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Chapter 28

HE-LHC operational challenges

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1. Introduction

A further increase in the operating energy of today's LHC will inevitably imply new operational challenges and exacerbate those already known from the development and operation of the current LHC up to its nominal energy of 7 TeV. As discussed in detail in Chapter 26, various options for the choice of the main bending field for a High Energy LHC are being developed by currently ongoing magnet R&D as a function of the desired target energy. While the choice of the detailed lattice might be further optimized for each energy option,[1] the fixed geometry of the existing LHC tunnel will dictate a more or less similar number of main dipole and quadrupole magnets to be installed along the 27 km circumference. In addition, the demanding requirements for beam steering and the quality of the magnetic fields will require a large number of distributed corrector magnets to be installed.

Combining magnets of the same type and powering them in series is an elegant way to optimize the number of power converters and auxiliary protection equipment required for such large scale facilities, as well as having a beneficial impact on machine availability. However, this increases the stored magnetic energy and voltage to ground for the operation of these magnet circuits considerably, both of which already present major challenges and design constraints for the magnets and powering components of today's LHC.

It is for this reason that, early on during the design process of the cold

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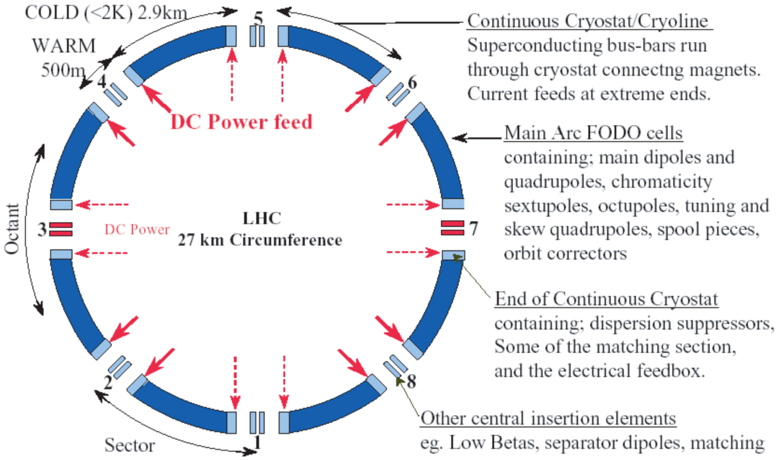

Fig. 1. Powering of the eight arc cryostats. Main circuits and most of the corrector circuits are powered from even LHC insertions, while some additional correctors are being powered from odd insertions.

powering system of the LHC, the decision was made to divide the machine into 8 independent and symmetrical sectors (see Fig. 1), with the main dipole and two main quadrupole magnet families being powered in series, composing three independent main circuits in each of them. This sectorisation comes in some sense naturally, as the superconducting magnets are interleaved in the case of the LHC with conventional, normal conducting magnets around the interaction regions due to the higher radiation levels. The superconducting magnets are housed within more than 40 different cryostats, including the eight 3 km long arc crystats. Even with this split, the inductance of each dipole circuit in one octant is 15 H with a stored energy at nominal current of more than 1 GJ.

Segmentation of the powering of such extended electrical systems also allows for easier installation, testing, commissioning and operation. This has proven to be a major asset, providing flexibility for parallel activities not only during the initial installation and commissioning period of the LHC but also for subsequent campaigns that need to be regularly executed after end-of year technical stops and the long maintenance shutdowns following the 3-year long operational periods. The following operational advantages with a sectorized machine have been confirmed during the initial two operational runs of the LHC machine, and are expected to remain equally valid for an HE-LHC upgrade, if not further enhanced due to the cryogenic separation of the Long Straight Sections from the arc as already realized for HL-LHC:

- Early commissioning experience from first powering subsectors, allowing the development of automatic tools that considerable enhanced efficiency for initial hardware commissioning period after installation
- Parallel commissioning and magnet training in several machine sectors (provided cryogenic capacity is available). Considering the unexpectedly large number of re-training quenches after thermal cycles, this has proven a vital asset for LHC re-commissioning after long shutdowns.
- Increased flexibility during preventive maintenance periods as well as for corrective actions during regular operation. Only concerned sectors will be switched off, while normal activities can resume elsewhere.

Initial concerns about the required tracking precision of the main dipole and quadrupole currents between the 8 independent sectors have been shown to be well within reach of today's state-of-the-art power converter controls electronics.[2,3] Similarly, the increase of the required high current powering equipment has not been found to have a significant detrimental effect on overall machine availability.[4]

2. Architecture and powering of magnet circuits in the HE-LHC

In the following, we will consider the second energy upgrade option described in Chapter 26, HE27, as an example to illustrate possible solutions to the challenges of stored energy and extraction voltage when using 16 T main dipole magnets.[5] Considering the use of this magnet technology as well for the HE-LHC, the stored energy in the superconducting magnet system will increase to about 41 GJ. In order to safely handle such energies, the magnets must be powered in several independent powering sectors inside a given LHC octant. In today's LHC, the energy stored in the 154 dipole magnets of one of the eight sectors is in the order of 1.1 GJ. In order to maintain the powering and magnet protection systems similar to the ones of the LHC (including the cold by-pass diode ratings), the baseline of the HE-LHC powering would be subdivided into 32 independent dipole circuits as detailed in Table 1. This will also allow the voltage and net power

Table 1. HE-LHC versus LHC dipole circuit parameters.

	LHC	HE-LHC
Number of circuits N_{cir}	8	32
Nominal current	11.9 kA	11.4 kA
Magnets in series	154	41
Energy	1.1 GJ	1.6 GJ
Apparent inductance	15 H	24 H
Ramp up time	20 min	20 min
Inductive boost voltage required from PC	150 V	230 V
Max PC net power during ramping	1.8 MW	2.6 MW

requirements for the power converters to be maintained in a comparable order of magnitude, while obviously adding additional complexity due to the required synchronization of 32 power supplies instead of the previous 8.

The subdivision into 32 independent circuits will allow voltages to ground during energy extraction to be maintained within acceptable limits and avoid excessive insulation requirements during design and operation of the magnets and the associated circuit powering components (in particular during a fast discharge of the energy after e.g. magnet quenches). Increasing the insulation voltage to ground beyond the present 3 kV for the LHC dipoles at cold would require developments in magnet technology, and would also make the interconnection and bus bar insulation significantly more difficult, a non-trivial task given the restricted space offered by the present LHC tunnel.

If a circuit powering scheme as depicted in (Fig. 2) is adopted, a single energy extraction system per dipole circuit could be envisaged. The extraction time could be further reduced compared to a resistor-based system by performing the extraction at constant maximum voltage, at the same time reducing operational losses and therefore resulting in a smaller environmental impact. On the contrary, the cold busbars and bypass diode ratings

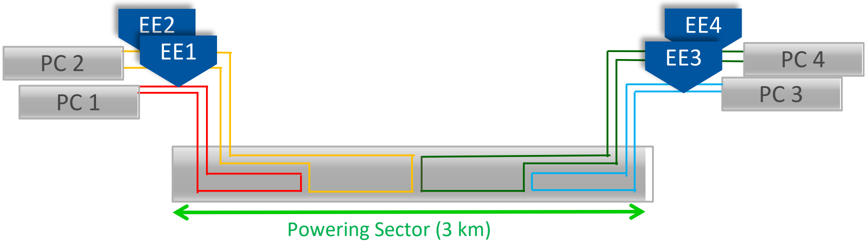

Fig. 2. Schematic of the dipole circuit architecture for HE-LHC.

will have to be carefully reconsidered as shown in (Table 2). To avoid long and costly superconducting links, additional cold busbars would have to be foreseen inside the cold masses of the main dipole and quadrupole magnet to feed the magnets in the middle of the long arc cryostat. The insertion of a second energy extraction system in the middle of the arc cryostat could be possible, but will require the creation of an additional small alcove in this mid-arc region, or, alternatively, the connection of the mid-point to the underground galleries in the arc extremities via an additional cold busbar system. Protection of quadrupole and corrector magnets for a HE-LHC is well within the capabilities of the current protection hardware already deployed in the LHC.

Table 2. Fast power abort of HE-LHC dipole circuit compared with LHC.

	Half of EE voltage	Discharge time constant	MIITs	Busbar copper cross-section
LHC	0.45 kV	100 s	$7 \cdot 10^3$ MA^{2}s	270 mm^2
HE-LHC	1.3 kV	106 s	$7 \cdot 10^3$ MA^{2}s	235 mm^2

3. Beam operation challenges

The increase of the center of mass energy for HE-LHC, assuming again HE27 as an example, will imply a factor of 4 higher stored energy in the particle beams than todays LHC, for which the damage limit can be derived from detailed energy deposition studies.[6] At top energy of 14 TeV and assuming similar normalized emittance to today's LHC, a localized loss of only $1.6e10$ protons (equivalent to about 7% of a nominal HE-LHC bunch) would already damage accelerator equipment. As for the LHC, the machine protection system (MPS) for HE-LHC should therefore be designed to prevent any uncontrolled release of energy stored in the magnet system and the particle beams. In view of the reduced quench margin in the superconducting magnets, the protection system must also be able to prevent, or at least minimize, beam induced quenches of the superconducting magnets. This includes resilience against beam losses from interactions of the main beam with dust particles that are inevitable present in the vacuum chamber [refer Chapter 6, Section 2.5], which will become an ever more challenging issue with increasing beam energy and intensity.

Additionally, the effect of flux-jumps that are an inherent feature of the proposed Nb3Sn based magnet technology, will have to be thoroughly studied in terms of quench protection as well as their potential effect on beam orbit, emittance growth and ultimately machine performance.[7,8]

The main principles of the LHC design are nevertheless still valid for HE-LHC, namely to define the aperture limitation in the ring and transfer lines by collimator's, to detect abnormal equipment and beam conditions with fast and reliable instrumentation, to provide passive protection for specific fast failures by beam absorbers and collimator's and to provide — wherever possible — diverse redundancy for the detection of the most critical failures. If the injection energy for HE-LHC remains 450 GeV, a modest upgrade of the current injection protection system should be adequate. However, due to the increased energy swing of the machine, the aperture at 450 GeV appears challenging for collimation. Future studies would be required for the correction of the non-linear errors at lower injection energies to reach the target dynamic aperture.[9,10] An increase of the injection energy (to 900 GeV or 1.3 TeV) implies the need to review the robustness of the concerned absorbers and collimators or to limit the number of bunches per injection.

To survive an asynchronous dump at nominal energy, different techniques are being explored, such as decreasing the kicker rise-time, modifying the optics around the extraction region and upgrading the robustness of the impacted absorbers. Similar studies, as already conducted for HL-LHC, are required for the HE-LHC to determine the acceptable level of halo population for collimators and absorbers to survive these most critical failure cases. The installation of dedicated fast beam loss monitors with nano-second resolution close to the injection and extraction absorbers would allow understanding and possibly reducing and mitigating some of the ultra-fast losses.

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