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BEAM TRANSFER TO THE FCC-hh COLLIDER FROM A 3.3 TeV BOOSTER IN THE LHC TUNNEL

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Abstract

Transfer of the high brightness 3.3 TeV proton beams from the High Energy Booster (HEB) to the 100 TeV centre-of-mass proton collider in a new tunnel of 80–100 km circumference will be a major challenge. The extremely high stored beam energy means that machine protection considerations will constrain the functional design of the transfer, for instance in the amount of beam transferred, the kicker rise and fall times and hence the collider filling pattern. In addition the transfer lines may need dedicated insertions for passive protection devices. The requirements and constraints are described, and a first concept for the 3.3 TeV beam transfer between the machines is outlined. The resulting implications on the parameters and design of the various kicker systems are explored, in the context of the available technologies. The general features of the transfer lines between the machines are described, with the expected constraints on the collider layout and insertion lengths.

MACHINE PROTECTION LIMITS

Present investigations of the feasibility of absorber blocks for the LHC injection protection for High Luminosity-LHC (HL-LHC) beam parameters show two limitations. The foreseen high brigthness beams could cause mechanical stresses in the absorbers beyond their damage level. Also, attenuation of primary particles to provide protection of downstream elements would not be guaranteed with the present design [1–3]. The beam energy at the HEB to FCC transfer is a factor 130 higher than in case of the SPS to LHC transfer. Thus, a staggered transfer of batches with a reduced number of bunches is envisaged. The reachable bunch filling as a function of the injection kicker rise time for different transferred beam energies is shown in Fig. 1. In order to fill 80% of FCC and assuming 5 MJ as maximum energy per transfer leads to a required kicker rise time of less than 0.28 μs. A total of 120 batches with 90 bunches each need to be transferred. In case of LHC as HEB, there would be 4 times 30 batches of 90 bunches. The time between batch transfers is dominated by the synchronisation between the HEB and FCC and beam quality checks. Between each transferred batch both machines have to be synchronised on the common frequency:

$$f_c = \frac{f_{rev,HEB}}{C_{FCC}} = \frac{f_{rev,FCC}}{C_{HEB}} \quad (1)$$

In case of LHC as HEB the common frequency is about 111Hz which defines the required recharging frequency of HEB extraction and FCC injection kickers. With a total number of about 30 transferred batches from LHC the minimum

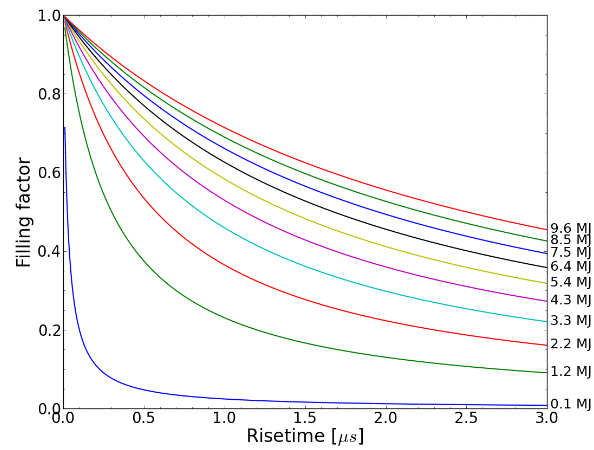

Figure 1: FCC bunch fill factor vs injection kickers rise time for different transferred beam energies. The foreseen filling of 80% is reached for HL-LHC energies (about 5 MJ) for a rise time of 0.28 μs.

injection time for one full LHC beam injected into FCC is 0.5 s.

INJECTION SYSTEM LAYOUT

The proposed injection system uses a Lambertson septum to deflect the beam horizontally onto the FCC orbit. The injected beam enters the septum with an offset in angle and position in both planes with respect to the ring orbit, Fig. 2. The vertical angle is reduced by off-centre passage through a quadrupole and finally compensated by a fast kicker system. In order to estimate the required kick angles we assume that the beam clearance at the level of the quadrupole is

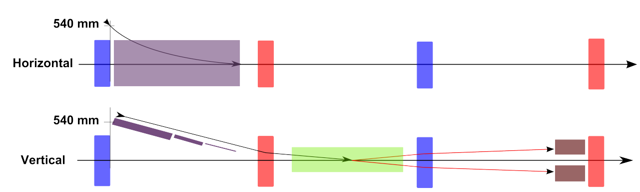

Figure 2: Layout of the injection system. Focussing (red) and defocussing (blue) quadrupoles build a FODO lattice. The Lambertson septum (violet), which is vertically aligned with the incoming trajectory angle, deflects the beam horizontally onto the orbit, and the kicker (green) compensates for the remaining angle in the vertical plane. The injection dump (brown) intercepts miskicked beam (red).

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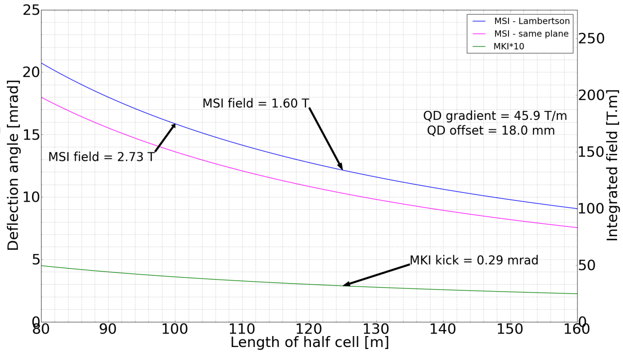

Figure 3: Kick angle and integrated field of septum (MSI) and kicker (MKI) as a function of the half cell length.

540 mm. The rms betatron beam size in FCC at injection amounts to ≈ 0.6 mm. Assuming ±10σ for the beam and ±3 mm for orbit and alignment tolerances, the beam stay clear diameter is 18 mm. The strength of the quadrupole is assumed as 45 T/m. The beam offset in the quadrupole between septum and kicker is 18 mm which leads to a minimum diameter of the vacuum chamber of 36 mm. The first septum blade is assumed to be 6 mm thick, which leads to a minimum beam opening of 24 mm at the entrance of the first septum. The kick angle and integrated field of septum and kicker as a function of the half cell length is shown in Fig. 3. The kicker angle is calculated such that the required opening at the septum entrance is reached. About 100 m half cell length is used for the arc FODO cells. This requires a kicker deflection of 0.36 mrad and a septum magnetic field of 2.73 T. By increasing the half cell length in the injection straight from 100 to 125 m, the kicker strength can be reduced to 0.29 mrad and the septum field is within reach of resistive magnet technology with 1.6 T. The required kicker and septum parameters are summarized in Table 1.

In order to provide space for vacuum equipment, instrumentation and protection elements, a half cell length of 150 m was chosen. Increasing the half cell length from 100 m to 150 m in the injection straight requires a rematching of the optics for the preferred 90° phase advance per cell. The resulting betatron function maxima in the injection cells are detuned from 365 m (arc cell value, [4]) to 620 m.

Table 1: Parameters of Kicker and Lambertson Septum at FCC Injection for a Half Cell Length of 125 m

Hardware Parameters	Unit	Kicker	Septum
Deflection	mrad	0.29	12.3
Integrated field	T.m	3.2	134
Available system length	m	120	90
Rise time	μs	0.28	-
Flat-top length	μs	2.25	≥2.25
Flat-top stability	%	±0.5	±0.5
GFR h/v	mm	18/18	18/18

INJECTION KICKER HARDWARE

The beam size would permit an aperture of 18 x 18 mm, however an aperture of 35 x 35 mm is presently assumed to allow for a suitable screen to shield the kicker magnet yoke from the circulating, high intensity, beam. Reflections and flat top ripple of the field pulse must be less than ±0.5%, a demanding requirement, to limit the beam emittance blow-up due to injection oscillations. A carefully impedance matched high bandwidth system would meet the stringent pulse response requirements. Thus the FCC injection system is foreseen to use multi-cell travelling wave kicker magnets, each connected by a matched transmission line to the main switch and terminated by a matched termination resistor. As a first iteration, the design of the FCC injection kickers is based on that of the LHC injection kicker system, which has an impedance of 5 Ω. The required field rise-time of 0.28 μs is dependent upon the rise-time of the current at the output of the magnet and the propagation delay (fill-time) of the pulse through the kicker magnet. Assuming a propagation delay of 0.2 μs, together with the assumed 5 Ω impedance, gives an allowable inductance of 1 μH per magnet. The aperture dimensions result in an inductance of 1.26 μH/m: allowing for fringe fields, at the ends of each magnet, the maximum length of each kicker magnet is 0.75 m. Assuming an overall magnetic length of 30 m (40 magnets), the required flux-density in the aperture is 0.106 T, compared to 0.11 T for the present LHC injection, and the current is 3 kA. The nominal input voltage of the magnet is 15 kV: the modulator would be designed to provide a magnet pulse input voltage of between 3.6 kV and 18 kV, to allow for high voltage conditioning of the kicker magnet.

The kinetic energy of the beam, at HEB to FCC transfer, is 3.3 TeV and the corresponding total beam energy is 650 MJ. This beam energy can cause considerable damage to equipment and thus the FCC injection system must be highly reliable to avoid mis-kicking beam. In general the beam can be mis-kicked due to three main types of faults, namely (a) triggering all the kicker switches asynchronously with respect to the injected or circulating beam, (b) the kicker switch turns on erratically i.e. without being triggered and (c) the magnitude of the kick strength is incorrect.

Triggering of the kicker switches asynchronously with respect to the beam is a controls issue and is not covered further in this paper. An incorrect magnitude of kick could result from several different faults, including an electrical breakdown in the kicker magnet, or faulty system components, cables or connectors. The voltage on the pulse power modulator can be monitored, shortly before triggering, to ensure that it is the correct value – if not extraction from the HEB would be inhibited: this is the same procedure as presently used for extraction from the SPS and injection into the LHC. To minimize the possibility of electrical flashover in the kicker magnet, cables and connectors, these components must be well designed and conservatively rated.

In general most kicker magnet systems installed at CERN use a modulator which employs thyratron switches and either

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Pulse Forming Networks (PFNs) or Pulse Forming Lines (PFLs). The thyratron switches are regularly used to switch high voltage (e.g. 60 kV) and high current (e.g. 6 kA) rapidly, providing current rise-times of several tens of ns. In order to minimize the probability of a thyratron erratic (turn-on without a trigger signal) the PFNs/PFLs are normally resonantly charged just before use: for the LHC injection system the PFN is designed so that resonant charging can commence 1.8 ms before injection. However, despite resonant charging, thyratron switches occasionally turn-on erratically. In addition, thyratrons have limitations with regards to their dynamic range.

Semiconductor switches are generally reliable, if properly utilized within their ratings: under these circumstances they are not prone to self-triggering. In addition, they allow a wide dynamic range, and maintenance is significantly reduced compared to gas switches. Thus, for the FCC injection system, it is desirable to use semiconductor switches instead of thyratrons. Furthermore, depending upon the switch technology, solid-state modulators can be opened when conducting full load current, hence, only a portion of the stored energy is delivered to the load during the pulse, therefore a PFL or PFN is not required. The switches potentially limit fault current in the event of a magnet (load) electrical breakdown and the source impedance can be low, thus source voltage does not need to be doubled.

Series and parallel connection of power semiconductor switches can potentially achieve designs with very high pulse power. Examples of suitable switch technologies for the modulator of the FCC injection system are the Marx Generator and the Inductive Adder, of which an extremely high precision prototype was built at CERN for CLIC based on MOSFETs (fast switching) [5]. Both of these technologies will be investigated, in collaborations with outside institutes, as potential replacements for thyratrons.

TRANSFER LINE LAYOUT

Several options for an FCC tunnel close to CERN are being studied taking into account civil engineering feasibility [6] and a possible connection to LHC [7]. For two different tunnel lengths of 93 and 100 km an optimisation of the connecting transfer lines between LHC and FCC is shown in Fig. 4. The 100 km long FCC version intersects with the LHC tunnel. A total of 160° horizontal bending is required for both lines to meet the injection straights in FCC. In the non-intersecting option for the 93 km tunnel the horizontal bending amounts to only 10° for both lines. Both transfer lines of the intersecting option measure 4 km, the transfer lines of the non-intersecting option 7.1 and 5.4 km. The intersecting option has 4.5 km less tunnel length but requires 150° more bending angle at 3.3 TeV. Assuming 5 T dipole fields, one degree of bending requires 40 m dipole length which adds up to a difference of 6 km in the total dipole length between the two versions. The vertical slopes reach up to 4% for the FCC depths assumed in this study. The optics layout of these lines could consist of a regular

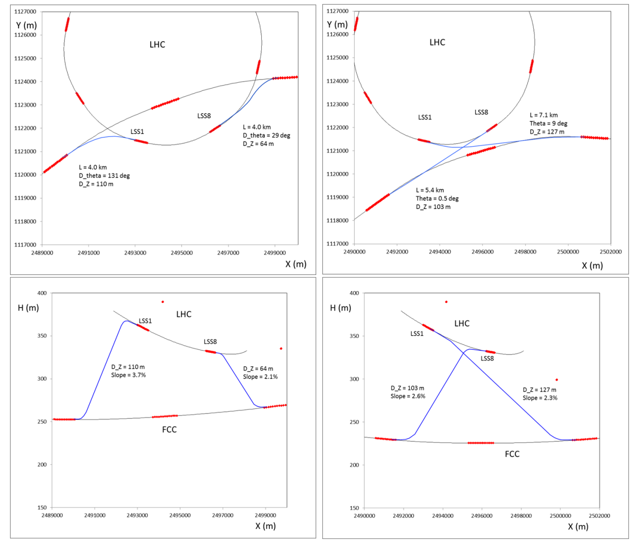

Figure 4: Transfer line geometries between LHC and FCC (left) for the intersecting option in horizontal (top) and vertical (bottom) planes and (right) for the non-intersecting option.

FODO lattice with two independently powered quadrupole sections on either side for optics matching. An important design constraint is given by the integration of an injection protection system. In an ideal case, the line would consist of a matching section to match to a regular FODO lattice with optimised optics functions for the bending magnets design. Further downstream a second regular structure could be placed which is - regarding the amplitude and phase of the optics functions - optimised for the injection protection system. The final section would be devoted to matching the transfer line optics to the FCC injection straight. In this scenario - in contrary to the present LHC injection protection system - a passive protection against bending magnet failures in the line would be given, separated from the main arcs.

CONCLUSIONS

The beam transfer from the HEB to FCC is mainly constrained by machine protection. A staggered transfer of about 90 bunches per batch is proposed for safe injection of the total beam energy of 650 MJ. In order to reach 80% bunch filling in the collider, the injection kicker rise time must not exceed 280 ns. A low impedance matched travelling wave kicker system, based on the LHC injection kicker design is proposed. Semiconductor switches instead of thyratrons are considered to minimize the probability of erratic turn-ons. Increasing the cell length in the injection straight allows normal conducting technology for the injection septum. The transfer line geometry between LHC and FCC has been studied for an intersecting and a non-intersecting tunnel version. The non-intersecting option requires 150° less bending which corresponds to about 6 km less integrated dipole field.

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