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Report

Availability Targets Scaled According to Assurance Complexity in the FCC-ee

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Abstract

The Future Circular Collider (FCC) is the leading proposal for the next generation of energy-frontier particle accelerators. Its first stage, the FCC-ee, schedules 185 days to physics each year, of which 80% must be spent at nominal parameters if integrated luminosity goals are to be reached. For comparison, the Large Hadron Collider (LHC) was available for 77% of the physics production in Run 2, 2016-2018. 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 paper presents a heuristic methodology to break down the global 80% availability requirement into the FCC-ee's main constituent systems. This quantifies availability targets that scale with the complexity (or "difficulty") of assuring availability. The contributions are threefold: First, this provides a benchmark against which to assess the severity of the FCC-ee availability challenge and the risk to availability from each system. Second, the presented methodology provides a platform to translate changes in one system's availability to that of the FCC-ee overall, which is applicable in numerous future studies. Third, the methodology is generally applicable to any future machine for which concrete and detailed designs are unavailable and may be re-utilized in numerous engineering applications.

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Contents

1 Introduction

The Future Circular Collider (FCC) is the leading proposal for the next generation of energy-frontier particle accelerators. It is proposed to run 91km adjacent to CERN's Large Hadron Collider (LHC) and Super Proton Synchrotron (SPS). With the capability to deliver unprecedented energy and luminosity, it would be the largest particle collider ever built. Operation is planned in two stages: First a lepton collider (FCC-ee) starting ∼2040, followed by a hadron collider (FCC-hh) starting ∼2065. The size and scale of these undertakings is such that the sheer number of components required to be simultaneously operational is a risk to its objectives and timeline.

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 LHC was available for 77% of the physics production in Run 2, 2016-2018 [3]. 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 paper presents a heuristic methodology to break down the global 80% availability requirement into the FCC-ee's main constituent systems. For the first time, this quantifies availability targets for each top-level system that scale with the *complexity* (or "difficulty") of assuring availability. The contributions of this are threefold:

1. This provides a benchmark against which to assess the severity of the FCC-ee availability challenge. By comparing this target availability with projected numbers based on current designs and similar existing machines, the risk to each system can be assessed.

2. The presented methodology provides a platform to translate changes in one system's availability to that of the FCC-ee overall. This is applicable to numerous future studies concerning, for example, budget allocation and performance/cost optimisation as new data emerges and system designs develop.

3. The methodology is also generally applicable to any future machine for which concrete and detailed designs are unavailable. This may be re-utilized in numerous engineering applications where reliability and availability are a concern.

The rest of this paper is structured as follows. Section 2 formally treats the proposed methodology relating to availability allocation. Section 3 describes the approach used to assess complexity based on aggregated expert opinion and historical LHC data. Section 4 displays and discusses results using this method, and compares this with achieved availability in the LHC. Finally, Section 5 concludes the topic, and Section 6 discusses the next steps.

2 Methodology

Availability is the proportion of scheduled physics days where the machine cannot deliver beam due to faults and/or failures in required components. This is given by

$$A = 1 - \frac{t_{\text{down}}}{t_{\text{total}}} \tag{1}$$

For the FCC-ee, the total time t_{total} is 185 physics days each year. Down time t_{down} is the time spent repairing and recommissioning following a fault. To achieve the 80% global availability requirement, overall down time must not exceed 20% (37 days).

The FCC-ee consists of multiple core systems (e.g. the Radio Frequency, Power Converters, Injector Complex, etc.), any of which may block the beam. Each system will contribute a certain proportion of down time and unavailability to the overall total. Down time is the product of the number of faults and mean time to repair. To achieve 80% global availability, each system must be designed such that its reliability and average repair time produce availability greater than a certain minimum. In the absence of concrete and detailed designs, bottom-up analysis is impossible. A top-down approach is presented.

2.1 Complexity

If each system is designed equally competently, down time will scale with the complexity (or "difficulty") of assuring availability in that system. Allocating softer targets to more complex systems with regards to availability assurance is the best way to produce realistic goals and the most efficient way to distribute resources among design teams.

Assume first that we can give this "complexity" a number C_s. For core systems $s = 1, ..., S$ the overall availability A relates to system availability A_s according to

$$A_s = A^{C_s} \tag{2}$$

Where

$$A = \prod_{s=1}^{S} A_s \ , \quad \sum_{s=1}^{S} C_s = 1 \tag{3}$$

The complexity of availability assurance is assessed heuristically with factors $f = 1, ..., F$, all of which influence the frequency and/or severity of faults occurring. Not exclusive to particle accelerators, the following six factors are chosen:

1. *Repair Time:* The average time to restore operation after a fault. This includes identification, diagnostics, access to the affected site, repair and recommissioning. This varies by system; but, particularly in the FCC, also by the system's location around the ring as a drive across the diameter could take 45 minutes or more.

2. *Criticality:* Some systems can fail partially without blocking the beam. For example, nominal operation can normally continue despite spurious readings from a handful of beam sensors. Other systems cannot partially fail, for example the extraction and beam dump system must be available in active beams due to safety reasons, and any

detected fault will block operation. This factor represents the fraction of a system's 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 interacting units that are described by the system. This factor represents the number of instances or elements that can independently block the beam. It distinguishes complex systems contained to a small number of units (e.g. experiments) from those with numerous occurrences distributed all around the ring (e.g. power converters).

4. *Technical Maturity:* At what stage of research and development is the enabling technology within the system? This factor scales from "largely theoretical and unsubstantiated" to "could buy it off the shelf". It is specific to the core functionality required by the system in order to deliver nominal parameters.

5. *Performance Time:* This factor is similar to Criticality, except with reference to scheduled operation time. Some systems are required to be available all year long to avoid down time, even during technical stops and shut down (e.g. cryogenics). Other systems are only required during active beam (e.g. the injector complex). Ceteris paribus, a system required all year will cause more unavailability than a system required only one day. This factor represents the fraction of the scheduled calendar year during which a failure will block the beam, causing unavailability.

6. *Environment:* Systems that operate under intense radiation conditions are generally more difficult to keep available. This factor represents the severity of conditions in which the system operates, particularly with regards to activation and synchrotron radiation.

Each factor relates only to the hardware in each system that can cause unavailability. For example, detectors within experiments may be extremely complex, but the accelerator can still operate and collide bunches with detectors offline - detectors are therefore excluded from assessment. In order to be included, hardware must have the ability to block the beam.

Each system s is given a score $\sigma_{sf} \in [1, 10]$ for each factor $f = 1, ..., F$. Score 10 represents the highest risk to availability: I.e. longest repair time, highest number of beam-blocking interlocks, highest number of units, lowest technical maturity, longest required operation period and most severe radiation conditions. The score is given relative to all other systems, and is therefore independent of any absolute numbers in each instance.

Various solutions to prioritise and combine scores σ_{sf} are presented and discussed in previous assessments on the Compact Linear Collider (CLIC) [8, 9] and FCC-hh [2]. Given the fifteen year R&D horizon for start of physics in the FCC-ee, technical maturity was deemed to be a dominant factor. The Bracha technique [11] was therefore chosen, which applies weights $\mathbf{w} = [w_1, ...w_s, ...w_S]^{\mathrm{T}}$ according to

$$w_s = \sigma_{s4} \sum_{\substack{f=1 \\ f \neq 4}}^{F} \sigma_{sf} \tag{4}$$

Where in this study $F = 6$ and integers f correspond with the enumerated factors above.

2.2 DEMATEL

The weight vector **w** may be used directly in eq. (11); however, at this stage it contains no information about the interaction between systems. The DEMATEL procedure (first presented [10]), adjusts **w** according to a system's Liability (the likelihood of it causing child faults in other systems) and Vulnerability (the likelihood of it being child to other system faults). This is to shift greater complexity onto systems with strong liability and weak vulnerability.

Induced down time is scored from 0 (no influence) to 3 (very high influence). An $S \times S$ relation matrix is constructed where element z_{pc} represents the downtime induced by parent system p on child system c

$$\mathbf{Z} = \begin{pmatrix} 0 & z_{12} & \dots & z_{1S} \\ z_{21} & 0 & \dots & z_{2S} \\ \vdots & \vdots & \ddots & \vdots \\ z_{S1} & z_{S2} & \dots & 0 \end{pmatrix} \tag{5}$$

This is first normalised

$$\mathbf{X} = \frac{\mathbf{Z}}{\max\limits_{p}\left(\sum\limits_{c} z_{pc}\right)} \tag{6}$$

And the total relation matrix defined

$$\mathbf{T} = \mathbf{X}(\mathbf{I} - \mathbf{X})^{-1} \tag{7}$$

Two vectors then emerge by taking normalised sums of rows and columns

$$\mathbf{L} = [l_1, ...l_s, ...l_S]^{\mathrm{T}}, \quad l_s = \frac{\sum\limits_{c} t_{pc}}{\sum_{p,c} t_{pc}} \tag{8}$$

$$\mathbf{V} = [v_1, ...v_s, ...v_S]^{\mathrm{T}}, \quad v_s = \frac{\sum\limits_{p} t_{pc}}{\sum_{p,c} t_{pc}} \tag{9}$$

Liability **L** describes the likelihood of system s being parent to faults in other systems. Vulnerability **V** describes that of system s being child fault of other systems. Weights are then adjusted according to

$$\hat{\mathbf{w}} = \mathbf{w} \circ (\mathbf{L} - \mathbf{V} + \mathbf{1}_S) \tag{10}$$

Where $\circ$ denotes the Hadamard product and $\mathbf{1}_S$ is an $S \times S$ matrix of ones. Complexity is then

$$\vec{C} = \frac{\hat{\mathbf{w}}}{\sum_{s=1}^{S} \hat{w}_s} \tag{11}$$

And availability targets are given from (3).

3 Assessment

Complexity scores σ_{sf} and DEMATEL relations z_{pc} were collected separately in two stages.

		Repair Time	Criticality	Intricacy	Maturity	Performance Time	Environment
Score		Average repair time for faults in this system 10: days 1: minutes	Fraction of the systems interlocks that can trigger a beam dump (% of total number of system interlocks) 10: >95% 1: <15%	Number of interacting units described by the system that can indenpendently block the beam 0: highly intricate system 1: less intricate system	Technological maturity of the enabling technology required to deliver core functionality to the system 8-10: Innovative 4-7: Existing 1-3: Established	Fraction of total operating time that the system is ***required*** to perform its function 10: Whole mission time 1: Instantaneous	Severity of radiation conditions in which the system operates 8-10: highly radioactive 4-7: average radioactive 1-3: low radioactive
System	Magnets						
	Power Converters						
	RF						
	Collimation						
	Transverse Damper						
	Beam Instrumentation						
	Machine Protection/Interlocks						
	Extraction Systems & Beam Dump						
	Vacuum						
	Cooling + Ventilation						
	Electrical Networks						
	Cryogenics						
	Top-up Booster Ring (BR)						
	SPS						
	Linac (+ chain pre-SPS)						
	Injection Systems						
	Experiments (accelerator side only)						
	Accelerator Controls (IT, etc.)						
	Access Infrastructure						
	Access System						

(a) Survey table used to apply scores σ_{sf}.

		Repair Time	Criticality	Intricacy	Maturity	Performance Time	Environment
Description:		The time needed to restore operation after a failure. This includes identification, diagnostics, access to the subsystem, repair and recovery. The FCC-ee will consist of infrastructure spanning 30km diameter. From one side to the other this is a ~45min drive. However, not all faults require personnel access and not all systems are evenly distributed. Score each system from 1-10 based on the relative severity of their average repair time. The scale below can serve as a guide.	This score is intended to reflect the impact of the systems failure on beam availability. Asuming that machine protection systems are in place, the Criticality represents the fraction of the system's interlocks that can block the beam; as opposed to those that produce warning flags or that can be compensated elsewhere. The precise number of interlocks is not necessary. Score each system from 1-10 to indicate the percentage of system faults that will likely cause beam unavailability. The scale below may serve as an optional guide.	This score reflects the number of interacting units that are described by the system. This factor represents the number of instances or elements that can independently block the beam. "If the system was a house of cards, how many levels/triangles would it have?" This is to distinguish complex systems contained to a small number of units (e.g. experiments) from those with numerous occurrences distributed all around the ring (e.g. power converters). Only the relative score matters. Score each system relative to the other systems using a number from 1-10, approximating with the scale below.	The FCC-ee conceptual design document states ambitious and unprecedented technical goals with respect to accelerator performance. But how ambitious and unprecedented? This score relates to the technological maturity of the enabling technology required to deliver these goals. An approximate scale is provided below. But, once again, it is the relative score that matters. For each system, complete the following sentence with a number from 1-10: *"The technology required to deliver the core functionality of this system is…"*	In order to maintain beam availability as per the yearly scheduled physics run, what percentage of the year is this system required to be operational? A system is "required" if its failure will lead to beam abort and/or unavailability. Each year of FCCee operation is scheduled 185 physics days, corresponding to 50% of the year. If a system is "required" only on physics days, this would have score 5. If a system is required all year long, even during YETS, this will have score 10. Mark each system score 1-10, with the approximate scale below.	A system experiencing harsh radiation conditions will tend to fail more and/or will require more development to avoid failures due to radiation. Score each system from 1-10 according to the severity of radiation conditions that its components would normally be designed to withstand.
Scale:	**10**	1+ days	95-100%	**10: Extremely Intricate** - e.g. the LHC	**10: *"Potentially Groundbreaking"*** - Viably proposed only recently. Most progress is theoretical and/or unsubstantiated.	95-100%	**10: Extremely Severe** - e.g. unshielded exposure to the beam
	9	12-24 hours	85-95%			85-95%	
	8	8-12 hours	75-85%		**8: *"Likely Groundbreaking"*** - Viably proposed only recently but progress is empirically demonstrated with a strong practical and experimental component.	75-85%	
	7	6-8 hours	65-75%		**7: *"Novel, Pioneering"*** - successfully implemented in existing accelerator systems, but only in a small number of specific high-performance applications. Numerous teething difficulties mean the full extent of this technology's benefits remain unclear.	65-75%	
	6	4-6 hours	55-65%			55-65%	
	5	3-4 hours	45-55%	**5: Middle of the road** - centre around this point if possible		45-55%	**5: Middle of the road** - centre around this point if possible
	4	2-3 hours	35-45%		**4: *"Novel, Poised"*** - soon to be rolled out for widespread adoption in a wide variety accelerator systems. Still considered 'new', but the benefits are clear and limitations well understood.	35-45%	
	3	1-2 hours	25-35%		**3: *"Industry Norm, High Performance"*** - Gradually replacing the existing status quo but mainly in high-spec low-tolerance applications. Commercial solutions exist, but tend to be expensive and niche.	25-35%	
	2	20-60 minutes	15-25%			15-25%	
	1	1-20 minutes	0-15%	**1: Extremely Simple** - e.g. a hex nut in the upper elevator shaft	**1: *"Industry norm, Status Quo"*** - The de facto standard used in industry everywhere. Commercial off-the-shelf solutions are readily	0-15%	**1: Extremely Low** - there's more radiation in my office

(b) Reference scale used to calibrate scores σ_{sf} between experts.

Figure 1: Material presented to each of 21 accelerator experts to assess complexity

3.1 Complexity

Complexity was assessed via interviews and aggregated scores from twenty-one accelerator experts at CERN. Care was taken to select those with a wide ("generalist") profile and diverse backgrounds from R&D to Operation. Each expert was provided with the survey fill table shown Fig. 1a and the reference scale in Fig. 1b. As scores are valid only relative to all other systems, each respondent was asked to fill out the whole table with a "best estimate", even if they are not a specialist in every particular field. This fully exploits the expert's professional intuition gained from a career spent working with particle accelerators, and allows for conjecture to be averaged over the sample population. 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.

M(p,c): degree to which system p affects system c in terms of induced downtime.
Would a failure in system p affect the operating state of system in column c?

0: No influence
1: Low influence
2: High influence
3: Very high influence

p	c	1 Magnets	2 Power Converters	3 RF	4 Collimation	5 Transverse Damper	6 Beam Instrumentation	7 Machine Protection/Interlocks	8 Extraction Systems & Beam Dump	9 Vacuum	10 Cooling + Ventilation	11 Electrical Networks	12 Cryogenics	13 Top-up Booster Ring (BR)	14 SPS	15 Linac (+ chain pre-SPS)	16 Injection Systems	17 Experiments (accelerator side only)	18 Accelerator Controls (IT, etc.)	19 Access Infrastructure	20 Access System	SUM
1	Magnets		1	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	**4**
2	Power Converters	1		0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	**2**
3	RF	0	0		1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
4	Collimation	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5	Transverse Damper	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
6	Beam Instrumentation	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
7	Machine Protection/Interlocks	1	0	0	0	0	0		0	0	0	0	1	0	0	0	0	0	0	0	0	**2**
8	Extraction Systems & Beam Dump	0	0	0	0	0	0	0		0	0	0	0	0	0	0	0	0	0	0	0	**0**
9	Vacuum	0	0	0	0	0	0	0	0		0	0	0	0	0	0	1	0	0	0	0	**1**
10	Cooling + Ventilation	0	1	0	1	0	1	0	0	0		0	1	0	0	0	0	1	0	0	0	**5**
11	Electrical Networks	1	3	3	0	1	0	0	0	1	0		2	1	1	1	1	1	0	0	0	**16**
12	Cryogenics	0	1	1	0	0	0	0	0	1	0	0		0	0	0	0	0	0	0	0	**3**
13	Top-up Booster Ring (BR)	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	0	**0**
14	SPS	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	0	**0**
15	Linac (+ chain pre-SPS)	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	0	**0**
16	Injection Systems	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	0	0	**1**
17	Experiments (accelerator side only)	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0		0	0	0	**1**
18	Accelerator Controls (IT, etc.)	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0		0	0	**2**
19	Access Infrastructure	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		0	**0**
20	Access System	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0		**0**
	SUM	**4**	**6**	**4**	**2**	**1**	**1**	**0**	**0**	**3**	**0**	**1**	**9**	**1**	**1**	**1**	**2**	**2**	**0**	**0**	**0**	

Figure 2: Relation matrix $\mathbf{Z}$ reasoned from expert interviews and LHC historical data in Run 2, 2016-2018.

3.2 DEMATEL

The relation matrix $\mathbf{Z}$ was populated based on LHC historical data from Run 2, 2016-2018 [3]

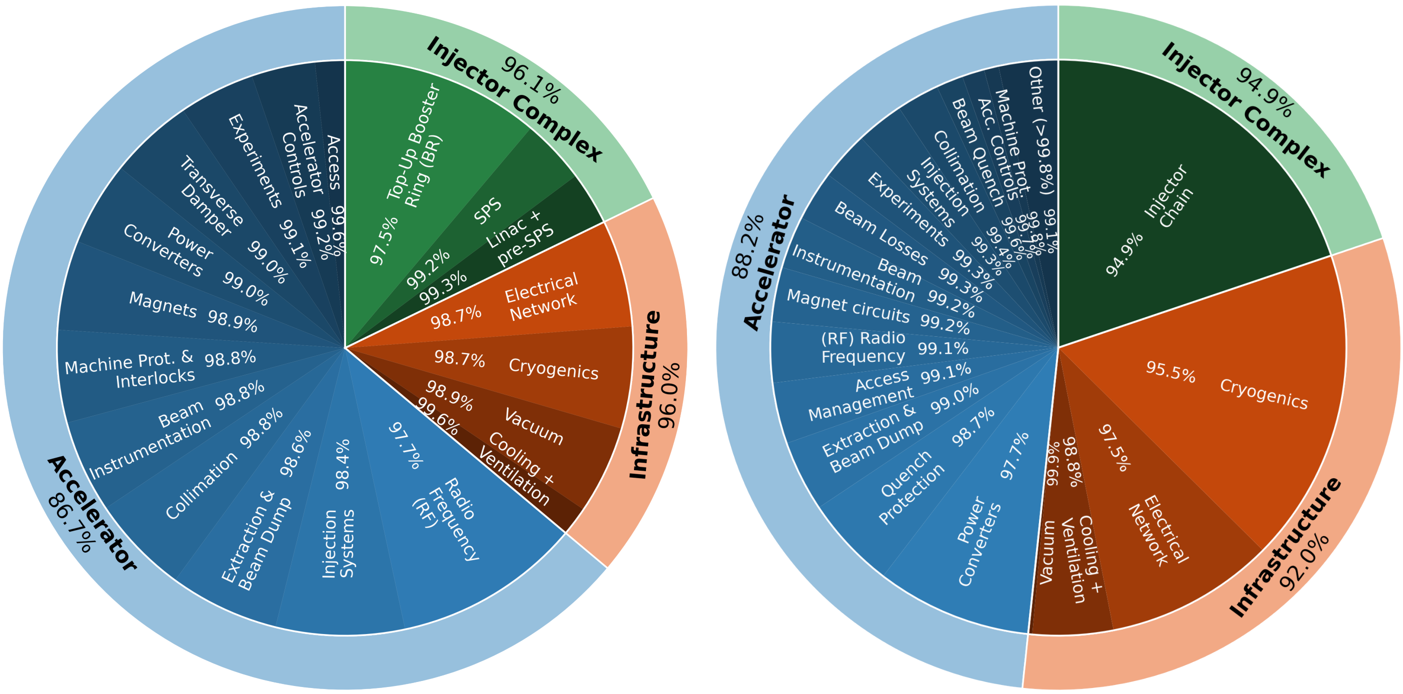
$$\mathbf{Z} = 3 \left\lceil \frac{\mathbf{N}}{\max\limits_{p,c} (n_{pc})} \right\rceil \tag{12}$$

Where $\mathbf{N}$ denotes the matrix of n_{pc}, the number of offspring faults from parent system p to child system c, and $\lceil \cdot \rceil$ is the ceiling function.

The list of core systems in the LHC is not the same as the FCC-ee. This required some rows and columns to be removed. Systems in the FCC-ee that are not present in the LHC (e.g. the top-up booster) were reasoned and adjusted according to similar systems and experience gained during interviews with experts. This delivers the relation table in Fig. 2

4 Results

Results are shown in Fig. 3 and compared with achieved performance in the LHC in Run 2, 2016-2018. The size of each slice represents the unavailability $(1 - A_s)$ allowed in the respective system.



(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 3: Accelerator availability by 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 [6]. The Electrical Network is responsible for many child faults caused by trips and glitches in the incoming supply [7]. 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 [6].

Some systems drop in rankings. Cryogenics is less complex in the FCC-ee since magnets are mostly warm. Power converters appear unexpectedly 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 [12]. The complexity is instead transferred to the top-up booster, where ramping requires large power fluctuations in short timescales.

5 Conclusion

To achieve physics goals with respect to integrated luminosity at nominal beam parameters, the FCC-ee must have an overall availability of 80%. This paper presents a heuristic methodology to break down this global requirement into main constituent systems. This quantifies, for the first time, availability targets for each top-level system that scale with the *complexity* (or "difficulty") of assuring availability. The contributions are threefold:

1. This provides a benchmark against which to assess the severity of the FCC-ee availability challenge. By comparing this target availability with projected numbers based on current designs and similar existing machines, the risk to each system can be assessed.

2. The presented methodology provides a platform to translate changes in one system's availability to that of the FCC-ee overall. This is applicable to numerous future studies concerning, for example, budget allocation and performance/cost optimisation as new data emerges and system designs develop.

3. The methodology is also generally applicable to any future machine for which concrete and detailed designs are unavailable. This may be re-utilized in numerous engineering applications where reliability and availability are a concern.

6 Outlook

With goals defined, the distance to these goals must be ascertained. For each system in Fig. 3a, 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.

This has already begun for the RF system, with results presented in [5, 4]. This study identified a 9% and 19% shortfall in global availability for the Z and W energy modes, respectively, if reliability and trip rate stay as they are in the LHC RF circuit. Multiple hardware and intervention-side solutions are explored, and collaboration with RF experts is ongoing in order to overcome this challenge.

Meanwhile, availability projection of the remaining systems will begin. The top-up booster is identified as the most complex system with regards to availability assurance in the FCC-ee. Projection will therefore continue with the Injector Complex, and subsequently all remaining systems to ensure that availability is adequately considered from the outset of the FCC design process.

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