

HIGH ENERGY BOOSTER OPTIONS FOR A FUTURE CIRCULAR COLLIDER AT CERN

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Abstract

In case a Future Circular Collider for hadrons (FCC-hh) is constructed at CERN, the tunnels for SPS, LHC and the 100 km collider will be available to house a High Energy Booster (HEB). The different machine options cover a large technology range from an iron-dominated machine in the 100 km tunnel to a superconducting machine in the SPS tunnel. Using a modified LHC as reference, these options are compared with respect to their energy reach, magnet technology and filling time of the collider. Potential issues with beam transfer, reliability and beam stability are presented.

REQUIREMENTS

If FCC-hh [1–3] is built at CERN, its injection booster should reuse the existing CERN proton and ion chains. This makes a repurposed LHC a clear candidate as a booster ring, but other options should also be considered. The other available tunnels that may be considered for a HEB are the SPS tunnel, which could reach a higher energy if superconducting magnets are used, and the FCC tunnel itself, which might house a HEB with iron-dominated magnets along with FCC-hh itself.

The HEB design should be such that it can fill roughly 80 % of FCC with 0.45–6.5 TeV protons in about 30 minutes. Even though the baseline injection energy for FCC-hh at CERN is 3.3 TeV, the HEB designs should still take into account a range of possible top energies, since the optimal transfer energy for FCC-hh is not yet known. For FCC-hh a higher energy is probably favourable, but for transfer to FCC a lower energy is favourable. Hence an optimum should be found taking both into account after the initial design stage. Lastly, it is important that the HEB be reliable and considerably easier to operate than FCC itself.

The FCC injection energy also determines the damage limit for the FCC injection protection (in terms of the maximal number of bunches that can impact the absorber without allowing a cooldown time). This limit scales non-linearly with beam energy, since the energy deposition in the absorber not only depends on the energy stored in the bunches but also on the secondary shower development, which is different according to energy. At the baseline energy of 3.3 TeV roughly 100 bunches can impact the absorber before the damage limit is reached, so a “staggered transfer” is deemed necessary. This would entail using multiple extractions to transfer a full booster ring to FCC, to ensure machine protection. As a consequence fast risetimes for the HEB extraction and FCC injection kickers are needed, with higher transfer energies requiring even faster risetimes to maintain a given

FCC-hh filling factor. It is currently assumed that the HEB extraction kickers will be identical to the FCC injection kickers. Injection system concepts for the FCC-hh collider have been developed for 3.3 TeV injection [4, 5]. This concept exclusively uses solid-state generators, such as the inductive adder [6], for multiple injections of short bunch trains. In case of a lower transfer energy, which would need a longer kicker flattop, alternative semiconductor based generators, such as the Marx generator [6], would be used.

The requirement for feasible transfer lines from the existing CERN complex is partly dependent on the location of the FCC tunnel. Currently two distinct options for the location of a 100 km tunnel in the Geneva area are under consideration. The so-called intersecting option passes directly under the LHC tunnel, in such a way that the two rings seem to intersect in a projection on earth’s surface. The non-intersecting option lies a few kilometers more toward the south-east, so that it does not pass underneath the LHC ring. The transfer lines for all booster options are longer but easier in the non-intersecting option, since the added distance grants a shallower slope and allows more space for the necessary bending. In this paper we will focus on the intersecting option for transfer.

LHC AS HEB

Many details about the use of LHC as a HEB can be found in [7], but we summarize the main changes needed to the machine here. We will need to make space for the extractions towards FCC, in order to do so we remove two beam crossings. It is desirable to keep RF, collimation and the beam dump system as they are; however, keeping the orientation of the beam dump while removing two crossings means that injection will have to be shifted from the outer to the inner rings. The physics experiments and low energy insertions will have to be decommissioned. The changes in LHC layout are depicted in Figs. 1 and 2, which show the current and future layout of LHC in case it is used as a HEB. The last important modification is to improve the speed of the ramp, which will be improved by roughly a factor 5. The existing LHC RF system, with a voltage of 16 MV at 400 MHz, is able to accelerate an LHC beam to 7 TeV in 2 minutes. The limiting factor however is the ramp in the main dipoles. After the modifications these will be able to ramp to 3.3 TeV in about 2.5–3 minutes [8, 9], so the RF will not need any changes.

The transfer lines for this option are rather demanding. Assuming transfer at 3.3 TeV to the FCC, in the intersecting layout option, leads to transfer lines with a maximum slope of about 8 %, assuming 8 Tesla magnets are available for

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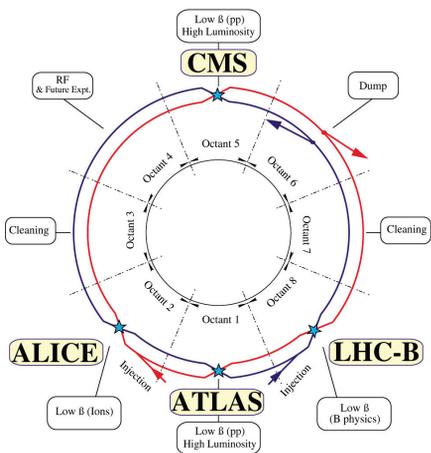


Figure 1: Current LHC layout.

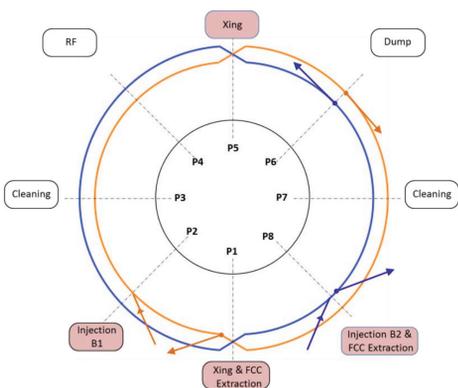


Figure 2: Envisaged layout of LHC as HEB.

the lines. In this design the combined length of the lines is 6.5 km, of which 4 km is superconducting. However, it should be possible to use such superconducting transfer lines, since the cryoplants available in points 1 and 8 will likely have sufficient capacity for them [10], seeing as the LHC will be operating at both lower intensity and lower energy.

With these adaptations LHC can be transformed into a HEB, which could fill the LHC with 3.3 TeV protons in roughly 40 minutes on paper. However, the LHC is a complex and demanding machine, which is likely to be expensive to operate and maintain in comparison to other HEB designs.

HEB AT SPS

The SPS tunnel could be used to house a new superconducting machine, which could function as the HEB for FCC-hh. Given that we want a reliable machine with a fast ramp ($0.1-1.0 \text{ T s}^{-1}$) the maximal field we assume is 7 to 7.5 Tesla. Given the SPS tunnel geometry this would mean a top energy of 1.4 to 1.5 TeV, which with the current SPS injection energy this means the SPS energy swing would be increased from about 20 to roughly 60. The feasibility of such a high energy swing is to be investigated along with a new magnet design. In case a lower energy swing is deemed necessary, an upgrade of the PS (the injector to the SPS) would also be needed. Additionally to the increased energy

swing in SPS, there will be an increased energy swing of about 30 in FCC, instead of the 15 in the baseline.

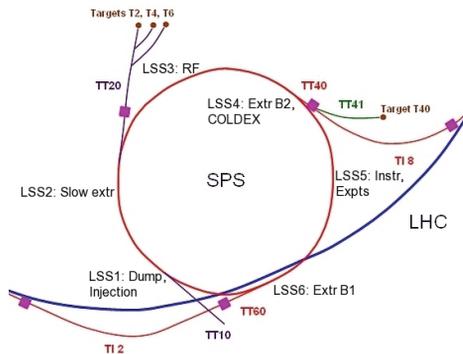


Figure 3: Current SPS layout.

The optimal location for the extractions is such that the beam circulates counter-clockwise, contrary to the present situation. This also implies changing the injection, but the appropriate transfer line is already in place from the era in which SPS was a collider. The layouts for the current and the new machine in the SPS tunnel are shown in Figs. 3 and 4. It is not yet clear what would happen to the transfer lines depicted in those figures.

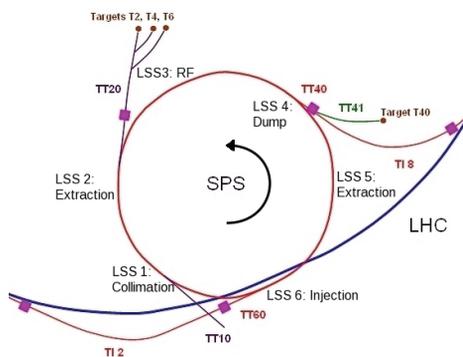


Figure 4: Envisaged HEB at SPS layout.

Collimation will be especially challenging in this machine, since the straight sections are only 128 m long. A collimation concept with momentum collimation in the dispersion suppressor and betatron collimation in the straight is under investigation.

In contrast to the LHC, this machine could have normal conducting transfer lines, albeit with a high slope of around 8.5 % at the maximum due to the fact that SPS is closer to the surface. However this slope might still be reduced in a future design optimization.

With an RF system similar to the existing SPS system (similar to half the LHC system) the beam could be accelerated to 1.5 TeV in a few tens of seconds, depending on the exact lattice parameters. If a new RF system would be needed, then the design will be driven by the large longitudinal emittance required at injection into FCC in order to cure transverse mode coupling instabilities (TMCI). It depends on the exact RF system and the final magnet design which of these will be limiting for the ramp speed of this machine. This design would need many cycles to fill FCC but since it would ramp quickly it is estimated that we would need

Table 1: HEB Parameter Summary

	LHC as HEB	HEB at SPS	HEB at FCC
Magnets	Superconducting, Double aperture	Superconducting, Fast ramping, Single aperture	Superferric, Single aperture, Polarity reversal
Energy	3.3 TeV (1–6.5 TeV)	1.5 TeV	3.3 TeV (1–5.5 TeV)
FCC filling time	40 min	34 min	29 min

about 34 minutes to fill FCC. However, this number is very sensitive to the maximal ramping speed that can be achieved, due to the large amount of ramps required to fill FCC.

HEB AT FCC

The third option we consider here is to house a second accelerator in the FCC tunnel. This would be a single aperture machine with a polarity reversal, for which magnetic fields of up to 2 T are considered, to stay within the range of iron dominated magnets.

In order to avoid any background or radiation damage to the experiments, and for integration reasons, this machine will need bypasses around the experimental insertions. The initial design for these bypasses uses the same bending radius and total bending angle as the FCC tunnel, to avoid added synchrotron radiation and ensure compatibility with the FCC-ee injector ring. This design needs 15.5 km of bypass tunnels. However, the FCC-ee injector will most likely be able to pass through the experimental cavern and thus we could consider a shorter bypass design using a smaller bending radius.

Magnetic crosstalk should be considered in the magnet designs for this option, so that it can be avoided. However crosstalk of losses could be a real challenge, especially near collimation and protection devices. It should be investigated whether there is a good strategy to monitor losses on both machines that ensures safe operation of both without too many unnecessary dumps.

A scaling of impedance and collective effects shows that a halfgap of about 39 mm will be needed in the dipoles. When using resistive magnets this would mean a peak dissipated power of about 1.1 GW, so superferric magnets (magnets with a superconducting drive cable, but a warm iron yoke) are seen as the only viable option. An optics which alternates focussing and defocussing combined function dipoles inside of the traditional FODO halfcell (which is still delimited by pure quadrupoles) looks promising. The optics functions are very similar to the standard FODO optics, while profiting from the combined function magnets in the form of a lower required quadrupole strength and avoiding the lack of flexibility typically associated with combined function lattices.

Using a machine with low field superferric magnets would open up the possibility of a very fast ramp. However, due to the large machine circumference, the energy gain per turn delivered by the RF system becomes the limiting factor. A reasonably sized RF system (similar to the current LHC system) would be able to ramp from 450 GeV to 3.3 TeV in

about 2 minutes. The machine would only have to ramp twice, since it is slightly longer than FCC, but only single aperture. This allows for an FCC filling time of 29 minutes, most of which is due to filling the booster using the current CERN injector chain.

OTHER OPTIONS

There are some other options, apart from the ones outlined above, which have not been studied in as much detail. One such option is to inject directly from the current SPS to the FCC at 450 GeV. This will lead to a demanding energy swing for FCC (a factor of 111), but at the moment feasibility is not ruled out. If this energy swing would be acceptable for FCC it would likely raise the cost of the collider somewhat because of the larger required aperture, but the injector would be cheap and simple and have minimal effect on the ongoing physics programmes.

Another option would be to replace LHC with a fast-ramping superferric or superconducting machine. This would be an intensive project, involving the decommissioning of the entire LHC machine, so at this moment other options seem favourable. However, if the constraints for the booster change or if other designs are deemed infeasible, this idea may be revisited.

Lastly there are many variants of the main booster options that are also considered, but the merit of such changes to the baseline will be evaluated as the study progresses.

CONCLUSION

There are three main options for the FCC-hh booster, each with their own advantages and challenges. These designs will be further explored so that a good comparison can be made and the best option can be selected.

If the baseline FCC injection energy of 3.3 TeV needs to be maintained then a booster in the LHC or FCC tunnel is mandatory. But the option of injecting at 1.5 TeV is also important to study, since it is compatible with all three injector options and it offers advantages for transfer and injection protection.

The main figures of merit already available for the booster designs are the extraction energies, estimated FCC filling times and the magnet technology used. These are summarized in Table 1.

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