

# CONCEPT OF BEAM-RELATED MACHINE PROTECTION FOR THE FUTURE CIRCULAR COLLIDER

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## Abstract

In the Future Circular Collider (FCC) study, a proton-proton circular collider (FCC-hh) is considered with a stored beam energy 20 times higher than that of the LHC. Any uncontrolled release of such energy could potentially result in severe damage to the accelerator components. Machine protection of the FCC-hh is hence very important and challenging. With a machine-protection strategy similar to the LHC, FCC would require up to three turns to dump the beam synchronously after a failure detection. Due to several possible ultrafast failures, which could lead to significant beam losses in a few turns, it is important to further reduce the reaction time of the machine protection system (MPS) for the FCC. Reducing the detection time of a failure by using faster beam monitors, e.g. diamond detectors, can reduce the time between a beam loss and the beam dump request. Communication delay of the interlock system to the beam dumping system can be reduced by using a more direct signal path. More than one beam-free abort gap will shorten the time required for the synchronization between the abort gap and the extraction kicker. Different failure scenarios are classified according to the speed of the failure onset and the subsequent increase of induced beam losses. The critical failure modes, their potential mitigations and impacts on the design of the MPS are presented.

## IMPORTANCE OF BEAM-RELATED MACHINE PROTECTION

In the Large Hadron Collider (LHC), the energy stored in one of the two counter-rotating proton beams reaches 360 MJ, assuming nominal beam parameters, i.e. 2808 bunches at 7 TeV with a bunch intensity of  $1.15 \times 10^{11}$  protons. This energy is sufficient to melt 500 kg of copper when heated from room temperature. For the Future Circular Collider FCC-hh [1], the beams will be accelerated up to 50 TeV in a 100 km tunnel. The nominal number of bunches per beam will be 10 400 and the bunch intensity will be  $1.0 \times 10^{11}$ , leading to an energy of 8.3 GJ stored in each beam, which is 20 times higher than at the LHC. As the proton energy increases, the quench limit of the superconducting dipole magnets in terms of protons lost per meter per second drops to  $5 \times 10^5$  p<sup>+</sup>/(m s) at 50 TeV, 15 times lower than that of the LHC at 7 TeV. For many failure cases, the beam energy would be concentrated on a spot size smaller than 1 mm<sup>2</sup>, making it even more destructive if a beam accident occurs. In the case of the 50 TeV FCC beam and a normalized emittance of

$\epsilon_{n,rms} = 2.2$  μm, the beam size will be 0.09 mm for a typical betatron function of 200 m. Thus, the beam energy density will be of the order of 200 GJ mm<sup>-2</sup>, about a factor of 150 higher than at LHC.

FLUKA simulations [2] have shown that one nominal FCC-hh bunch with a beam size of 0.2 mm is already sufficient to evaporate part of copper material around the beam. A safe beam intensity, which is a vital concept for the initial commissioning and setup of the machine at 50 TeV, has been defined as  $5.0 \times 10^8$  protons to maintain a reasonable safety margin with respect to the estimated damage limit. This number is also important for the definition of the required dynamic range of beam instrumentation devices that will interact with the Machine Protection System (MPS). In a worst-case failure scenario, a large number of bunches can be lost at the same place. This could occur e.g. during beam injection or extraction due to a wrong deflecting angle. If this happens, an effect known as hydrodynamic tunnelling [3, 4] will become significant, i.e. subsequent bunches will penetrate deeper into the target because the material density around the axis has been reduced substantially by the strong radial shock wave generated by the previous bunches. To simulate this phenomenon, it is necessary to run an energy deposition code like FLUKA and a hydrodynamic code like BIG2 [4] or Autodyn [5] iteratively. Simulations showed that the full 50 TeV FCC-hh beam would penetrate 350 m in copper with a beam size of  $\sigma_{x,y} = 0.2$  mm [6].

## CLASSIFICATION OF FCC-HH FAILURE MODES AND MITIGATION STRATEGIES

The criticality of beam-related failures depends on the amount of beam energy lost and on the time scale of the losses. Based on the speed of the failure onset and the subsequent increase of induced beam losses, one can distinguish three main failure categories as following:

- Ultrafast failures: This includes single-passage beam losses during injection and extraction [7], ultrafast equipment failures like phase jumps of crab cavities leading to intense beam losses within a few turns [8], missing beam-beam deflection during beam extraction [9] or quench heater firings [10]. Since the failure occurs on a timescale that is smaller than the minimum required time to detect and extract the beam, protection from such specific failure cases relies entirely on passive protection devices, i.e. beam absorbers and collimators that need to be correctly positioned close to the beam to capture the particles that are accidentally deflected.

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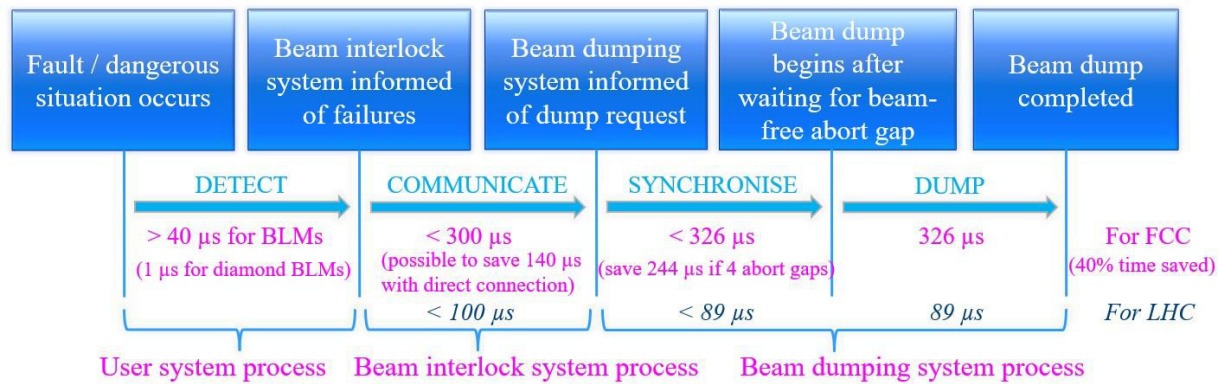


Figure 1: Reaction time of the Machine Protection System from fault detection to beam dump.

- **Fast failures:** This includes Unidentified Falling Objects (UFOs) [11], fast equipment failures like power supply failures of magnets installed at positions with high beta function or with short time constants of field decay, resulting in a beam lifetime of the order of a few ms (tens of turns). The majority of such failures lead to fast movements of the orbit or fast emittance growth. Protection against such events relies on monitoring the hardware systems and a fast detection of the failure onset directly at the source. An example is the monitoring of magnet currents using a Fast Magnet Current Change Monitor [12]. Monitoring of the hardware systems must be complemented by fast beam loss and beam position monitoring. For all fast failures it is important that the beams are dumped as soon as possible. Fast magnet failures are very likely to occur during the operation of the FCC-hh, since more than 5000 main dipole and quadrupole magnets will be installed, together with a large number of normal conducting magnets in collimator insertions, orbit correctors, etc. Experience from other accelerators indicates that thunderstorms lead frequently to trips of power converters, potentially as well for a large amount of converters leading to correlated failures. Collimator jaw positions, expressed in the transverse beam size  $\sigma$ , are adjusted typically at a position between  $5\sigma$  and  $9\sigma$  for efficient beam cleaning. A beam displacement of up to  $1.5\sigma$  during 2 ms is just acceptable, assuming that 1 ms is needed to dump the beam. If the beam displacement happens faster, the damage limit of the collimators might be exceeded before the beam is dumped completely. 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  $\beta$  beating of 20% within 2 ms [13]. Studies showed that critical failures are quenches of superconducting magnets at positions with very high beta functions (low-beta triplets) and powering failures of normal conducting magnets with fast field decay (separation dipoles). For normal conducting magnets installed in areas with high beta function, a large enough time constant for the field decay has to be ensured when designing the powering circuits. Otherwise, the magnet could be con-

nected in series with a superconducting solenoid to increase the time constant for the field decay and relax the parameters for the protection system.

- **Slow failures:** This includes power converter failures, magnet quenches or RF failures that lead to a beam lifetime in the order of one second. If the failure is detected properly, there is enough time to dump the beam. However, recurring faults might lead to increased radiation levels.

## MACHINE PROTECTION REQUIREMENTS AND SYSTEM OPTIMIZATION

The machine protection strategy for FCC-hh will be based on the remarkably successful layout of the LHC MPS [14], which has allowed a safe and reliable operation without beam accidents and with high availability for almost 10 years. In the LHC, collimators define the aperture during operation, so that beam-induced quenches of the superconducting magnets can be avoided as much as possible. Dedicated beam dilutors provide passive protection against ultrafast beam losses e.g. during injection or extraction failures. Fast and reliable instrumentation and beam monitoring systems actively detect element failures and abnormal beam parameters (for example, beam loss rates) that are able to trigger a beam dump request before damage thresholds are reached. A Beam Interlock System (BIS) provides the highly reliable transmission of the dump request from the monitoring system to a beam dumping system. In case of a failure, the beam is extracted as fast as possible from the ring and disposed into a dedicated beam stopper. The extraction kicker magnets of the beam dumping system are triggered during a particle-free abort gap, to prevent particle losses during the kicker rise time (synchronous beam dump). The beam is then extracted in a single turn. Other kickers installed in the extraction line dilute the energy density, and the beam is disposed on a beam dump block designed to withstand the impact of the full beam with dilution.

During the entire operation cycle, beam permit loops are used to actively transmit the beam dump requests from a large variety of critical equipment to the beam dumping system. The number of elements that should be capable of triggering a beam dump for FCC-hh will exceed 100 000 [15].

The requirements of the BIS for FCC-hh are high reliability, high availability and short system reaction time. The reaction time is the delay between the event requiring a beam dump and the time that the beam will be completely extracted. Here, the acceptable delay between the beam dump request and the extraction of the last bunches is determined by the beam density distribution and by the speed by which the beam is moved transversely due to the fault event. From the experience of LHC, the tails in the transverse beam halo population are more intense than expected from a Gaussian distribution. It was observed that around 5% of the beam population is stored in the tails above 3.5 beam  $\sigma$  (compared to 0.22% in case of a Gaussian distribution) [16]. Here, the use of a hollow electron lens [16, 17] could deplete the proton population in the beam halo, and thus increase the acceptable delay between the occurrence of the failure and the beam dump. On the other hand, the presence of a beam halo allows an early and very valuable detection of beam movements or instabilities by the Beam Loss Monitors (BLMs) at the position of the collimators. This could still be guaranteed by relying on a few witness bunches, with a larger halo population than the cleaned bunches. In addition, the beam halo population could be monitored directly, e.g. with an adapted synchrotron light monitor, triggering a beam dump if the intensity in the halo increases above a pre-defined threshold.

As illustrated in Fig. 1, the reaction time from a fault occurrence to the full beam being dumped is composed by four main contributions [15]: 1) Failure detection, 2) Communication between BIS and beam dumping system, 3) Synchronization with the particle-free abort gap, and 4) Beam extraction. For LHC, the longest delay time to extract the beam completely after the initial detection of a failure (Steps 2 to 4), is close to three beam revolutions. This corresponds to a delay of almost 300  $\mu\text{s}$ . With the larger ring of FCC-hh, this delay would increase to approximately 1 ms, which might be critical for some of the fast failures. The reaction time can be reduced by implementing the measures listed below.

- Reduce failure detection time: The detection time strongly depends on the failure type. For LHC, the BLMs are among the most important and fastest detectors of a failure with a minimum time delay, including the electronics delays, of around 80  $\mu\text{s}$ . For FCC, this delay could be shortened to around 1  $\mu\text{s}$  by using faster detectors at aperture limitations, e.g. diamond detectors [18], silicon detectors [19], or Cherenkov fibers [20], equipped with faster read-out electronics. The detection time could be further improved by monitoring beam losses with a bunch-by-bunch resolution [18, 19] at aperture limitations and sensitive areas, e.g. in the triplet and collimation region, and connecting these signals directly to the interlock system. An interlock on the derivative of the beam losses measured by a distributed beam loss system or an interlock on the derivative of the total beam current would allow a faster detection, especially for large beam losses distributed all around the machine.

UFO induced quenches in the FCC could be avoided more effectively if the beam losses were directly detected between the beam and the superconducting coils, in contrast to today's LHC BLMs that are located outside of the cryostat. Possible options are fast diamond BLM type detectors behind the beam screens distributed over the superconducting magnets, a continuous optical fibre close to the beam aperture or, as a third option, a thin superconducting wire with a very low quench threshold in the magnet's cryostat, close to the beam aperture. In the last case, the beam could be dumped in case of a quench of this superconducting wire before the quench threshold of the magnets would be reached.

- Reduce communication time: The communication time is the time that the dump-request signal needs to travel along the beam interlock loop to the beam dumping system. For FCC, the delay is estimated to be 300  $\mu\text{s}$  in maximum. Here, time can be gained by making one or several direct connections across the ring or by maintaining a short distance between the beam dumping system and the collimation system, where losses will most frequently be seen first. Based on the current FCC-hh layout [1], using a direct signal path from the betatron collimation insertion 'J' to the extraction insertion 'D' instead of using signal transmission cables through the arc, could save about 140  $\mu\text{s}$ . The use of additional BLMs with a direct link to the beam dumping system, without passing through the BIS, can reduce the required communication time for certain failure cases [21]. In addition, this approach increases the overall reliability because the trigger signal will be propagated to the beam dumping system even in case of a BIS failure.
- Reduce synchronization time between the extraction kickers and the particle free abort gap: For FCC, this delay would amount to 330  $\mu\text{s}$  in case of using one beam-free abort gap, as presently done at LHC. The time can be shortened by introducing multiple abort gaps. With four abort gaps, it could be reduced by up to 3/4 of a turn, i.e. by 244  $\mu\text{s}$  for FCC. As a last resort, the direct trigger of an asynchronous beam dump could be considered for especially critical ultrafast failure cases.

## SUMMARY

The FCC-hh Machine Protection System will be based on the successful strategy adopted for LHC, and summarized in more detail in [22]. The main requirements are the reliability, availability and fast reaction time of the system. Improvements in several key areas are needed. This includes the reduction of the overall MPS reaction time, the faster monitoring of beam losses based on detectors with nanosecond resolution, the improved control of the decay time constant of magnet power converters to avoid that beam losses build up too fast in case of failures, and, last but not least, the efficient control and monitoring of the transverse beam profile, e.g. by using a hollow electron lens or equivalent devices.

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