2.13 Lessons from the LHC and Technology Advances for HL-LHC

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2.13.1 Introduction

The Large Hadron Collider was designed for proton-proton collisions at 14 TeV centre-of-mass with a luminosity of 10^{34} $cm^{-2}s^{-1}$. Its actual performance in terms of both peak and integrated luminosity is remarkable; see Fig. 1.

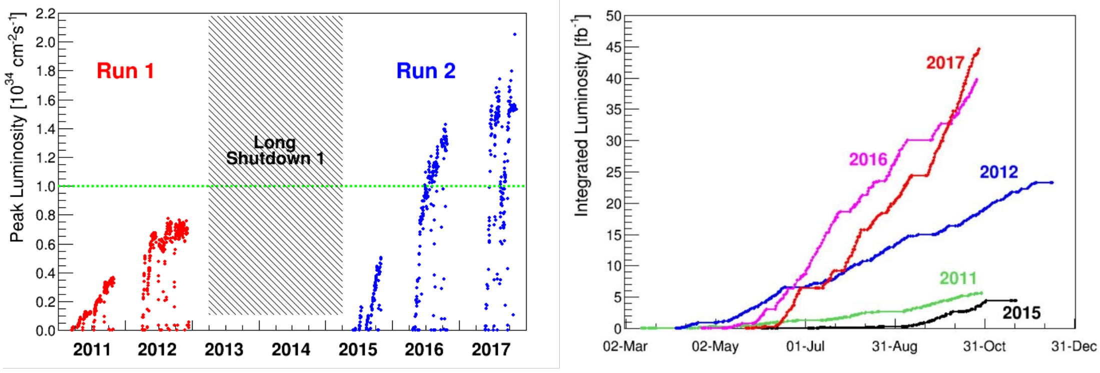

Figure 1: **LHC peak (left) and integrated luminosity** (courtesy J. Wenninger and CERN).

The LHC was developed starting in 1983, the first beam was injected in 2008, and the first real physics collisions were delivered in 2010. The beam energy was slowly increased, from 3.5 TeV in 2011 via 4 TeV in 2012 to 6.5 TeV since 2015. After the Long Shutdown 2, or "LS2" (2019-20), the collision energy is expected to reach the design value of 7 TeV, which still requires and additional magnet training campaign.

During LS2 (2019-20) the injector complex will be upgraded [35]. The following Long Shutdown "LS3" (2024-25) will witness a major upgrade in the LHC itself [36,37]. Together the two upgrades will enable a ten-fold increase in the integrated luminosity.

2.13.2 Lessons from the LHC

These lessons had been assembled and reviewed for the FCC Week in Washington [38]. Three types of lessons are distinguished: (1) LHC specifics and compromises coming from building the LHC machine in the old LEP tunnel, (2) experience for specific concerns raised in the design phase, (3) important lessons learned from the LHC installation, and (4) Important lessons learned from the LHC operation.

Among LHC constraints from the pre-existing tunnel figure the dispersion suppressor, whose geometry was defined by the LEP FODO cell, and which for the LHC, with its longer cell length, required quadrupole tuning for dispersion matching; the combined experimental interaction and injection regions, implying risk of beam loss and detector damage and imposing additional constraints and elements for optics matching and machine protection; the radiation to electronics components in the tunnel resulting in limited underground space for installation of sensitive components (e.g. power converters), impacting machine availability and efficiency, and ultimately requiring a "superconducting link" to power converters installed far away and a new cavern for the HL-LHC.

One LHC specific design choice was the powering in 8 separate sectors (stored electro-magnetic energy per sector ≈ 1GJ) which required power-converter tracking at the ppm level; the LHC power converters perform exceedingly well, and indeed track the main-magnet currents at the ppm level. A second design choice is the common triplet for both beams and for the debris leaving the IR, with a warm separation dipole D1 and efficient triplet cooling. Some machine protection issues were uncovered for the warm magnets. A third specific design choice is the anti-symmetric optics design, driven by the goal to facilitate a simultaneous optics matching for Beam1 & Beam2. The dispersion is not anti-symmetric with respect to the IP, which is addressed by dedicated trim quadrupole circuits in the dispersion suppressor section that break the strict antisymmetry of the insertion region. This design choice should be reassessed for future machines like the FCC (which could operate e.g. with flat beams etc.). In addition, the series powering of Beam1 and Beam2 quadrupoles limits the flexibility of choosing different phase advances for the two beams. Also this choice could be reassessed for the FCC. Power converter noise at locations with $\beta > 4$ km has been a specific concern, and was addressed by the triplet powering layout (in series for intrinsic compensation).

A major concern in the LHC design phase has been the noise from klystron-driven superconducting RF, where the actual LHC experience has been excellent. As another positive news, the LHC mechanic and dynamic apertures are excellent thanks to sorting and to the exquisite magnet field quality. Differently from past superconducting hadron storage rings, for the LHC there is an excellent agreement between predicted and observed dynamic aperture, which is attributed to the almost noise-free power converters and radiofrequency system as well as to the excellent optics control. Electron-cloud effects appeared late on the LHC design table. Mitigation measures could not be fully incorporated by a redesign of the beam screen. Surface conditioning by "beam scrubbing" and the flexibility of the LHC injector complex for preparing different beam types and bunch separation patterns have been the primary means for raising the beam current and achieving the design luminosity. Emittance blow-up had been a big worry for the beam instrumentation and lead to careful estimates for the LHC. Again, the performance of the machine is superb also in this regard. A novel tune measurement principle ("BBQ" for base band tune measurement) helped keeping the emittance growth low. A positive surprise has been the hadron beam-beam limit: experience at the SppS, Tevatron and HERA suggested strong limits for the maximum acceptable beam-beam parameter. The LHC achieved higher than expected beam-beam parameters, which again is attributed to the low level of noise.

Sorting during installation was initially judged difficult due to small sample number with the original delivery and installation schedule (≈10). A problem with the LHC cryogenic supply line in the tunnel (QRL) during the installation delayed the installation process of the magnets and provided a unique opportunity for the magnet sorting: almost all of the 1200 LHC dipole magnets were stored on the CERN site before their installation. This allowed sorting by geometry and field quality. The LHC operation clearly benefits from the sorting. This scheme requires significant space on site, and also sufficient capacity for cryostating and testing. The LHC demonstrated the capability for tackling major problems, such as the QRL problem, collapsed plug-in modules (RF shielded vacuum interconnections between the magnets), collapsed He cooling lines in the triplet magnets, He leaks and electric shorts in the DFB powering lines and a major accident in 2008 based on faulty inter-magnet connections. The Superconducting Magnets and Circuits Consolidation (SMACC) effort after the aforementioned incident was a monumental effort involving over 350 persons, including ~1,000,000 working hours of preparation and requiring the opening, validation and consolidation of all magnet interconnections.

Concerning lessons from commissioning and Run2, the beam lifetime had initially been expected to be rather poor and featured sharp spikes, leading to overly pessimistic estimates of intensity limitations (at e.g. ≈ 20% of the nominal value). An unexplained noise sources exciting the beam, like the so-called 'hump', raised concerns initially. Luckily, this effect disappeared after the first year of operation. Its origin has still not been fully understood, albeit it disappeared after all undisrupteble power supplies (USP) have been changed in the machine. The LHC operation also revealed the importance of a powerful, flexible and mature injector complex, allowing the production of various kinds of beams, such as 8b4e (8 bunches followed by 4 empty bunches) for e-cloud mitigation, a "bunchlet" scheme for enhanced scrubbing, a batch compression, merging and splitting scheme (BCMS) as low emittance option, and an 80 bunch injection scheme to SPS. Time needed for cryogenic maintenance has led to a new running paradigm, alternating 3years of operation with a long shutdown. The definition of 'good' magnets during production (fast training to 'ultimate' current) turned out not to be correlated to the magnets ability to keep its training after installation in the tunnel. Several magnets feature a 'de-training' of their ability to reach the nominal operating field in the tunnel, requiring a time consuming re-training campaign in the tunnel. This led to the choice of a reduced 'efficient' beam energy, where the design beam energy of 7 TeV had to be lowered to 6.5 TeV in order to reduce the required time for magnet training in the tunnel and to arrive at an efficient running schedule. The machine efficiency has been limited by "UFO's", sharp losses that have been attributed to beam collisions with Unidentified Falling Objects in the vacuum chamber, radiation to electronics, and loss spikes. Beam aborts were triggered by very small beam losses, indicating that margins do exist. Only 30% of all fills in the LHC Run1 have been terminated by operators. Electron-cloud scrubbing, changes to the bema-loss-monitor thresholds and a position optimization of sensitive electronics in the tunnel after the Long Shutdown 1, have drastically improved the availability.

The co-called "snap back" at the start of the ramp and other dynamic effects are under control thanks to detailed magnet measurements and an elaborated magnet modelling procedure that takes into account the magnet powering history and is integrated into the LHC controls system (no need for reference magnets). The LHC has achieved a very high level of machine reproducibility and stability. The machine reproducibility is key for high efficiency of the cleaning insertions and for machine protection. Troublesome losses in the Dispersion Suppressor suggest that future projects should, already in the design stage, integrate collimators in the dispersion suppressor.

2.13.3 **Novel Technologies for the HL-LHC**

The LHC Injector Upgrade in LS2 consists in the development of a new H^- source, connecting the new H^- LINAC4 accelerator to the PS booster, implementation of charge exchange injection into the PS booster, increasing the booster extraction energy, and instability mitigations and RF upgrades in the SPS. The LIU upgrades will approximately double the beam brightness and also the total intensity of the beam available for injection into the LHC.

The High-Luminosity LHC upgrades during LS2 and LS3 include: new final-triplet quadrupoles with larger aperture, based on Nb_3Sn superconductor with a peak field at the coil of about 12 T; additional collimators in the dispersion suppressors of the betatron cleaning insertion, enabled by more compact Nb_3Sn dipoles with a field of 11 T – the first time this type of superconducting magnet is installed in a collider; new low-impedance robust collimator jaws; novel crab-cavity RF systems; a novel cold powering scheme based on superconducting links; etc.

2.13.4 **Outlook**

The lessons learned from the LHC and the novel technologies developed for HL-LHC prepare the ground for future higher-energy hadron colliders like HE-LHC or FCC-hh, which will require 100's or 1000's of Nb_3Sn dipole and quadrupole magnets with a peak field in excess of 15 Tesla, bright proton beams, robust absorber and collimator materials, low impedance components (collimators and vacuum system) and RF crab cavity systems.

2.13.5 **References**

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2.14 FCC-hh Design Highlights

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2.14.1 **Introduction**

The FCC-hh will provide proton-proton collisions with 100 TeV centre-of-mass energy, about seven times more than LHC, with a luminosity much higher than in HL-LHC. For the ultimate parameters the luminosity can reach up to $3 \times 10^{35} cm^{-2} s^{-1}$ and allows to reach an integrated value of $17.5 ab^{-1}$, corresponding to the physics goals [1].

In the following, the layout and main parameters of FCC-hh are presented first followed by the luminosity considerations. Limited space then allows for only a few key design highlights and prevents to cover the full range of important topics.