TOPOLOGIES FOR THE KICKER SYSTEMS OF THE FCC-ee COLLIDER AND INJECTORS

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Abstract

A central part of CERN's Future Circular Collider study (FCC) is a ~91 km circumference lepton collider and its injector complex. This contribution outlines the various kicker systems needed to transport the lepton beams from the electron source up to the collider dump system. The individual system requirements are presented, and the choice of design parameters and technology options for both beamline elements and pulse generators are discussed. Potential challenges such as the fast rise time of 82 ns for the damping ring kicker system working at 200 Hz repetition rate are highlighted, together with considerations on energy recovery. Ferrite loaded kicker magnet topologies are compared with system concepts employing strip lines. The paper concludes with a summary on the feasibility aspects and a recommendation for eventually needed prototype studies.

INTRODUCTION

The FCC-ee machines are specifically designed for the precision study of top quarks, Z, W and H bosons. The collider operates in four distinct modes, each tailored to produce these fundamental particles during separate time intervals. [1]

The pre-injector complex consists of a linear accelerator chain including a positron source, a damping ring (DR) and a high energy Linac. This part of the FCC facility is foreseen to deliver electron and positron beams at a rate of 200 Hz to the booster ring. In the Booster, 20 GeV particles are accumulated and accelerated to the final collider collision energy. The particles are then transferred to the collider ring in smaller batches, injected in opposite directions and are brought to collision at four interaction points.

This operational strategy, combined with strict requirements of optics and beam dynamics, imposes significant challenges for the design and operation of kicker systems dedicated for injection, extraction and dump. The requirements for the six kicker systems are detailed in Table 1 whilst the individual design proposals are further outlined in the subsequent chapters.

DAMPING RING

Ferrite loaded kicker magnets as well as stripline type arrangements have been considered for the DR application. The latter was found to be feasible and the most suitable to satisfy the fast rise and fall time requirements. Powered by a novel semiconductor driven inductive adder (IA) pulse generator topology [2] the system will achieve the pulse requirements and provide an excellent stability.

A simplified circuit of the DR system design is shown in Fig. 1 and its parameters are summarized in Table 3. The same system design suits both: injection and extraction.

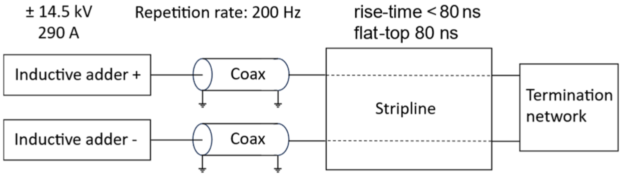

Figure 1: Simplified DR kicker schematic.

The stripline inputs are fed by two 50 Ω coaxial cables whilst the two coaxial outputs are to be terminated with a matched termination network as outlined in [3]. Odd and even modes of the stripline need to be carefully optimized as the impedance matching of both modes is crucial for the flat top pulse quality (better than ±0.5%) and beam impedance matching. Further studies to optimize the output impedance matching are required.

Table 1: FCC-ee Kicker Requirements [4]

	Damping ring	**Booster injection**	**Booster extraction**	**Booster dump**	**Collider injection**	**Collider dump**
Energy [GeV]	1.54-2.36	20	45 – 182.5	45 – 182.5	45 – 182.5	45 – 182.5
Available length [m]	0.5	5.5	10	15	4	15
Total kick angle [mrad]	3	0.09	0.429	0.3	0.072	0.3
Aperture (beam stay clear) (⌀) [mm]	30	30	60	60	60	60
Rise / fall time [ns]	82	25	1000	1000	1000	1000
Flat top length [µs]	0.08	0.08	30 - 304	304	30 - 304	304
Flat top quality [%]	±0.5	±0.5	±0.5	5	±0.5	5
Repetition rate [Hz]	200	200	10	1	10	0.1

Given the relatively high repetition rate of 200 Hz, power losses are a concern. Unfortunately, energy recuperation in the IA is not feasible with the current stripline magnet design. Only a ferrite-loaded magnet, operated in short-circuited mode [2], would enable this functionality.

BOOSTER

The booster comprises three kicker systems for injection, extraction and dump. Whilst for injection a stripline design is proposed, the extraction and dump systems will make use of ferrite loaded kickers. The main parameters for all three booster systems are summarized in Table 2.

Table 2: System Parameters for the Booster (TL – Transmission Line Kicker, LI – Lumped Inductance Magnet)

	Booster inj.	**Booster extr.**	**Booster dump**
Kicker / Systems	1/2	10/2	6/2
Technology	stripline	ferrite TL	ferrite LI
Impedance [Ω]	50	10	10
Current [kA]	0.3	2	1.2
Voltage [kV]	±16	13	12
Element aperture [mm]	30	70	70
Integrated field [mT.m]	4	26.5	30
Effective length [m]	1	1	1
Physical length [m]	1.4	1.4	1.4

Booster Injection Kicker

A stripline design has been selected for the injection kicker system to comply with the required fast rise and fall times of 25 ns. The short flat top duration of 80 ns allows for either an inductive adder or very short PFL lines. The latter is proposed out of cost-performance consideration and needs to be combined with a fast solid-state switch e.g. the recently developed impact ionization mode switching of thyristors [5]. Figure 2 shows a simplified system schematic.

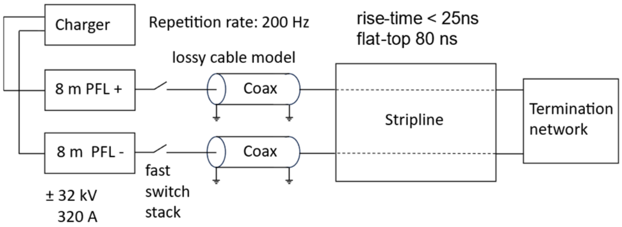

Figure 2: Simplified Booster Injection schematic.

The stripline must be well designed to achieve the field homogeneity requirements. Numerical field simulations were carried out comparing several cross sections, finally resulting in a half-moon shaped electrode design offering the best field homogeneity parameters. Figure 3 shows the proposed geometry and related field homogeneity.

To limit the stripline impact on the circulating beam it is crucial to match, using an appropriate terminating resistor network, the characteristic impedance in both the even and odd modes, while achieving the required field quality of ±0.5% [3]. However, for the same stripline it is impossible to tune both impedances to the same value.

In odd mode, when the kicker is on, the two conductors inside the beam line device have opposite voltages and its characteristic impedance dominates the pulse parameters. Proper impedance matching of the odd mode is therefore important for the quality of the flat-top ripple and rise time.

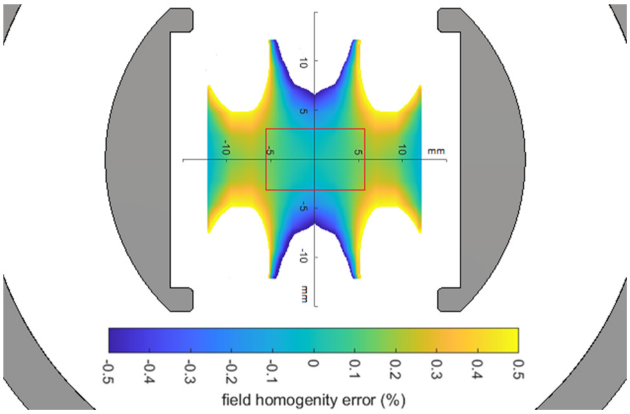

Figure 3: Stripline cross-section and field homogeneity with required good field region in red.

In even mode, when the kicker is off, the impedance represented by the electrodes, seen the circulating bunches passing through their aperture, influences the induced voltages. This mode, especially any unwanted mismatch between even mode stripline impedance and termination, is therefore critical for exciting resonances.

Further impedance matching optimization studies are to be carried out, i.e. considering a termination network on the load side of the stripline as discussed in [3]. This termination method requires also a resistor between the electrodes which needs special attention as an in vacuum design is challenging to implement regarding power losses and vacuum compatibility whilst an outside vacuum design would suffer from parasitic inductance.

Booster Extraction Kicker

For the booster extraction a ferrite loaded transmission line kicker magnet with an impedance of 10 Ω is the preferred choice. The magnet will be connected to the pulse generator using five parallel coaxial cables of CLP50 type. The long flat top duration of up to 304 μs for the extraction and dump makes an inductive adder design inefficient. A conventional Pulse Forming Network (PFN) based generator employing a solid-state switch is therefore proposed. The system topology is outlined in Fig. 4. Stripline topologies cannot be efficiently used for this application since both the power losses and the PFN charging voltage would be high. The power losses for the ferrite loaded system are still significant and estimated to be ~6 kW per magnet module. Figure 4 illustrates the simplified system topology.

A numerical 3D simulation model of the magnet has been developed and analysed. CMD5005 ferrite is used for the magnet yoke and discrete titanium dioxide capacitors for the magnet cell capacitance. The ferrite properties and their variation in the frequency range, measured as described in [6] have been included in the model. The results from the time domain simulation of the integrated magnetic field showed that the booster extraction magnet design fulfils the field requirements.

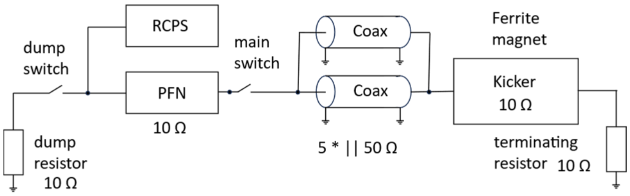

Figure 4: Simplified Booster Extraction topology.

Keeping the beam coupling impedance low is crucial to ensure both magnet integrity and limit its impact on beam quality and operation. For this reason, an LHC injection kicker type beam screen [7] has been studied for the FCC booster and collider application. It provides a well-defined path for the beam image current whilst allowing the fast kicker field still to penetrate without significant attenuation or delays.

Booster Dump Kicker

The booster dump shall safely dispose any beam. Therefore, two systems, one for electrons and one for the counterclockwise circulating positrons, are needed. A robust design using lumped inductance magnets has been developed. The generator choice will depend on the final beam acceptance parameters: if a relatively precise flat top is needed a PFN or Marx topology type generator is required, otherwise a LHC beam dump system type generator [8], featuring a main capacitor discharge stage boosted by droop compensation stages, will be implemented. Regardless of the generator topology it must provide the same deflection independently of the beam energy.

COLLIDER

Collider Injection

Since the required kick angle is much smaller than for the booster extraction, for a given beam energy, a stripline kicker is proposed for the collider injection system. Its pulse length can vary between 30 μs and 304 μs. The latter together with the flat-top quality requirements constrain the generator choice: a robust PFN topology will be needed to provide the maximum pulse length with a ±0.5% flat top tolerance at a 10 Hz repetition rate. The design parameters for the stripline option are summarized in Table 3.

As an alternative to the striplines, ferrite loaded magnets have also been studied. A transmission line kicker magnet design, as proposed for the booster injection, has been preliminarly considered and is expected to work well. However, for the collider injection it would be more advantageous to use the same lumped inductance magnet modules as used for the booster dump system but in combination with a more precise pulse generator. This choice still needs to be further studied as the predicted post pulse ripple, with the present design, would not be compliant with the collider specifications. Filter networks or a sophisticated inductive adder generator with ripple suppression [9] might overcome this issue.

Collider Dump

The collider beam dump will be very similar to the booster dump only requiring adjustments for different location and optics. The same magnet modules and generator topologies will be used. Compared to the booster dump the collider operates at fixed energy hence no beam energy tracking is needed.

For the booster and collider kickers in general the radiation environment might be an issue concerning the specialized coaxial high voltage cables used. Special care must be taken for the location of connection boxes and cable routing therefore further studies are needed.

Table 3: System Parameters for DR and Collider (LI – Lumped Inductance Magnet)

	DR	**Collider injection**	**Collider dump**
Elements / Systems	1/2	2/2	6/2
Technology	stripline	stripline	ferrite LI
Impedance [Ω]	50	50	10
Current [kA]	0.3	0.2	1.2
Voltage [kV]	±14	±15	12
Element aperture [m]	30	30	70
Integrated field [mT.m]	3.8	10.8	30
Effective length [m]	1	3	1
Physical length [m]	1.5	3.6	1.5

CONCLUSION

The still evolving requirements for the FCC-ee complex have been summarized and presented together with a preferred design for each of the six kicker systems. Simulation models for striplines and ferrite loaded magnets, including their generators, have been established to validate the basic feasibility for the given constraints. No showstoppers were found but several challenges identified. An early prototyping of the DR system is recommended to verify the rise and fall time of the inductive adder driven system for the 200 Hz repetition rate as well as to validate the high voltage feedthroughs and stripline terminations. Furthermore, an R&D laboratory system of a generic lumped inductance module for the collider is required to study the ripple suppression in detail. Further work is needed to adapt to changing requirements and to harmonize the kicker subsystems across the FCC machines. For the booster and collider accelerators, protection considerations and requirements need to be fully considered and will likely impact on the system segmentation.

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