POSSIBLE REUSE OF THE LHC AS A 3.3 TeV HIGH ENERGY BOOSTER FOR HADRON INJECTION INTO THE FCC-hh

B.Goddard, W. Bartmann, M. Benedikt, W. Herr, M. Lamont,
P. Lebrun, M. Meddahi, A. Milanese, M. Solfaroli Camillocci, L.S. Stoel
CERN, Geneva, Switzerland

Abstract

One option for the injector into a 100 TeV centre-of-mass energy frontier proton collider FCC-hh [1] in a new tunnel of 80–100 km circumference is to reuse a suitably modified LHC as 3.3 TeV High Energy Booster (HEB). The changes that would be required to the existing LHC insertions are described, including the types and numbers of new magnets and circuits. The limitations on the maximum LHC ramp rate and minimum cycle time discussed. The key question of the minimum FCC filling time achievable with technically possible upgrades is examined, together with the issues of decommissioning for the elements which would need to be removed from the machine. The potential performance reach of the modified LHC as 3.3 TeV HEB is quantified, and implications for FCC-hh discussed.

MAIN DESIGN CONSIDERATIONS

Initial studies have shown that beam transfer from both LHC P1 and P8 is preferable to optimise the orientation of the collider with respect to the local geology in the Geneva area and to minimise the length and overall bending angles of the new transfer lines. It is desirable to minimise changes to the LHC lattice and machine configuration, avoiding changes to highly activated zones. Beam parameters are summarised in Table 1. The low number of bunches per transfer is determined by the damage potential of the 3.3 TeV beam [2].

Table 1: Parameters of Beams to Inject into FCC-hh

Parameter	Unit	Value (option)
Beam energy	TeV	3.3
Bunch spacing	ns	25 (5)
Bunch population		1.0 (0.2)$\times 10^{11}$
H/V emittance (norm.)	mm.mrad	2.2 (0.44)
RMS bunch length	cm	8.0
Bunches per transfer		50-100
Turnaround time	h	5.0

Transfer Energy

The injection energy of the FCC-hh collider is assumed to be 3.3 TeV, based on the ratio of injection to collision dipole field. In view of possible changes to the baseline HEB energy e.g. as a result of the collider dipole magnet aperture optimisation, the LHC machine layout changes have been made to reach as high an energy as possible compatible with all other constraints.

Number and Length of Rings, and Crossing Points

The use of both LHC rings is assumed, both to decrease the filling time by a factor two and to minimise the length of transfer lines required (or avoid polarity reversal). The cost will be in the duplication of many circuits and instruments, higher complexity and lower availability. The lengths of the two rings should be identical to simplify the RF manipulations and re-phasing required for transfer to the collider, and from the SPS to the HEB. There thus need to be at least two crossings placed azimuthally opposite, which do not need to be at the centre of the respective LHC long straight sections. The lengths of both rings should be the same as the existing LHC 26.659 km, to maintain the present ratio of 27/7 with the 6.912 km circumference of SPS.

Machine System Locations

Injection should remain in P2 and P8, to avoid additional civil engineering for 450 GeV beamlines. With the layout proposed and only two crossings the injections would need to be into the inner rings, which is feasible but entails some reorganisation of the layouts in P2 and P8. The beam dump system should remain in P6, to avoid decommissioning of the highly active dump blocks, and to avoid additional civil engineering for the dump lines and dump caverns. The two collimation systems (betatron and momentum cleaning) are assumed to remain in their locations in P7 and P3 respectively. This avoids the issue of decommissioning or moving the highly activated systems, and having to modify the accelerator and its infrastructure in these activated areas. The 400 MHz RF accelerating system is assumed to remain in its present location in P4.

Extraction Towards FCC Collider

The two extraction systems for transfer of the beams to the FCC-hh collider are assumed to be located in P1 and P8. For an overall layout where the 100 km collider intersects the LHC machine, LHC Beam 1 would be extracted from P1 and Beam 2 from P8, Fig. 1 (top). For a layout where a 80 km collider does not intersect the LHC ring, the direction of extraction from these two points is inverted. Integration of the extraction system in P8 together with the existing injection is feasible for 3.3 TeV but is likely to rely on the HEB extraction energy being lower than 7 TeV. In P1 the accommodation of the extraction with crossing dipoles will also be likely to limit the transfer energy.

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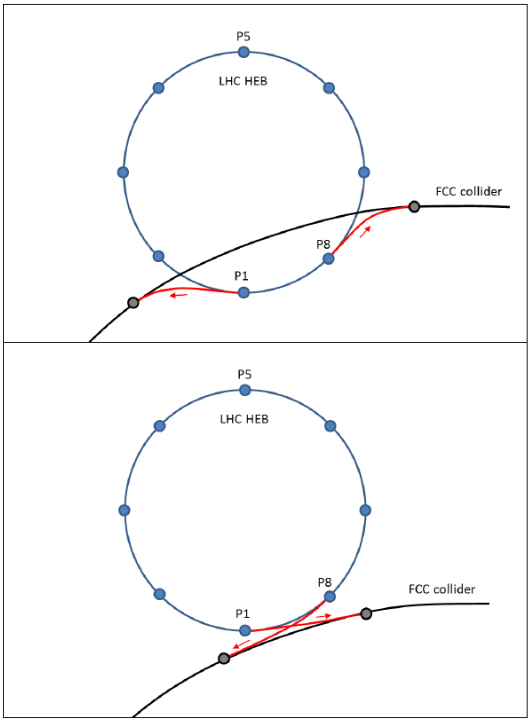

Figure 1: Beam extraction from HEB P1/P8 and layout of transfer lines, for the two configurations studied.

CHANGES TO LHC INSERTIONS

The main layout issue is the combination of a new extraction system in P8, for either clockwise or counter-clockwise beams, with the Beam 2 injection system. Of note is the requirement to inject into the inner ring in both IR2 and IR8, to avoid massive changes to the dump insertion and dump beamlines. This is a consequence of only having two beam crossings. Optimisation may be possible, e.g. arranging a double crossing in IR6 together with the dump which would allow injection into the outer rings in IR2 and IR8 and avoid the displacement of the injection elements.

Modifications to IR1

The low-β insertion will be removed and the matching section from Q6 inwards modified. A new extraction channel for one beam is needed, together with a beam crossing which can be arranged in a relatively long drift using the superconducting (SC) D2 magnets which will then be available. To provide the 80 m space for the crossing, the existing matching quadrupole layout will be changed. The horizontal β-function with the new layout is shown in Fig. 2.

Modifications to IR2

The low-β insertion will be removed and the matching section from Q5 inwards modified. The injection layout needs to be modified, with a downstream shift of the septum, Q5 and kicker to allow injection into the inner ring without major changes to the transfer line geometries. Across the remainder of the IR a straightforward FODO transport will be installed, without any beam crossing.

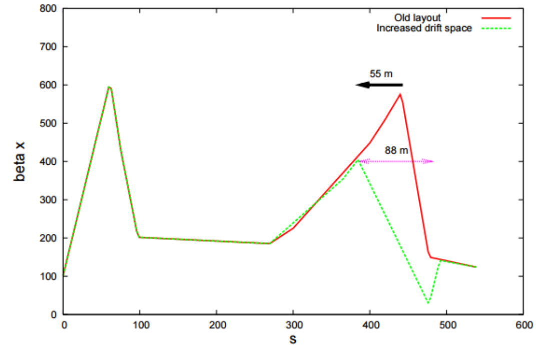

Figure 2: Horizontal β-function for rearranged optics to accommodate both extraction and crossing in IR1.

Modifications to IR5

The low-β insertion will be removed and the matching section from Q4 inwards modified. A FODO transport will be installed, together with a crossing in a relatively long drift using the SC D2 magnets. In a future optimisation, it may prove to be possible to leave in place the triplets and crossing elements, and existing matching sections quadrupoles.

Modifications to IR8

This is the most complicated insertion, particularly with the injection and extraction on the same beam if the FCC collider intersects the LHC ring. As for IR2, the injection layout needs to be modified with a downstream shift. A new extraction channel will be needed, the low-β triplet removed and the matching section from Q5 inwards modified.

COLLIDER FILLING TIME USING LHC

The turnaround of the FCC-hh collider is assumed to be 4-5 hours [3], comparable to that achieved on average by LHC during physics Run 1 [4]. The actual filling time of the collider should be at most about 30 minutes, to avoid it starting to dominate the turnaround. Ramping the LHC at its present rate would result in filling times in excess of 90 minutes, and so the present ramp rate needs to be increased by a factor of at least 5.

Ramping LHC at 50 A/s

The feasibility of ramping the main LHC dipoles (and all other circuits) at 5× the present rate (i.e. 50 A/s for the dipoles, instead of 10 A/s presently) has been studied. The protection diodes have a turn-on voltage of about 6 V, which corresponds to 60 A/s. No premature ramp-rate induced quenching is expected at 100 A/s, from tests made on LHC dipoles. For the quench protection system (QPS), after a quench the other dipoles in the arc start ramping down at 120 A/s without triggering the QPS, and so 100 A/s does not require changes to the QPS. For the cryogenic load, a ramp to full current in 1200 s deposits 480 J/m (from hysteresis and eddy currents) producing a ΔT in the LHe bath of 0.05 K, with the system dimensioned for a ramp down from full current to zero in 80 s in case of need, or 3000 J/m. This

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would provoke a ΔT of about 0.32 K. Ramping at 50 A/s even to nominal 7 TeV current is therefore conceivable.

The main change is in the voltage during ramp-up. One arc has an inductance of 15.7 H, developing 160 V when ramping at 10 A/s. The magnets are tested at 1.9 kV, so assuming a maximum allowed voltage of 1000 V, the maximum possible ramp rate for the present powering sectorisation would be about 64 A/s. So 50 A/s is possible, for 800 V induced, with new power convertors or more powering sectorisation of each arc. Other main circuits have been checked and can follow the energy function at this ramp rate (at 50 A/s the main quadrupole string only develops 12 V inductive).

Overall 50 A/s for the linear part of the ramp looks feasible with changes only to the power convertors and possibly powering sectorisation. Beyond 50-60 A/s it looks more difficult as many other aspects start to be relevant, like the protection diodes, QPS and cryogenic load.

The ramp also contains parabolic and exponential parts, Fig. 3, to ensure that the time derivatives of the current are also smooth. The initial 20 A change in current is critical for snapback and chromaticity. This part could be speeded up in a new ramp, to 9 s, with feed-forward correction from the LHC magnetic model. The ramp up to 3.3 TeV would take 156 s, and so a HEB cycle time of 312 s is assumed, allowing for maybe 10 seconds at flat top and assuming a slightly faster ramp-down where control of dynamic effects for the beam is not relevant.

With four LHC ramps to 3.3 TeV the minimum filling time is 39 minutes, using a ramp with 50 A/s in the linear part and assuming the present cycle times in the LHC injector chain. This requires approximately 300 PS cycles, each 3.6 s long; 32 SPS cycles, each needing an additional 10.8 s ramping time; and 4 LHC ramp-up and -down cycles.

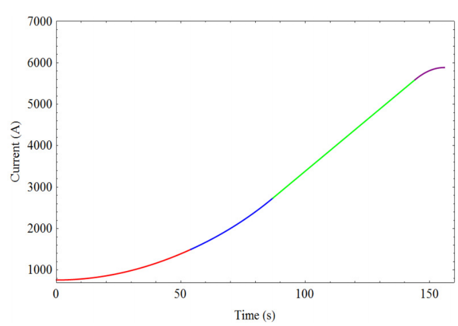

Figure 3: Main dipole current for 156 s LHC ramp-up with 50 A/s linear ramp rate (green).

Areas for Filling Time Improvement

The possible improvements for the existing complex are to speed up the PSB basic period from 1.2 to 0.6 s, to use single batch injection into the PS, and to speed up the LHC ramp by reducing the time for round-in and -out from 60 to 30 s. All of these improvements together would reduce the minimum filling time of the collider slightly to 31 minutes, but would not be without cost and performance challenges.

FEASIBILITY OF MODIFICATIONS

The modifications required to the LHC are basically in all of the present experimental insertions plus the powering of the dipoles (below), with the excavation of two new transfer lines to the FCC collider plus the construction of the appropriate junction caverns in the LHC in IR1 and IR8. From previous civil engineering experience it is clear that this work will take several years during which LHC will not be operational.

The modifications will require the removal of basically all machine elements in the four experimental IRs, unless the present triplet and crossing can remain in IR5. The experiments themselves will probably need to be physically removed, to provide space for the reinstallation of the required machine elements, and also the necessary supporting structures across the experimental caverns. Partial alternatives such as removing only the inner detectors will be investigated as part of the optimisation process.

The expected activation levels of the machine components have been scaled from LS1 measurements using the expected dose [5]. Assuming a 12 month cooldown time before starting work, the maximum dose levels expected at 40 cm are in the range of 100 μSv/h at key components, which is essentially the same as expected in the long shutdowns during HL-LHC operation. A full analysis of the decommissioning and removal steps is needed, based on which components have to leave the LHC tunnel, to assess whether this is acceptable for collective dose or whether longer cooling times are needed to reduce the ambient dose further.

If the total time is counted for cooldown, removal of accelerator systems, civil engineering and reinstallation of accelerator systems, a shutdown of the LHC for at least 5 years seems likely.

CONCLUSION

A 3.3 TeV injector added to the present LHC injector chain is needed to fill FCC-hh. Several options exist, but reusing the LHC as HEB offers a number of clear advantages over the alternatives of building a new HEB, not the least of which is the possibility to concentrate resources and effort onto the flagship collider project. Four of the eight LHC straight sections need substantial modifications, with the addition of two extraction systems, the modification of the injection systems and the removal and replacement of the present crossing and low-beta insertions. The RF, collimation and beam dump systems remain untouched. To achieve a collider filling time of around 30-40 minutes the LHC ramp rate would need to increase fivefold to 50 A/s, which requires new main power convertors. The main concerns for the reuse of LHC will be the high power consumption for the LHe cryogenic system, the operating cost and also the age of the LHC when FCC-hh comes on line. These aspects all need to be considered in the overall optimisation.

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