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AVAILABILITY AND LUMINOSITY IN THE FUTURE CIRCULAR ELECTRON-POSITRON COLLIDER (FCC-ee)

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Abstract

The Future Circular Electron-Positron Collider (FCC-ee) is CERN's leading proposal for the next generation of energy-frontier particle accelerators. To reach integrated luminosity goals, it aims to be operational for minimum 80 % of the scheduled 185 physics days each year. For comparison, the Large Hadron Collider (LHC) achieved 77 % in 2016-2018. There are additional challenges in the FCC-ee due to its size, complexity and ambitious technical objectives. Availability is therefore a significant risk to physics deliverables. This paper presents the framework used to analyse availability and luminosity in the FCC-ee. To showcase its capabilities, first, a top-level system deconstruction reveals significant shortfall in forecasted W mode integrated luminosity, as well as important conclusions for the RF system. Second, two proposed technologies are simulated to overcome constraints in the Z, W operation cycle. Of these, pre-polarised bunch injection (PPBI) shows tremendous advantage for shielding integrated luminosity from a challenging availability environment.

INTRODUCTION

At 91 km circumference, the Future Circular Collider (FCC) would be the largest collider ever built. Collisions are planned in two stages: First, leptons (FCC-ee) starting ~2045; then hadrons (FCC-hh) for ~2070. For both, the sheer number and complexity of components required to simultaneously function is a risk to objectives and timeline.

The FCC-ee schedule has 185 days for physics each year, of which a minimum percent must be at nominal parameters to reach integrated luminosity goals. Availability is the proportion of physics days where the machine can deliver beam, i.e. without down time or repairs. The FCC-ee aims for minimum 80 % [1, 2]. For comparison, the 27 km Large Hadron Collider (LHC) was available for 77 % of physics production in 2016-2018 [3]. Additional challenges in the FCC-ee, like its size, complexity and ambitious technical objectives, make availability a significant risk to its physics deliverables.

Availability assurance in the FCC-ee has three steps:

1. **Targets:** An availability requirement for each core system has been allocated [4].
2. **Forecasts:** Using current designs and similar existing systems, the availability of each core system is forecasted using a Monte Carlo simulation platform [5].
3. **Solutions:** Solutions to improve availability are discussed and simulated [2, 6, 7].

To showcase the potential of this methodology, this paper presents two examples from recent studies and experiments.

AVAILABILITY MODEL

There are four energy modes in the FCC-ee, named after the particle or interaction under study: Z, W, ZH and $t\bar{t}$.

Energy Calibration

A principle task for the FCC-ee is ultra-precise measurement of electroweak (Z and W) observables, for which an accurately determined collision energy is key. This involves beam energy calibration every 10-15 minutes using non-colliding polarised pilot bunches (*pilots*), which circulate simultaneously with the main colliding bunches. The energy of these pilots is measured by resonant depolarisation (RDP), where the frequency of a kicker magnet is adjusted until the pilot's polarisation vanishes.

Pilot bunches are polarised in the main ring at the start of every fill using wiggler magnets, a process that takes roughly 2 h. Wigglers are then turned off before injection of the main colliding beam. Pilots then have a combined Touschek and gas scattering lifetime less than 20 h [8], after which the beam must be dumped to re-fill with polarised pilots.

In ZH and $t\bar{t}$ modes, the energy spread makes RDP impossible. Measurement is instead achieved by observing collisions at the interaction point (IP). This is significantly less accurate, but removes the need for polarisation at the start of every fill. Further, with top-up injection, physics can continue theoretically indefinitely, until a beam dump occurs due to machine fault or schedule end. In these modes, pilots are used to verify optics before full energy injection.

Baseline Operation Cycle

Energy calibration imposes distinct operation cycles, Figure 1:

1. *Set Up:* Equipment is prepared for injection.
2. *Pilot Bunch Injection:* Pilots are injected and equipment/optics is adjusted.
3. *Polarisation:* Z and W modes only. Wigglers are turned on to prepare pilots for RDP. Duration ~2 h.
4. *Fill:* Wigglers are turned off and the main colliding bunches are injected. Duration t_f, Table 1.
5. *Adjust:* Final adjustments are made to equipment and beam.
6. *Physics:* Collisions begin. With top-up injection, flat luminosity can be maintained.
7. *Burn Off:* If the injector complex fails, luminosity decays with lifetime τ, Table 1; before beam dump.
8. *Down for Repair:* On equipment failure, the accelerator is stopped for repair.

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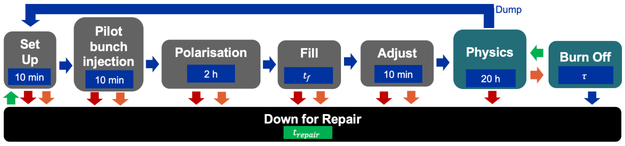
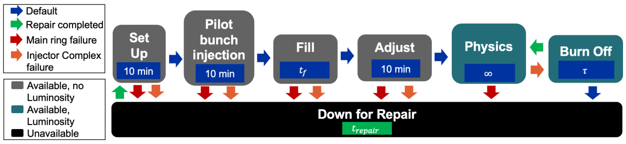


(a) Z and W modes



(b) ZH and $t\bar{t}$ modes

Figure 1: Baseline Operation Cycles in the FCC-ee.

Alternative Operation Cycles

Two R&D opportunities exist to overcome limitations in the Z, W cycle, Figure 1a.

1. *Indefinite Physics:* If pilot lifetime can be made longer than the natural polarisation time, a pilot could be topped up following measurement and allowed to naturally re-polarise. Physics can then continue indefinitely.
2. *Pre-Polarised Bunch Injection (PPBI):* If pilots can be polarised prior to injection, this phase could be eliminated entirely. This would also achieve indefinite physics, rendering the same cycle as $ZH, t\bar{t}$, Figure 1b.

SIMULATION

The collider is simulated with the Monte Carlo tool *AvailSim4* [5]. This permits statistical analysis of fault event sequences within a hierarchy of components. Basic components (e.g. RF cavities) are at the bottom of the hierarchy. Faults in basic components may cause failure of their parent component (e.g. the RF system) only if a redundancy limit is exceeded. Only failures can cause a phase change.

Default time spent in each phase is shown in blue, Figure 1. Faults may occur in any phase except Down for Repair. On failure, the default phase sequence is interrupted according to red (main ring) and orange (injector complex) arrows. Following failure, a repair process restores the default phase sequence via the green arrows.

Faults are categorised in two types: *Remote* repair can be done from the control room, e.g. by resetting components or via robot maintenance. *Human* repair requires intervention by personnel, so a drive time between 20 min and 1 h is added to simulate approach to the fault location.

Key simulation inputs are the probability distributions concerning fault rate and repair time, as well as formulation of redundancy. This must be tailored to each individual system. It will eventually be completed for all systems; but currently only the RF has been thoroughly treated.

RF System

Superconducting cavities are horizontally tested to 10 % voltage margin. This means nominal beam energy could theoretically be preserved with up to 10 % of cavities unavailable. In practice, this was previously believed possible only for ZH and $t\bar{t}$ modes, where beam current is low [6, 7]. However, recent research has shown this is also possible in Z and W despite high beam loading [9].

Table 1: Simulation Parameters

Energy Mode	$\boldsymbol{Z}$ 45.6 GeV	$\boldsymbol{W}$ 80 GeV	$\boldsymbol{ZH}$ 120 GeV	$\boldsymbol{t\bar{t}}$ 182.5 GeV
# RF Cavities*	136	320	376	1352
t_f (min)	7.7	2.5	1.52	1.45
τ (min)	15	12	12	11
$L_4{}^{\dagger}$ $(10^{34}/cm^2s)$	141	20	5	1.25
$L_2{}^{\dagger}$ $(10^{34}/cm^2s)$	230	28	8.5	1.55
$\hat{L}_{int}$ (ab^{-1})	150	10	5	1.5
Operation years	4	2	3	5
# Iterations	100	100	100	100

*Divided between main rings and booster. †Subscript refers to the number of IPs.

Many cavity trips can be repaired remotely, so theoretically while the beam is active. However, this is non-trivial for design of the low level electronics. Both rules are simulated: (1) RF cavities with remote type faults can be reset and brought back online during active beam. (2) They must wait until down for repair to be brought back online.

All Other Systems

In the absence of bespoke formulation, the remaining systems are assumed to meet their availability targets A_s [4]. Exponential distributions are used, where mean time to repair (MTTR) is consistent with similar systems currently in operation around the CERN accelerator complex. Mean time between failures (MTBF) for system s is then given

$$MTBF_s = \frac{A_s}{1 - A_s} MTTR_s \tag{1}$$

Repair Schedule

Redundant fault repair scheduling can have significant effect on availability. Three schedules are modelled:

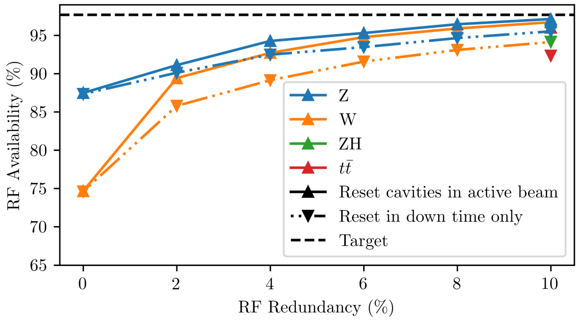
1. *Optimal:* All repairs begin immediately during down time. Redundant repairs are cancelled if not complete before operation can resume.
2. *Blind:* All repairs begin immediately during down time and finish before operation can resume.
3. *Realistic:* Remote repairs are attempted for one hour from the control room. If operation can be restored during this time, any remaining redundant faults are left untreated. If operation cannot be resumed, technicians are sourced to begin and finish all human repairs.

Luminosity

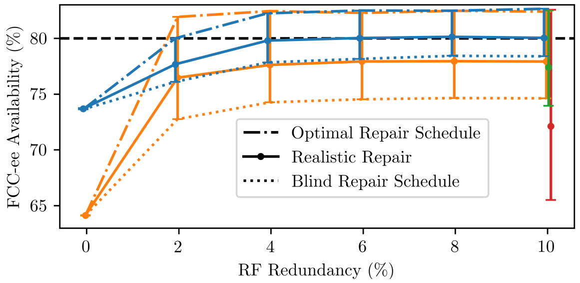
Luminosity per IP is smaller for more IPs due to the beam beam effect [10]. By tracking the time spent in each operation phase, integrated luminosity is calculated

$$L_{int} = \begin{cases} NL_N t, & t \in \text{physics} \\ NL_N \tau (1 - e^{-\frac{t}{\tau}}), & t \in \text{burn off} \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

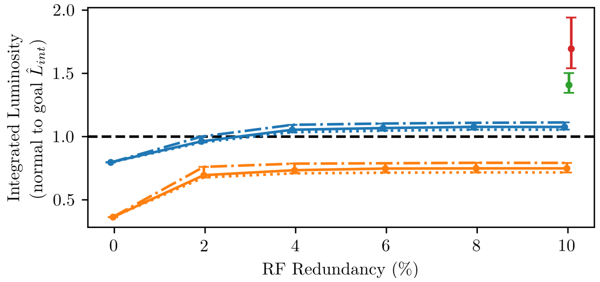
Where N is the number of interaction points and L_N is the corresponding luminosity as per Table 1. In the first two years of Z, W operation, and first year at $t\bar{t}$, reduced luminosity is expected at 50 % and 65 %, respectively [2].



(a) Availability of the RF system in isolation.

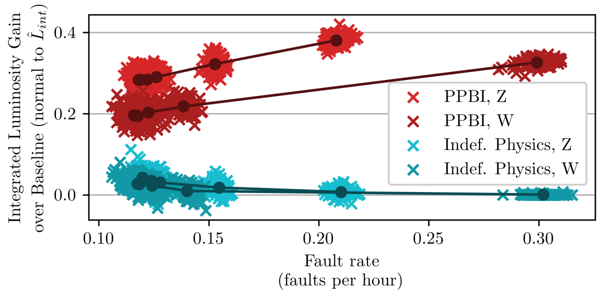


(b) Availability of the FCC-ee overall.

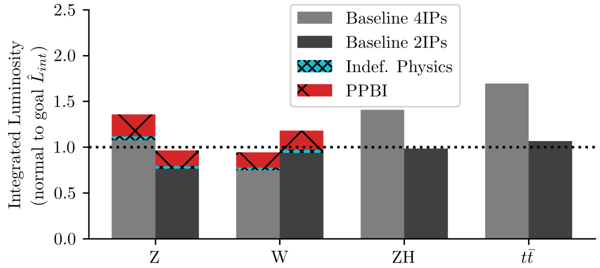


(c) Integrated luminosity.

Figure 2: Availability and Luminosity of the FCC-ee.



(a) Gain in luminosity of two possible R&D Opportunities.



(b) Overall luminosity of four and two IPs.

Figure 3: Luminosity for alternative operation cycles. 10 % RF redundancy and realistic repair schedule is used.

RESULTS

Figure 2a shows forecast RF availability assuming no other faults occur. The target 97.7 % from [4] is not achieved in any energy mode. The effect of the ability to bring cavities back online in active beam is significant if redundancy is deployed.

Figure 2b shows FCC-ee availability when all systems are combined. With optimal scheduling, redundancy can be better exploited as cavities can be repaired in parallel with blocking faults. For realistic and blind schedules, the number of RF cavities increases exposure to long and sub-optimal repair durations. In all schedules, the ability to bring cavities back online in active beam is negligible, so is not shown. This is because the same effect is achieved in the shadow of blocking faults from other systems.

Figure 2c shows corresponding integrated luminosity normal to the goal in each energy mode ($\hat{L}_{int}$ in Table 1). The W mode is clearly well short of physics goals. In Z, the minimum required RF redundancy is 4 %, beyond which gains from increased redundancy are marginal.

Figure 3a compares luminosity gain for the two alternative operation cycles using the same simulation data. PPBI shows consistently higher gain 15-40 % over the baseline. Its rewards grow with fault rate, because it adds two hours luminosity every instance of down time. The opposite is true for indefinite physics, which reduces to zero at higher fault rates where the accelerator can rarely sustain physics beyond 20 hours without failures.

Figure 3b shows luminosity for four [2] and two IPs [1]. The rise for W at two IPs is due to different expected luminosity reductions in [1] and [2]. PPBI brings integrated luminosity significantly closer or over the goal in Z, W modes.

CONCLUSION

This paper showcases recent achievements of the FCC-ee availability study. The RF system is modelled, and resulting effects on availability and luminosity of the overall FCC-ee are simulated using a Monte Carlo approach. Several noteworthy conclusions are evident.

Foremost, the simulation shows that forecasts for integrated luminosity in the W mode are significantly below their goal. This assumes all systems except RF meet their availability target, and predictions may decrease even further once all systems are simulated in detail.

Two R&D opportunities are studied that could overcome technical limitations in the Z, W operation cycle. PPBI shows luminosity gain 15-40 % over the baseline. Further, the positive effect becomes even more relevant as overall fault rate rises. It is general to all systems and technologies in the accelerator, and requires no change to equipment reliability or repair time. PPBI may prove extremely valuable to physics targets in this challenging availability environment.

Meanwhile, useful outcomes are also gained for the RF system. Simulations in the Z mode establish a minimum RF redundancy at 4 %. The ability to bring cavities back online during active beam is negligible, as the same can be achieved during down time from other systems.

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