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# Chapter 10

# Machine Protection and Cold Powering

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## 1. Introduction

In the HL-LHC era the bunch intensity will nearly double as compared to the design value of the LHC. Therefore, the stored energy per beam will also nearly double from 360 MJ to about 700 MJ [1]. This increases the criticality of existing beam failure cases and requires the upgrade of protection elements in the injection and dump regions of the LHC (see Chapter 9).

At the same time several optics parameters will change. To achieve the very small beam sizes in the interaction points of IR1 and IR5, the $\beta$ functions will nearly triple in the respective final focusing magnets, which requires the installation of novel large aperture quadruple magnets based on $Nb_3Sn$ superconductors. These magnets will be installed in a complex nested circuit arrangement and require highly reliable and redundant quench protection systems [1, Chapter 7]. Furthermore, the $\beta$ functions will increase by a factor of four and three, respectively, in the separation and recombination dipole magnets, the so-called D1 and D2 [1, Chapter 3]. These changes will significantly increase the effect of failures in these elements on the beam.

The implementation of $Nb_3Sn$ based magnets for the first time in an accelerator raises the question of their damage limits in view of the impact of beam or high density particle showers in case of accepted failures and especially for failures beyond design.

The LHC will also see the installation of new accelerator equipment like crab cavities, coupling loss induced quench systems or a full remote alignment system for the majority of elements installed in the straight sections of IR1 and 5. These new systems will introduce new failure cases in the LHC, which require dedicated interlocks.

## 2. New Fast Failures and Interlocks

The new $Nb_3Sn$ final focusing quadrupole magnets, also known as Q1, Q2 and Q3 in IR1 and 5 will be equipped with quench heater strips and the novel Coupling Loss Induced Quench (CLIQ) system [1, Chapter 7] [2] as part of the quench protection system. Detailed studies have shown that, if they are triggered, when the beams are still circulating in the LHC, both systems can cause unacceptable beam losses within less than 1 ms, which is equivalent to about 10 LHC turns [3–5]. These losses could cause critical damage to accelerator equipment or the close by experimental detectors. In case of a magnet quench, the quench detection system, therefore, needs to first initiate a beam dump request via the LHC's Beam Interlock System (BIS) [6] before triggering the discharge of the quench heater power supplies and the CLIQ systems. These strict requirements are new for the LHC quench protection system, but can be fulfilled without any negative side effects. This mitigates the failure in case of a regular quench in one or more of the inner triplet quadrupole magnets.

However, a spurious discharge of a single quench heater power supply or a single CLIQ system cannot be fully excluded and can still cause critical losses [4, 5]. In case of a spurious discharge of one of the CLIQ units of the Q2, critical loss levels would be reached after only 450 $\mu$s from the beginning of the event. This leaves only 170 $\mu$s to detect the spurious discharge, as about 280 $\mu$s — slightly more than 3 turns — are required for the signal transmission via the beam interlock system and the extraction of the two beams [7]. Therefore, the quench detection system also has to provide a fast interlock to mitigate spurious discharges of quench heater power supplies and CLIQ systems in the new inner triplet circuits of the HL-LHC era.

Due to the large $\beta$ functions in the separation and recombination dipoles — D1 and D2 — quench heater discharges in these magnets can also have an important impact on the LHC beam. Therefore, the requirements described above for the inner triplet circuits also apply here, with the exception that these magnets are only protected by quench heaters.

The HL-LHC project also contributed to the design and integration studies of hollow e-lens systems in each beam for beam collimation. While this system is not part of the current HL-LHC baseline, an eventual installation after the start of the HL-LHC operation would allow partial depletion of the beam halo in a radius of about two beam $\sigma$ outside the cut of the primary collimators [8]. The partial depletion of the beam halo can reduce the criticality of fast failures, which cause a sudden movement of the beam, as it increases the time margin between the onset of the failure and reaching critical loss levels in the collimation system. This effect is relevant in the case of failures in magnet protection systems and crab cavities which feature dedicated fast interlocks. Also, the criticality of the missing beam-beam kick will be reduced by the partial depletion of the beam halo [4].

However, in case the failure detection relies solely on beam loss monitors, the depleted halo can increase the criticality of the failure, as it might reduce the time between reaching the interlock threshold of the beam loss monitors and reaching critical loss levels in the collimation system. This was carefully studied and discussed in [9]. The studies show that the beam halo should not be depleted by significantly more than 50%. Otherwise, in case of a symmetric quench in one of the new inner triplet magnets, the time between reaching the interlock threshold in the beam loss monitors and reaching critical loss levels in the collimation system will be too short to safely dump the beams before damage occurs. It has to be noted that the quench detection system will reliably detect the symmetric quench and initiate the timely firing of the quench protection elements. However, to avoid spurious dumps and allow for detection thresholds in the order of 100 mV, the quench detection system requires a discrimination time in the order of 10 ms, whereas critical loss levels will already be reached after less than 8 ms. Therefore the protection against the effect of symmetric quenches on the beam has to rely on the detection of losses by the beam loss monitors.

The situation is similar in the case of an accidental coherent excitation of the full HL-LHC beam by the transverse damper, as it does not have a dedicated interlock. Furthermore, similar beam losses can be caused by fast transverse beam instabilities.

## 3. Circuit Protection

The backbone of the magnet and circuit protection for the new superconducting circuits in the HL-LHC era is the highly reliable Universal Quench Detection System (UQDS) [10–12]. Due to its adaptability it can be used to protect such different circuit elements as Nb-Ti and $Nb_3Sn$ based superconducting magnets as well as $MgB_2$ based superconducting links, Nb-Ti bus-bars and HTS current leads. The UQDS features, among other things, current dependent thresholds — required to immunise the quench detection system against flux jumps in $Nb_3Sn$ magnets at low current levels, which would otherwise cause spurious triggers of the quench protection systems. Furthermore, the UQDS is equipped with a high bandwidth communication field bus which allows efficient transmission of high resolution data, in case of a quench with a time synchronisation significantly shorter than 1 ms. This is especially important to validate the correct functioning of the magnet and circuit protection systems in case of a quench in one element or during a fast power abort in the new inner triplet circuits [1, Chapter 7]. These will become the most complex circuits in the LHC, featuring four power converters, cold and warm by-pass diodes [13, 14], crowbars and the novel Coupling Loss Induced Quench Systems [1, Chapter 7] [2].

Several of the new HL-LHC circuits will be protected by a novel generation of energy extraction systems, which are equipped with in-vacuum circuit breakers, allowing for highly reliable extraction of the circuit energy and low maintenance [1, Chapter 7] [15].

## 4. Damage limits of Nb-Ti and $Nb_3Sn$ superconductors due to beam impact

With the increase in bunch intensity and stored energy in the HL-LHC era, failure cases, which lead to high levels of high energy particle showers into superconducting magnets like injection or dump failures, become more critical. To understand the criticality of such events for superconducting magnets, detailed studies have been performed to determine the damage limits of superconducting strands based on Nb-Ti and $Nb_3Sn$ due to the impact of high intensity proton beams [14, 16–19]. The hadronic showers developing during such an event lead to a sudden temperature rise in the strand material. The temperature rises to peak levels of several hundred Kelvin within one to a few micro seconds, depending on the length of the proton pulse. Due to the very localised energy deposition, the hot-spots are accompanied by high temperature gradients in the strand material. Both effects lead to high levels of stress, which can damage the superconductor.

For Nb-Ti strands no degradation of the critical current density $J_c$ has been observed up to hot spot temperatures of 1150 K. However, for peak temperatures above 800 K, the RRR at the beam impact reduces significantly to below 100. This reduction of the conductivity in the copper matrix leads to a reduction of the minimum quench energy, which can potentially cause thermal instabilities in the strand and make the operation of a superconducting magnet difficult [14].

For $Nb_3Sn$ strands a significant degradation of $J_c$ was observed for hotspot temperatures above 460 K and temperature gradients above 200 K/mm after the beam impact. Thermo-mechanical simulations allowed the identification of the two main damage mechanisms in $Nb_3Sn$ strands [19]. The first is the breaking of filaments in the strand due to high axial strain. This was also confirmed by microscopic analyses of the impacted samples. The second is the degradation of the second critical field $B_{c_2}$ due to residual strain between the copper matrix and other copper/bronze phases present in the strand. Although both mechanisms cause a reduction of $J_c$, filament breaking is by far the dominating effect [14].

## 5. Cold Powering Systems

The power converters for the HL-LHC superconducting magnets will be installed in new radiation-free galleries about 10 m above the LHC tunnel. The electrical connection between the power converters and the magnets will be provided by novel cold powering systems, eight in total, that incorporate a Superconducting Link [20, 21]. A Superconducting Link transfers the current from the power converters, at room temperature, to the liquid helium environment of the magnets. It consists of several cables, which are made from ex-situ $MgB_2$ superconducting wire. The $MgB_2$ wire has a diameter of 1 mm. It contains 37 $MgB_2$ filaments (50–55 $\mu$m average diameter) each surrounded by a niobium diffusion barrier, and embedded in a matrix consisting of Nickel and Monel. The Monel is copper plated ($\sim 15$ $\mu$m) and tin plated ($\sim 1$ $\mu$m). The $MgB_2$ wires are reacted — and therefore superconducting — before cabling. Their minimum bending diameter is about 100 mm. The $MgB_2$ cables are rated at DC currents ranging from 600 A to 18000 A [22]. They are electrically insulated and twisted together to form a multi-cable assembly that optimises electro-magnetic and mechanical behaviors. The multi-cable assembly contains up to nineteen cables and is housed inside a flexible cryostat. The cryostat is made from two concentric corrugated pipes. It provides the thermal insulation and the cryogenic environment for the cables. A Superconducting Link transfers DC currents of up to 120 kA at 25 K. The multi-cable assembly is cooled by forced flow of helium gas. It has an external diameter of about 90 mm. The protection of the $MgB_2$ cables was studied during the R&D phase of the project [23]. A resistive transition in the cables is a rare event. It can be generated by an accidental event like loss of vacuum insulation inside the cryostat. If the critical temperature of the $MgB_2$ is exceeded, a voltage is generated along the superconducting cables. The resistive zone propagation along the cables is in the range of 10 cm/s–20 cm/s. The transition is detected at a voltage threshold of about 100 mV. When this voltage is reached, a power abort is triggered and the active protection system of the respective magnet circuit is activated. The amount of copper stabilizer included in the cables is such that the hot spot temperature reached during the transient is less than 60 K. This limited increase in temperature enables a fast cool-down of the Superconducting Links after the resistive transition.

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