CERN-ACC-2023-0019

jack.heron@cern.ch

Report

Machine Protection and Availability in the FCC-ee

J. W. Heron, L. Felsberger, C. Hernalsteens, C. Wiesner, D. Wollmann, J. Uythoven and F. Rodriguez-Mateos
CERN, Geneva, Switzerland

Keywords: Machine Protection, Availability, Down Time, Reliability, Repair, Maintenance, Future Circular Collider, FCC, FCC-ee

Abstract

The FCC-ee will combine high stored beam energy with small vertical emittance. The loss of only a small part of the beam into accelerator equipment, collimators or passive absorbers could be extremely destructive. Therefore, a highly reliable machine protection system is required for the entire accelerator chain. Further, the FCC-ee schedule has 185 days allocated to physics each year, of which a minimum percent must be spent at nominal parameters if integrated luminosity goals are to be reached. Machine protection and availability are vital considerations from the outset of the design stage. This paper presents the current status and outlook for both topics relating to analysis, research and development (R\&D). First, relevant topics in machine protection are discussed. Fault mechanisms are treated as well as key considerations such as minimum reaction time, beam loss detection, dust interaction, fast failures and quench protection. Next, availability assurance is considered. Three steps are proposed: (I) Coarsely define system availability targets scaled to the complexity of delivery. (II) Establish the projected availability based on existing designs and similar systems. (III) If the latter is insufficient, study how this can be improved.

Geneva, Switzerland
November 2023

Contents

1 Introduction

The FCC-ee will combine high stored beam energies of up to 20 MJ per beam with extremely small vertical emittance ($\mathcal{O}$ 1.0 pm) [9]. The loss of only a small part of the beam into accelerator equipment, collimators or passive absorbers can cause serious damage. Therefore, a highly reliable machine protection system is required for the main colliding rings, the top-up booster and likely the rest of the injector chain.

Meanwhile, the FCC-ee schedule has 185 days allocated to physics each year, of which a minimum percent must be spent at nominal parameters if integrated luminosity goals are to be reached. With regards to maintenance, the FCC-ee involves unique challenges relating to its size, complexity and ambitious technical objectives. This makes availability a significant risk to its physics deliverables.

Machine protection and availability are vital considerations from the outset of the design stage in the FCC-ee. This paper presents the current status and outlook for analysis as well as research and development (R&D) in both fields.

2 Machine Protection

To define the requirements and parameters of the different machine protection sub-systems, a complete catalogue of failure cases needs to be established. Specifically, failures that can lead to sudden beam losses and equipment damage. This has been done previously for the LHC [54], the HL-LHC [4, 37, 38] and FCC-hh [2, 8, 43]. The catalogue of fault mechanisms must contain, among others:

- Beam injection failures in top-up mode for the injected and stored beam;
- Beam extraction failures;
- Powering failures of the normal conducting and superconducting circuits;
- Effects of magnet protection elements on the beam;
- Effects of failures in the RF systems on the stored beam;
- Effects of failures in the wide band feedback system on the stored beam;
- Beam dust interactions;
- Fast beam instabilities;
- etc.

The time structure and the criticality for each failure case has to be studied. Based on the outcome of these studies, mandatory reaction times of the machine protection system will be derived and the architecture of the machine protection system can be defined.

Several topics are immediately apparent. Each will be dealt with in turn in the following sections.

2.1 Lower Limit on Reaction Time

In the LHC, the shortest possible time between detection of a critical fault through the machine protection system and the safe extraction of the two beams is about three turns, or $\sim 270\mu s$. The observed sudden beam losses in SuperKEKB [31] indicate that reaction times of three turns, which would translate in the case of FCC-ee to $\sim 910\mu s$, will not be sufficient. Therefore, the source of the sudden beam losses in SuperKEKB has to be identified and mitigation scenarios developed for the FCC-ee. At the same time, new technologies for the fast transmission of beam dump and interlocking requests using novel fast interlock channels with transmission times in the microsecond range must be studied and developed.

2.2 Beam Loss Detection

In the FCC-ee, beam loss detection is especially challenging due to the high levels of synchrotron radiation emitted by the beams. Therefore, the radiation field due to synchrotron emissions as well as beam losses must be studied. Beam loss monitors that can distinguish the different sources of radiation can then be developed, and their time response optimised to the levels required for machine protection.

2.3 Beam Dust Interaction

The interaction of dust particles with the circulating beam has been observed in many accelerators since the early 1960s [53]. In the LHC, beam-dust interactions have had an important impact on machine availability and caused tens of quenches [35]. Similarly, SuperKEKB experienced a significant amount of dust-related beam aborts [59] and developed mitigation methods, for example a specialised knocking device to dislodge dust particles from the top of the vacuum chamber. The dynamics of dust movement in the beam pipe and following beam-dust interaction has been studied in detail for the LHC [36, 7] and is well understood. These studies must be extended to lepton colliders like the FCC-ee. Simulation models for lepton accelerators should be benchmarked with the observed beam-dust interactions at SuperKEKB. This will allow their effect on protection, performance and availability to be evaluated for the FCC-ee. Up to now, understanding of dust particle charging, release and migration mechanisms in the vacuum system of particle accelerators is very limited. These mechanisms are key to mitigation of their detrimental effect on machine performance and damage potential, and must be studied with high priority.

2.4 Fast Beam Instabilities

While the stored beam energy in the FCC-ee is lower than the LHC, its beam brightness is much higher. As a result, even 2% of the beam intensity is expected to exceed the material limit of the most robust absorbers, such as graphite or reinforced carbon, currently used in high energy colliders [22]. In the event of a fast failure, interaction of the stored beam with protection absorbers, collimators and other accelerator equipment could be highly destructive. In such cases, hydrodynamic tunneling has been studied for the LHC and the FCC-hh in detail [57, 10, 11, 42]. Similar studies must be performed for FCC-ee failure cases as well as failures beyond design.

2.5 Quench Protection

The final focusing quadrupoles around the four experiments of the FCC-ee will be superconducting. Therefore, the impact of fast beam losses into these magnets has to be carefully studied and compared to cases in LHC and HL-LHC [49, 48, 62, 61, 27, 26, 5]. The quench protection system for these circuits may be an important source of fast failures, as has been observed for the HL-LHC [28]. The impact of the quench protection system on the circulating beam needs to be carefully studied and mitigations implemented during the design of the magnet system and its protection.

The circuits of the final focusing magnets may require radiation tolerant cold by-pass diodes as part of their protection system. These diodes have to be developed together with industry and their radiation tolerance experimentally validated, as performed for those in the LHC main dipole and quadrupole circuits [18, 17, 16] and for the triplet circuits of the HL-LHC [63, 61].

3 Availability

The FCC-ee schedule has 185 days allocated to physics each year, of which a minimum percent must be spent at nominal parameters if integrated luminosity goals are to be reached. Availability is the proportion of these physics days where the machine cannot deliver beam. Accounting for phases of operation where no luminosity is produced (e.g. set up, fill, adjustments, etc.), the FCC-ee Conceptual Design Report [1, p. 377] sets the minimum global availability requirement at 80%.

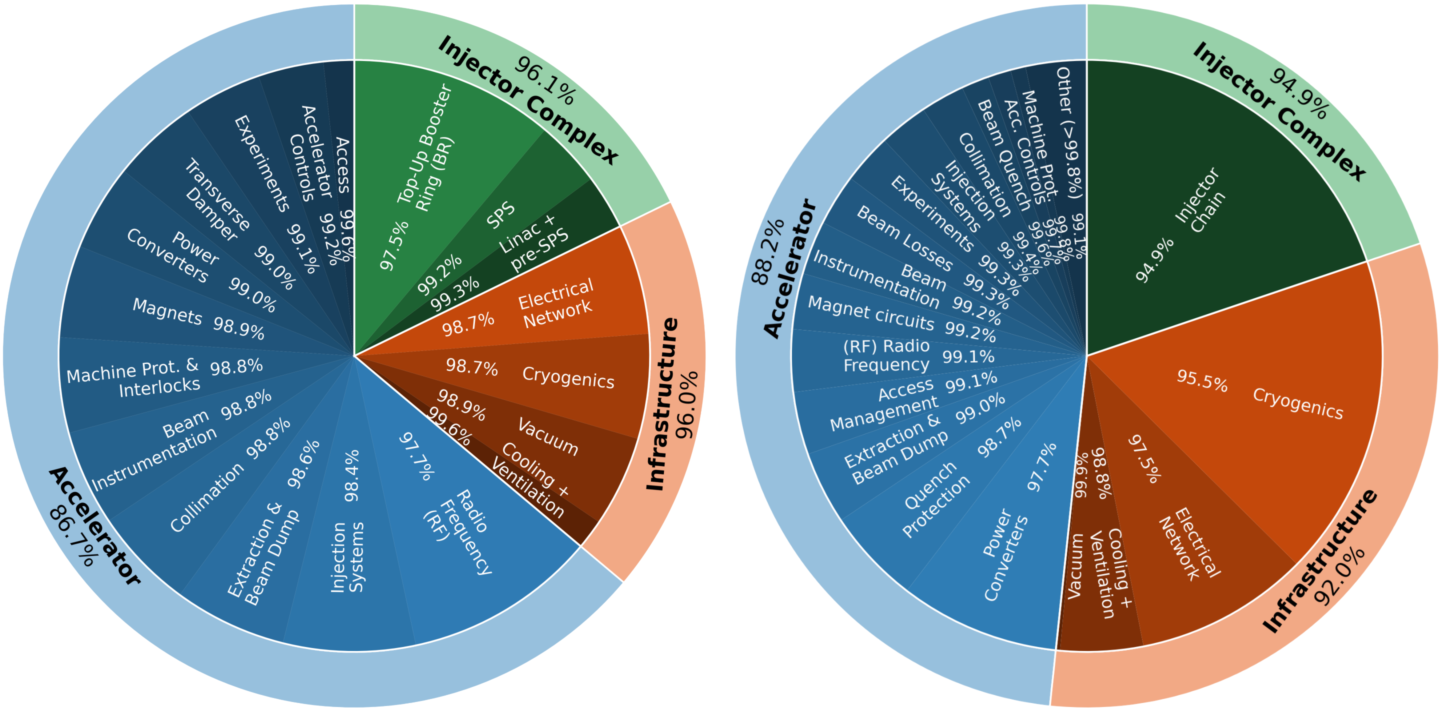
For comparison, the Large Hadron Collider (LHC) was available for 77% of the physics production in Run 2, 2016-2018 [13]. The additional challenges in maintaining the FCC-ee, like its size, complexity and ambitious technical objectives, make availability a significant risk to its physics deliverables.

This chapter considers how to account for availability in the FCC-ee. This begins by breaking the accelerator down into its main constituent systems. Three steps are then proposed: (I) Coarsely define reasonable availability targets scaled to the complexity of delivery. (II) Establish the projected availability based on existing designs and similar systems. (III) If the latter is insufficient, study how this can be improved. These are presented in Sections 3.1-3.3.

3.1 Coarsely define availability targets

To talk sensibly about availability, we must have reasonable goals in mind for what is acceptable. The global 80% requirement corresponds to a specific amount of down time each year, to which each constituent system contributes. The “complexity” of availability assurance varies between systems, and respective targets may be scaled accordingly. This section seeks to systematically quantify this complexity.

The global minimum $A = 80\%$ is divided between systems $i = 1, ..., N$ (Radio Frequency,



(a) FCC-ee required availability to achieve the global minimum 80%.

(b) LHC measured availability in Run 2, 2016-2018, to achieve the global outcome of 77%.

Figure 1: Accelerator availability by system

Power Converters, Injector Complex, etc.) via complexity c_i

$$A_i = A^{c_i}, \quad \text{where} \quad A = \prod_{i=1}^{N} A_i \tag{1}$$

This c_i is assessed heuristically via six metrics, with score 1-10 relative to all other systems:

1. *Repair Time:* The average time for system repair. Includes identification, diagnostics, access, repair and recovery. In the FCC, it may also include a 45 minute drive.
2. *Criticality:* The fraction of system interlocks that can block the beam; as opposed to those that produce warning flags or that can be compensated elsewhere.
3. *Intricacy:* The number of complexly interacting parts. This distinguishes complex systems contained to a small number of units from those with numerous occurrences.
4. *Technical Maturity:* From "largely theoretical and unsubstantiated" to "could buy it off the shelf", how new is the system's enabling technology?
5. *Performance Time:* The fraction of time the system needs to function. Ceteris paribus, a system required all year causes more unavailability than a system required one day.

6. *Environment:* The severity of radiation conditions in which the system operates.

The processing of these scores to produce c_i, A_i is adequately treated in a separate report [29], as well as studies on the Compact Linear Collider (CLIC) [51, 52] and FCC-hh [6], so will not be repeated here. In summary, the Bracha method [56] is used as technical maturity is deemed to be dominant. The DEMATEL procedure [55] is then applied, which weights each system according to the net probability of it causing child faults in other systems. For this, the relation matrix was constructed from LHC data [13] with liability gauged by the number of child faults beneath each system and vulnerability by the parent faults above.

The six metrics were assessed via interviews and aggregated scores from twenty-one accelerator experts with a wide ("generalist") profile and diverse backgrounds from R&D to Operation. The result is a collective opinion from CERN's intellectual body that balances a broad range of visions for the FCC-ee and mediates between disputed or unsettled specifics. Results are shown in Fig. 1 and compared with achieved performance in the LHC in Run 2, 2016-2018. The size of each slice represents the unavailability $(1 - a_i)$ allowed in the respective system.

The accelerating Radio Frequency (RF) and Top-Up Booster Ring were consistently viewed as most complex with regards to availability assurance, and therefore given the lowest availability requirements. In the Injection Systems, tolerances in orbit, kicker and septum fields must be designed to give tolerable background noise that allows for data taking in the experiments during injection [30]. The Electrical Network is responsible for many child faults caused by trips and glitches in the incoming supply [44]. Vacuum systems, while quasi-routine in the LHC, encounter complications at the FCC-ee interaction region and machine detector interface where there is synchrotron light at highest power and critical energy [30].

Some systems drop in rankings. Cryogenics is less complex in the FCC-ee since magnets are mostly warm. Power converters appear unusually low - this is explained by top-up injection. Since the main collider rings operate at constant energy, their converters contend with a small range of power and are comparatively straightforward [60]. The complexity is instead transferred to the top-up booster, where ramping requires large power fluctuations in short timescales.

3.2 Establish availability projections (RF system)

With goals defined, the distance to these goals must be ascertained. For each system in Fig. 1a, the projected availability must be assessed by scaling performance in comparable accelerators to existing designs. By comparing target and projected values, an overall feasibility assessment of availability in the FCC-ee is produced.

Projected availability is studied in Monte Carlo simulation using the AvailSim4 [14] framework, a discrete event tool developed in-house at CERN for analysing availability and reliability in complex systems. The simulation consists of six operation phases, shown in Fig. 2, according to the top-up injection fill cycle:

1. *Set Up:* Magnets are cycled, RF units are set and equipment is prepared for injection, 10 minutes.
2. *Fill:* Bunches are injected into the main colliding rings via the injector complex, including the top-up booster, 5 minutes.

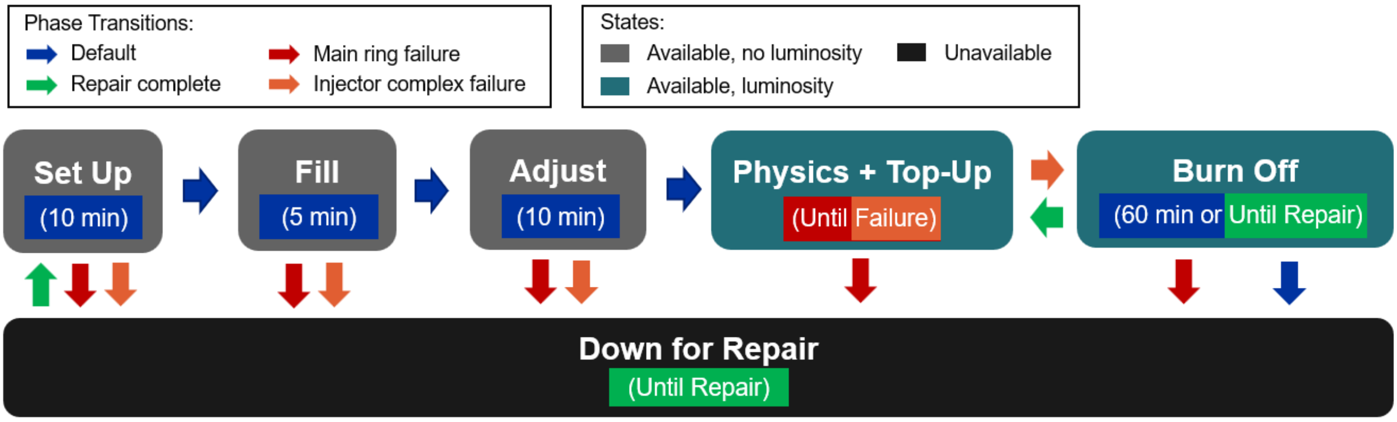


Figure 2: Monte Carlo model for FCC-ee fill cycle

3. *Adjust:* Final adjustments are made to equipment and beam in preparation for collisions, 10 minutes.
4. *Physics + Top-Up:* Collisions begin and luminosity is produced. With top-up injection, this continues until equipment failure.
5. *Burn Off:* If the injector complex fails, the main colliding beams can be maintained with decaying luminosity for approximately 60 minutes, after which the accelerator goes down for repair.
6. *Down for Repair:* If the main colliding rings fail in any phase, or any system fails during initialisation (phases 1-3), the accelerator is stopped for repair.

The accelerator moves through each of these phases by default according to the blue arrows. Faults and failures may occur in any phase except Down for Repair. On failure, the default phase sequence is interrupted according to the red (main ring) and orange (injector complex) arrows. Following failure, a repair process restores the default phase sequence according to the green arrows. The default times indicated in each phase are reasoned from the LEP operation cycle [12] and research in [46].

Projected availability must be assessed individually for each system. Until this is explicitly modelled, the availability in Fig. 1a is assumed. By replacing target with projected availability, this Monte Carlo approach permits holistic assessment of the overall accelerator performance.

Projection has begun with the RF system, since it is evaluated as one of the most complex systems for availability assurance in the FCC-ee. The configuration for each energy mode (Z, W, H and $t\bar{t}$) is summarised in Tab. 1 [50]. All superconducting accelerating RF cavities will be horizontally tested to a margin 10% above their nominal voltage. Therefore, theoretically, nominal beam energy can be preserved if no more than 10% of the cavities are unavailable. Practically, this is feasible only for the H and $t\bar{t}$ modes, where the beam current is relatively low. In Z and W, the level of beam loading is such that a tripped cavity must dump the beam to prevent further damage to equipment. For the purposes of availability, there are two models: In (Z, W) there is 0% redundancy and in $(H, t\bar{t})$ there is 10%.

Energy Mode	$\boldsymbol{Z}$		$\boldsymbol{W}$		$\boldsymbol{H}$		$\boldsymbol{t\bar{t}}$	
	45.6 GeV		80 GeV		120 GeV		182.5 GeV	
	main*	booster	main*	booster	main†	booster	main†	booster
Voltage (MV)	80	140	1050	1050	2100	2100	9200‡	11300
Cavity voltage (MV)	1.43	5.83	7.95	18.75	7.95	18.75	18.85	18.83
Gradient (MV/m)	3.81	6.23	10.61	20.01	10.61	20.01	20.12	20.10
Beam current (mA)	1280	128	135	13.5	53.4	3	10	0.5
# Cells / cavity	1	5	2	5	2	5	5	5
# Cavities	56	24	132	56	264	112	752‡	600

Table 1: RF configurations in FCC-ee [50]
*Per beam; †Both beams; ‡Includes cavities from H mode

RF faults and resulting repair times are modelled probabilistically. RF faults are categorised in two types: *Short Faults* are reparable via remote reset; *Long Faults* require human intervention and cannot be repaired while the beam is running. For example, a booster cavity can be repaired in Burn Off only if the fault is Short. Note that a fault is not the same as failure. In $(H, t\bar{t})$, a Short fault can be repaired without changing phase provided the total number of tripped cavities does not exceed 10%. However, if the fault is Long, repair must wait until the accelerator is Down for Repair.

Key simulation inputs are the four probability distributions governing occurrences and repair times for Short and Long Faults. These are fitted to LHC run time data [13], where a 45 minute drive is added to the Long Fault repair time to accommodate the longer distances a technician would have to drive to repair the FCC-ee. The four distributions describe faults in a single cavity, so exposure to RF trips rises with the number of cavities in each mode.

The simulation is a projection of the FCC-ee if the reliability and repair time per RF circuit stay as they are in the LHC. Each energy mode was simulated through 100 years of operation, with results shown in Fig. 3 (assuming every system apart from the RF achieves its availability target defined in Fig. 1a). The drop in availability from Z to W is explained by the greater number of cavities and therefore greater exposure to RF faults. While the number of cavities also increases through $(H, t\bar{t})$, the 10% voltage redundancy in these modes keeps availability above the 80% global requirement for all systems.

Clearly, projections for the (Z, W) modes are inadequate. In W, the availability of the RF system alone brings global availability to 61%. Granted, these projections are modelled from the LHC, which is a significantly different machine. But little consolation is found in other systems: The KEK-B superconducting cavities were more similar to the (Z, W) configuration, with beam current 1400 mA and 6 MV/m accelerating gradient. These saw five times the trip rate per cavity of the LHC, until they dropped the beam current by 30% in 2007 [3, 41].

3.3 How can we do better?

Evidently, a solution must be found for RF availability in the Z and W modes. This section discusses and analyses five possible answers.

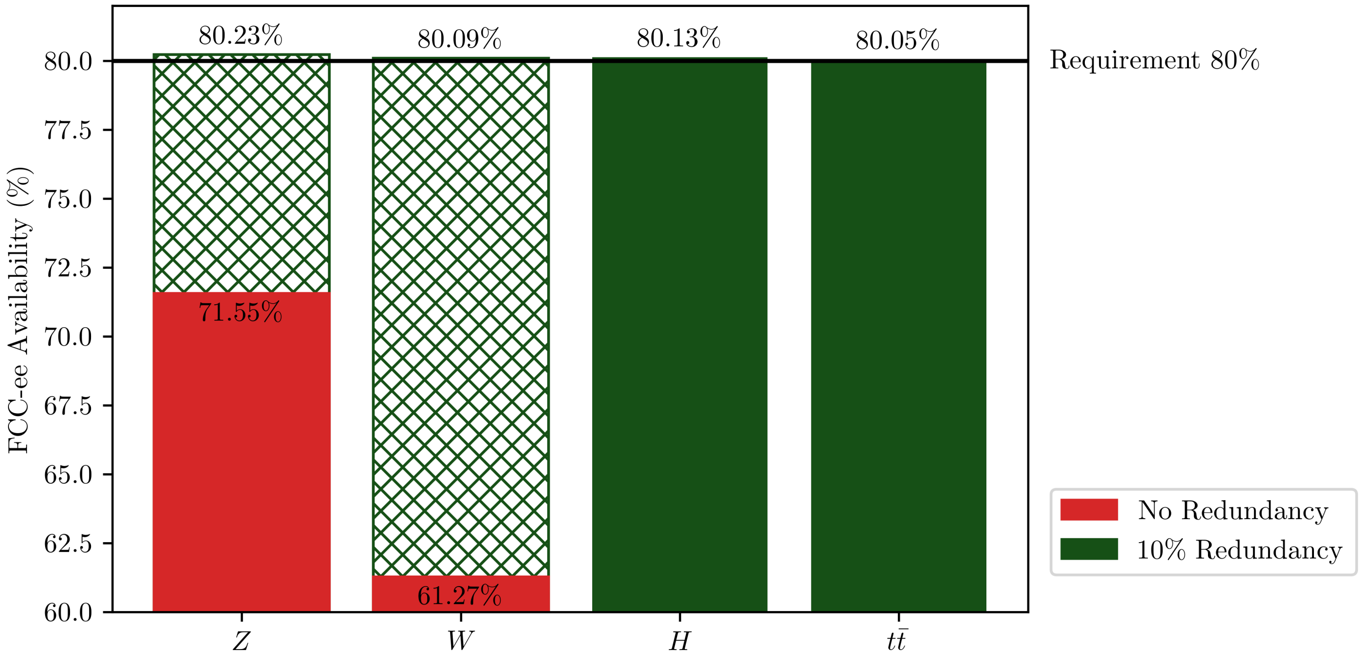
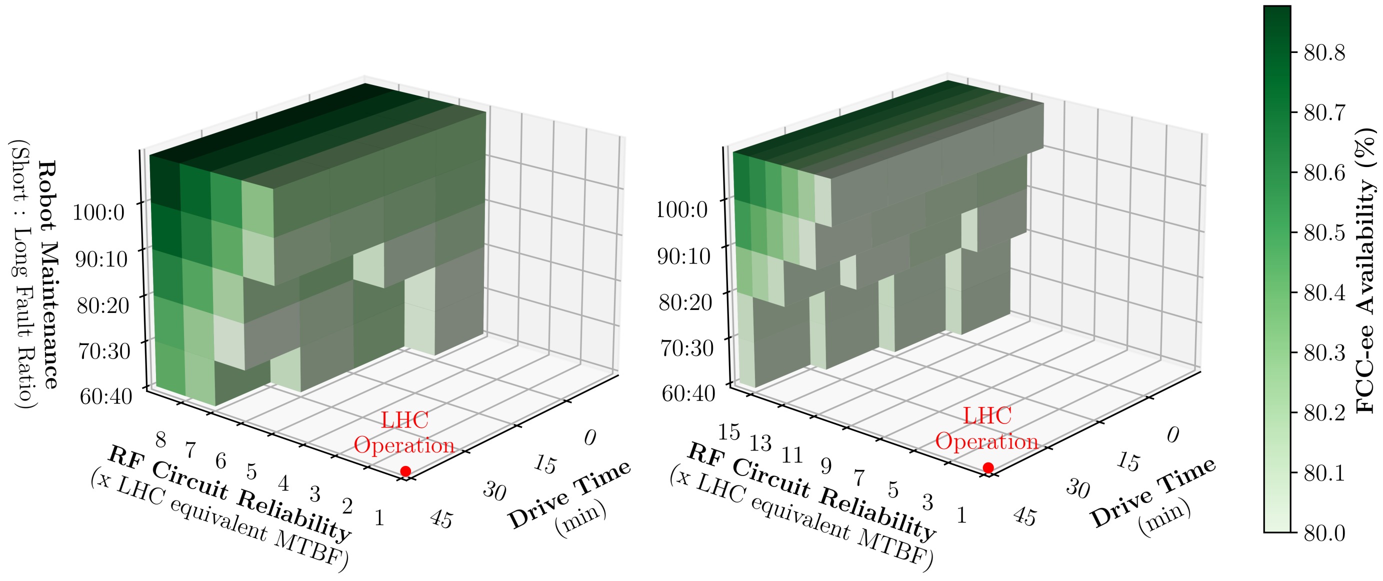


Figure 3: Projected availability of the FCC-ee based on LHC experience in the RF system (assuming all other systems meet targets in Fig. 1a). In Z and W modes, no redundancy is possible as the level of beam loading will require beam dump on any cavity trip. The hashed bars show projected performance if a solution for 10% redundancy can be found.

(1) Ferroelectric Fast Reactive Tuning: Current projections in the (Z, W) modes assume that beam dump is required on any cavity trip. However, cavities at all energy modes in the FCC-ee will be horizontally tested with the same 10% voltage margin. Therefore, if the beam dump requirement can be relaxed, the same redundancy seen in $(H, t\bar{t})$ could be emulated. Practically, this is possible if the tripped cavity can be rapidly detuned before significant damage is inflicted on the circuit. A candidate technology for this is ferroelectric fast reactive tuning with response time in the order of $4\mu s$ [34]. The technical feasibility of this solution still requires research; but projections, illustrated by hashed bars in Fig. 3, show that the ability to preserve the beam on a cavity trip would adequately meet availability requirements in the Z and W modes.

(2) RF Circuit Reliability: If a solution to preserve the beam after a cavity trip cannot be found, a radical departure from the LHC paradigm is required. The most obvious solution is to make the hardware more reliable. Analysis of the Super Proton Synchrotron (SPS) RF system in [24] showed significant availability gain by exploiting the natural redundancy in solid state power amplifiers. This experience is mirrored by implementations at SOLEIL [39, 40] and ESRF [32]. At the current state-of-the-art, the constraint is the volume required per kW, which is significantly greater than traditional vacuum tubes. Broadly speaking, the challenge is to find opportunities that do not significantly alter the footprint and/or complexity of the RF system overall. The key metric here is the Mean Time Between Failures (MTBF) per RF circuit, quantified for illustration (see Fig. 4,5) in multiples of the LHC equivalent value.



(a) Z mode

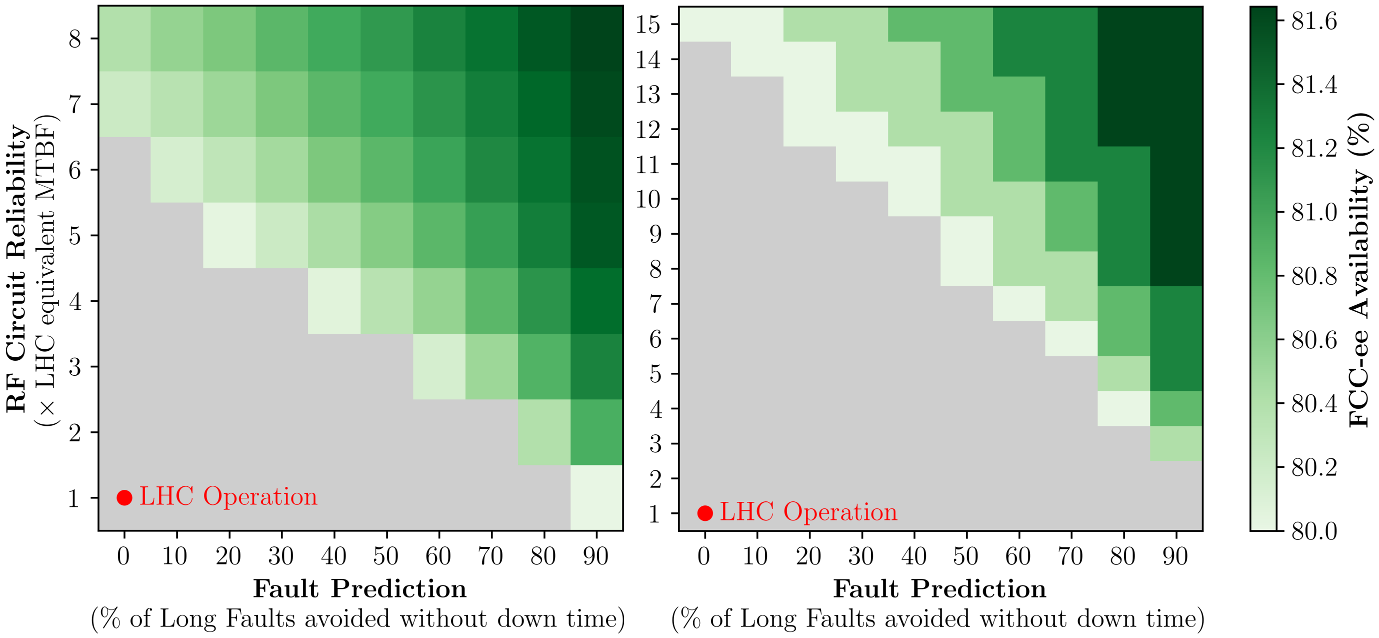
(b) W mode

Figure 4: FCC-ee availability projections with increments in drive time, robot maintenance and RF hardware reliability.

(3) Drive Time: To drive the diameter of the FCC ring will take 45 minutes or more depending on traffic. This is a significant time penalty, incurred every time a human is required to make a repair. Technologically simple solutions exist to reduce this: Teams of technicians could be distributed around the ring, or even transported by helicopter. These solutions are constrained by feasibility from a logistics and budget perspective, but would require little Research and Development (R&D) work to implement. A reduction in drive time is simulated by adjusting the time penalty applied in the event of Long Faults (i.e. those that require human repair).

(4) Robot Maintenance: With enhanced and targeted R&D, many visions are possible. One is to design the FCC-ee like it is to operate in outer space, i.e. with no human intervention during its 15+ year operation cycle. In this case, robots must replace human technicians in the event of faults. This is a topic for which there is significant progress [19]. If more faults were reparable without human intervention, not only would the drive time be eliminated but also more repairs could be achieved while the beam is running. This solution is modelled by the ratio of Short:Long faults (currently 60:40 for the LHC RF system [13]).

(5) Fault Prediction: Finally, opportunities exist in the exciting research space of fault prediction, condition-based maintenance and digital twins: With sensor readings fed into a live simulation, the health of active components can be understood in real time, delivering advanced warning of deterioration and/or upcoming faults. At the next technical stop, a team can be ready with all the necessary parts, tools and skills to quickly make the repair without any disruption to the operation schedule at all. The ability to pre-emptively replace components in response to a change in asset health also prevents the consequences of faults occurring, i.e. child faults in other systems and collateral damage. Techniques to achieve fault prognosis and predictive/prescriptive maintenance form part of an active and vibrant



(a) Z mode

(b) W mode

Figure 5: FCC-ee availability projections with increments in fault prediction and RF hardware reliability.

research field. They generally fall into two categories: Physics-Based and Data-Driven models. Physics-based models, e.g. [47, 33, 21], derive a specific mathematical formulation for each intended purpose using well understood physical concepts. This form of analysis is highly mature; however, the various required assumptions and approximations often lead to a significant amount of physics being ignored. Data-driven models, e.g. [45, 25, 20, 23, 15, 58], include black box and machine learning techniques. These can describe both known and unknown physics by constructing nonlinear statistical representations of inputs and outputs; however, they are brittle to the quality and volume of their training dataset. Fault prediction models are generally time consuming and costly to develop, therefore it is assumed these will only be implemented for serious faults - i.e. human-repair faults starting with the longest repair times. This solution is quantified by the percentage of Long Faults that are correctly predicted and avoided.

Availability projections for the FCC-ee with increments in solutions *(2)-(4)* are shown in Fig. 4. With a pure hardware reliability approach, a seven- and fifteen-fold improvement in LHC RF circuit MTBF is required for the Z and W modes, respectively, if acceptable availability is to be achieved. Robot maintenance and drive time have the potential to bring this goal-post closer by no more than 30%.

Availability projections for fault prediction are shown Fig. 5. Here, the relation is almost linear such that 90% fault prediction eliminates the need to improve reliability in the Z mode, and reduces to three-fold requirement in W.

4 Conclusion and Outlook

Machine protection and availability are vital considerations from the outset of the design stage in the FCC-ee. This paper presents the current status and outlook for analysis as well as research and development (R&D) in both fields.

4.1 Machine Protection

Machine protection will play an important role to ensure a safe and efficient exploitation of the FCC-ee. Various important topics are discussed. However, detailed studies on failure cases and protection hardware must be performed to ensure an adequate design of the machine protection system.

4.2 Availability

Availability is a significant risk to physics targets in the FCC-ee. A design according to the LHC archetype is unlikely to achieve integrated luminosity goals, and a groundbreaking transformation in operation and maintenance paradigm is required. This chapter deconstructs availability in the FCC-ee and discusses relevant assurance solutions.

The problem is tackled system by system, for which a three step approach is demonstrated: (I) Coarse availability requirements are defined. (II) Projected availability is established. (III) Where the latter is insufficient, solutions are proposed.

In Step (I), a heuristic methodology is presented to scale availability requirements according to their complexity. For the first time, this quantifies availability requirements for each top-level system in the FCC-ee. The contributions of this are twofold: First, it provides a benchmark for each system to assess the combined severity of the FCC-ee availability challenge. Second, the methodology provides a platform to translate changes in one system's availability to that of the FCC-ee overall. This is essential as system designs develop and new data emerges, and is applicable to many future availability studies such as budget allocation and performance/cost optimisation.

In Step (II), projected availability of the RF is established assuming LHC performance as prototype. Results show that while forecasts for H and $t\bar{t}$ are acceptable, those for Z and W modes are highly inadequate. The key difference lies in the ability to preserve the beam if 10% of cavities trip in $(H, t\bar{t})$, which is not possible in (Z, W). A solution must be found.

In Step (III), solutions to the availability challenge are discussed. If a technique can be found to avoid beam dump on cavity trip in the (Z, W) modes, the resulting redundancy would deliver acceptable availability, assuming LHC reliability and repair times can be maintained. Candidate technologies for this are available, and research must be conducted to establish their feasibility. If beam dump cannot be avoided, a fifteen-fold improvement in the reliability per cavity circuit is required in the W mode. However, this requirement can be significantly reduced by exploiting R&D opportunities on the intervention side. Reducing the drive time associated with human-repair faults, and increasing the proportion of faults that are reparable during active beam by robot maintenance, can reduce the requirement by no more than 30%. Meanwhile, the scope for fault prediction is vast and, if properly exploited, this research space could deliver game-changing advantage.

The near term research outlook is to assess the feasibility of rapid cavity detuning in effort to exploit redundancy in the (Z, W) modes. Meanwhile, a break down of historical faults in the LHC RF system will be conducted to identify opportunities for hardware redundancy and fault prediction. In the longer term, steps (II) and (III) shall be repeated for all the other systems in Fig. 1a to ensure that availability is adequately considered in the FCC-ee design process and its risk is eliminated towards integrated luminosity targets.

References

[1] A. Abada et al. FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2. *European Physical Journal: Special Topics*, 228(2):261–623, 6 2019.

[2] A. Abada et al. FCC-hh: The hadron collider. *The European Physical Journal Special Topics*, 228(4):755–1107, 2019.

[3] Tetsuo Abe, Kazunori Akai, Nobumasa Akasaka, Kiyokazu Ebihara, Eizi Ezura, Takaaki Furuya, Kazufumi Hara, Teruya Honma, Kenji Hosoyama, Shigeru Isagawa, Atsushi Kabe, Tatsuya Kageyama, Tetsuya Kobayashi, Yuuji Kojima, Katsumi Marutsuka, Shinji Mitsunobu, Hajime Mizuno, Yoshiyuki Morita, Fujio Naito, Hirotaka Nakai, Hiroshi Nakanishi, Kota Nakanishi, Sigeshi Ninomiya, Michiru Nishiwaki, Masaaki Ono, Hiroshi Sakai, Masaaki Suetake, Tsuyoshi Tajima, Takeshi Takahashi, Susumu Takano, Yasunao Takeuchi, Yasuchika Yamamoto, Yoshishige Yamazaki, Masato Yoshida, Shin Ichi Yoshimoto, and Kazuo Yoshino. Performance and operation results of the RF systems at the KEK B-factory. *Progress of Theoretical and Experimental Physics*, 03A006, 3 2013.

[4] O. Aberle et al. *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report.* CERN Yellow Reports: Monographs. CERN, Geneva, 2020.

[5] F. Abusaif. Investigations on nbti superconducting racetrack coils under pulsed-current excitations. In *Proc. 14th International Particle Accelerator Conference*, number 14 in IPAC'23 - 14th International Particle Accelerator Conference, pages 3688–3691. JACoW Publishing, Geneva, Switzerland, 05 2023.

[6] Andrea Apollonio. Conclusions on FCC Availability Studies. In *FCC Week*, Amsterdam, 2018.

[7] P. Bélanger, R. Baartman, G. Iadarola, A. Lechner, B. Lindstrom, R. Schmidt, and D. Wollmann. Charging mechanisms and orbital dynamics of charged dust grains in the lhc. *Phys. Rev. Accel. Beams*, 25:101001, Oct 2022.

[8] M. Benedikt, A. Chance, B. Dalena, D. Denisov, M. Giovannozzi, J. Gutleber, R. Losito, M. Mangano, T. Raubenheimer, W. Riegler, V. Shiltsev, D. Schulte, D. Tommasini, and F. Zimmermann. Future circular hadron collider FCC-hh: Overview and status, 2022.

[9] Michael Benedikt, Alain Blondel, Olivier Brunner, Mar Capeans Garrido, Francesco Cerutti, Johannes Gutleber, Patrick Janot, Jose Miguel Jimenez, Volker Mertens, Attilio Milanese, Katsunobu Oide, John Andrew Osborne, Thomas Otto, Yannis Papaphilippou, John Poole, Laurent Jean Tavian, and Frank Zimmermann. FCC-ee: The Lepton Collider: Future Circular Collider Conceptual Design Report Volume 2. Future Circular Collider. Technical Report 2, CERN, Geneva, 2019.

[10] Juan Blanco Sancho. Machine Protection and High Energy Density States in Matter for High Energy Hadron Accelerators, 2014. presented 04 Feb 2014.

[11] Florian Burkart. Expected damage to accelerator equipment due to the impact of the full LHC beam: beam instrumentation, experiments and simulations, 2016. Presented 20 Jun 2016.

[12] A. Butterworth, P. Brown, O. Brunner, E. Ciapala, H. Frischholz, G. Geschonke, E. Peschardt, and J. Sladen. The LEP2 superconducting RF system. *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 587(2-3):151–177, 3 2008.

[13] CERN. Accelerator fault tracking. https://aft.cern.ch/.

[14] CERN. Availsim4. https://gitlab.cern.ch/availsim4/availsim4.

[15] Owen Convery, Lewis Smith, Yarin Gal, and Adi Hanuka. Uncertainty quantification for virtual diagnostic of particle accelerators. *Phys. Rev. Accel. Beams*, 24:074602, 7 2021.

[16] Giorgio D'Angelo, Zinour Charifoulline, Reiner Denz, Mathieu Favre, Dietrich Hagedorn, Arnaud Monteuuis, Felix Rodriguez-Mateos, Andrzej Siemko, Krzysztof Stachon, Arjan Verweij, Andreas Will, and Daniel Wollmann. Performance of the large hadron collider's cryogenic bypass diodes over the first two physics runs, future projects, and perspectives. *IEEE Transactions on Applied Superconductivity*, 30(4):1–4, 2020.

[17] R. Denz, A. Gharib, and D. Hagedorn. Radiation Resistance and Life Time Estimates at Cryogenic Temperatures of Series Produced By-Pass Diodes for the LHC Magnet Protection. *AIP Conference Proceedings*, 711(1):763–772, 06 2004.

[18] R. Denz and D. Hagedorn. *Expected Lifetime of By-Pass Diodes for the LHC Magnet Protection Subjected to Liquid Helium Temperatures and Irradiation*, pages 375–382. Springer US, Boston, MA, 2000.

[19] Mario Di Castro, Hannes Gamper, Luca Buonocore, Eloise Matheson, and Alessandro Masi. Robotic solutions for the inspection and remote maintenance of particle accelerators. In *Proceedings of FCC Week 2023*, London, United Kingdom, 2023.

[20] Yann Donon, Alexander Kupriyanov, Dmitriy Kirsh, Alberto Di Meglio, Rustam Paringer, Igor Rytsarev, Pavel Serafimovich, and Sergey Syomic. Extended anomaly detection and breakdown prediction in LINAC 4's RF power source output. In *2020 International Conference on Information Technology and Nanotechnology (ITNT)*, pages 1–7, 2020.

[21] D. Dotson, M. Drury, R. May, and C. Reece. Use of Simple X-ray Measurements in the Performance Analysis of Cryogenic RF Accelerator Cavities. Technical report, Thomas Jefferson National Accelerator Facility, Newport News, Virginia, 23606, USA, January 1996.

[22] Yann Dutheil and R.L. Ramjiawan. Top-up injection baseline scenario. In *Proceedings of FCC Week 2023*, London, United Kingdom, 6 2023.

[23] C. Emma, A. Edelen, M. J. Hogan, B. O'Shea, G. White, and V. Yakimenko. Machine learning-based longitudinal phase space prediction of particle accelerators. *Phys. Rev. Accel. Beams*, 21:112802, 11 2018.

[24] L Felsberger, A Apollonio, T Cartier-Michaud, E Montesinos, J C Oliveira, and J Uythoven CERN. Availability Modeling of the Solid-State Power Amplifiers for the CERN SPS RF Upgrade. In *12th International Particle Accelerator Conference*, pages 2308–2311, Campinas, SP, Brazil, 2021. JACoW Publishing.

[25] E. Fol, R. Tomás, J. Coello de Portugal, and G. Franchetti. Detection of faulty beam position monitors using unsupervised learning. *Phys. Rev. Accel. Beams*, 23:102805, 10 2020.

[26] D. Gancarcik. Damage experiment with superconducting sample coils - experimental setup and observations during beam impact. In *Proc. 14th International Particle Accelerator Conference*, number 14 in IPAC'23 - 14th International Particle Accelerator Conference, pages 3653–3656. JACoW Publishing, Geneva, Switzerland, 05 2023.

[27] D. Gancarcik. Energy deposition simulations for a damage experiment with superconducting sample coils. In *Proc. 14th International Particle Accelerator Conference*, number 14 in IPAC'23 - 14th International Particle Accelerator Conference, pages 3649–3652. JACoW Publishing, Geneva, Switzerland, 05 2023.

[28] Cédric Hernalsteens, Meritxell Villén Basco, Oskari Kristian Tuormaa, Bjorn Hans Lindstrom, Emmanuele Ravaioli, Christoph Wiesner, and Daniel Wollmann. Effect of a spurious cliq firing on the circulating beam in hl-lhc. *Proceedings of the 13th Int. Particle Accelerator Conf.*, IPAC2022, 2022. SeriesInformation Proceedings of the 13th Int. Particle Accelerator Conf., IPAC2022, Bangkok, Thailand.

[29] John W. Heron, Lukas Felsberger, Daniel Wollmann, Jan Uythoven, and Felix Rodriguez-Mateos. Availability targets scaled according to assurance complexity in the FCC-ee. CERN-ACC-NOTE-2023-0020, 2023. `https://cds.cern.ch/record/2880189`.

[30] Bernhard Holzer. Private communication, 3 2023. CERN.

[31] H. Ikeda. Observation of sudden beam loss in SuperKEKB. In *Proc. 14th International Particle Accelerator Conference*, number 14 in IPAC'23 - 14th International Particle Accelerator Conference, pages 698–701. JACoW Publishing, Geneva, Switzerland, 05 2023.

[32] J. Jacob, G. Gautier, M.L. Langlois, and J.M. Mercier. 352.2 mhz – 150 kw solid state amplifiers at the esrf. In *International Particle Accelerator Conference (IPAC 2011)*, 2011.

[33] Eiji Kako, Taro Konomi, Takako Miura, Hiroshi Sakai, and Kensei Umemori. Degradation and Recovery of Cavity Performances in Compact-ERL Injector Cryomodule. In *Proceedings of the 18th Int. Conf. on RF Superconductivity*, volume SRF2017, pages 5 pages, 2.013 MB, 2018. Artwork Size: 5 pages, 2.013 MB ISBN: 9783954501915 Medium: PDF Publisher: JACoW, Geneva, Switzerland.

[34] A Kanareykin, I Ben-Zvi, A Castilla, B Freemire, C Jing, A Macpherson, S Poddar, and N Shipman. Ferroelectric fast reactive tuner for srf cavities - material properties and its applications. In *Proceedings of FCC Week 2023*, London, United Kingdom, 2023.

[35] A. Lechner, P. Bélanger, I. Efthymiopoulos, L. Grob, B. Lindstrom, R. Schmidt, and D. Wollmann. Dust-induced beam losses in the cryogenic arcs of the CERN Large Hadron Collider. *Phys. Rev. Accel. Beams*, 25:041001, Apr 2022.

[36] B. Lindstrom, P. Bélanger, A. Gorzawski, J. Kral, A. Lechner, B. Salvachua, R. Schmidt, A. Siemko, M. Vaananen, D. Valuch, C. Wiesner, D. Wollmann, and C. Zamantzas. Dynamics of the interaction of dust particles with the LHC beam. *Phys. Rev. Accel. Beams*, 23:124501, Dec 2020.

[37] B Lindstrom, P Bélanger, L Bortot, R Denz, M Mentink, E Ravaioli, F Rodriguez Mateos, R Schmidt, J Uythoven, M Valette, A Verweij, C Wiesner, D Wollmann, and M Zerlauth. Fast failures in the lhc and the future high luminosity lhc. *Phys. Rev. Accel. Beams*, 23:81001, 8 2020.

[38] Bjorn Hans Filip Lindstrom. Criticality of fast failures in the high luminosity large hadron collider, 2021.

[39] P. Marchand. Review and Prospects of RF Solid State Power Amplifiers for Particle Accelerators. In *International Particle Accelerator Conference (IPAC)*, pages 2537–2542, Copenhagen, Denmark, 8 2017. European Spallation Source.

[40] Patrick Marchand, Moussa El Ajjouri, R. Lopes, F. Ribeiro, and T. Ruan. Development of high rf power solid state amplifiers at soleil. In *Proc. of the International Particle Accelerator Conference (IPAC)*, 2011.

[41] K. Nakanishi, M. Nishiwaki, T. Kobayashi, and K. Hirosawa. SRF systems for KEKB and SuperKEKB. In *Proceedings of the 62nd ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2018)*, pages 256–263. Joint Accelerator Conferences Website (JACoW), 2 2019.

[42] Y. Nie, C. Fichera, L. Mettler, F. Carra, R. Schmidt, N. A. Tahir, A. Bertarelli, and D. Wollmann. Simulation of hydrodynamic tunneling induced by high-energy proton beam in copper by coupling computer codes. *Phys. Rev. Accel. Beams*, 22:014501, Jan 2019.

[43] Y. Nie, R. Schmidt, J. Uythoven, C. Wiesner, D. Wollmann, and M. Zerlauth. Machine protection strategy of next generation high-energy circular accelerators. *Phys. Rev. Accel. Beams*, 2023. submitted.

[44] Jesper Nielsen. Private communication, 3 2023. CERN.

[45] Christoph Obermair, Thomas Cartier-Michaud, Andrea Apollonio, William Millar, Lukas Felsberger, Lorenz Fischl, Holger Severin Bovbjerg, Daniel Wollmann, Walter Wuensch, Nuria Catalan-Lasheras, Mar çà Boronat, Franz Pernkopf, and Graeme Burt. Explainable machine learning for breakdown prediction in high gradient RF cavities. *Phys. Rev. Accel. Beams*, 25:104601, 10 2022.

[46] K Oide. Injection time for the collider rings. Technical report, UNIGE/CERN, Geneva, Switzerland, 11 2022.

[47] Charles Peters, Alexander Aleksandrov, Willem Blokland, Mark Crofford, Douglas Curry, Craig Deibele, George Dodson, John Galambos, Glen Johns, Thomas Justice, Sang-Ho Kim, Thomas Pelaia II, Michael Plum, and Andrei Shishlo. Superconducting Radio Frequency Cavity Degradation Due to Errant Beam. In *Proceedings of the 6th Int. Particle Accelerator Conf.*, volume IPAC2015, pages 3 pages, 1.620 MB, 2015. Artwork Size: 3 pages, 1.620 MB ISBN: 9783954501687 Medium: PDF Publisher: JACoW, Geneva, Switzerland.

[48] Vivien Raginel. Study of the Damage Mechanisms and Limits of Superconducting Magnet Components due to Beam Impact, Jun 2018. Presented 04 Jul 2018.

[49] Vivien Raginel, Marco Bonura, David Kleiven, Karolina Kulesz, Matthias Mentink, Carmine Senatore, Rudiger Schmidt, Andrzej Siemko, Arjan Verweij, Andreas Will, and Daniel Wollmann. First experimental results on damage limits of superconducting accelerator magnet components due to instantaneous beam impact. *IEEE Transactions on Applied Superconductivity*, 28(4):1–10, 2018.

[50] Tor Raubenheimer. Fcc accelerator overview. In *Proceedings of FCC Week 2023*, London, United Kingdom, 6 2023.

[51] O Rey Orozco, A Apollonio, M Jonker, and J Uythoven. Availability Allocation to Particle Accelerators Subsystems by Complexity Criteria. In *9th International Particle Accelerator Conference*, pages 2009–2012, Vancouver, BC, Canada, 2018. JACoW.

[52] Odei Rey Orozco. Availability estimation methods based on systems complexity. Technical report, CERN, Geneva, Switzerland, 7 2017.

[53] R. Schmidt. Overview of beam-dust issues in accelerators. Workshop on Dust Charging and Beam-Dust Interaction in Particle Accelerators, CERN 13.-15.06.2023.

[54] R Schmidt, R Assmann, E Carlier, B Dehning, R Denz, B Goddard, E B Holzer, V Kain, B Puccio, B Todd, J Uythoven, J Wenninger, and M Zerlauth. Protection of the CERN Large Hadron Collider. *New Journal of Physics*, 8(11):290, nov 2006.

[55] S. M. Seyed-Hosseini, N. Safaei, and M. J. Asgharpour. Reprioritization of failures in a system failure mode and effects analysis by decision making trial and evaluation laboratory technique. *Reliability Engineering and System Safety*, 91(8):872–881, 8 2006.

[56] A. Silvestri, D. Falcone, G. Di Bona, A. Forcina, C. Cerbaso, and V. Duraccio. A new method for reliability allocation: Critical flow method. *Lecture Notes in Mechanical Engineering*, 20:249–261, 1 2015.

[57] Naeem A. Tahir, Ruediger Schmidt, Markus Brugger, Ralph Assmann, Alexander Shutov, Igor V. Lomonosov, Viktor Gryaznov, Antonio Roberto Piriz, Serban Udrea, Dieter H. H. Hoffmann, Vladimir E. Fortov, and Claude Deutsch. Generation of warm dense matter and strongly coupled plasmas using the High Radiation on Materials facility at the CERN Super Proton Synchrotron. *Physics of Plasmas*, 16(8):082703, 08 2009.

[58] Chris Tennant, Adam Carpenter, Tom Powers, Anna Shabalina Solopova, Lasitha Vidyaratne, and Khan Iftekharuddin. Superconducting radio-frequency cavity fault classification using machine learning at jefferson laboratory. *Phys. Rev. Accel. Beams*, 23:114601, 11 2020.

[59] Shinji Terui, Hiromi Hisamatsu, Takuya Ishibashi, Ken-ichi Kanazawa, Kyo Shibata, Mitsuru Shirai, and Yusuke Suetsugu. Observation of Pressure Bursts in the SuperKEKB Positron Ring. In *9th International Particle Accelerator Conference*, 6 2018.

[60] Benjamin Todd. Private communication, 3 2023. CERN.

[61] Andreas Will. Damage mechanisms in superconductors due to the impact of high energy proton beams and radiation tolerance of cryogenic diodes used in particle accelerator magnet systems, 2021.

[62] Andreas Will, Yan Bastian, Axel Bernhard, Marco Bonura, Bernardo Bordini, Lorenzo Bortot, Mathieu Favre, Bjorn Lindstrom, Matthijs Mentink, Arnaud Monteuuis, Anke-Susanne Müller, Andreas Oslandsbotn, Ruediger Schmidt, Carmine Senatore, Andrzej Siemko, Krzysztof Stachon, Alexander Usoskin, Mika Vaananen, Arjan Verweij, and Daniel Wollmann. Beam impact experiment of 440 GeV/p protons on superconducting wires and tapes in a cryogenic environment. page THPTS066. 4 p, 2019.

[63] Andreas Will, G. D'Angelo, R. Denz, D. Hagedorn, A. Monteuuis, E. Ravaioli, F. Rodriguez Mateos, A. Siemko, K. Stachon, A. Verweij, D. Wollmann, A.-S. Mueller, and A. Bernhard. Characterization of the radiation tolerance of cryogenic diodes for the High Luminosity LHC inner triplet circuit. *Phys. Rev. Accel. Beams*, 23:053502, May 2020.