Concept of beam-related machine protection for the FCC-hh

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Abstract

Energies stored in the FCC-hh magnets and beams are 20 times higher than that of the LHC. Any uncontrolled release of these energies could potentially result in severe damage to the accelerator components. Quench limit of the superconducting magnets becomes 15 times lower than that for LHC. Machine protection of the FCC-hh is hence very important and challenging. With a machine protection system similar to the LHC, FCC would require up to three turns' to dump the beam synchronously after detection of a failure. The reaction time of the machine protection system can be reduced by several strategies. The time for failure detection can become shorter with faster hardware and beam monitors, e.g. using diamond detectors as fast beam loss monitors. Communication time for the interlock system to the beam dumping system can be reduced by using a more direct signal path instead of going through the arc. More than one beam-free abort gap can shorten the time required for synchronization. Different operational and failure scenarios are classified according to beam lifetime, i.e. the speed of the failure onset and the subsequent increase of induced beam losses. We put emphasis on so-called ultrafast failures including crab-cavity failures, fast failures such as magnet failures at high beta function positions or with short time constants of field decay, and slow failures. A list is presented, summarizing the critical failure modes and proposing potential mitigation strategies.

I. IMPORTANCE OF MACHINE PROTECTION

In the LHC, energy stored in one of the two counter rotating proton beams could reach 362 MJ, under nominal beam parameters, i.e., 2808 bunches at 7 TeV with a bunch intensity of 1.15×10^{11} [1]. This energy is sufficient to melt 500 kg of copper from room temperature. Energy stored in the beams will be doubled for HL-LHC or more for HE-LHC, compared with the LHC. For FCC-hh, the beams will be accelerated up to 50 TeV in a 100 km tunnel [2]. The nominal bunch number in one beam is 10400 and the bunch intensity is 1.0×10^{11}, leading to a beam energy of 8.3 GJ, 20 times higher than that of the LHC, as shown in Fig. 1. As the proton energy increases, quench limit of the superconducting magnets drops to 0.5×10^{6} $p^{+}/(m\ s)$, 15 times lower than that of the LHC [3]. Moreover, the beam energy normally concentrates on a spot size of <mm^2, making it even more destructive if beam accident occurs. In the case of the 50 TeV FCC beam, the normalized emittance is $\varepsilon_{\mathrm{n,rms}} = 2.2$ µm, the beam size will be 0.09 mm with a betatron function of 200 m. The beam energy density will be of the order of 200 GJ/mm^2.

To provide a reference for quick assessment of beam impact on components in FCC-hh and its injector chain, energy depositions of protons in copper and graphite have been simulated using the Monte-Carlo code FLUKA [4]. The proton energy ranged from 50 MeV to 50 TeV, and three representative beam sizes were selected at each energy sample [5]. Part of the results is plotted in Fig. 2. For a beam size of 0.2 mm, one nominal bunch with 1.0×10^{11} protons at injection energy of 3.3 TeV can melt copper around the peak of energy deposition. As the proton energy increases to the top energy of 50 TeV, one bunch is sufficient to evaporate copper.

In one of the worst cases, a large number of bunches can be lost at the same place, which could happen during injection and extraction due to a wrong deflecting angle. If this happens, hydrodynamic tunneling [6-8] will likely become significant, i.e., subsequent bunches will penetrate deeper into the target because material density around the axis has been reduced substantially by the strong radial shock wave generated by previous bunches. It is therefore necessary to run the energy deposition code and a hydrodynamic code iteratively to simulate this phenomenon and hence assess potential damages caused to accelerator components. Simulations coupling FLUKA and BIG2 showed that the penetration depth of a full nominal LHC beam with a rms beam size of $\sigma_{x,y} = 0.2$ mm was about 35 m in copper [8], while in graphite, the penetration depth reached 25 m with $\sigma_{x,y} = 0.5$ mm [9]. Recent simulations illustrated that the 50 TeV FCC beam would penetrate 350 m in copper when $\sigma_{x,y}$ was 0.2 mm [10], and 1.3 km in water if $\sigma_{x,y}$ was 0.4 mm [11]. The water target was studied for the FCC beam to examine the possibility of a water beam dump without the need for dilution kickers. The study suggested that the beam size must be increased from 0.4 mm to centimeters to make the water tank shorter and allow the use of a beam window separating the beam transfer line and water. Otherwise, a beam with small beam sizes could easily melt the beam window. As for the coupling of FLUKA and BIG2 [12-14], the method coupling FLUKA and ANSYS-Autodyn has also been benchmarked against the HiRadMat experiment [15]. More case studies are planned for FCC and other high-beam-power accelerators.

Severe beam accident happens not often, but it did happen. In 2004, the full Super Proton Synchrotron (SPS) beam (288 bunches, 3.4×10^{13} protons, 450 GeV) was once extracted with a wrong angle due to switch-off of the septum [16]. Vacuum chamber (stainless steel) of one magnet in the transfer line was severely damaged. Both of the vacuum chamber and the magnet had to be replaced. Interlocking system and operational procedures were modified afterwards to avoid similar incident.

Besides the beam energy, the FCC-hh magnets will store much more energy, i.e. 160 GJ. Any uncontrolled release of these energies could potentially result in severe damage to the accelerator components. Therefore, safe operation of high-energy colliders highly relies on robust machine protection systems. Thanks to the well-designed and proper-functioning machine protection system [17-19], the LHC has been running safely with high availability and reliability and hence impressive luminosity performance [20]. At present, the operating beam energy in the LHC has reached 6.5 TeV, very close to the designed top energy.

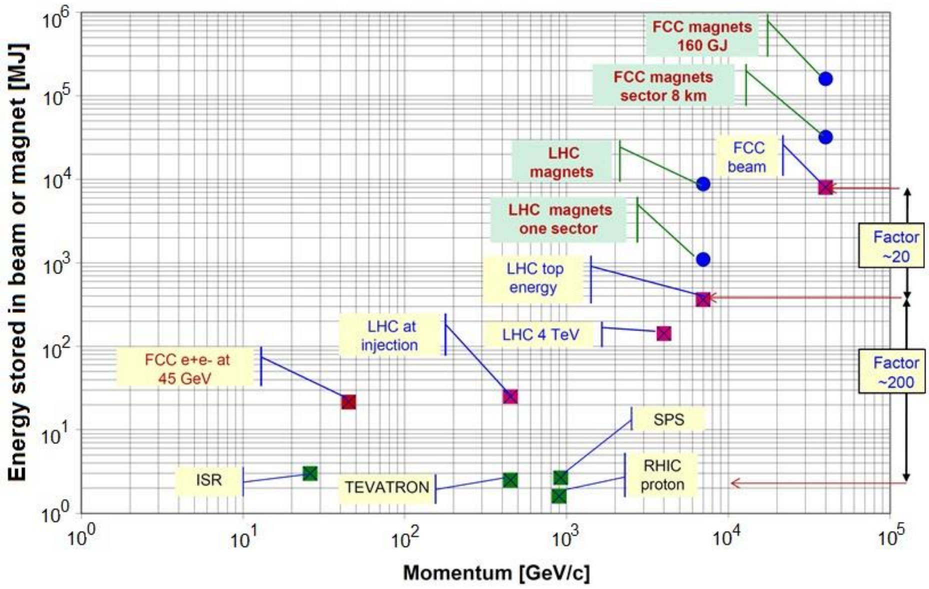


Fig. 1. Comparison of energies stored in accelerator beam or magnet.

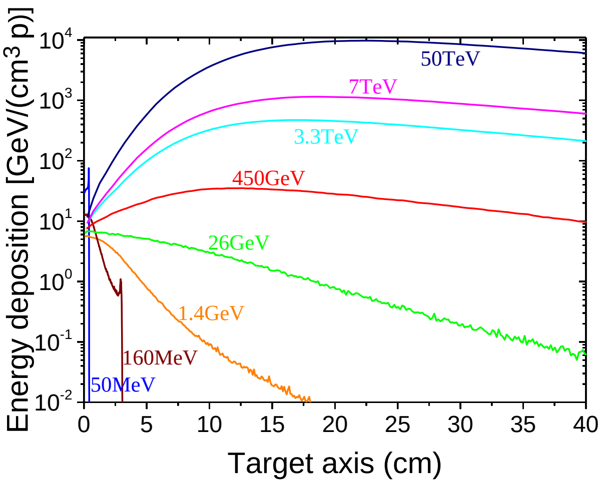


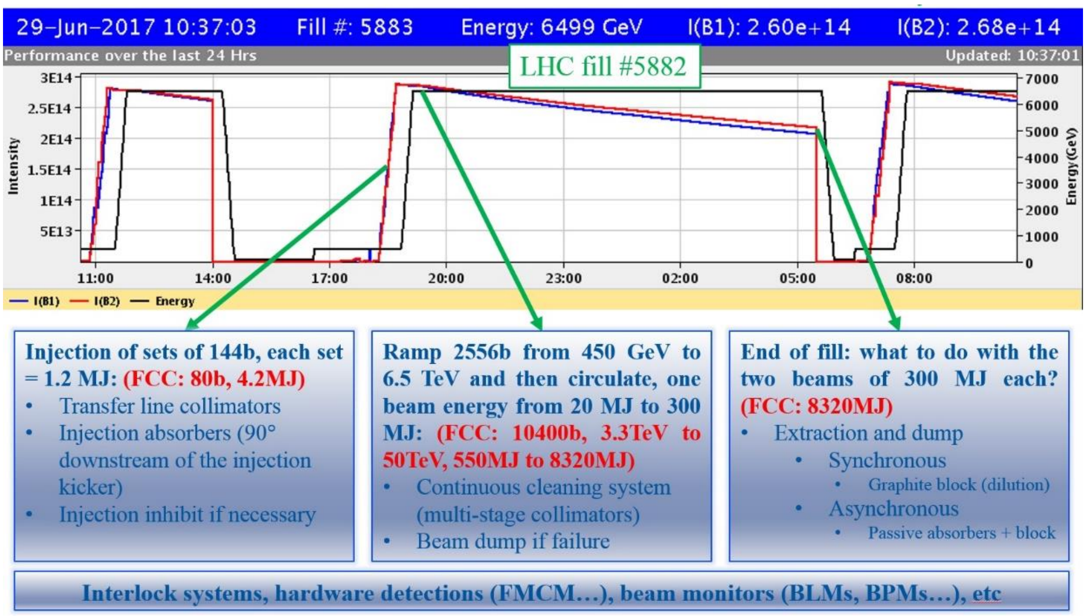
Fig. 2. Energy deposition per incident proton as a function of the depth into the solid copper target along the axis. The beam size is constant (0.2 mm) for the energies from 50 MeV to 50 TeV.

II. GENERAL STRATEGIES OF MACHINE PROTECTION

For the operation of accelerators with high power beams or sub-systems with large stored energy, machine protection involves all the methods and technologies to identify, mitigate, monitor and manage the technical risks, if failure modes can result in substantial damage to accelerator systems or significance interruption of operations [17]. It includes an ensemble of hardware and software systems, commissioning and operational procedures, and so on. There are several general requirements for the protection systems. The first one is to protect the accelerator equipment from damage and superconducting magnets from quenching. The second one is to protect the beam, i.e., protection systems should only dump the beam when necessary. Unnecessary ('false') beam dumps should be avoided in order not to compromise availability. The third one is to provide evidence. In case of failure, complete and coherent diagnostics data should be provided to accurately understand what has caused the failure and if the protection systems have functioned correctly. In this part, we focus on beam-related machine protection, including analysis of critical failure modes leading to fast beam losses and proposing protection strategies based on various failure scenarios [21, 22].

FCC-hh machine protection can use the same general strategies as for the LHC. In the LHC machine protection systems, collimators are responsible to clean the beam halo via both momentum collimation and betatron collimation by defining the aperture during routine operation, so 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 arise extremely fast during e.g. injection or extraction. Fast and reliable instrumentation and beam monitoring systems detect actively element failures and abnormal beam parameters (for example, beam loss rate) that are able to trigger a beam dump request before damage thresholds are reached. Beam interlock systems provide highly reliable transmission of the dump request from the monitoring system to a beam dumping system. The beam dumping system waits for the particle free abort gap for switching on the extraction kicker magnets (in the case of 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.

Proper functioning of the machine protection systems is needed over the whole operation cycle, as shown in Fig. 3. During the cycle, beam interlock system collects the beam dump requests from many systems. Scaling from LHC, the number of interlock channels will exceed 100 000 in the case of FCC-hh [23, 24]. A simplified schematic drawing is shown in Fig. 4.



Injection of sets of 144b, each set = 1.2 MJ: (FCC: 80b, 4.2MJ)
- Transfer line collimators
- Injection absorbers (90° downstream of the injection kicker)
- Injection inhibit if necessary

Ramp 2556b from 450 GeV to 6.5 TeV and then circulate, one beam energy from 20 MJ to 300 MJ: (FCC: 10400b, 3.3TeV to 50TeV, 550MJ to 8320MJ)
- Continuous cleaning system (multi-stage collimators)
- Beam dump if failure

End of fill: what to do with the two beams of 300 MJ each? (FCC: 8320MJ)
- Extraction and dump
  - Synchronous
    - Graphite block (dilution)
  - Asynchronous
    - Passive absorbers + block

Interlock systems, hardware detections (FMCM…), beam monitors (BLMs, BPMs…), etc

Fig. 3. Machine protection over the whole LHC operation cycle, and implications for the FCC-hh.

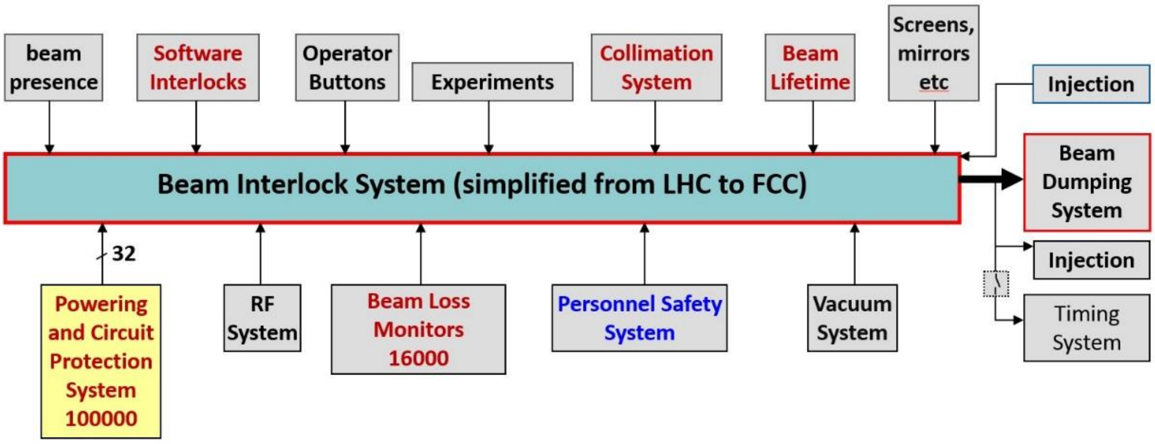


Fig. 4. Interlock channels provided by various user systems for the beam interlock system.

III. CLASSIFICATION OF FCC-HH FAILURE MODES AND STRATEGIES

Figure 5 shows the time needed for a beam dump after a fault has occurred. For both the LHC and FCC, a time up to three 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. Different operational and failure scenarios are classified according to beam lifetime, i.e. the speed of the failure onset and the subsequent increase of induced beam losses. As can be seen in Table 1, there are three main failure categories:

- Ultrafast failures (Table 2): e.g. single-passage beam losses during injection and extraction [25, 26], ultrafast equipment failures like phase jump of crab cavity leading to dramatic beam losses in 3 turns [27-29], missing beam-beam deflection during beam extraction [30], quench heater firing [31], and so on. In these cases, active protection based on fault detection and reaction is not possible because the failure occurs on a timescale that is smaller than the minimum detection and dump time. Passive protection from such specific failure cases relies therefore on beam absorbers and collimators that need to be correctly positioned close to the beam to capture the particles that are deflected accidentally. Sometimes asynchronous dump must be executed.
- Fast failures (Table 3): such as UFOs [32], fast equipment failures like magnet failures at high beta function positions 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 fast failures lead to beam 'instabilities' (fast movements of the orbit or emittance growth). Protection against such events relies on fast hardware monitors (such as FMCM [33]), and fast beam loss and beam position monitoring. The beams must be dumped as fast as possible.
- Slow failures (Table 4): e.g. power converter failures, magnet quenches, RF failures that lead to a beam lifetime of the order of second. Beam should be dumped if necessary.

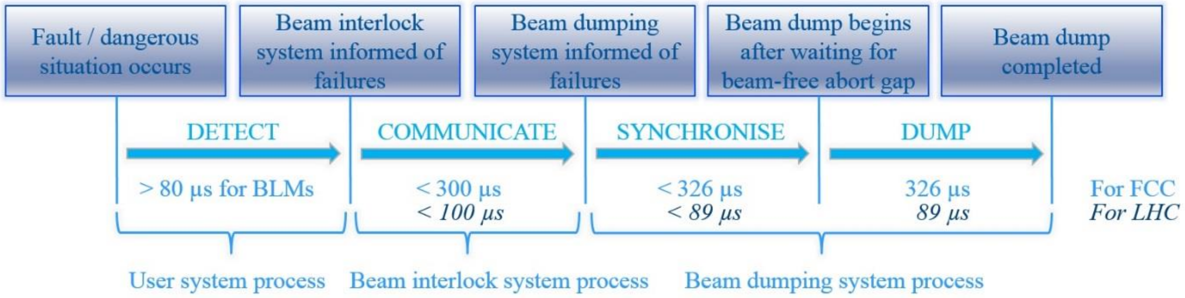


Fig. 5. Reaction time of the machine protection system to dump the beam after a failure.

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

Beam Lifetime	**Beam Power Lost**		**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	230 kW	Steady beam loss, acceptable operating conditions (expected during early operation)	Operation acceptable, collimators must absorb large fraction of beam energy
12 min	500 kW	116 MW	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	8320 MW	Slow failures (powering failures, magnet quenches, RF failures, …)	Detection of failure, beam must be dumped when necessary
A few ms (tens of turns)	~100 GW	~ TW	Fast failures (UFOs, fast equipment failures, e.g., magnet failures at the highest beta function or with short time constant)	Fast detection of hardware failures or beam losses, beam dump as fast as possible
1 turn or a few turns	Up to 4 TW	Up to 26 TW	Ultrafast failures (Single-passage beam losses during injection and extraction; ultrafast equipment failures, e.g., phase jump of crab cavity, leading to dramatic beam losses in 3 turns)	No time to extract the beam in a controlled way, passive protection with collimators and absorbers (made of novel or sacrificial materials) is required, sometimes asynchronous dump must be executed

We first consider fast magnet failures, which are likely to occur during operation of the FCC-hh, since more than 5000 main dipoles and quadrupoles will be installed, together with a number of warm magnets in collimator insertions, transverse dampers, orbit correctors and so on. Failure scenarios that could cause a beam lifetime of a few ms, i.e., a fast beam loss, are of great concern.

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

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

where B_0 is the nominal magnetic field, t is time after the failure, τ is the natural time constant of the field decay, determined by the inductance L and resistance R, $\tau = L/R$. τ 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:

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

A typical time constant σ_t for a quench is >100 ms [34].

For a dipole magnet, the field error results in closed orbit distortion (in maximum) [19, 35]:

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

where β_{magnet} and β_{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 $\alpha_{\text{error}} = \alpha_0 \cdot \frac{\Delta B_{\text{error}}}{B_0}$. 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 [36]:

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

where Δk 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 β-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 Δx_{off}.

Collimator jaw positions, expressed in the transverse beam size σ, are adjusted typically between 5 σ and 9 σ for efficient beam cleaning. It is reasonable to say that a beam displacement of up to 1.5 σ 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 β-beat of 20% within 2 ms.

Various magnet failures have been analyzed according to the existing beam optics design of the FCC-hh, and the most critical ones are listed in Table 3. The study 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.

All the studied typical failure modes are reported in Tables 2-4, including the failure scenarios, potential consequences, mitigation strategies. Some of the most critical failure modes include wrong deflecting angle applied to the beam during injection and extraction, phase jump of crab cavities, missing beam-beam deflection due to non-simultaneous dump of the two beams, quench heater firing on the circulating beam, powering failure of the normal conducting separation dipole, quench of one magnet of the low-beta triplet beside the interaction points, UFOs, ADT/orbit corrector misfires, aperture reduction or beam pipe obstruction due to movable devices, and so on. Except for the dedicated mitigation strategies proposed for certain failure modes, several specific requirements to mitigate the fast and ultrafast failures of FCC are described in the next section, some of which might be helpful to mitigate these failures in general.

Table 2: Ultrafast failures of FCC-hh

Studied failure mode	**Consequences**	**Mitigation strategies**	**Remarks**
Wrong deflecting angle of injected beam due to injection kicker failure	Large number of bunches lost at the same place in the accelerator	1) Transfer line collimators 2) injection absorber	See "Injection and extraction" part for more details and other failure modes during injection and extraction
Wrong deflecting angle of beam due to energy-tracking failure or extraction kicker (or septum) failure during extraction	Large number of bunches lost at the same place in the accelerator or dump line	1) Two-sided protection absorbers for septum and other magnets	
Dilution kicker failure	Dump block irradiated by higher-intensity beam without nominal dilution	1) Dump block designed to survive from 90% dilution mode 2) Or, using water dump	

For crab cavities (CCs), voltage/phase changes exponentially with a time constant of $\tau = 2Q_{ext}/\omega$ due to equipment failure, or faster due to quenches or multipacting. In the worst case, phase could jump 90° in one turn	Beam center could be deflected of the order of σ in one turn, leading to significant beam losses in 3 turns	1) Increase Q_{ext} and ω, and the number of CCs per beam per IP side 2) Avoid simultaneous failures of multi-cavities 3) Multi-cavity feedback for field-error compensation 4) Hollow e-lens to deplete halos 5) Make phase advance between CCs and collimators close to 90°	For the fastest CCs failure, probably no time to extract the beam in a controlled way, passive protection and asynchronous dump would be needed
Absence of beam-beam deflection due to the non-simultaneous extraction of the two beams	Fast deflection of the remaining circulating beam, unacceptable losses on some primary collimators if the beam halo is populated	1) Deplete and control the beam halo population using e-lens 2) Monitor the halo population and interlock on it	In the LHC, perturbation up to 0.6 σ has been measured at 4 TeV, and 1.1 σ has been predicted in simulations for HL-LHC.
Effect of quench heater firing on the circulating beam	Current discharge induces a magnetic field deflecting the beam quickly	1) Dump the beams before the current discharge in the quench heater is triggered	Orbit distortion of 400 µm was measured in LHC after quench of a dipole. The beam would be deflected in the aperture within one turn for HL-LHC triplet quench heater.
Others?			

Table 3: Fast failures of FCC-hh

Studied failure mode	**Consequences**	**Mitigation strategies**	**Remarks**
Powering failure of separation dipole “D1” in IRA/IRG (if NC)	The beam can be displaced quickly from nominal orbit, leading to fast beam losses	1) Time constant of the field decay must >33 s 2) Connect a SC solenoid in series to increase the time constant 3) Detect failure at hardware level (e.g., FMCM) 4) Detect initial influences of the failure on the beam (fast BPM, BLM, etc) 5) Dump beam as fast as possible	One of the fastest failure modes, but can be mitigated by using the SC solenoid to slow down the field decay
Quench of 1 magnet of D1 (if SC)		1) Fast detection of the quench 2) Time constant of the field decay must >100 ms	Need to be careful about the time constant
Quench of 1 magnet of the low-β triplet	Tune change and β-beating, leading to resonances and beam instabilities	1) Fast detection of the quench 2) Time constant of the field decay must >140 ms	Need to be careful about the time constant

UFOs	Beam instabilities and fast beam losses	1) Fast detection of initial effects on the beam and trigger dump 2) Make use of the conditioning effect along the machine run	Lead to significant beam losses in ms at LHC
ADT/orbit corrector misfires	Fast beam deflections	1) Avoid coherent excitation of transverse dampers	
Vacuum valve/screen reduces aperture or obstructs beam pipe	Aperture reduction and fast beam losses	1) Accurate control of these movable devices	
Vacuum leak/wire scanner error scatters the beam	Beam scattering and fast beam losses	1) Fast detection of initial effects on the beam and trigger dump	
Beam instability due to too high beam current/e-clouds	Fast beam losses	1) Fast detection of initial effects on the beam and trigger dump	
Others?			

Table 4: Slow failures of FCC-hh

Studied failure mode	**Consequences**	**Mitigation strategies**	**Remarks**
Powering failure of other warm magnets	Change of the closed orbit	1) After detection of failure or abnormal beam parameters, dump the beam rapidly if necessary	Radiation levels should be paid attention to. Normally have enough time for synchronous dump
Quench of 1 main dipole or quadrupole	Change of the closed orbit or optics	1) After detection of failure or abnormal beam parameters, dump the beam rapidly if necessary	
RF accelerating cavity failures	More particle population on the tail due to dephasing	1) After detection of failure or abnormal beam parameters, dump the beam rapidly if necessary	
Others?			

IV. SEVERAL REMARKS FOR THE MACHINE PROTECTION OF FCC-HH

Considering the potential destructive high-energy FCC-hh beam, and the high requirement to reduce the reaction time of the machine protection systems, several strategies are remarked here, some of which have been applied in the LHC, some not.

- Failure detection
  - Detect failure at hardware level (FMCM, …) and dump before beam is influenced.
  - Detect initial consequences on beam (beam orbit movement monitor, fast beam loss monitor, fast beam current change monitor).
  - Fast BLM: ns-resolution at aperture limitations (Diamond [37]/silicon detectors [38]); Cherenkov fibre [39].
  - Interlock on the derivative of the losses measured by the distributed beam loss system. This would allow a faster reaction time and avoid unnecessary preventive dump.
  - Monitor beam halo population using e.g. the synchrotron light monitor and interlock on it.
  - Monitor beam losses at the aperture limitations and sensitive areas e.g. triplet with a bunch-by-bunch resolution [37, 38] and connect the signals to the interlock system.
- Communication between beam interlock system and beam dumping system

    - During transmission of the dump request (e.g. from betatron collimation insertion “J” to extraction insertion “D”), use a more direct signal path instead of going through the arc. This could save 145 μs in maximum.

- Synchronization time needed for the extraction kickers
    - More than one beam-free abort gap can shorten the time required for synchronization.
    - It is possible to have 4 gaps without luminosity loss, a time of 3/4 turn might hence be saved [40].
- Beam intercepting devices
    - 50 TeV proton is much more destructive than 7 TeV one.
    - New materials for collimators, absorbers, windows are needed.
    - From the experience of LHC, transverse beam halo population is more than that indicated by a Gaussian distribution. Explicitly, around 5% of the beam population is stored in the tails above 3.5 beam σ (compared to 0.22% in case of a Gaussian distribution) [41]. Hollow e-lens [41, 42] will be helpful to deplete proton population of beam halos, and thus slow down the speed to reach damage limit of collimators after beam loss begins. The halo cleaning system must be able to keep several bunches with halo in order to detect beam losses before they become too critical.
- Powering failure of normal conducting magnets
    - For critical warm magnets regarding powering failure, connecting them with a superconducting solenoid in series would increase the time constant for orbit changes and relax the parameters for the protection system.
- Beam induced magnet quench
    - Avoid magnet quench by using a superconducting wire with a quench limit slightly lower than the one of the magnet. The wire is inserted along the coil between the cold bore and the coil. The detection of a quench along this wire would generate a beam dump request to stop beam losses from developing further before the magnet quenches.
- Dilution kicker failures
    - Study beam impact on graphite block (hydrodynamic tunneling might be significant, radiation degradation could happen).
- Water beam dump without dilution
    - Need to make the beam size much larger (order of cm) in front of the dump block to allow the existence of a window that can survive after all bunches passing through it.
    - Need simulation studies coupling FLUKA and a hydrodynamic code.
- If the beam dumping system is unavailable when a beam dump is requested [43]
    - To drive a sacrificial dump block in the beam (to be replaced after irradiated by the entire beam).
    - Massive absorbers around the beam (outside the collimators) that protect the accelerator (but not the collimators).
    - Very challenging design for such destructive beams.
- If the beam dumping system becomes unavailable during stable beam operation
    - “Dump” the beam in another safe way, e.g., slow scrape using collimators.

V. SUMMARY

Concept considerations of beam related machine protection of the FCC-hh have been summarized. The most critical equipment (magnet) failures that could potentially lead to ultrafast or fast beam losses have been described. Potential mitigation strategies have been proposed. Several measures to reduce the reaction time of the machine protection system have also been discussed. Such studies may provide inputs for the powering design of magnets as well as for the interlock system. 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.

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