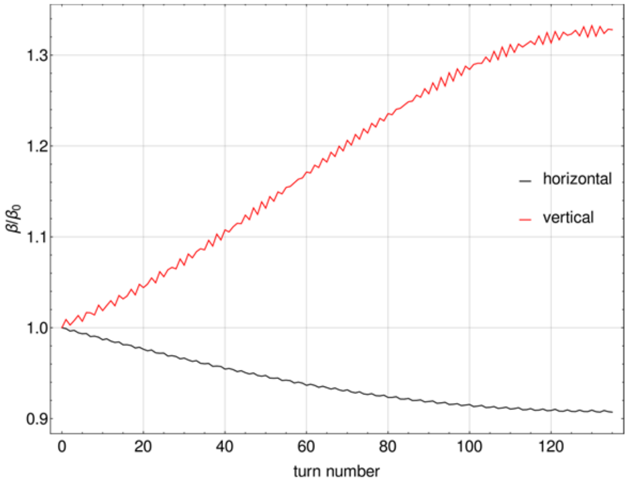

Figure 4: β-beating at the collimators in case of a spurious CLIQ firing in the Q2 magnet.

CONCLUSIONS

Simulations have shown that the discharge of quench heaters and CLIQ can affect the circulating LHC beam. These results were confirmed by dedicated beam experiments. For future magnets, the QH connection schemes should be chosen such to minimize the skew dipole kick, e.g. in a quadrupole way. For the HL-LHC era it should also be ensured that the beams are dumped before the QHs and CLIQs are fired. In case of a spurious triggering, QHs should not be a concern, as only one of many QH circuits would fire and lead to only a fraction of the calculated kicks. The firing of CLIQ units should be interlocked to avoid dipole kicks on the beam of up to 0.7 sigma and beta beating greater than 10%.

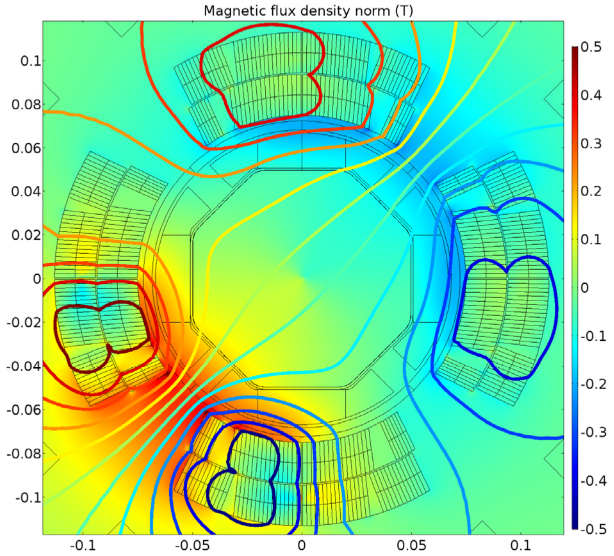

Figure 5: Magnetic flux density and flux lines at the first current peak (20ms) of a discharge of one of the CLIQ units in a Q3 magnet.

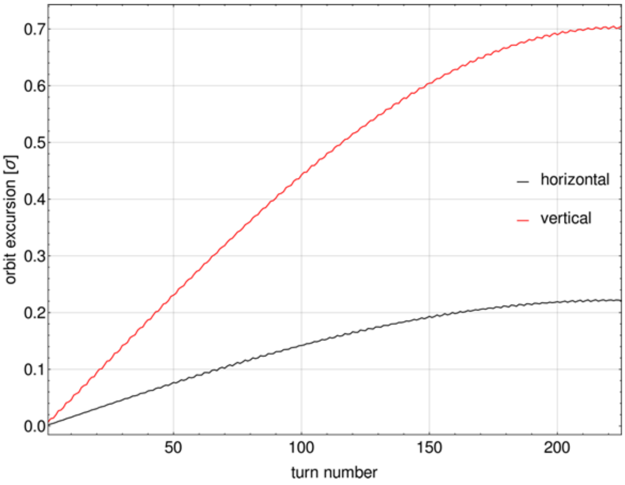

Figure 6: Beam orbit excursion in case of the spurious firing of a CLIQ unit in the Q3 magnet.

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