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OPTIMIZATION OF THE FCC-hh BEAM EXTRACTION SYSTEM REGARDING FAILURE AVOIDANCE AND MITIGATION

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Abstract

A core part of the Future Circular Collider (FCC) study is a high energy hadron-hadron collider with a circumference of nearly 100 km and a center of mass beam energy of 100 TeV. The energy stored in one beam at top energy is 8.3 GJ, more than 20 times that of the LHC beams. Due to the large damage potential of the FCC-hh beam, the design of the beam extraction system is dominated by machine protection considerations and the requirement of avoiding any material damage in case of an asynchronous beam dump. Erratic operation of one or more extraction kickers is a main contributor to asynchronous beam dumps. The presented study shows ways to reduce the probability and mitigate the impact of erratic kicker switching. Key proposals to achieve this include layout considerations, different hardware options and alternative reaction strategies in case of erratic extraction kicker occurrence. Based on these concepts, different solutions are evaluated and an optimized design for the FCC-hh extraction system is proposed.

REQUIREMENTS AND LAYOUT

The beam extraction system is located in a dedicated insertion with an available length of 2.8 km for extracting both beams [1, 2].

The layout is based on novel septa (MSD) technologies, i.e. the Superconducting Shield (SuShi) and Truncated Cosine Theta septum, which enable higher fields than a Lambertson septum with the same apparent septum blade thickness (25 mm) and a consequent reduction of the MSD system length from ~180 to 70 m [3, 4]. In contrast to the double plane extraction using a Lambertson, the Sushi and Truncated Cos-Theta septa require a single plane extraction with a vertically deflecting extraction kicker system (MKD), as illustrated in Fig. 1. A high frequency dilution kicker system (MKB) creates the required sweep pattern for the beam to be absorbed in a graphite beam dump (TDE) at the end of the 2.5 km dump line. A focusing triplet in the dumpline is used to reduce the required aperture at the vertical dilution system and hence relax the kicker hardware parameters.

The design of the extraction and especially the MKD system [5, 6] is mainly driven by machine protection, with the main priority of always safely extracting the beam. Additional constraints are added by the requirement of both surviving and avoiding fast and ultrafast failures (failures causing a trajectory change of approximately 10 σ in <3 µs and thus requiring passive protection). This primarily concerns the asynchronous beam dump, i.e. a beam abort asynchronous to the abort gap, resulting in ~40 bunches being swept across the quadrupole protection (TCDQ) and septum protection absorber (TCDS) during the MKD rise time.

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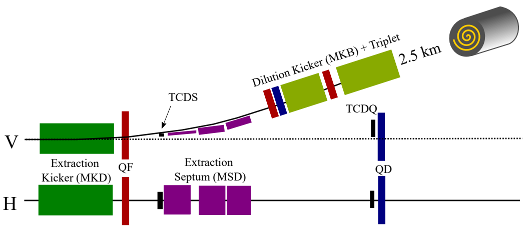

Figure 1: Schematic layout of the extraction system, illustrating both planes. Dimensions are not to scale.

In addition to the above mentioned requirements, the following considerations impact the chosen MKD baseline:

1) To increase availability, the entire system layout is designed to enable operation with a reduced number of MKD and MKB. Septa apertures, dilution pattern and MKD rise time have been designed such that a kick strength reduction of at least 10% can be accepted for nominal operation. For the baseline, which foresees a segmentation of 150 magnets, this implies that failure of 15 magnets is accepted and repair of faulty modules is hence only required during the subsequent scheduled technical stop. However, the trajectory acceptance of the triplet in the dumpline and the resulting distortion of the sweep pattern has still to be assessed.

Additionally, the design aims at minimizing 2) the probability and 3) the impact of a single failing MKD, which is intrinsic to a highly segmented system. Latter allows to avoid dumping asynchronously in case of a pre-firing MKD by not immediately re-triggering the remaining MKD but instead leaving the miskicked beam in the collider to dump synchronously with the next abort gap ('1.5 σ-oscillation').

The baseline design consists of 150 MKD and 85 MKB, which is a result of balancing the above listed advantages of a highly segmented system with the increasing complexity due to the higher number of modules. The corresponding hardware parameters are listed in Table 1. Alternative system layouts are outlined in Table 2 and will be referred to for comparison to the baseline (BL). The alternatives include an even higher segmented system with 300 MKD (A1) as well as a system with 30 MKD but a higher complexity of a single generator, similar to LHC (A2). Option A3 describes a system with 30 modules but relaxed hardware parameters due to an increased rise time, which would however require an alternative protection scheme and optics layout using sacrificial absorbers. As will be described below, layouts A2 and A3 are based on alternative switch architectures.

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Table 1: Approximate MKD and MKB Parameters for the Considered Lumped Inductance Magnets and Generators.

Parameters	**Unit**	**MKD**	**MKBH**	**MKBV**
Deflection	mrad	0.045	0.13	0.25
Integrated Field	Tm	7.5	22	42
System length	m	120	57	110
Magnetic length	m	90	43.5	83.5
Modules	#	150	29	56
Module length	m	0.6	1.5	1.5
Rise time	µs	1	5	5
Capacitor voltage	kV	5	12	19
Peak current	kA	4	12	16
Flattop length	µs	$\geqslant 326$	-	-
Flattop stability	%	± 5	± 5	± 5
GFR[1] h/v (∅)	mm	45/33	24/24	34/40
Aper. h/v (∅)	mm	61/49	30/30	40/46
Inductance[2]	µH	0.75[3]	2.3	2.6
Frequency	kHz	-	50	50
$\frac{\Delta\nu}{\nu}$ mismatch	-	-	±0.2%	±0.2%

Table 2: Comparison of Different MKD System Layouts (BL: Baseline, A1-A3: Alternative Layouts).

	Unit	**BL: 150**	**A1: 300**	**A2: 30**	**A3: 30**
# Miss. MKD	#	15	30	3	3
Rise time	µs	1	1	1	5
Voltage	kV	~5	~2.6	~20	~6
Asynch.: absorb.	-	OK	OK	OK	sacrif.
Asynch.: TDE	-	OK	OK	OK	OK
Altern. switch	-	no	no	n/y	yes
‘1.5 σ-osc.’ OK	-	yes	yes	n/y	yes

ERRATIC EXTRACTION KICKER AND ASYNCHRONOUS BEAM DUMP

Load on Absorber and Beam Dump

The MKD rise time is restricted by the requirement for the TCDQ and TCDS to survive the impact of the increased energy deposition in case of an asynchronous dump, independent of the chosen MKD segmentation. A minimum bunch separation of at least ~2 mm at the TCDS and the TCDQ is required assuming a beam size of $\sqrt{\beta_x\beta_y} > 1$ km [6], which defines the MKD rise time to be 1 µs (0 − 100%). FLUKA [7, 8] simulations evaluating the load on the protection absorber in case of an asynchronous dump result in a maximum temperature of 1400°C for the TCDS and 1000°C for the TCDQ, which is acceptable for an assumed damage limit of the absorbers (>1800°C) [9]. This rise time limit is respected for the BL, A1 and A2. As already mentioned, option A3 is based on an increased $\tau = 5$µs. Sacrificial absorbers are required as the energy deposition exceeds the damage limit in this case.

[1] GFR: Good field region
[2] incl. a correction factor ($\xi = 1.2$) for stray and cable inductance
[3] incl. the impact of ~2 µm Ti beam screen

Based on the most recent sweep pattern a survival of the TDE can be guaranteed for all MKD segmentation proposals [10]. However, the increased rise time in case of A3 reduces the peak load to values close to the nominal case and provides more flexibility of reducing the radius of the sweep pattern and thus the size of the dump core.

Avoiding Asynchronous Dumps, ‘1.5σ - Oscillation’ and Multiple Abort Gaps

The main reason for asynchronous beam aborts in LHC is a pre-firing MKD. Relaxing the hardware requirements for a newly designed system helps reducing the probability of this failure. The required capacitor voltage in case of the proposed baseline with 150 modules is ~5 kV. Option A3 with 30 modules would require ~20 kV, which is comparable to 27 kV required for the MKD generators of LHC. Advancements in switch technology would be of advantage to enable an implementation of the baseline based on a single IGBT (Insulated-gate bipolar transistor) switch.

Independent of the effort to reduce the probability of erratic MKD triggering, the number of asynchronous dumps can be reduced by the concept of the above mentioned ‘1.5 σ-osc.’. A high segmentation reduces the impact of one erratic MKD. Figure 2 illustrates an analytical estimation of the number of protons impacting the primary collimator (TCP, 7.2 σ settings, $\Delta\mu \approx 270°$) for a single erratic module as a function of the system segmentation. A Gaussian transverse beam distribution is assumed. For segmentations above ~65 modules, the losses are lower in case of the synchronous dump with the preceding oscillation than for the immediate asynchronous dump. A threshold of $1.5 - 2.5 \cdot 10^{11}$ p+ impacting the TDI is chosen as a preliminary damage limit. At the same time, tracking studies for the losses in the collimation system show, that for a miskick of up to 2.7σ acceptable loss levels are obtained ($< 2 \cdot 10^{11}$p+) [11], which agrees with the analytical approximation.

Pre-fire of 1 out of 150 modules results in a 1.45σ-osc., which leaves margin for additional offsets. Beta-beating of 20% increases the oscillation to 1.6σ. Additional effects such as beam loading in case of an off-centre passage through the crab cavities (CC) have to be studied in more detail (offset of $\Delta x \approx 1$ mm in the CC in case of worst case phase advance). First estimations of contributions due to beam-beam effects result in negligible additional contributions: Head-on effects add a deflection of 0.05σ, a similar contribution for long range beam-beam effects is expected.

Hence, restricting the segmentation to 150 leaves sufficient margin for additional errors, with the potential for a future reduction to ~100 modules. A layout with 300 MKD (A1) is identified to be over designed concerning the impact of a single erratic (0.75 σ-osc.). However, the positive impact on availability due to the increased redundancy should be evaluated. A further interesting aspect of A1 for beyond-baseline studies is avoiding also the synchronous beam abort in case of an erratic MKD and instead damping the introduced oscillation in order to continue operation.

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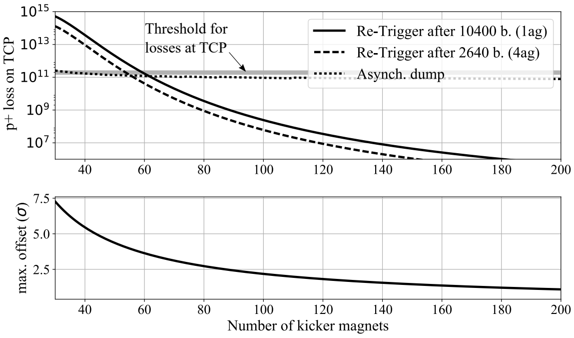

Figure 2: Top: Losses at TCP for different abort strategies for a single erratic MKD. Bottom: Maximum miskick.

An option to further decrease the impact of the '1.5 σ-osc.' is to consider multiple abort gaps and thus enable a faster synchronous beam abort. With the specified FCC-hh filling factor of 80% (10400 bunches) 4 abort gaps with a length of 1.5 µs can be accommodated (130 batches with 80 bunches, injection gap of 0.43 µs and two batches for pilots).

Alternative MKD Layouts and Trigger Strategies

One alternative system layout is based on alternative MKD switch topologies in order to suppress erratic triggering of solid state switch stacks. An architecture based on two switches, located either in series or in a crowbar architecture is used to inhibit the current through the magnet in case of an erratic switch, as described in more detail in [12]. This enables the concept of the '1.5 σ-osc.' also for segmentations below 70 modules and hence motivates options A2 and A3. However, as described in [12], a high dV/dt can be problematic for mitigation of the erratic by the second switch. Option A3 thus reduces the required capacitor voltage by increasing the rise time to 5 µs, as mentioned above. This concept becomes interesting if the probability for other causes of asynchronous dumps than erratic MKD can be proven to be minimized. However, such a system design features reduced redundancy (3 missing MKD accepted) and repair might be required before the next technical stop. Furthermore additional failure modes contribute to required maintenance, due to the necessity for nominal operation of both switches. Thus, the impact on reliability of such a system needs to be evaluated in detail.

An additional idea, which however has not been studied in detail yet, is to install a kicker with inverted field downstream of the MKD system. This 'anti-MKD' is triggered in case of an erratic MKD to oppose the miskick.

TRIGGER AND RE-TRIGGER SYSTEM

First assessments of the requirements for the trigger and re-trigger system indicate fundamental differences between the LHC and FCC-hh trigger distribution systems.

Avoidance of the asynchronous dump in case of a single pre-firing MKD implies the necessity for a differentiation between single and multi erratics by the re-trigger system. Whereas in case of a single pre-firing MKD a synchronous re-triggering with the next abort gap is foreseen, immediate asynchronous re-triggering is required in case of a multi-erratics (i.e. due to electromagnetic coupling or faults of the trigger system).

In addition, the maximum allowed re-trigger time τ_{RT} for different percentages of pre-firing MKD has been estimated and visualized in Fig. 3. For first assessments τ_{RT} is defined as the average time interval from the occurrence of an erratic until triggering of all remaining MKD. The estimation is based on rough approximations for the critical local impact on the protection absorber (10 bunches within 7 σ) and collimation section (4 bunches impacting the primary collimator). If a simultaneous trigger of 3-10% of the MKD (e.g. due to a spurious trigger fanout) cannot be excluded at hardware level, $\tau_{RT} < 0.4$ µs is necessary to guarantee survival of the betatron collimation system. If a simultaneous trigger of 10-67% cannot be excluded, $\tau_{RT} < 0.6$-1 µs needs to be fulfilled for survival of TCDS and TCDQ. Detailed studies based on refined damage limits of the protection absorbers should be conducted.

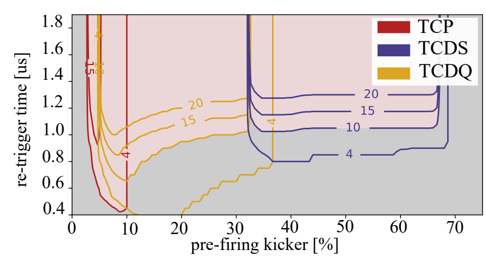

Figure 3: Number of bunches impacting in a critical transverse interval at the TCP, TCDS and TCDQ, depending on the relative number of pre-firing MKD and re-trigger time. Red: not acceptable; grey: acceptable.

CONCLUSION

Failure scenarios of the FCC-hh extraction system have been identified and assessed regarding probability minimization and failure mitigation. The kicker systems are chosen to be highly segmented in order to increase availability. The high segmentation relaxes the hardware parameters, simplifies the generator topology and hence reduces the failure probability of a single module.

It is proposed to avoid asynchronous dumps by not re-triggering in case of an erratic MKD but to leave the miskicked beam for one additional turn in the collider and dump synchronousely with the next abort gap. The impact of this oscillation has been evaluated and defines the lower limit of the final MKD segmentation. For the chosen baseline, the losses in the collider due to this oscillation are lower than in case of the asynchronous beam dump and can be further reduced by considering multiple abort gaps.

The high MKD and MKB segmentation is further motivated by the demand to enable continued operation with a reduced kick strength in case of a faulty module. A repair of the faulty system is only foreseen for the subsequent scheduled technical stop.

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