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Chapter 30

The LHC as FCC injector

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The re-use of the modified LHC is presently the reference baseline for the High Energy Booster (HEB) injector[1] into the FCC-hh hadron collider,[2] although a number of other promising options exist. As part of the FCC study, the transformation of the LHC into the last acceleration stage into the new collider has been investigated in some detail, including the key aspects of new insertion designs and faster ramping. Performance aspects including energy reach, flexibility and filling time of the collider have been considered, and the transfer lines linking the HEB to the FCC have been defined. This chapter describes the required performance, the required changes which would be needed to the existing LHC machine and discusses the remaining challenges for LHC operation as FCC-hh injector. The study was based on the FCC-hh machine layout defined in the Conceptual Design Report in 2018:[3] the design continues to evolve, which could have an impact on the changes needed in specific LHC straight sections, but the main considerations on the feasibility of reuse of LHC remain valid.

1. Requirements for FCC-hh injector

The FCC-hh concept is for an accelerator of 91 km circumference which will collide protons and ions at about 50 TeV per beam. The HEB should be able to fill roughly 80% of the collider with 3.3 TeV protons in about ∼30 minutes, several times per day. This corresponds to 10400 bunches spaced by 25 ns with a bunch intensity of 1×10^{11} protons and a normalized emittance of 2.2 μm. A list of the most relevant beam parameters for the FCC-hh injector complex is given in Table 1. A 5 ns option has also been considered, which would mean some changes to the upstream machines in

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Table 1. Beam parameters for the FCC injector complex.

Parameter	Baseline	Ultimate
Injection energy	3.3 TeV	3.3 TeV
Number of bunches	10,400	52,000
Bunch spacing	25 ns	5 ns
Bunch intensity	1×10^{11} p	0.2×10^{11} p
Normalized emittance	2.2 μm	0.44 μm
Turn around time	5 h	4 h
Max. FCC filling time	30 min	30 min
LHC duty cycle for FCC filling	0.10	0.125

the present LHC injector chain, or a new set of pre-injectors to match any changing physics needs.

The baseline FCC-hh injection energy is 3.3 TeV. Higher energy is favourable in terms of impedance, beam stability, aperture and energy (field) swing, but a lower energy is favourable for transfer to FCC and simplicity of the injector complex, lower capital and operating cost for the HEB, as well as opening more options for its realisation.

The FCC-hh injection energy also determines the number of bunches which can be transferred safely to the FCC,[4] because of damage limits of the injection protection absorbers. This limit scales non-linearly with beam energy, as the energy deposition in the absorber also depends on the secondary shower development. At the baseline energy of 3.3 TeV, only ∼80 bunches can safely impact the absorbers, so a staggered transfer is necessary, affecting the kicker design parameters and filling scheme. Around 100 of these multiple extractions are needed to fill the FCC collider.

Other important requirements are that the HEB should be reliable with highest possible availability, and also that it should be considerably easier and cheaper to operate than FCC itself.

The duty cycle for FCC filling is (for the ultimate beam) only about 12%, which means that the LHC could be available for the remainder of the time for its own dedicated physics program — either at 3.3 TeV or at full energy, if the new insertion designs with crossings remain compatible. A discussion of possible alternatives is beyond the scope of this chapter, see e.g. Ref. 5 for more details.

2. Reuse of existing LHC as 3.3 TeV HEB

The study baseline of reusing LHC as HEB is conceptually the most straightforward way to inject at 3.3 TeV into FCC-hh. In this scenario using LHC as HEB injector for FCC would still rely on the whole existing injection chain, including the SPS. In the version studied, to make space for the extractions towards FCC two beam crossings in experimental Interaction Points (IPs) have to be removed. Depending on which crossing points will be removed, the total circumference of Beam 1 and Beam 2 in the LHC might no longer be identical. This is not an issue for the HEB but might impact the potential remaining LHC physics program beyond the FCC injection. Suppressing the crossing in IR2 and IR8 keeps the circumference of the two LHC beams identical. The locations and layouts of the existing RF, collimation and beam dump systems are maintained; however, keeping the orientation of the beam dump while removing two crossings means that injection will have to be shifted from the outer rings to the inner rings. The physics experiments and low beta insertions will have to be decommissioned. The changes in LHC layout are depicted in Fig. 1. In view of other possible uses of the LHC, the study aimed at keeping the energy reach of the LHC to 7 TeV, e.g. in the design of the beam crossings, while designing extraction and transfer lines to 3.3 TeV is needed for the FCC-hh.

The other important requirement is to speed up the LHC ramp, which will have to be improved by roughly a factor 5, to 50 A/s, to keep the overall FCC filling time in the ~1 hour regime. This requires new main power

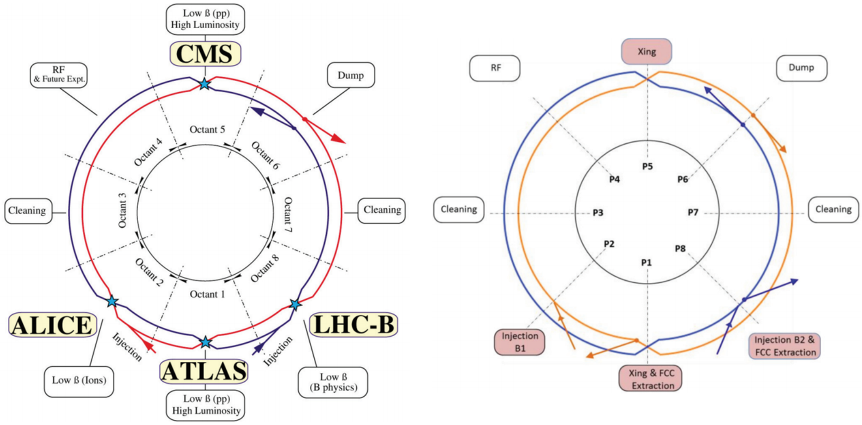

Fig. 1. Existing (left) LHC layout, illustrating possible changes for use as HEB (right).

converters as well as changes to other systems, such as quench protection. At this stage, it is not clear if such a modification of the power converters will be implemented with the same accuracy that is required for storage ring operation. These aspects all need to be considered in the overall optimisation. The existing LHC RF system, with a voltage of 16 MV at 400 MHz, is able to accelerate an LHC beam to 3.3 TeV in 1 minute, but the limiting factor is the ramp of the main dipoles.[6] After the modifications these will be able to ramp to 3.3 TeV in about 3 minutes, so the RF will not need any changes. As far as the RF system is concerned, the FCC-hh requirements are still less demanding then the nominal LHC and HL-LHC operation.

The early part of the ramp will also need to be changed from the baseline operational LHC Parabolic-Exponential-Parabolic-Linear (PELP), which would otherwise take over half of the total ramp duration. In one of the few FCC tests in the LHC machine, a simpler Parabolic-Parabolic-Linear-Parabolic (PPLP) ramp was developed and tested successfully in 2017,[7] and shown to save 1.5 minutes per ramp with no adverse effect on the beam. This has actually been adopted as the operational LHC ramp since 2018, and has saved a total of about 10 hours per year of operation (a direct benefit of the FCC studies for the present LHC physics program).

2.1. *Insertion modifications*

For compatibility with the FCC-hh version studied, the main layout features per LHC straight section are summarised below:

- IR1: new beam 1 extraction system plus beam crossing plus decommissioning of ATLAS;
- IR2: injection to inside ring plus decommissioning of ALICE;
- IR3: no changes to momentum collimation;
- IR4: no changes to RF system;
- IR5: decommissioning of CMS, plus beam crossing;
- IR6: no changes to beam dump;
- IR7: no changes to betatron collimation;
- IR8: injection to inside ring plus new beam 2 extraction system plus decommissioning of LHCb.

2.1.1. *IR1*

The new extraction system in IR1 can be very similar to the current beam dump extraction system in LSS6. However, a modification is needed by opening up the space between the Q4 and Q5 downstream the septum to accommodate the needed beam crossing. In the easier case of leaving all distances between the Q5 upstream the septum to the Q4 downstream the septum unchanged, a space of 75 meters is available between the downstream Q4 and Q5 which is not enough to facilitate a beam crossing at 7 TeV.

There are several possibilities for realizing the beam crossing in this region, the details of which are discussed in [3]. Assuming four of the 11 T dipoles developed within the HL-LHC framework can be used in this crossing, 98 meters are needed between the downstream quadrupoles (a simple copy of the IR6 dump extraction would allow crossing only up to 4.5 TeV). Shifting the downstream Q4 and the septum further upstream reduces the maximal extraction energy but increases the maximal energy at which the crossing can operate. By changing the drift after the kicker to 123 m and the one after the septum to 121 m, enough space is created between Q4 and Q5 to facilitate the 7 TeV crossing.

This would be a realistic layout for 3.3 TeV extraction, although the needed kicker switch technology in terms of dI/dt exceeds present technology by a factor 2.6 which means technological advances in this area would be a key R&D topic. Higher energy transfer would need further improvement.

2.1.2. *IR2*

The injection in IR2 needs to be changed from the outer to the inner ring. In order to do so, while still maintaining the optics at the injection elements, all injection elements need to be shifted by 16 meters. This shift of the septum, Q5, protection devices and kicker along with optics matching at the septum entrance and preserved Q5 strength are essential to this proposed layout. Q4 and other quadrupoles can be changed, as long as the optics constraint of 90 degree phase advance between kicker and injection protection device (TDI) is respected. The TDI may be moved to facilitate this. However, if Q4 and the TDI location are changed, or if extra quadrupoles are added between Q4 and the TDI, new studies of the injection system failure cases are needed to ensure proper machine protection.

The only other elements present in this region are the added quadrupoles, used to introduce a FODO-like structure that keeps the optics functions close to those for the arc. Hence there are no spatial restrictions, which allows us to replicate the current LHC injection system without introducing new constraints to the maximal LHC energy.

Note that even though the added quadrupoles have been located in approximately symmetric and at equal distances, their placement does not influence the injection system. Some flexibility in placement of these quadrupoles for optics considerations, since they will not have any effect on the injection system.

2.1.3. *IR8*

In IR8, in addition to the injection system that needs to be changed from the outer to the inner ring, an extraction system may need to be installed. The injection system is thus to be moved by 16 meters, as in IR2. The FCC layout chosen will determine if the extraction system should be on the inner ring or the outer ring. In the following, the extraction on the outer ring is illustrated.

Similar to the situation in IR2, optics matching at the septum entrance and preserved Q5 strength are important for these layouts, while other quadrupole strengths can be changed, as long as the optics constraint of 90 degree vertical phase advance between kicker and TDI is respected.

While extraction on the outer ring is easier than the case where injection and extraction are on the same ring, the layout with the injection system does not have enough space for the present dump extraction system. This is because the quadrupoles used around the injection kicker on the inner ring now determine the distance in which the extraction system needs to reach a large enough clearance. Another problem encountered is the required 90 degree phase advance between the kickers and their respective protection elements. Due to this requirement it becomes necessary to move the protection device further away.

This layout is a realistic one for 3.3 TeV extraction, requiring a factor 2.1 advance in kicker technology. If we would again assume that the kicker limit changes by a factor 5, then if needed we could reach an extraction energy of 7.0 TeV by moving the septum back by 13 meters and adding three more septum modules.

2.2. *Other considerations*

The design of the beam transfer lines from the LHC to FCC-hh[8] is dependent on the location of the FCC tunnel. The version of the FCC tunnel described for this study passes directly under the LHC tunnel, which could allow for normal-conducting transfer line magnets depending on the detailed FCC-hh layout and orientation.

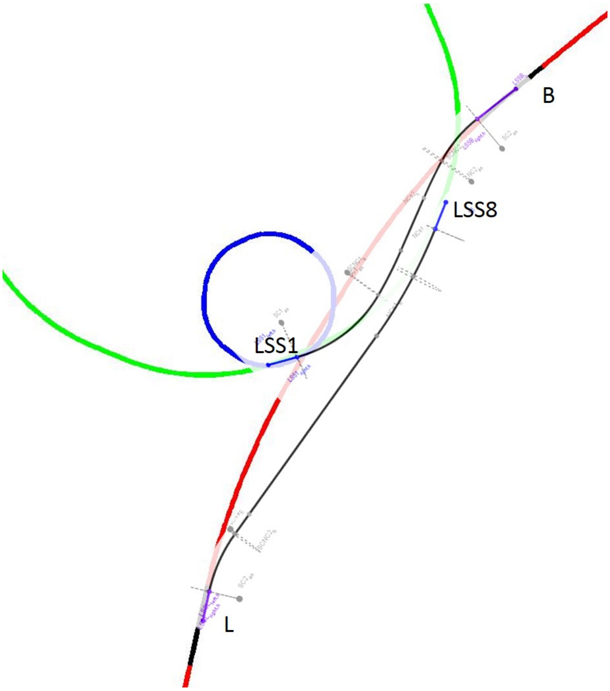

Fig. 2. Transfer lines from 3.3 TeV LHC HEB (red) to FCC, from LSS1 and LSS8. With this layout version the transfer lines could be fully normal-conducting.

Decommissioning of the LHC experiments is likely to be one of the cost-drivers for the conversion of LHC to FCC HEB. The activation levels in IR1 and IR5 at the end of LHC physics operation are expected to be at around 1 mSv/h level, with a large amount of material to decommission. Work on dose estimation, handling and decommissioning work is required, using the available detailed dose rate maps to compute job doses once work scenarios are available.

With the most recent FCC implementation roadmap, the construction and operation of FCC-ee before FCC-hh would mean that LHC as FCC-hh injector would not be required for about 20 years after the end of HL-LHC operation. Although it would leave more time for cool-down of radio-active equipment, this long delay poses important feasibility issues in terms of keeping equipment and expertise available. It therefore reduces the attractiveness of directly reusing LHC as FCC- hh injector.

The possibility of operating LHC as a Fixed-Target facility between filling the FCC has also been studied;[5] here the problems are the integration of a slow-extraction system into the superconducting, small aperture LHC machine, the issues associated with designing the extraction hardware at such a high rigidity, and also the small annual number of protons on target that could be realised due to the long LHC ramp time.

One important remaining concern for the reuse of LHC will be the high power consumption for the LHC cryogenic system, in addition to the operating resource cost and also the age and related availability of the LHC when FCC-hh comes on line.

2.3. *3.3 TeV Superconducting (4 T) HEB 27 km in LHC tunnel*

If 3.3 TeV injection energy is mandatory, another interesting option would be to replace LHC in the same tunnel with a fast-ramping, relatively low-cost, superferric or superconducting machine, which would need a field of 4 T to reach 3.3 TeV. The machine could be twin-aperture, although this would increase the cost substantially, both for the magnets and also for powering, instrumentation and other ancillary systems. Alternatively it could use polarity reversal to minimise the length of transfer line to FCC, depending on the detailed cost trade-off. Such a machine would follow the existing LHC geometry and layout, re-using the injection and dump transfer lines, but differently configured in terms of injection and extraction systems.

Although the capital cost might be higher than modifying the present LHC, this could be an attractive option in terms of operating cost, consumption and maintainability, compared to reusing the existing LHC magnet system.

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