CONSIDERATIONS FOR THE INJECTION AND EXTRACTION KICKER SYSTEMS OF A 100 TeV CENTRE-OF-MASS FCC-hh COLLIDER

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Abstract

A 100 TeV centre-of-mass energy frontier proton collider in a new tunnel of ~100 km circumference is a central part of CERN's Future Circular Colliders (FCC) design study. One of the major challenges for such a machine will be the beam injection and extraction. This paper outlines the recent developments on the injection and extraction kicker system concepts. For injection the system requirements and progress on a new inductive adder design will be presented together with first considerations on the injection kicker magnets. The extraction kicker system comprises the extraction kickers itself as well as the beam dilution kickers, both of which will be part of the FCC beam dump system and will have to reliably abort proton beams with stored energies in the range of 8.5 Gigajoule. First concepts for the beam dump kicker magnet and generator as well as for the dilution kicker system are described and its feasibility for an abort gap in the 1 µs range is discussed. The potential implications on the overall machine and other key subsystems are outlined, including requirements on (and from) dilution patterns, interlocking, beam intercepting devices and insertion design.

INJECTION SYSTEM

The injection kicker system into the FCC is mainly dominated by the stored beam energy of the injected beam. For machine protection reasons the maximum batch length is defined to be not longer than 2.25 µs for 3.3 TeV beam. Several injection energies are being reviewed [1] whilst this paper only focuses on the 3.3 TeV beam injection. To achieve, nevertheless, a reasonable filling factor the system rise time has been defined as ≤280 ns with a repetition rate of 115 Hz. All requirements are summarized in Table 1.

Magnet

The required fast rise time suggests the utilisation of transmission line type kicker magnets similar to those used for injection into the LHC. Together with the system impedance, the magnet filling time will define the magnet length and number of units. Preliminary calculations show current values of up to 2.6 kA and voltages of up to 13 kV. The magnet will be an in-vacuum type design, to be equipped with a sophisticated beam screen optimized for beam impedance and fast pulsed fields.

Pulse Generator

The pulse generator for injection of 3.3 TeV beam has to be fast (<100 ns) to allow for a reasonable magnet filling time. For reliability reasons the design has been constrained on solid state switches. The short pulse length of 2.25 µs allows to consider an inductive adder (IA) type generator as a promising option.

Table 1: Injection and Extraction Kicker Requirements.

Parameter	Injection	Extraction
Available length [m]	130	130
Kinetic Energy [TeV]	3.3	3.3-50
Angle [mrad]	0.3	0.13
Pulse length [µs]	2.25	330
Flat top tolerance [%]	±0.5	± ~5%
Field rise time [µs]	0.28	1

The IA consists of a stack of several 1:1 transformers (Fig. 1). Pulse capacitors are discharged through semiconductor (SC) switches into the primary winding. To keep the inductance of the primary circuit as small as possible the primary winding completely encloses the transformer core. The secondary winding passes through the middle of all transformer cores (Fig. 1). The cylindrical design strongly influences the main parameters such as output impedance and pulse propagation time. The number of layers defines the output voltage and the number of parallel branches, on the primary side of the transformer, defines the output current. Major components of the IA are the SC-switches, pulse capacitors, magnetic cores and high voltage freewheeling diodes [2].

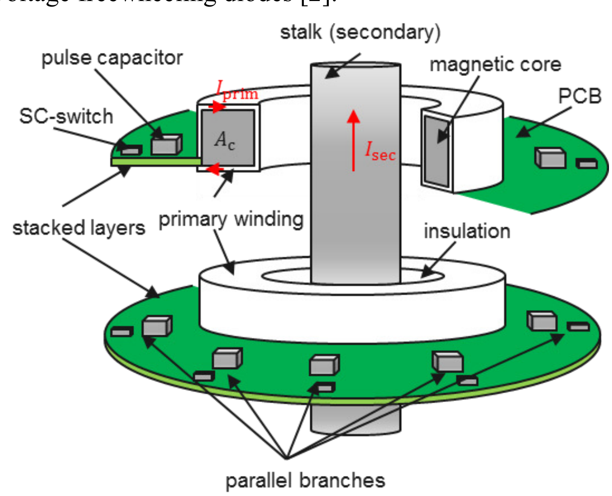

Figure 1: Schematic illustration of two inductive adder layers.

Advantages of the IA compared with other options such as pulse forming line (PFL) or pulse forming network (PFN) and their associated switches are [2]:

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- Moderate requirements for switch technology hence SC-switches can be used: no thyratrons are necessary;
- All primary circuits are referenced to ground: High voltage occurs only at output connectors;
- Redundancy can be built in easily;
- Modular design: Device is scalable, easy to adapt to certain applications.

Due to saturation effects of the magnetic core the maximum pulse length is limited to approximately 3 µs, mainly depending on the voltage per layer and material properties.

- Insulation material

An important aspect of the IA is the insulation material between the primary and secondary transformer winding. Several materials have been analysed: air, oil, water, FC-77 and epoxy. Oil turned out to be the most suitable candidate in terms of required system impedance, dimensions, rise time, costs and practicability. The minimum dimension of the stalk diameter for a 5 Ω impedance and oil as dielectric is 6.2 cm which results in an oil insulation thickness of only 1.3 mm. To ease the production of the insulation gap and to provide compatibility with the CLIC prototype a stalk diameter of 10.4 cm has been chosen resulting in an insulation gap of 2.2 mm.

- Semiconductor switches

Suitable SC-switches for the IA need to have fast rise and fall times, low on-state resistance as well as high voltage and current ratings to reduce the number of layers and parallel branches. Modern SiC MOSFETs are the most promising family of currently available SC-switches. Voltages of up to 1700 V and peak currents of more than 100 A with rise times below 10 ns are feasible. As this “wide band gap” technology is rather new, further development can be expected.

- Pulse capacitors

The pulse capacitors used in the IA must have very low inductance and suitable voltage and current ratings. To guarantee long life times the charging voltage should be derated. For the FCC IA a capacity of 52 µF and peak current values of 110 A are needed. Adding an analogue modulation (1Ω) layer in the stack reduces the capacity requirements down to a value of ~33 µF (or lower). A drawback of the analogue modulation layer is that it reduces the output voltage and hence more layers are needed to compensate this effect [3]. Custom made capacitors for this application are available and need to be tested under appropriate conditions.

- Magnetic cores

Probably the most critical component of the IA, not only from the technical point of view but also in terms of costs, is the magnetic core. A nanocrystalline, tape wound core will be used. For the required pulse parameters a core cross section of $A_c = 25\ cm^2$ is required. The inner diameter is defined by the system impedance, voltage and insulation material. The core height will be kept small to reduce output pulse rise time, and the outer diameter is currently dependent on production constraints. Packing factors in the range of up to 73 % can be reached for the core. Important parameters of the magnetic core are the linear flux density swing, saturation flux density, core losses and magnetizing inductance [4]. To avoid saturation the material saturation flux density needs to be as high as possible (>1 T) and biasing will be necessary to use the entire flux density span (ΔB = 2 T). The core losses should be low and the magnetizing inductance high to reduce the magnetizing current in the primary loop. Samples of cores have been ordered for tests and measurements.

- High Voltage Diodes

The high voltage diodes in the primary circuits of the IA carry the magnetizing current when the SC-switch is turned off. During a possible fault in which one layer is not turning on, the diodes offer a path for the load current and hence need to be fast switching to avoid over voltages.

Prototype Construction and Challenges

Component samples have been ordered for characterization, test and measurements to be done later in 2016 resulting in the final component selection. A prototype will be built in 2017 to prove the feasibility of pulse length, low ripple, rise time and reliability. The design of the IA prototype for the FCC study will be based on the design for the prototype IA for the CLIC DR kicker systems [3]. The components discussed can be tested with existing test equipment. The mechanical design needs to be adapted to realize oil insulation and magnetic core dimensions.

Main challenges will be the realization of the small insulation gap as well as the fast rise time and long flat top. As a further option the development of a radiation hard generator is envisaged.

EXTRACTION KICKER SYSTEM

The extraction kicker system comprises the extraction kickers as well as the beam dilution kickers, both of which will be part of the FCC beam dump system and will have to reliably abort p+ beams with stored energies in the range of up to 8.5 GJ. Whilst different extraction insertions are still being discussed [5] all of them comprise the same basic kicker concepts further outlined in this paper.

Extraction System

First technical considerations on different kicker concepts have been outlined [6] and the most promising solution of a segmented kicker system has been further followed. The advantage of the segmented system is that up to 300 units per beam allow for a kick strength per unit which is not exceeding an one sigma oscillation in a pre-fire failure, reducing significantly the probability of an asynchronous dump event. But more importantly the short magnets also provide a low inductance and hence allow for a shorter system rise time of 1 µs, imposing significantly less beam load onto the protection devices during asynchronous dump failures [7]. In addition the lower current and voltage per unit, in comparison with the existing LHC dump system, results in reasonable generator design values, beneficially influencing the switch selection and system reliability. Table 2 shows a summary of preliminary design parameters for the extraction and dilution systems.

Table 2: FCC-hh Extraction and Dilution Kicker System - Preliminary Design Parameters.

Parameter	Extraction	Dilution (h/v1/v2)
Current [kA]	7.5	9 / 10.8 / 11
Voltage [kV]	10	22 / 20.5 / 19
B [T]	0.25	0.85 / 0.5 / 0.4
Magnet length [mm]	300	0.85 / 0.9 / 0.9
Pole gap [mm]	36	40 / 81 / 104
Inductance [μH]		5 / 4.8 / 4.4
Number of magnets	300	48 / 39/ 48
Rise time [μs]	1	50 kHz

The 300 mm long single-turn lumped inductance magnets will be outside vacuum requiring ceramic vacuum chambers. Each magnet will be powered by its own generator.

Dilution System

The FCC-hh 50 TeV bunch energy density at the dump absorber has been reviewed and requirements for dilution have been formulated [5, 8]. In order to allow for a conventional carbon absorber a sophisticated dilution kicker system is required. Several dilution patterns have been analysed [9] and optimized towards a pattern which is reasonably reproducible by kicker hardware: a spiral will be painted from the outside to the inside, thus requiring a vertical and horizontal kicker system oscillating at the same frequency (~50 kHz) with an amplitude decay from 100% to ~50% within 350 μs. Such a pattern permits a bunch separation of >1.8 mm (for 25 ns beam) and a spiral pitch of >40 mm hence no trace crossing or bunch overlay. The absorber will be in the range of 600 mm radius. Figure 2 shows the energy density deposited in the dump block for a dilution pattern with fixed frequency (30 kHz).

The horizontal dilution kicker system will also be segmented and comprises 48 outside vacuum magnets each with a length of 0.85 m. The segmentation has the advantage that the impact of faulty modules is less significant and, importantly, the smaller unit length inductance allows for a 3 turn coil design which reduces the current to 9 kA at a driving voltage of 22 kV. The vertical system has to cope with the increasing horizontal aperture: hence two vertical magnet types with different apertures have been introduced. Nevertheless, the resulting reduction in magnetic field requires currently 39 magnets of type 1 and 48 of type 2, both types powered with 11 kA and 20 kV. Horizontal and vertical systems would use the same generator design which provides the required current and voltage parameters with a 50 kHz sinus oscillation. The vertical system would hence be triggered 5 μs after the horizontal one, which is acceptable for scheduled dumps (as the horizontal system can be triggered 5 μs before the extraction kickers) but which will be an issue during asynchronous dump events. Here the beam would be painted on the horizontal axis first before the spiralling finally starts after 5 μs. This resulting crossings are a potential issue for the dump material. The implications need to be studied.

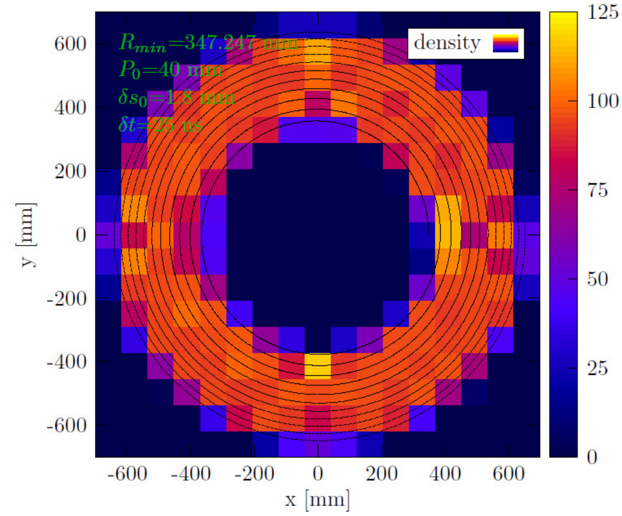

Figure 2: Dilution pattern for fixed frequency generators (30 kHz).

CONCLUSIONS

Concepts for injection and extraction systems for the FCC-hh collider have been developed and outlined in this paper. For both, system requirements have been analysed, system configurations have been developed and first hardware solutions were proposed. The conceptual feasibility has been shown to be within the constraints and input parameters outlined. Further studies are needed to optimize the concept, fully prove the hardware feasibility and consider potential additional constraints such as radiation impact on electronics and system reliability. Although the basic system design exclusively uses modern solid-state generators, the foreseeable future development in this field needs to be anticipated and integrated in the final design study.

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