DESIGN AND EVALUATION OF INJECTION PROTECTION SCHEMES FOR THE FCC-hh INJECTOR OPTIONS

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Abstract

The Future Circular Collider (FCC) study considers several injector scenarios for FCC-hh, the proposed 100 TeV centre of mass hadron collider located at CERN. The investigated options include amongst others to use the LHC at 3.3 TeV or a superconducting SPS at 1.3 TeV as a High Energy Booster (HEB). Due to the high energy of the injected proton beam and the short time constant of injection failures, a thorough consideration of potential failure cases is of major importance. Further attention has to be given to the fact that the injection is – as in LHC – located upstream of the side experiments. Failure scenarios are identified for both injector options, appropriate designs of injection protection schemes are proposed and first simulations are conducted to validate the protection efficiency.

REQUIREMENTS AND INJECTION LAYOUT

The injector complex of FCC-hh [1] makes use of the existing injector chain at CERN. Both, the LHC at 3.3 TeV and a superconducting upgrade of the SPS (scSPS) at 1.3 TeV, are considered as injector options. In either case, a fast double plane injection using vertically deflecting normal conducting Lambertson septa (MSI) and horizontally deflecting injection kickers (MKI) is envisaged, as illustrated in Fig. 1. The main parameters are listed in Table 1. The injection at 3.3 TeV is considered as the baseline and is therefore emphasized in this paper. Cross-links will be made to the 1.3 TeV injection to highlight the key differences.

A staggered transfer from the HEB based on injection batches with a reduced number of bunches is necessary to stay below the damage limit of the injection protection absorbers in case of injection failures. Figure 2 shows the reachable FCC fill factor as a function of the MKI rise time for different transferred beam energies. Energy deposition studies for the injection dump result in a maximum allowed number of 80 bunches per transfer [2]. The FCC baseline aims at providing a fill factor of 80%. Additionally in total approximately 10 μs of beam free gaps need to be provided for distributed abort gaps and low intensity beam injections.

This restricts the MKI risetime to <0.430 μs, as can be seen in Fig. 2. A frequency of 10 Hz is chosen for recharging the MKI and transferring all 130 injection batches from the HEB in the LHC tunnel to FCC.

Table 1: Main Requirements for the Injection Hardware

<table>
<thead>
<tr>
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<th>scSPS (1.3 TeV)</th>
<th>LHC (3.3 TeV)</th>
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<tr>
<td>Kicker</td>
<td>2.0 Tm (0.18 mrad)</td>
<td>0.79 Tm (0.18 mrad)</td>
</tr>
<tr>
<td>Septa</td>
<td>92 Tm (9.8 mrad)</td>
<td>36.2 Tm (9.8 mrad)</td>
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TRANSFERLINE LAYOUT, FAILURES AND PROTECTION

Various aspects were considered for the geometrical layout of the transfer lines (TL) [3, 4]. The required tunnel length is balanced with a feasible slope, acceptable dipole field and sufficient straight lengths for matching and collimation sections at the extremities of the TL. This results in designs requiring 7.2 T dipoles for the LHC-FCC and 1.8 T dipoles for the scSPS-FCC transfer, as outlined in Table 2 and illustrated in Fig. 3.

The layout avoids a combination of superconducting (SC) and normal conducting (NC) dipoles in the same TL, as different protection schemes would be required based on different time constants of dipole failures. The LHC-FCC
Table 2: Approximate layout parameters of the TL to FCC for the different HEB options (listed from the HEB extraction to FCC injection).

<table>
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<tr>
<th>Transfer line</th>
<th>Quench</th>
<th>Power Converter Trip</th>
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<tr>
<td>LHC to FCC</td>
<td>~1 σ</td>
<td>≪ 1 σ</td>
</tr>
<tr>
<td>scSPS to FCC</td>
<td>-</td>
<td>~1-2 σ</td>
</tr>
</tbody>
</table>

Figure 3: TL geometry from LHC and scSPS to FCC.

Failure modes of the IA have been identified and qualitatively compared to the PFN. A similar analysis is still to be done for the MG to further compare the MG and the IA regarding machine protection. The maximum pulse duration of the IA is expected regarding the acceptable number of impacting bunches. As illustrated in Fig. 4, the energy deposited by hadronic showers in the Nb3Sn cables of the downstream quadrupoles is in the order of a few 10 J/cm³. This is at very low probabilities. Another intrinsic layout difference is the high modularization of the system, which consists of 18 generators. Each generator is built of 20 layers with 24 branches, each containing one MOSFET switch. The simulations have been conducted to validate the energy deposition in the absorber itself as well as the protection efficiency.

**Injection Dump and Protection Efficiency**

As injection dump (TDI) a 6 m graphite absorber is foreseen, consisting of a segment of 2.5 m with a density 1.4 g/cm³ and a 3.5 m long segment with 1.8 g/cm³. Additionally, 1 m stainless steel masks are planned to protect the downstream quadrupoles from showers. FLUKA [12, 13] simulations have been conducted to validate the energy deposition in the absorber itself as well as the protection efficiency. The impact of 80 bunches with an impact parameter of 1 σ (grazing impact) at 3.3 TeV was simulated as a worst case scenario for both, TDI robustness and downstream losses. The simulations are based on the latest optics version, which features an increased beam size at the absorber for both planes (βx = 37 m, βy = 932 m). A maximum temperature of 1200°C is obtained in the TDI. Refering to latest HiRadMat results [14], a margin of at least a few tens of percent is expected regarding the acceptable number of impacting bunches. As illustrated in Fig. 4, the energy deposited by hadronic showers in the Nb3Sn cables of the downstream quadrupoles is in the order of a few 10 J/cm³. This is at very low probabilities. Another intrinsic layout difference is the high modularization of the system, which consists of 18 generators. Each generator is built of 20 layers with 24 branches, each containing one MOSFET switch. The simulations have been conducted to validate the energy deposition in the absorber itself as well as the protection efficiency.
Table 4: Failure modes of the Inductive Adder as pulse generator for FCC-hh injection kicker. Failure probabilities (Prob.) and severity (Sev.) are categorized qualitatively [h: high, m: medium, l: low, vl: very low]

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<tbody>
<tr>
<td>Err./miss. branch/layer</td>
<td>trig. fault, short/OP sw., SEB,...</td>
<td>m</td>
<td>&lt; 0.2/0.3</td>
<td>vl</td>
<td>cont. OP, no dump</td>
</tr>
<tr>
<td>Err./miss. system</td>
<td>spurious/missing trig.</td>
<td>l</td>
<td>100/139</td>
<td>m</td>
<td>full/synch. dump</td>
</tr>
<tr>
<td>Erratic IA</td>
<td>spurious trig.</td>
<td>vl</td>
<td>5.6/7.7</td>
<td>h</td>
<td>graz./synch. dump</td>
</tr>
<tr>
<td>Missing IA</td>
<td>missing trig.</td>
<td>l</td>
<td>5.6/7.7</td>
<td>h</td>
<td>graz./synch. dump</td>
</tr>
<tr>
<td>Magnet</td>
<td>vacuum flashover</td>
<td>m</td>
<td>94 – 106%</td>
<td>1-h</td>
<td>full/synch. dump</td>
</tr>
</tbody>
</table>

Figure 4: Transverse energy density (J/cm³) in the coils of the downstream quadrupole in case of MKI failure.

Injection precision is another major contributor to be considered for the maximum error at the TDI and is dominated by the flat-top ripple of the MKI, which translates to an oscillation of 0.7 σ. A similar contribution of the extraction kicker from the HEB is expected. Restricting the current specification for the flat-top precision from ± 0.5% to ± 0.25% would reduce the contribution of the injection precision to values similar as in LHC (~0.35 σ) [20]. This is also of relevance concerning reduction of injection oscillations and subsequent emittance growth. However, this ripple implies an increased beam size at the TDI, which reduces the impact in case of a MKI failure.

A further implication of the small horizontal beam size at the TDI (σₓ = 0.15 mm for FCC, in comparison to 0.58 mm in LHC) is that approximately 0.5% of the impacting p⁺ are scattered with large angles in case of grazing impact. These protons with amplitudes larger than 15.5 σ are subsequently lost in the injection insertion. However, the dominant factor for the deposited energy in the SC coils of the downstream quadrupoles are still hadronic showers. It is nevertheless of interest to estimate the impact of different σₓ and σₓ⁺ on the relative number of protons, which are scattered with large angles. Increasing σₓ by a factor of 2 would already reduce the relative number of lost p⁺ by 20-30%. Ongoing studies focus on determining the losses for varying combinations of σₓ and σₓ⁺ (based on the FCC-hh and LHC lattice) with the scattering routine pycollimate [19]. This will enable an optimization of the optics design regarding injection protection. Further studies will refine the attenuation requirements and compare the obtained losses with the damage limit of the downstream elements.

In addition, similar studies as for the injection protection have to be carried out for the extraction from the HEB, with the main challenge that re-triggering in case of an erratic of the extraction kicker and hence extracting into the TL has to be avoided.

CONCLUSION

First considerations of failure scenarios and protection schemes for the beam transfer from the High Energy Booster to FCC-hh are outlined and evaluated. The transfer line geometry has been updated to fulfil machine protection requirements. However, the limited length of the straight sections at the extremities of the LHC-FCC transfer line poses a challenge for collimation schemes.

Novel kicker pulse generator technologies feature reduced probabilities of worst case failures in comparison to the systems used in LHC. Protection for the worst case impact can still be guaranteed with the outlined injection protection system. Tracking studies are ongoing to refine the settings of the injection dump and evaluate the impact of optics changes in order to maximize the protection efficiency.
REFERENCES


