PRELIMINARY ESTIMATE OF BEAM INDUCED POWER DEPOSITION IN A FCC-hh INJECTION KICKER MAGNET

A. Chmielinska*, CERN, Geneva, Switzerland, EPFL, Lausanne, Switzerland
M.J. Barnes, W. Bartmann, F. Burkart, B. Goddard, CERN, Geneva, Switzerland

Abstract

The Future Circular Collider for hadrons (FCC-hh) will require a fast injection kicker system that is highly reliable and that does not limit accelerator performance. Important considerations in the design of such a system are machine protection constraints, collider filling factor and hence rise and fall times of the kicker magnet field. Fast rise time kicker magnets are generally ferrite loaded transmission line type magnets with a rectangular shaped aperture. The beam coupling impedance of the kicker magnets is crucial, as this can be a dominant contribution to beam instabilities. In addition, beam-induced heating of the ferrite yoke due to the real component of the longitudinal beam coupling impedance needs to be controlled: if the ferrite temperature exceeds the Curie point this impacts the ability to inject beam and hence the availability of the machine. This paper presents estimates for the beam induced power deposition in the ferrite yoke, based on a calculated FCC beam spectrum and an analytical model of longitudinal impedance for unshielded kicker magnets.

INTRODUCTION

Important requirements for the FCC injector design are to re-use the existing CERN proton and ion chains, provide a machine filling factor of 80%, and ensure reliable and relative ease of operation. Several conceptual designs are being reviewed [1], nevertheless the baseline injection energy for the FCC-hh at CERN is 3.3 TeV. In this case, the LHC is expected to be modified and used as a High Energy Booster (HEB) injector. Detailed considerations about the beam transfer from HEB into the FCC-hh are discussed in [2]: in the present paper, several aspects are reviewed and an update on beam parameters effecting the kicker system is presented. In particular, the injection system design strongly depends on the stored beam energy of the injected beam. From High Luminosity LHC (HL-LHC) upgrade studies [3], the maximum beam energy at injection is ~4.2 MJ, thus only 80 bunches can be safely transferred at a time. Hence, in order to achieve the required FCC filling factor in the most efficient way, each FCC ring should be filled 4 times by 33 batches of 80 bunches. Provided that the ramping speed for the LHC as a HEB can be increased by a factor of 5, the collider will be filled with protons within 40 minutes. For nominal FCC operation, the bunch intensity is 1.0×10^{11} protons, the bunch spacing is 25 ns and the bunch length is 8 cm. A detailed description of beam parameters required for the physics run is given in [4].

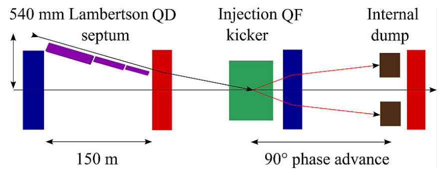

Figure 1: Injection system layout.

INJECTION SYSTEM

The schematic layout of the injection insertion is shown in Fig. 1. The Lambertson septum vertically deflects the injected beam and the kicker magnet compensates for the remaining angle in the horizontal plane: a defocusing quadrupole (QD) bends the beam outward in the horizontal plane, thereby reducing the required kicker strength. In addition, the deflection required takes into account the quadrupole cryostat radius of 540 mm. The rms beam size at injection is ~0.8 mm. Assuming $\pm15\sigma$ for the beam diameter, ±2.5 mm for orbit distortion and alignment errors and ±1.5 mm for injection oscillations, the minimum beam pipe diameter is 32 mm. The internal beam dump is located downstream of the kicker magnet and provides protection against mis-kicked beam. Although the injection region has a FODO lattice with a half-cell length of 150 m, to provide space for a normal-conducting septum, vacuum equipment and protection devices, it is desirable to utilize a shorter kicker system length for beam impedance and stability reasons. However the length must be consistent with the ability of the pulse generator to supply the required current. In addition, the required deflection angle reduces with decreasing physical length of the kicker magnets. Hence, in the present design, the kicker magnet system will be reduced to ~40 m and moved to the end of the half-cell, with a phase advance of 90° in both planes to the internal dump.

INJECTION KICKER MAGNET

The design of the injection kicker magnet has to be optimized for numerous conflicting requirements. Aspects, which significantly influence the kicker magnet hardware are the envelope of the injected beam and the compatibility with the pulse power generator. At present there is not an impedance budget for the FCC kicker magnets. However, as mentioned above, the length of the FCC injection kicker magnet installation will be optimized - to limit beam coupling impedance for the installation, but consistent with the capabilities of the pulse generator. Also, for high beam current and short bunch length, the beam coupling impedance can be an issue and, together with the beam spectrum, can result in a high power deposition in the kicker magnet: hence impedance shielding might be a critical feature. However

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* agnieszka.chmielinska@cern.ch

a suitable beam screen, placed in the aperture of each kicker magnet, will increase the aperture dimensions. For the FCC kicker magnet design, two options are studied. In the first approach, the horizontal and vertical dimensions of the rectangular aperture are considered to be equal to the minimum FCC beam pipe diameter of 32 mm. For the second option the aperture is increased to 48 mm, to allow for a beam screen with a thickness of 8 mm (as per LHC injection kicker magnet beam screen [5]). If there is a need for a beam screen, certain criteria have to be fulfilled: (1) adequately low, broadband, beam coupling impedance, (2) fast field rise time, (3) good high voltage behaviour and (4) suitable low Secondary Electron Yield (SEY).

To inject 80 bunches separated by 25 ns, the field flat-top duration must be 2 µs. To limit beam emittance blow-up due to injection oscillations, the reflections and the flat-top ripple of the field must be lower than ±0.5%. Based on the proposed filling pattern, the FCC injection kicker system field rise time must not be greater than 0.43 µs (including any field overshoot, undershoot, or ripple outside of the tolerance of ±0.5%). The field fall time requirements are less strict: the target FCC abort gap duration is ~1µs, hence the kicker field fall time must be no longer than this to not disturb the circulating beam. To meet the requirements for the field rise time, a transmission line type magnet will be used, similar to the one used for injection into the LHC [5].

Several possibilities are being considered for the FCC injection kicker pulse generator, nonetheless a promising option is the Inductive Adder (IA) [6]. Thus, hardware parameters of the FCC injection kicker magnet have been selected to match the IA operational requirements. An IA uses magnetic cores [7]: to limit the size, cost and propagation delay through the IA, the output voltage must be kept at a reasonably value [8]. In general, to aim for lower voltage, the fast kicker magnets have low characteristic impedance, but consistent with the rise time requirements: hence, a characteristic impedance of 6.25 Ω has been chosen. For the IA, the propagation delay per stack for 6.25 Ω is comparable with the delay for a 5 Ω characteristic impedance. However, an important advantage of 6.25 Ω, in comparison with 5 Ω, is the larger gap of the secondary insulation – which significantly reduces the electrical field in this region [6].

In order to provide the required kick angle, several aspects have to be considered. Reducing the effective magnetic length, requires a higher magnetic flux density and thus a larger pulse current. A NiZn ferrite is generally used for the yoke of a fast kicker magnet: a suitable ferrite typically has a saturation flux density of 0.3 T at ambient temperature, and a lower value at higher temperature. Hence the overall kicker magnet length must be chosen to limit the maximum value of the flux density, in the ferrite yoke, to a value comfortably below the saturation flux density. To make a compromise between the requirements for the injection system and the capabilities of the IA, a pulse current of 2.5 kA was chosen. This corresponds to a magnetic effective length of ~30 m and magnetic flux density, in the aperture, of 0.07 T with the beam screen or ~25 m and 0.1 T with no beam screen. The rise and fall times of the current pulses from the IA are expected to be less then 75 ns. Hence, the allowable propagation delay of the kicker magnet is ~0.355 µs, which is longer than quoted in [2], thereby allowing an increase of the length of individual magnet modules: this will reduce the number of generators and hence cost and improve the kicker magnet performance in terms of field ripple. Based on the above, the main specifications for FCC injection kicker magnet are summarized in Table 1.

Table 1: Injection Kicker Parameters

Parameter	**Injection**
Kinetic Energy [TeV]	3.3
Angle [mrad]	0.18
Pulse duration [µs]	2.0
Flat top tolerance [%]	±0.5
Field rise time [µs]	0.43
Voltage [kV]	15.7
Current [kA]	2.5
System impedance [Ω]	6.25
System magnetic length [m]	30-40
Min. aperture dimensions [mm]	32-48

BEAM INDUCED HEATING

Electromagnetic interaction between beam particles and the surrounding environment is characterized by the beam coupling impedance. In the transverse and longitudinal planes, the imaginary and real parts of the beam coupling impedance might critically affect beam stability [9]. In addition, the real part of the longitudinal beam impedance determines energy loss of beam particles, and thus the beam induced heating in accelerator components. In fact, the power deposition induced by a beam composed of n bunches, each populated by N_b protons, travelling through the structure of longitudinal impedance of Z_l is [10]:

$$\Delta P = 2q^2 n^2 f_0^2\ N_b^2 \sum_{p=1}^{\infty} |\widehat{\lambda}_{beam}(pf_0)|^2 \mathrm{Re}[Z_l(pf_0)], \qquad (1)$$

where q is the proton charge, f_0 is the revolution frequency and $\widehat{\lambda}_{beam}$ is the Fourier transform of the normalized beam charge distribution. In extreme cases, the power deposition in a kicker magnet may provoke temperature rise of the ferrite yoke beyond the Curie point: hence, special impedance reduction techniques would be required [11–14]. For circular colliders, such as FCC, where high intensity beam may circulate through the aperture of the kicker magnets for many hours, it is essential to evaluate the beam induced heating in the kicker magnet at the design stage and take further action regarding possible impedance screening.

The following sections of this paper present an analytical approach to estimating the power deposition, based on a calculated FCC beam spectrum and the Tsutsui model.

The analysis has been performed for two types of ferrite: 4A4, which is often the baseline used for electromagnetic simulations at CERN, and 8C11, which is used in many fast kicker magnets at CERN.

The FCC beam spectrum was evaluated, by calculating the Fourier Transform of periodic signal consisting of Gaussian pulses [15]. The observed peaks, at specific frequencies, depend on the filling pattern, the structure of beam bunches and gaps for the kicker rise time. For operation with 25 ns bunch spacing and for nominal FCC beam parameters, the power spectrum consists of sharp lines separated by 40 MHz. Assuming a filling pattern of 80 bunches per batch, and 132 batches each separated by 0.43 µs, side-band harmonics will occur every 0.41 MHz and 3.11 kHz, but with an amplitude of less than <1% of the main lines.

In these studies, a theoretical calculation of the longitudinal impedance has been based on the Tsutsui model. This approach is valid for unshielded ferrite kicker magnets and for an ultrarelativistic beam [16]. Although the model does not take into account the C-shape of the magnet yoke, it has been shown to be in excellent agreement with results of coaxial wire impedance measurements performed for SPS-MKE magnets without serigraphy [13].

The geometrical model consists of two ferrite blocks surrounded by a perfect conductor, as shown in Fig. 2. The beam passes through the vacuum region at x=y=0. To keep consistency with [17], the half-width and half-height of the ferrite aperture are respectively a and b.

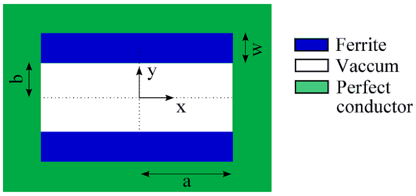

Figure 2: Tsutsui model.

The longitudinal impedance per unit length is given by:

$$\frac{Z_l}{L} = j\frac{Z_0}{2a}\sum_{n=0}^{\infty}\frac{1}{\frac{\frac{k_{xn}}{k}(1+\epsilon_r\mu_r)\mathrm{shch}+\frac{k_{yn}}{k}(\mu_r\,\mathrm{sh}^2\mathrm{tn}-\epsilon_r\,\mathrm{ch}^2\mathrm{ct})}{\epsilon_r\mu_r-1}-\frac{k\,\mathrm{shch}}{k_{xn}}}, \tag{2}$$

where Z_0 is the impedance of free space, L the device length and k the wave number. The expansion coefficients of the electromagnetic field in vacuum are k_{xn}=2(n+1)π/(2a) for n = 0,1,2... and k_{yn}=(($\epsilon_r\mu_r$ − 1)k^2 − k_{xn}^2)$^{1/2}$. In addition, sh = sinh($k_{xn}b$), ch = cosh($k_{xn}b$), tn = tan(−$k_{yn}w$) and ct = cot(−$k_{yn}w$). Relative permeability μ_r and permittivity ϵ_r for ferrite 4A4 and 8C11 were extrapolated from [18].

Figure 3 shows the real part of longitudinal impedance, calculated from Eq. 2, together with an FCC beam spectrum, evaluated for aperture dimensions of both 32 mm and 48 mm. For the larger aperture dimensions, not considering shielding, the real impedance is higher at frequencies below 2 GHz: this is where the real impedance contributes most to power deposition as there is higher power in the beam spectrum. The impedances calculated for ferrite 4A4 and 8C11 are similar in the frequency range of interest.

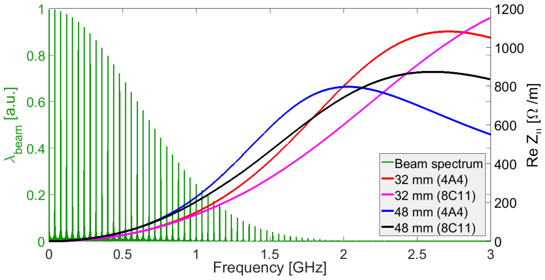

Figure 3: Longitudinal impedance and FCC beam spectrum.

Estimates of power deposition in an unshielded FCC kicker magnet, due to the beam coupling impedance, are presented in Table 2: the resulting heat load per meter length of magnet depends on aperture dimensions. A further analysis using Eq. 2 shows that power deposition depends mainly on fundamental harmonics in the beam spectrum: neglecting the gaps in the filling pattern reduces the power deposition by less than 1%. From [19], measurements show that with a heat load above ~160 W/m, the resulting ferrite temperature exceeds the Curie point. Since the FCC injection kicker magnets would consist of similar ferrite as the MKIs, which are also housed in a vacuum tank, it is presently assumed that the 160 W/m is also an upper limit for the FCC injection magnets. Hence, the analysis presented shows that it is probably necessary to suitably screen the FCC injection kicker magnets from the beam.

Table 2: Power Deposition Estimation, for Unshielded Kicker Magnets, with an Aperture of 32 mm or 48 mm

	ΔP_{4A4} [W/m]	ΔP_{8C11} [W/m]
32 mm	208	202
48 mm	312	301

CONCLUSION

The FCC injection kicker system parameters have been optimized to meet the requirements concerning machine protection during beam transfer, required filling factor, compatibility with the pulse power generator and low beam coupling impedance for the installation. The power deposition in the kicker magnet has been determined based on a calculated FCC beam spectrum and the Tsutsui model for longitudinal beam coupling impedance. Preliminary studies strongly suggest that beam induced heating, of unshielded magnets, would be a major limitation for a kicker magnet performance and hence shielding is necessary. Numerical simulations are required to study more complex kicker structures and to investigate solutions for screening the ferrite yoke from high intensity beam.

ISBN 978-3-95450-182-3

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