CONSIDERATIONS FOR THE BEAM DUMP SYSTEM 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 80–100 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 dump system, which for each ring will have to reliably abort proton beams with stored energies in the range of 8 Gigajoule, more than an order of magnitude higher than planned for HL-LHC. The transverse proton beam energy densities are even more extreme, a factor of 100 above that of the presently operating LHC. The requirements for the beam dump subsystems are outlined, and the present technological limitations described. First concepts for the beam dump system are described and the feasibility discussed, highlighting in particular the areas in which major technological progress will be needed. The potential implications on the overall machine and other key subsystems are described, including constraints on filling patterns, interlocking, beam intercepting devices and insertion design.

INTRODUCTION

CERN is leading an international collaboration for the conceptual design of colliders housed in a new tunnel of 80-100 km circumference in the Geneva region. In the frame work of the FCC-hh collider study [1] a major challenge will be the safe disposal of the up to 8 GJ beams. The extraction system must function with extreme reliability during beam presence, from 1st injection up to extraction with top level beam energy, to minimize the risk of severe damage to the machine. The dumping action must be synchronized with a particle free abort gap and the magnetic field of the extraction and dilution elements must closely track the beam energy. Asynchronous emergency dump action, allowed in the LHC, needs to be avoided as far as possible as it would be a major issue for the protection devices. The beam rigidity is more than seven times higher than in the LHC: this, together with machine protection considerations imposes ambitious hardware parameters. In addition the stored beam energy itself presents a serious challenge for the interception and dump devices. An overview of the relevant FCC-hh parameters is given in Table 1. Three different extraction concepts are being studied [2] and are further outlined in this paper together with the main extraction system elements.

Table 1: FCC-hh Parameters [2]

Beam parameter	Unit	Injection	Extraction
Kinetic Energy	TeV	3.3	50
Beta/Gamma		~1/3518	~1/53290
Revolution time	µs	~333	~333
Magnetic rigidity	T·km	11.0	166.8
Emittances (transv.)	µm	2.2	2.2
Stored beam energy	GJ	0.65	8.5

EXTRACTION CONCEPTS

All extraction concepts assume a fast extraction scheme, with one dedicated dump system per beam, which extracts the beam in a single turn towards an external dump block. Therefore fast kickers, strong septa and dilution kickers are needed. Other versions of these designs with special insertion magnet concepts, e.g. quadrupoles which allow for beam passage through the cryostat, are under consideration and would require lower strengths for the kickers and/or septa. The abort gap for all versions is assumed to be 3 µs.

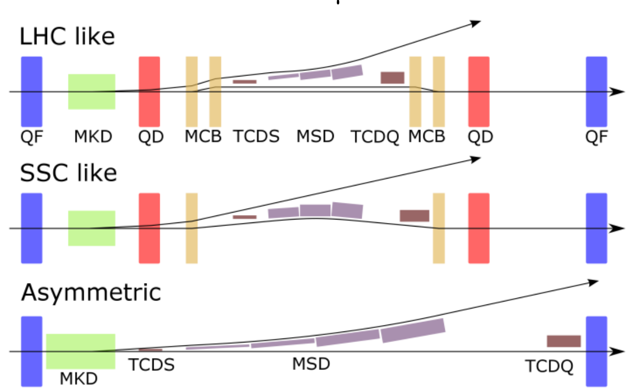

Figure 1: Preliminary insertion concepts.

LHC Scaled / LHC Like Concept

The LHC beam dump system (LBDS) [3] has been reviewed and scaled to the FCC energies as a first approach. This design uses a kicker (MKD, Fig. 1) and septum (MSD) placed around a quadrupole (QD), to enhance the kick. For the first purely scaled system hardware parameters were not advantageous hence in a "LHC like" version the optics were tuned and an extraction bump was introduced at the septum, which requires the use of four 50 T·m dipoles (MCB).

SSC-like Concept

This concept is inspired by the SSC beam dump system design [4], which uses an inverted septum as part of the extraction bump. Such a septum uses the field free region for the extraction channel whilst the good field region creates a constant bump in the circulating beam. This gives a better control of the field seen by the circulating beam, but requires a very stable current and careful septum field design. As in the previous design the kicker and septum are placed around a quadrupole which enhances the extraction. The optics for this design are very similar to those of the LHC scaled design.

Asymmetric Concept

An asymmetric concept is being investigated, aiming to provide enough physical space to accommodate a highly segmented kicker system ensuring that the kick of a single kicker module at extraction energy causes an oscillation that is small enough to fit within the aperture for a single turn (assumed: 1σ oscillation). It requires the β-function (in the bending plane) at the kicker to be reduced in order to limit this oscillation, but the β-function at the septum to be increased for better kick efficiency and to have beam dilution for the protection elements near the septum. For this concept a long central drift of 640 m is chosen.

CONSIDERATIONS ON EXTRACTION SYSTEM ELEMENTS

Studies for a simply scaled LHC extraction system have been made (Table 2, 3), however the resulting required magnetic lengths exceed the available length for both kickers and septa. Hence improvements have been developed for the optics, as already outlined and for the hardware elements.

Conventional Extraction Kicker

A LHC type lumped inductance magnet was studied for performance improvements to serve all presented optics concepts. A reduction of aperture (due to the smaller beam size in the FCC) to 36 mm would bring already an increase in B-field by a factor 1.5 whilst increasing the current would provide another factor 1.3, resulting in twice the field strength compared to the LHC MKD magnet. Such a system is feasible and would fit the given beam line length requirements, but a slightly longer abort gap would be preferred to avoid to challenging switch parameters. This is however in contradiction with machine protection considerations to have a fast rise time and hence limit the amount of swept beam during asynchronous dump failure cases.

Segmented Kicker System

First considerations show that an asynchronous beam abort will be a design challenge for the protection elements either material wise or to fit into the physical space limitations together with septa and kickers. In order to avoid these issues a concept was developed to generally minimize the risk of asynchronous beam abort. Already for the LHC the risk of pre-firing was limited by excluding the use of thyratron switches: nevertheless, in order to mitigate the occasionally assumed asynchronous dumps, a sophisticated protection system (TCDS, TCDQ) was installed [3, 5].

Table 2: FCC-hh Kicker Parameters

Parameter	LHC scaled	LHC like	SSC like	Asym.
B.dl [T.m]	46	22	25	25
Available length [m]	100	100	100	125
Magnets	108	25	28	290
Magnetic length [m]	153	37	42	87
B-field [T]	0.3	0.6	0.6	0.3
Aperture (v) [mm]	56	36	36	36

A segmented FCC kicker system will consist of a considerably increased number of magnet modules so that an individual module only provides a max. kick which does not introduce an oscillation exceeding 1σ if seen by the circulating beam. Thus two or more simultaneous erratics are required to result in an asynchronous dump: the remaining low probability for asynchronous beam dumps might be low enough to allow for sacrificial protection devices and will have to be studied in more detail. A max. acceptable circulating beam oscillation of one σ has been assumed and together with a β-function of 150 m it allows for a max. kick angle of 0.52 µrad per module hence requiring around 290 modules to provide the full kick. This architecture also brings the current down to a more comfortable level of 8 kA for a single turn coil compared to 18 kA for LHC.

Septa

The safe extraction of the FCC beam poses challenging requirements for the dump septa. As a first iteration the current LHC topology has been scaled to the new parameters. Table 3 gives an indication of the preliminary figures for the different concepts being studied.

Table 3: FCC-hh Septa Parameters

Parameter	LHC scaled	LHC like	SSC like	Asym.
B.dl [T.m]	400	284	334	317
Available length [m]	200	200	300	344
Magnetic length [m]	442	<200	<300	<344
B-field [T]	1	1.4	1.2	1

Using the present LHC technology with normal conducting Lambertson septa would require a large number of 108 units yielding high cost and reducing

ISBN 978-3-95450-168-7

reliability [6]. Furthermore the DC power consumption of the scaled LHC system is estimated to be in the vicinity of 3 MW per beam. Optimisations with respect to construction and operation cost are being investigated. Hence a more compact high field system could reduce the complexity and increase the overall reliability and will provide more flexibility in the design of the extraction insertion in view of the total beam energy of the FCC. Several septa topologies will be examined which include high field Lambertson designs with normal or superconducting coils. Massless geometries with no active parts in the beam path are being considered as advantageous when dealing with mis-steered or swept beams. Lastly, the study will focus on superconducting 4 or 6 T topologies [7] as a standalone solution or as a downstream complement to a normal conducting septum.

Protection Devices and Dump

The FCC beams pose a severe challenge for the robustness of protection devices. Compared to the LHC, the energy density in absorber materials increases not only due to the higher proton energy, but also due the smaller angular opening of secondary particle showers. Depending on the β–function at the absorber location, already a single 50 TeV bunch can induce damage in typical absorber materials presently used at the LHC (e.g. Graphite or carbon-reinforced carbon). For accident scenarios like an asynchronous beam dump, it might be necessary to employ sacrificial absorbers.

In order to safely absorb 8.5 GJ beams in a LHC-like dump core, beams need to be sufficiently diluted across the dump cross section. A first estimate of the minimum sweep path length can be derived from the required lateral separation between neighbouring bunches such that the peak temperature is at an acceptable value (~1500°C).

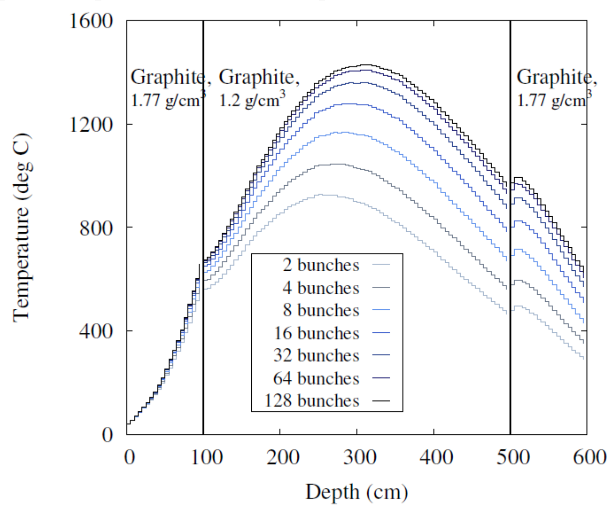

Figure 2: Longitudinal peak temperature profile induced by 50 TeV proton bunches (1×10^{11}) in a LHC-like dump core. Bunches are assumed to have a size of 400 µm (=1σ) and a transverse separation of 1.6 mm.

Figure 2 illustrates the longitudinal temperature profile of 50 TeV bunches in a LHC-like dump made of different Graphite sections. Assuming a bunch intensity of 1×10^{11} p^+ and a beam size of 400 µm, a minimum separation of 1.6–1.8 mm is needed to fulfil the above temperature criterion. For 10600 bunches, this would imply a minimum sweep path length of 20–24 m (considering gaps in the filling scheme). The results shown in Fig. 2 only reflect the contribution of adjacent bunches (like in a linear sweep), but neglect the possible contribution of neighbouring spirals in the sweep pattern. More detailed energy deposition and thermo-mechanical studies are needed to determine temperatures and stresses.

Beam Dilution

An Archimedean spiral has been considered to paint the beam on a ~20 m long path with constant velocity (Fig.3). The minimum distance between the spiral arms will need to be studied in detail with final beam parameters to ensure that material limits are not exceeded. The basic oscillation frequency (increasing amplitude and decreasing frequency) will be around 35 kHz. The exact number of horizontal and vertical dilution kicker will be optimized considering the available dump line length. Additional standalone quadrupoles between and after the horizontal and vertical dilution kickers to enhance the kick will be investigated.

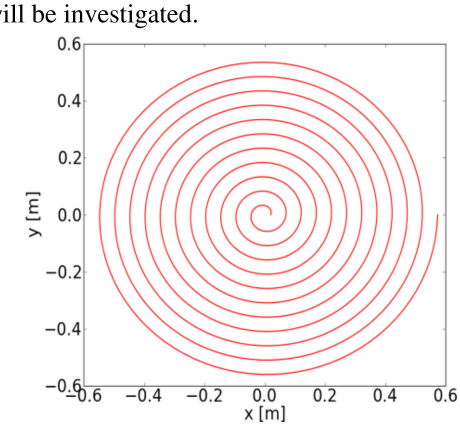

Figure 3: Preliminary dilution pattern.

CONCLUSION

First considerations of the FCC-hh beam dump system have been made: different optics concepts are being studied and preliminary hardware options are elaborated to evaluate their feasibility. A purely scaled LHC version can already be excluded but an improved LHC like concept with tuned optics, additional bumpers and improved magnet parameters is still under investigation. A different SSC-like approach is also being further investigated. The asymmetric optics concept which allows for a segmented kicker design seems very attractive and would be preferred from a machine protection point of view. The concept of a very high reliability extraction system with sacrificial protection devices needs detailed studies and will be further followed. The dump block itself will need to be larger in diameter compared to the present LHC one to allow painting of the beam with sufficient bunch separation. A challenging part will be the integration of the beam dilution kickers.

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ISBN 978-3-95450-168-7