Chapter 1

Collider Design and Performance

1.1 Requirements and Design Considerations

1.2 Parameter Optimisation

1.3 Design Challenges and Approaches

1.4 Optics Design and Beam Dynamics

1.5 Operation and Performance

The FCC-hh life-cycle is expected to last 25 years, consisting of five 5 -year long operation periods [Sch15]. Baseline parameters are assumed to be used in the first two operation periods ('runs') and the ultimate parameters in the last three periods. Given the overall production goal of 17.5 ab^{-1} over the FCC-hh lifecycle, the integrated luminosity goals for the individual runs have been set to: i) baseline parameters: 1.25 ab^{-1} and ii) ultimate parameters: 5 ab^{-1}.

Figure 1.1 shows a reference schedule for FCC-hh operation. The first run starts with an extensive commissioning period, which could overlap with the construction phase, as some of the systems can be commissioned while the collider is being built. Later runs start with a 1.5 years shutdown. Within a run, the time allocated for proton physics is assumed to last 2.5 years, which also guarantees 3 months of ion physics per run. Combining proton and ion physics runs over the FCC lifecycle, one obtains 165 months of physics in 25 years. This leaves 9 months for machine commissioning, studies and short scheduled technical stops per run. The number and strategy for managing short technical stops can be reviewed based on the needs imposed by individual system designs, but should not exceed the allocated time.

The illustrated operation schedule imposes several challenges on machine design, requiring: (i) an efficient commissioning strategy; (ii) high individual system reliability for extended maintenance -free operation (iii) optimised management of technical stops (e.g. addressing present limitations related to the needs of the cryogenic and cooling systems), including injectors (iv) efficient machine cycles, with minimization or turnaround time.

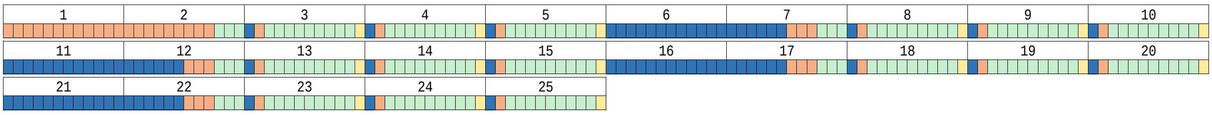

Figure 1.1: Operations schedule of the FCC-hh.

Operational cycles consist of a collision phase, or 'physics production phase', and a turnaround phase, required to reach collisions. The minimum turnaround for FCC-hh is set to 1.8 h (table 1.1). Nevertheless it is assumed that due to inefficiencies and faults the mean turnaround time will be 3-4 hours [Sch15]. Table 1.1 details the breakdown of the cycle phases, including the LHC experience. The LHC ramp-down time is artificially longer, as it is dominated by failure recovery times, which are mostly cleared during this phase. Given the fact that the optimum collision time will only last 3.5 hours for ultimate parameters, the FCC production efficiency will be highly dependent on the average turnaround time. This implies an even higher importance of the injection phase and of injectors' performance. New injection schemes are under study for FCC [SBB^{+}16]. Based on LHC experience, the current injection process could be improved by (i) adding beam diagnostics in the injectors to help identifying beam quality issues as close as possible to the source; (ii) having fast diagnostics for understanding the cause of rejected injections. ; (iii) an improved synchronization and coordination with the injectors [Jac16].

Reaching the set physics goals for FCC-hh requires about 70 % availability [Sch15], defined as the ability for the machine to perform operational cycles (collision and turnaround phases), i.e. the probability of not being in fault state. Comparable availability figures have been reached with the LHC in the 2016-2017 runs [TPA16] [TPAW17]. Nevertheless considering the increasing machine complexity and the introduction of an additional injector in the baseline scenario, achieving the target availability poses major challenges for system designs. A simple scaling from LHC figures accounting for the increased system complexity indicates that for FCC it is mandatory to think about innovative design schemes for new systems. Figure 1.2 (left) shows the evolution of the FCC-hh integrated luminosity production as a function of the global machine Mean Time To Failure (MTTF) and Mean Time To Repair (MTTR), allowing to identify an acceptable availability parameter space for FCC systems. Figure 1.2 (right) shows instead the sensitivity of the FCC-hh integrated luminosity production on the availability of the injector

Table 1.1: Technical performance targets for FCC-hh turnaround cycle [AAB+16], theoretical limit for LHC turnaround [BCL+04] and observed minimum and mean turnaround times in 2017 [Poj17] in minutes.

Phase	**FCC target**	**LHC theoretical**	**LHC min 2017**	**LHC mean 2017**
Setup	10	10	-	-
Injection	40	16[a]	28.0	77.1
Prepare ramp	5	-	2.3	5.0
Ramp-Squeeze-Flat top	20+ 5+3	20	20.2+13.4+2.8	20.5+18.1+4.5
Adjust	5	-	3.3	7.9
Ramp down	20	20	36	153.2[b]
Total	108 (1.8 h)	$\approx$ 70 (1.2 h)	106.0 (1.8 h)	286.3 (4.8 h)

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[a] This assumes 20 seconds-long SPS cycles.

[b] The ramp down phase includes the recovery time from failures.

chain, setting an overall goal of 80-90 %, depending on the MTTF. These considerations make the superconducting SPS an interesting alternative to the baseline option [BBB+17]. Further studies should identify the best injector option taking into account: availability, beam quality, available magnet technologies, capital investment to build a new superconducting machine or for consolidation of the existing CERN complex and operational expenditures.

In addition, some general recommendations can be given for systems designs: (i) design intrinsically reliable systems with built in redundancy and remote diagnostic capabilities, to reduce the number of spurious beam aborts; (ii) reduce to the minimum systems exposed to radiation in the tunnel to limit the number of Single Event Effects (SEE); (iii) invest in advanced fault diagnostic and remote maintenance techniques (e.g. robotic maintenance) to reduce intervention and logistics time. (iv) define a strategy for spare part management, with high priority for critical systems (e.g. cryogenic system, beam dump, etc.).

The potential impact that design changes driven by such considerations would have on operation and production can be evaluated with accelerator availability modelling based on Monte Carlo simulations [NAG+16]. These analyses allow predicting integrated the luminosity production for different operating scenarios and deriving availability budgets for individual systems to guide their designs. Such models should be maintained and updated as the machine design evolves. The aim should be to reach a global optimization of the machine design while taking into account constraints like costs and technical feasibility of different options.

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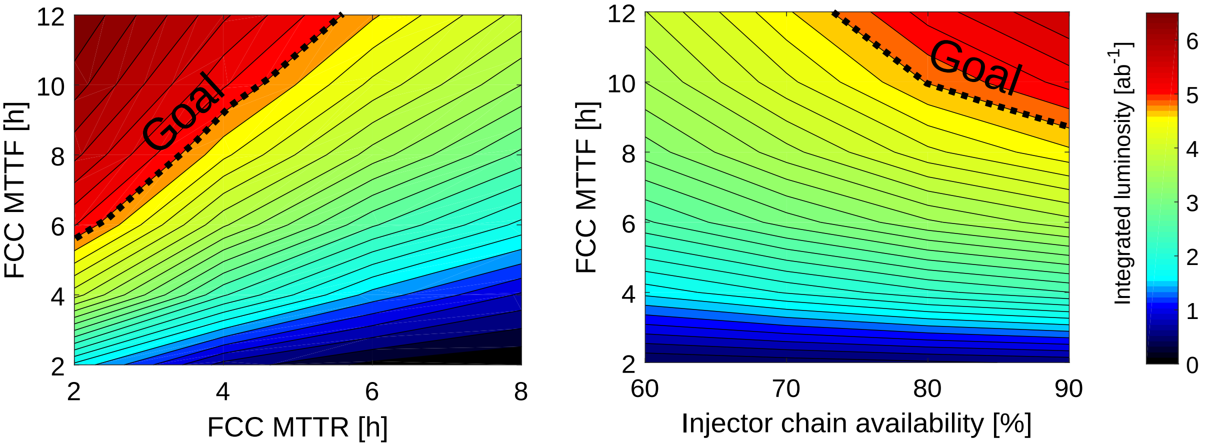

Figure 1.2: Affect of reliability, recoverability and injector availability to integrated luminosity with ultimate parameters.

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