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

E. Renner*[1], M. J. Barnes, W. Bartmann, C. Bracco, R. Bruce, F. Burkart, B. Goddard, M. Hofer[1], A. Lechner, L. S. Stoel[1], F. M. Velotti, C. Wiesner, D. Woog, CERN, Geneva, Switzerland
[1]also at Vienna University of Technology, Vienna, Austria

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.

* elisabeth.renner@cern.ch

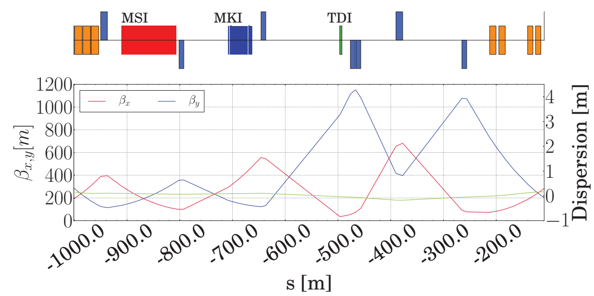

Figure 1: Injection optics (excerpt from dispersion suppressors to separation dipoles upstream of the side experiment).

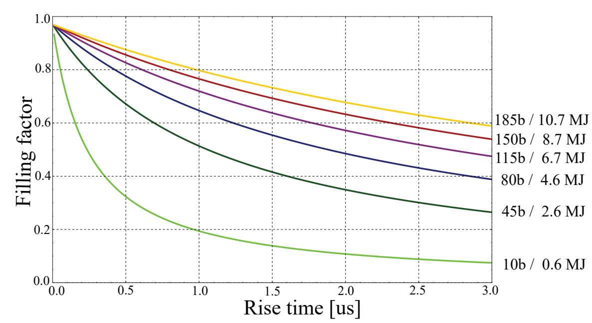

Figure 2: FCC bunch fill factor as a function of the injection kicker rise time for different transferred beam energies.

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 1: Main Requirements for the Injection Hardware

	scSPS (1.3 TeV)	LHC (3.3 TeV)
Kicker	2.0 Tm (0.18 mrad)	0.79 Tm (0.18 mrad)
Septa	92 Tm (9.8 mrad)	36.2 Tm (9.8 mrad)

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Table 2: Approximate layout parameters of the TL to FCC for the different HEB options (listed from the HEB extraction to FCC injection).

LHC TLs	**straight**	**SC (7.2 T)**	**straight**	**SC (7.2 T)**	**straight**	**max. slope**	**# FODO**	**# MB (6 m)**
LHC1 - IPB	0.1 km	2.3 km	0.1 km	1.6 km	0.05 km	2.1%	40	480
LHC8 - IPL	0.5 km	0.5 km	4.9 km	1.0 km	0.5 km	1%	70	845
SPS TLs	**straight**	**NC (1.8 T)**	**straight**	**NC (1.8 T)**	**straight**	**max. slope**	**# FODO**	**# MB (14.3 m)**
SPS3 - IPB	0.4 km	0.4 km	1.6 km	1.5 km	0.5 km	3.9%	41	246
SPS5 - IPL	0.3 km	2.4 km	0.6 km	2.1 km	0.5 km	2.7%	53	318

Table 3: Estimated Miskick for Failures of the TL Dipoles

Transfer line	**Quench**	**Power Converter Trip**
LHC to FCC	~1 σ	$\ll 1\ \sigma$
scSPS to FCC	-	~1-2 σ

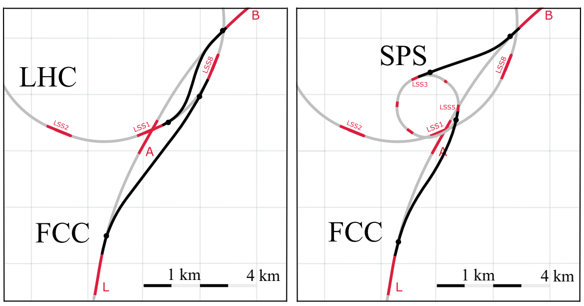

Figure 3: TL geometry from LHC and scSPS to FCC.

transfer only requires absorbers at the beginning of the TL to protect the SC TL and FCC from extraction failures. A full phase space covering collimation system at the end of the TL, as for LHC, is not required due to the large time constants of the SC dipoles and thus slow field change in case of failures. Such a system, however, is required for the NC scSPS-FCC transfer. Table 3 lists the estimated beam displacement after 4 ms (reaction time of active protection/ interlock systems) for main failure scenarios of the TL dipoles. The considerations are based on a preliminary TL design using LHC FODO cells and time constants taken from similar magnet families in LHC [5,6]. The estimates for the power converter trip describe the failure of a single magnet and hence are increased when an entire circuit is considered.

The intensity of the injection batch is $80 \cdot 10^{11}$ p$^+$. Consideration of $1 \cdot 10^{10}$ p$^+$ as a first estimate for the safe-beam intensity at 3.3 TeV [7, 8] results in a required attenuation of 1/800. To meet this requirement, graphite absorber blocks with a length >3 m are foreseen as TL collimators.

INJECTION PROTECTION

Injection Kicker Failures

Meeting the requirements for the fast risetime, a minimized probability of an erratic and recharging with 10 Hz would not be possible with currently used thyratron based pulse generators, such as the Pulse Forming Network (PFN) that is used in LHC [9]. Therefore, the Marx Generator (MG) [10] and the Inductive Adder (IA) [11] are studied as novel pulse generator technologies.

Failure modes of the IA have been identified and qualitatively compared to the the PFN. A similar analysis is still to be done for the MG to further compare the MG and the IA regarding machine protection. In comparison to the PFN, which discharges entirely when deflecting one injection batch, the IA is only discharged marginally (1-2%) and is thus constantly charged at maximum voltage. This implies that erratics at a kick strength different than nominal have 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. This results in a total of 480 switches per generator. A consequence of this design is a reduced probability of failures at critical kick strengths, i.e. 4-8% of the total kick. Failure scenarios and impacts are summarized in Table 4.

The most critical failure case in the current design is the missing trigger of 1 out of 18 IAs, which would result in a grazing impact, i.e. ±2 σ impact parameter. This case, however, is expected to be avoided at design level in future studies. It has to be noted that in contrast to the PFN, the IA and MG store energy for pulses of >2 μs (equal to one injection batch). As a consequence limitation of the pulse length in case of a spurious MKI trigger has to be guaranteed. One proposed solution, for the IA, is ensuring saturation of the magnetic core.

Injection Dump and Protection Efficiency

As injection dump (TDI) a 6 m graphite absorber is forseen, consisting of a segment of 2.5 m with a density 1.4 g/cm^3 and a 3.5 m long segment with 1.8 g/cm^3. 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 (β_x = 37 m, β_y = 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/cm^3. This is at

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Table 4: Failure modes of the Inductive Adder as pulse generator for FCC-hh injection kicker. Failure probabilities (Prob.) and severity (Sev.) are catagorized qualitatively [h: high, m: medium, l: low, vl: very low]

Failing System	**Cause**	**Prob.**	**Kick [% / σ]**	**Sev.**	**Impact/Reaction**
Err./miss. branch/layer	trig. fault, short/op sw., SEB,...	m	< 0.2/0.3	vl	cont. OP, no dump
Err./miss. system	spurious/missing trig.	l	100/139	m	full /synch. dump
Erratic IA	spurious trig.	vl	5.6/7.7	h	graz./synch. dump
Missing IA	missing trig.	l	5.6/7.7	h	graz./synch. dump
Magnet	vacuum flashover	m	94 – 106%	l-h	full /synch. dump

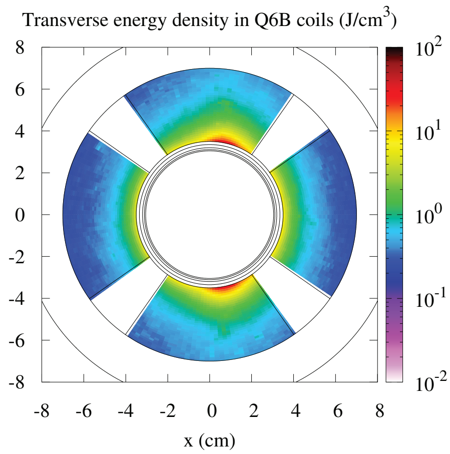

Figure 4: Transverse energy density (J/cm^3) in the coils of the downstream quadrupole in case of MKI failure.

least one order of magnitude below a first estimation of the damage limit determined by material tests in the HiRadMat facility, as reported in [15].

First studies result in a TDI aperture setting of 8.5 σ[1], based on collimation settings scaled from HL-LHC (secondary collimator at 8.4 σ). The FCC aperture strategy aims at ensuring an aperture of 15.5 σ throughout the machine, which is therefore considered for the design of the injection protection system [16]. However, the current lattice (V9) still contains aperture bottlenecks in the dispersion suppressors [17, 18]. A first estimate of the protected downstream aperture in case of a worst case MKI failure is thus of interest, which is mainly restricted by the maximum errors related to the TDI settings. The current design is sensitive to mechanical alignment and manufacturing errors. Scaling the combined mechanical LHC errors of ± 0.2 mm [19] (equal to 0.3 σ_{LHC}[2]) to ± 0.3 mm results in a contribution of ~2 σ, due to the small horizontal beam size (0.15 mm). An increased horizontal beam size at the TDI would be of advantage to facilitate TDI alignment and guarantee protection of smaller apertures.

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 (σ_x = 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 σ_x and $\sigma_{x'}$ on the relative number of protons, which are scattered with large angles. Increasing σ_x 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 σ_x and $\sigma_{x'}$ (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.

[1] σ: beam size based on the norm. emittance of FCC-hh (2.2 µm)
[2] ϵ_n = 3.5 µm, LHC (Ultimate)

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