# BEAM RELATED MACHINE PROTECTION OF THE FUTURE CIRCULAR COLLIDER

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*Abstract*

In the Future Circular Collider (FCC) study, each nominal proton beam at top particle energy of 50 TeV has an energy of 8500 MJ, which is more than 20 times the energy of today's Large Hadron Collider (LHC) beam. Machine protection of such a high-energy and high-energy density accelerator becomes very challenging. In this paper, preliminary considerations of beam related machine protection issues of the FCC will be reported. Based on the current optics design, a few major critical equipment failures that could potentially lead to very fast (within a few turns) beam losses have been studied. The serious failure scenarios that have been considered, typically occurring at locations with high beta functions, include powering failures of normal conducting magnets, quenches of superconducting magnets as well as critical RF failures. Some fundamental questions related to the beam interlock system, e.g., the need for additional particle free abort gaps to shorten the synchronization time before executing a beam dump, will be discussed.

## INTRODUCTION

In order to achieve the integrated luminosity goal, machine protection systems of high energy colliders are designed to protect the accelerator equipment, to protect the beam, as well as to provide evidence to understand and solve failures [1, 2]. The first priority is to protect equipment from damage, followed by the second priority to protect superconducting magnets from quenching. Machine protection of the Future Circular Collider (FCC) [3, 4], especially the circular proton-proton collider (FCC-hh) becomes extremely challenging due to unprecedented energies stored in the magnets and circulating beams. For example, each nominal FCC-hh beam (10600 bunches with bunch intensities of $1.0\times10^{11}$) at top proton energy of 50 TeV has a stored energy of about 8500 MJ, which is more than 20 times the beam energy of today's Large Hadron Collider (LHC). The two FCC-hh beams can melt 20 tons of copper. Any uncontrolled release of the beam energy could cause serious damage to equipment. The tentative layout of the FCC-hh leads to a circumference of 97.75 km that is 11/3 times the size of the LHC. Superconducting dipoles providing up to 16 T magnetic field are needed to deflect the beams accordingly. For superconducting magnets in the FCC-hh, the quench limit in units of protons lost per unit length per second is as low as $0.5\times10^6$ p m$^{-1}$ s$^{-1}$ at 50 TeV [5], i.e. 15 times lower than for the LHC. It indicates that quenches could occur in case of fast losses of $10^{-10}$-$10^{-9}$ of the nominal number of protons in a FCC-hh beam at 50 TeV. Considering proton loss rates at the minimum allowed beam lifetime of $\tau_b$ = 0.2 h, local cleaning inefficiency of collimators in a cold magnet should be lower than the very challenging level of $\leq 3.4\times10^{-7}$ m$^{-1}$. Safe operation of such high-energy colliders highly relies on robust collimation systems.

In this paper, preliminary considerations of beam related machine protection issues of the FCC-hh will be reported. Based on beam dynamics analysis, failure mode studies have been performed to answer the critical question: what equipment failures may influence the beam and lead to very fast beam losses.

## EXECUTION OF BEAM DUMP

In machine protection strategies, collimators are responsible to clean the beam halo via both momentum collimation and betatron collimation by limiting the aperture during routine operation such that beam induced quenches of the superconducting magnets can be avoided to the maximum extent. Dedicated beam absorbers and collimators provide passive protection against abnormal beam losses that may arise extremely fast during e.g. injection or extraction of beams. Fast and reliable instrumentation and beam monitoring systems actively detect element failures and abnormal beam behaviours (for example, beam loss rate) and may trigger a beam dump request before damage thresholds are reached. Beam interlock systems provide highly reliable transmission of the dump request from the monitoring systems to a beam dumping system. The beam dumping system waits for a particle free abort gap for switching on the extraction kicker magnets (i.e., synchronous beam dump), extracts the beam from the ring in a single turn, dilutes the energy density, and disposes the beam onto a beam dump block that is designed to withstand the impact of the full beam.

Figure 1 (based on [6]) shows the time needed for a complete beam dump after a fault occurs. For both the LHC and FCC, a time up to 3 beam revolutions is needed to dump the beam completely and synchronously after failure detection, which corresponds to 1 ms in the case of the FCC. It is important to note that the response time will depend on how many particle free abort gaps and beam dumping systems are foreseen along the ring. Primary analysis shows that a second abort gap may reduce the response time by 0.5 turn, while a second beam dumping system may also save about 0.5 turn's time. Around one turn's time could be saved with two abort gaps and two dumping systems, which are both evenly distributed.

## TIME CONSTANT FOR BEAM LOSS

Steady losses of a small fraction of the beam is unavoidable even under normal operation conditions due to

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ISBN 978-3-95450-182-3

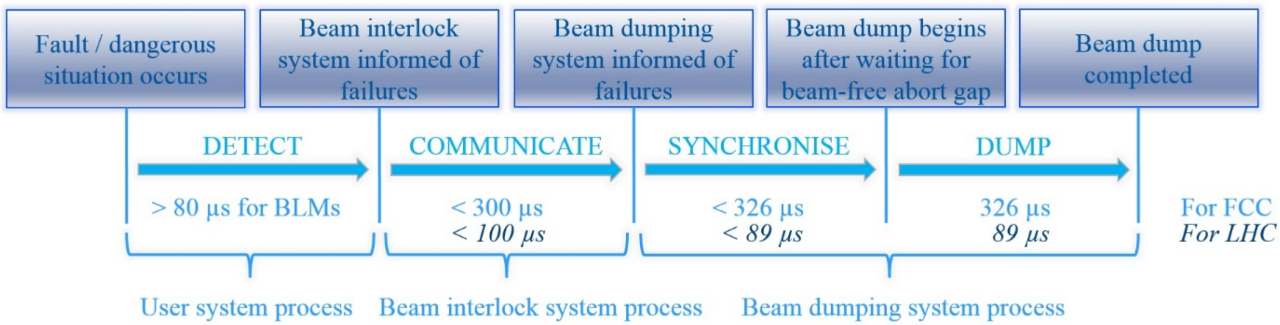


Figure 1: Execution process of a beam dump after failure detection.

Table 1: Beam Losses and Protection Strategies for Different Operation and Failure Scenarios

| Beam Lifetime | Beam Power into Environment | | Scenario | Strategy & Remark |
|---|---|---|---|---|
| | LHC | FCC | | |
| 100 h | 1 kW | 23 kW | Optimum operating conditions | (Possible) upgrade of the collimation system after some years of operating experience |
| 10 h | 10 kW | 236 kW | Acceptable operating conditions (expected during early operation) | Operation acceptable, collimators must absorb large fraction of beam energy |
| 12 min | 500 kW | 11806 KW | Particular operating conditions (during change of optics, tuning, collimator aperture setting, etc) | Operation only possible for short time (~10 seconds), collimators must be very efficient |
| 1 s | 362 MW | 8500 MW | Fast beam loss (standard equipment failures) | Detection of failure, beam must be dumped rapidly |
| A few ms (multi-turns) | ~100 GW | ~ TW | Very fast beam loss (fast equipment failures, e.g., magnet powering failures or quenches) | Detection of failure or beam losses, beam dump as fast as possible |
| 1 turn | 4 TW | 26 TW | Single-passage beam loss (failures at injection or during beam dump, potential damage of equipment) | Beam dump not possible, passive protection relies on collimators, absorbers (sacrificial materials) |

imperfections of the machine, proton-proton collisions and beam-gas collisions, which together result in a beam lifetime of several tens of hours. Accidental losses are related to equipment or operation failures and may reduce the beam lifetime to seconds. Beam losses and protection strategies for different operation and failure scenarios are classified in Table 1 (based on [7]). For comparison, the case of the LHC is listed as well. In the case of ultra-fast losses where the beam lifetime is 1 turn or less, only passive protection provided by dedicated collimators and absorbers is possible. As mentioned previously, it is expected to take up to 1 ms until the full beam is extracted after a failure is detected. Therefore, failure scenario that could cause a beam lifetime of a few ms, i.e., a very fast beam loss, is of great concern. Such very fast losses can be caused by magnet failures, RF failures of crab cavities, beam instabilities, beam pipe obstructions due to movable equipment like vacuum valves, unidentified falling objects (UFOs) and so on.

## VERY FAST FAILURE MODES

The failure scenarios considered first are magnet failures, which are likely to occur during operation of the FCC-hh, since more than 5000 main dipoles and quadrupoles will be installed, in addition to a number of warm magnets in collimator insertions, transverse dampers, orbit correctors and so on.

Powering failures (power supply trip and the subsequent disappearing voltage) of magnets lead to an exponential field decay and hence a field error $\Delta B_{\mathrm{error}}(t)$:

$$\Delta B_{\mathrm{error}}(t) = B_0\left(1 - e^{-\frac{t}{\tau}}\right), \qquad (1)$$

where $B_0$ is the nominal magnetic field, $t$ is time after the failure, $\tau$ is the natural time constant of the field decay, determined by the inductance $L$ and resistance $R$, $\tau = L/R$. $\tau$ is typically of the order of seconds for normal conducting magnets, while it is much longer (up to hours) for superconducting magnets. A quench of a superconducting magnet results in a Gaussian field decay:

$$\Delta B_{error}(t) = B_0\left(1 - e^{-\frac{t^2}{2\sigma_t^2}}\right). \qquad (2)$$

A typical time constant $\sigma_t$ for a quench is >100 ms [8].



ISBN 978-3-95450-182-3

Table 2: Studied Failure Scenarios That Could Potentially Lead to Very Fast Beam Losses at FCC-hh

| Magnet Name | Failure Scenario | $l$ | $B_0$ | $\alpha_0$ or $k$ | $\beta$ | $\tau$ or $\sigma_t$ | Comment |
|---|---|---|---|---|---|---|---|
| Separation dipole 'D1' in IRA / IRG | Powering failure of all the 4 MBXA magnets | 12.5 m | 4.27 T | 0.32 mrad | 25 km (left) 61 km (right) | > 33 s | Less critical |
| Separation dipole 'D1' in IRA / IRG | Quench of 1 magnet | 12.5 m | 4.27 T | 0.32 mrad | 61 km (right) | > 100 ms | Need to be careful |
| Low-$\beta$ triplet quadrupoles | Quench of 1 magnet (MQXC.3RA) | 30.8 m | 86 T/m | $5.1\times10^{-4}$ m$^{-2}$ | 77 km | > 139 ms | Need to be careful |
| Main dipole | Quench of 1 magnet | 14.3 m | 15.92 T | 1.366 mrad | 335 m (max.) | > 55 ms | Less critical |
| Main quadrupole | Quench of 1 magnet | 6.3 m | 357 T/m | $2.1\times10^{-3}$ m$^{-2}$ | 350 m (max.) | > 8.6 ms | Less critical |
| Warm dipole in collimation insertion | Powering failure of MBW.A6R3.B1 | 9.1 m | 1.45 T | 0.079 mrad | 718 m | > 270 ms | Need to be careful |
| Warm quadrupole in collimation insertion | Powering failure of MQWA.D4R3.B1 | 8.3 m | 29 T/m | $1.7\times10^{-4}$ m$^{-2}$ | 1068 m | > 23 ms | Less critical |

For a dipole magnet, the field error results in closed orbit distortion (in maximum) [9]:

$$\Delta x = \frac{\sqrt{\beta_{\mathrm{magnet}} \cdot \beta_{\mathrm{test}}}}{2\sin(\pi Q_x)} \cdot \left(\alpha_0 \cdot \frac{\Delta B_{\mathrm{error}}}{B_0}\right), \quad (3)$$

where $\beta_{\mathrm{magnet}}$ and $\beta_{\mathrm{test}}$ are the beta functions at the location of the magnet and the location of the observation point, respectively. The horizontal betatron tune $Q_x$ is 111.31 and $\alpha_0 = \frac{B_0 \cdot l \cdot c \cdot e}{E}$ is the nominal deflection angle in rad ($l$ is the length of the magnet, $E$ the beam energy, $c$ light speed in vacuum and $e$ elementary charge). Error in deflection angle is $\alpha_{\mathrm{error}} = \alpha_0 \cdot \frac{\Delta B_{\mathrm{error}}}{B_0}$. It can be seen that orbit distortion is serious if the failing magnet is located at a position where the beta function is high or the magnet has fast field decay. For a quadrupole magnet, the field error results in a maximum tune change of [10]:

$$\Delta Q = \frac{\beta_{magnet} \cdot l \cdot \Delta k}{4\pi}, \quad (4)$$

where $\Delta k$ is the change of the normalized quadrupole gradient, $k[\mathrm{m}^{-2}] \approx 0.3 \frac{\partial B_y}{\partial x}[\mathrm{T/m}]/E[\mathrm{GeV}]$. It also leads to a $\beta$-beat of $\frac{\Delta\beta}{\beta} \leq \frac{1}{2\sin(2\pi Q)} \cdot \frac{l \cdot \Delta k}{4\pi}$ and a dipole kick $\alpha_{error} = l \cdot \Delta k \cdot \Delta x_{off}$ if there is initially an orbit offset $\Delta x_{\mathrm{off}}$.

Collimator jaw positions, expressed in the transverse beam size $\sigma$, are adjusted typically between 5 $\sigma$ and 9 $\sigma$ for efficient beam cleaning. It is reasonable to say that a beam displacement of up to 1.5 $\sigma$ during 2 ms is reluctantly acceptable. If the beam displacement is faster, the damage limit of collimators might be exceeded before the beam is dumped successfully. This limit defines the minimum time constant of the field decay for a dipole kick. For quadrupoles, the limitation is estimated by allowing a tune change of 0.01 or a $\beta$-beat of 20% within 2 ms [10].

Various magnet failures have been analyzed according to the existing beam optics design of the FCC-hh, as listed in Table 2. This list, which will be completed, shows that the critical failures are quenches of superconducting magnets having very high beta functions and powering failures of warm magnets that have fast field decay. Consequences of combined magnet failure, e.g., separation dipoles in both interaction regions IRA and IRG failing simultaneously, could of course be much more severe depending on the phase advances between the elements. Such combined failure modes have rather low probability to occur, so the risk is low. Other failures that could induce very fast losses, including abnormal beam deflection by transverse dampers or orbit correctors, wrong beam rotation in the crab cavities and many others, will be studied further in the near future as the optics design becomes more stable and mature.

## SUMMARY AND FUTURE WORKS

Preliminary considerations of beam related machine protection of the FCC-hh have been reported. The most critical equipment (magnet) failures that could potentially lead to very fast (within a few turns) beam losses have been described. Further efforts are being made to complete this list. Such studies may provide inputs for the powering design of magnets. In addition to the response time of the machine protection system, robustness and reliability of the protection components are rather critical, in order to withstand beam impact of up to 50 TeV protons which are potentially destructive. For energy deposition of protons in solid copper and graphite materials, an integral FLUKA simulation covering all typical beam energies and beam sizes of FCC-hh and its injector chain has been performed. The study providing a reference for quick assessment of beam impacts on copper and graphite targets, is being summarized and will be reported soon [11].




ISBN 978-3-95450-182-3

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