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FCC-hh turn-around cycle

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Abstract — **The turn-around cycle time of a collider is defined as the time spent between the end of stable beams and the start of the next stable beams period, and its calculation is of fundamental importance. On one side it is a crucial ingredient for the computation of the optimal time spent in luminosity production, which defines the integrated luminosity per fill or store. On the other side, combined with the availability and reliability of the machine, it allows to perform a detailed breakdown of the operational performance of the collider over an operational season, i.e. percentage of time in stable beams and beam in the machine with respect to down time. This paper presents a preliminary operational cycle definition for the hadron-hadron Future Circular Collider, as a base line for estimating the corresponding turn-around time. The cycle definition is based on the Large Hadron Collider (LHC) operational cycle. Two turn-around times are presented, the theoretical one and a more realistic one based on the LHC experience.**

1. Introduction

The efficient operation of an accelerator relies, firstly, on the proper identification of all the critical and complex operational activities that bring the machine from injection to luminosity production. Secondly, it relies on the optimal gathering of those activities into coherent phases that build up the operational cycle. The phases are made of tightly coupled tasks that need to be carried out in strict order and have to be accomplished successfully to allow the accelerator to make a transition from one state to the next.

The time spent in each of the phases in order for the control system to execute the different tasks needed to bring the machine from the end of the physics production, which is signalled by the dump of the beams, to the beginning of the next physics production period is called the theoretical turn-around time.

Experience in existing machines, like the LHC, shows that the experimental turn-around time is longer than the theoretical one due to different reasons. First of all, unavoidable human actions take time and cannot be deterministically quantified. Secondly, the injection phase when a large amount of high intensity bunches have to be transferred is very complex, and, as will be made clear in this document, it is very difficult to make this time reproducible from fill to fill. And lastly, but certainly not least important, if poor availability and reliability of the equipment are an issue this can negatively influence the turn-around time due to the tight relation with machine availability and reliability.

In any case, the rational organization of the cycle eases the yearly analysis of collider operational performance to find ways to optimize the turn-around time. This is extensively done at LHC [1-4].

2. FCC-hh operational cycle

The FCC-hh [5] is a hadron collider with superconducting magnet technology, designed for very high energy and beam intensity, with a high number of bunch trains to be transferred from the injectors, and with high luminosity experimental insertions, similar to the LHC. Therefore the LHC nominal cycle structure is adopted for FCC-hh, it is depicted in Figure 1. In the following, an explanation of the different cycle steps is given. The cycle steps's names match one to one the so-called LHC Beam Modes [6].

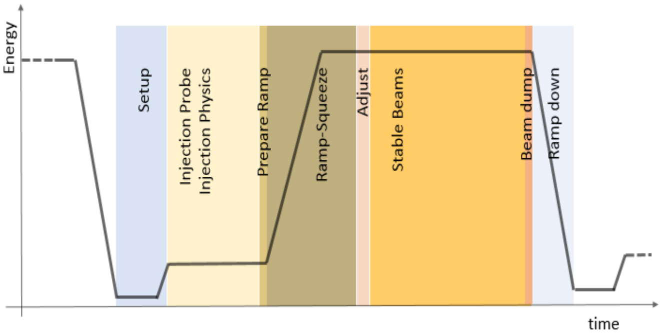

Figure 1: FCC-hh operational cycle, very similar to the LHC cycle, is made of nine phases each described in Section 2.

2.1 Setup

During this phase all accelerator sub-systems are prepared for injection: collimators, radio frequency system (RF), beam instrumentation, injection and extraction kickers, electrical circuits, etc. It includes the ramp to injection energy and a handshake with the experiments to get the green light for injection [7]. In LHC an important part of the accelerator subsystems start the preparation for injection during the ramp-down phase. If possible this should also be attempted at FCC-hh because it speeds up the preparation time.

2.2 Injection probe beam

A potential source of single-turn failures at injection are the LHC magnets, since a wrong current value or aperture problem could cause the injected beam to be lost. To prevent such an eventuality only a low, non-damaging intensity can be injected when there is no beam circulating in LHC. Injection of beam exceeding this intensity requires some circulating beam to be present [8]. For this reason an injection probe beam exists in LHC. It is assumed that same machine protection argument will apply to FCC-hh. On top of this, the injection of low intensity bunches is used to measure and correct tune, coupling, chromaticity, phase error, orbit, etc, to have the machine ready for the physics beam.

2.3 Injection physics beam

Filling of the machine with all the required nominal intensity bunches.

2.4 Prepare ramp

The preparation for the ramp phase requires moving injection protection collimators to parking positions; preparing and loading the functions in the electrical circuits, the RF system, collimators, transverse dampers, etc.; and the preparation of all the feedbacks for the ramp.

2.5 Ramp-Squeeze

During this phase the ramp start event is sent by the LHC central timing system to all the concerned equipment and the ramp proceeds automatically. No manual actions are done at this stage; everything is driven by functions and feedbacks. At the end of this phase the machine is at flat top energy and with squeezed beams at the interaction points.

2.6 Adjust

The separation bumps at the interaction points are assumed to be on, therefore, the beams do not yet collide during the previous phases. During adjust those bumps are collapsed and the machine is prepared for stable beams. In order to achieve this, all the relevant functions need to be recalculated and the feedbacks prepared for the last step before the stable beams is declared. It could be possible to attempt a combine squeeze-collide to provide with the necessary landau damping in case of beam instabilities are an issue during the squeeze.

2.7 Stable beams

Stable beams is the luminosity production phase with luminosity optimizations done with a given frequency to keep the beams head on. If low luminosity experiments present, those will undergo continuous luminosity levelling around the luminosity target.

2.8 Beam dump

Beams are dumped; eventually a handshake with the experiments is performed before.

2.9 Ramp-down

The magnets go back to pre-injection plateau currents. As said before, part of the accelerator subsystems start the preparation for injection during the ramp-down.

3. FCC-hh turn-around time

The turn-around time is defined as the time spent between the end of a fill or store in stable beams, signalled by the beam dump, and the start of the stable beams phase of a following fill. During this time, all the activities highlighted in the previous section are performed. In this section two turn-around times are calculated based on the LHC experience and some extrapolations when appropriate. The first one is the theoretical time, and the second one is the turn-around achieved in practice by LHC based on the analysis of the time spent at the different cycle steps during LHC operation in 2015. Obviously the turn-around time in practice is substantially larger than the theoretical one, and as it will become clear in the following, the major contributors to the degradation of the turn-around time are the injection phase and the different equipment faults that appear during operation, which contribute significantly to the down time.

3.1 Setup

A setup time of 10 minutes is assigned to FCC-hh. This time includes the ramping up of the magnets to injection current and all the tasks that could not be performed in parallel to the ramp-down.

3.2 Injection phase

Currently three options for injecting into FCC-hh are being studied in detail and the corresponding injection time has been calculated and presented in [9]. The first option reuses the LHC as injector but with a factor 5 faster ramping time. The second foresees building a dedicated high-energy booster (HEB) inside the same FCC tunnel. The last option considers the upgrade of the SPS to reach a flat top energy of 1550 GeV to inject into FCC. In [9] the injection time is calculated as the filling time plus the ramp-up and ramp-down time of the injectors, plus an additional contingency time of 10 s for each of the options mentioned above. No extra possible overheads are included. Table 1 compiles the flat top energies expected at each machine and the number of transfers from one injector to the next including the number of bunches per transfer. The three alternatives assume that the first injectors in the chain are the Linac 4, with 160 MeV flat top energy, and the Booster, with 2 GeV flat top energy.

Opt	PS	SPS	LHC	100 km HEB	FCCinj	Tinj (min)
	Flat top energy (GeV)					
	Number of transfers and total number of bunches					
LHCx5	26	450	3300		3300	40
	72 b	9 PS->SPS = 648b	2x4 SPS->LHC = 2592 b/ring		4 LHC->FCC = 10368 b/ring	
HEB @FCC	26	450		3300	3300	29
		10 PS->SPS=720b		15 SPS->HEB =10800 b	1 HEB->FCC = 10800 b/ring	
HEB@SPS	45	1550			1550	34
	80 b	8 PS->SPS=640 b			2x17 SPS->FCC =10880 b/ring	

Table 1: Summary of the three options considered up to now to inject into FCC-hh. The table compiles the flat top energies expected at each machine and the number of transfers from one injector to the next including the number of bunches per transfer. The three alternatives assume that the first injectors in the chain are the Linac 4, with 160 MeV flat top energy, and the Booster, with 2 GeV flat top energy. The last column gives the injection time calculated as the filling time plus the ramp-up and ramp-down time of the injectors, plus an additional contingency time of 10 s.

As indicated in the table, the maximum injection time, 40 minutes, corresponds to the LHC option. Therefore, this is the time assigned to the FCC theoretical injection time for the calculation of the cycle turn-around time.

In the following a comparison between the theoretical injection time in LHC and the practical one is made. The LHC theoretical injection time is calculated multiplying the number of transfers required to fill both rings, times the SPS super cycle (SC) length. Typically 22 injections are required to fill LHC with 2808 bunches per ring. Since the SPS SC is almost never devoted to the LHC filling but serves other clients, the typical maximum SC length is 59 s. Thus, 22 minutes are required to fill LHC for physics.

LHC injection phase requires, however, carrying out different actions and measurements, which cannot be avoided and implies that the injection time will always be greater than the theoretical one. The actions and measurements at LHC are described in the following:

1. Pilot bunch injection (~1e10 p+) (pilot reinjection might be required)
2. Measurement and correction of tune, chromaticity, coupling, orbit and phase error.
3. Injection of 2x12 nominal intensity bunch train per beam. This intermediate beam is part of the nominal beam but, at the same time, aims at checking transfer line stability and injection oscillations. If the beam transfer quality is not good, a transfer line steering needs to be done, which can require several 12-bunch injections. In the end the beam has to be dumped to start the nominal injection for physics. This process can be very lengthy. If, on the other hand, the quality of the beam transfer is good, then beam emittance is measured with wire scanners.
4. Injection of the rest of the physics beam.
5. Once the machine is full starts the “prepare ramp” phase.

Points 1 and 2 belong to the phase called “injection probe beam”, the equivalent to Section 2.2, while points 3 to 5 belong to the “injection physics beam” phase, the equivalent to Section 2.3. An analysis of the 2015 data has been carried out [3] showing that on average 25 minutes are spent in injection probe beam mode, and 50 minutes in injection physics beam. Therefore, on average LHC spends 75 minutes in the injection process, almost a factor 3.5 above the theoretical minimum injection time of 22 minutes.

At this point it is interesting to understand where the issues that prevent to reach the theoretical time are. One clear aspect is that there are unavoidable measurements that need to be done before the injection physics beam starts, like measurement and correction of the beam parameters and the transfer lines steering when needed. However, there are other issues which clearly point towards a need for improvement. A detailed study has been performed in [10], the most important areas where improvement is needed are injection software performance and reliability, central timing system latency, beam quality from injectors, injector’s super cycle performance, and hardware limitations from equipment due to electron cloud or beam intensity.

3.3 Prepare ramp

In order to estimate the time spent in the prepare ramp phase, the LHC average over the 2015 fills is used. As explained in [4], the average time is 5 minutes, however, due to cryogenics stabilization requirements, some fills stayed in the prepare ramp mode up to 35 hours. These exceptional fills are not taken into consideration and just the average over fills without cryogenic issues is taken as reference. The time assigned to the FCC theoretical prepare ramp time for the calculation of the cycle turn-around time is the average time achieved in LHC, i.e. 5 minutes.

3.4 Ramp-Squeeze

The ramp time from injection energy to 50 TeV is extensively discussed in [11] and accounts for 20 minutes, as the current ramp time in LHC. The key points that make possible to get the same time as in LHC today is that the FCC powering layout subdivides each of the FCC half arcs (8 km long) in two powering sectors reducing significantly the circuit inductance. The ramp time has a large impact on the peak power. For 20 minutes it is a factor 22 larger than in LHC, however, there are ways of decreasing the power peak while preserving the ramp time as discussed in [11].

FCC-hh baseline squeeze is from 5 m to 1.1 m, i.e. approximately half of the LHC squeeze, which from 11 m down to 0.8 m in ATLAS and CMS in 2015 took 12.5 minutes. However, the squeeze could be combined with the ramp, or at least part of it, such an important amount of the squeeze time remains in the shadow of it. Therefore, the theoretical time assigned to the FCC-hh squeeze is three minutes.

Once the machine is at flat top and the beams are squeezed, it could be necessary to spend a few minutes performing some operations in preparation for the adjust phase. On the other hand it might not be necessary or these preparations could be included in the adjust phase itself. In any case, a five minutes contingency is added to the ramp-squeeze for the calculation of the turn-around.

3.5 Adjust

During 2015 LHC operation the average time spent in the adjust phase was 10 minutes [3] with a long queue extending up to half an hour. Has become clear after the analysis of these data that the time spent in adjust can be easily optimized to 5 minutes. Therefore, the time assigned to the FCC theoretical adjust time for the calculation of the cycle turn-around time is the target to be achieved in LHC for Run 2, i.e. five minutes. However, depending on the initial beam separation and the strength of the magnets, this time could be different.

3.6 Beam dump and ramp-down

In LHC the programmed beam dump preparation takes 5 minutes because this is the time needed by the experiments to prepare the detector for the dump. In any case this happens during the stable beams phase and every detector starts the shut-down of the sub detectors at their earliest convenience. Therefore no time is assigned to the beam dump phase in the calculation of the turn-around time for FCC-hh.

Once the beams are dumped, the beam dump mode is broadcast for few seconds because it is needed by the experiments to signal the end of the physics run. It is followed immediately by the beam mode ramp-down. In order to calculate the ramp-down time in FCC it is assumed that all main power converters are four-quadrant which allows bringing the machine down in 20 min, so the same time as the ramp-up. In LHC the magnets are not four quadrants and the ramp down time is 40 minutes, twice the ramp-up time.

Before making the final calculation of the time-around in FCC-hh, next section summarises the time-around in an operating machine like LHC to illustrate that theoretical times and experimental ones can be really different.

4. LHC turn-around time distribution in October 2015

As mentioned in the introduction, accumulated experience in existing machines, like the LHC, shows that the experimental turn-around time is longer than the theoretical one due to different reasons. On one hand, unavoidable human actions take time and cannot be deterministically quantified. On the other hand, the injection phase when a large amount of high intensity bunches have to be transferred is very complex, making it very difficult to achieve reproducibility from fill to fill. And last but not least, there is a tight relation between the turn-around time and the availability and reliability of the accelerator. To illustrate this last statement Figure 2 shows the distribution of the turn-around time of all the fills in October 2015. This period is representative of a typical period of luminosity production with 25 ns bunch separation, more than 1500 bunches and on top of this the machine configuration was kept constant from fill to fill.

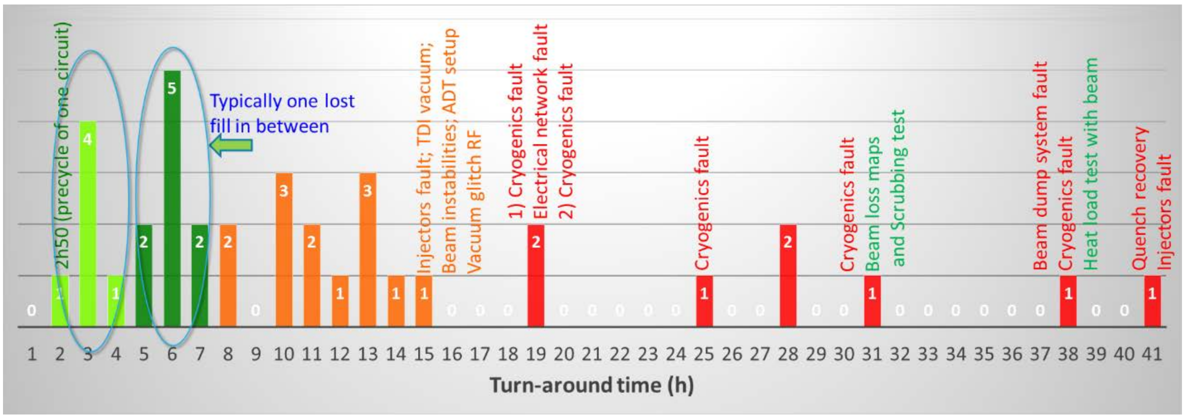

Figure 2: Distribution of the turn-around time of all the fills in October 2015. This period is representative of a typical period of luminosity production with 25 ns bunch separation, more than 1500 bunches and on top of this the machine configuration was kept constant from fill to fill.

As seen in Figure 2 none of the fills made the LHC theoretical minimum of ~ 1.8 hours. In the Figure four categories can be identified:

1. Fills close to the theoretical value with three hours of average turn-around time (light green).
2. Fills with an average value of six hours (dark green). Those are attempts to reach stable beams during which one fill has been lost in between.
3. The third category corresponds to attempts to reach stable beams during which miscellaneous faults appeared with short to medium recovery time (orange).
4. The last category corresponds to attempts with very long recovery time faults.

Clearly the turn-around time in an accelerator is dominated by the availability and reliability of the equipment, injectors, technical infrastructure, and for superconducting machines, also by the cryogenics system and the quench recover time. Without including fills with turn-arounds bigger than 15 hours, the average turn-around in LHC in October 2015 was 6.8 hours.

Very different is the distribution of the turn-around time in a machine without problems derived from the very high beam intensities and the cryogenic load as illustrated by Figure 3, which corresponds to the turn-around time of LHC during the PbPb operation in 2015. Only the first three categories out of the four of Figure 2 are present, which is a very encouraging result meaning that mastering the availability and reliability of the cryogenic system and the side effects of the high intensity beams (the Pb beams have a bunch intensity which is 10% of the nominal proton intensity), can improve significantly the turn-around time.

5. Total theoretical turn-around time in FCC-hh

Table 2 compiles the time in minutes spent in each of the phases explained in Section 3. As indicated in the table, the theoretical turn-around time in FCC-hh is 1.8+/-0.2 hours, which is very similar to the theoretical turn-around in LHC, and therefore, a remarkable result for a machine that is almost four times bigger than LHC.

Table 2 compiles in the third raw the time spent in the different phases of the LHC cycle using data from fills that made it into stable beams in October 2015 as explained in Section 4. The average time spent in the SETUP phase cannot be calculated straight forward using the time spent in beam mode SETUP. In case of major down time in LHC due to a fault that requires long recovery time, the beam mode is set to NO BEAM, and later to CYCLING if a pre-cycle of the LHC magnets is needed. So in order to compute the average SETUP time shown in the table, the average times spent in injection, prepare ramp, ramp, squeeze, flat top, adjust and ramp down have been subtracted to the total turn-around time of 6.8 hours and the remaining time has been assigned to SETUP.

The third column of the table illustrates how a real machine behaves. However it is very difficult to project the same result into FCC-hh, a machine that will be built in more than 30 years from now. Therefore, at this stage of the project it is not known how the practical time for FCC-hh will look like, it will heavily depend on the availability and reliability of the accelerator and its injectors. Of paramount importance is to really work hard to get the highest availability and reliability already from design phase.

Mode	**Theoretical Time (min/hour)**	**Practical Time in LHC (min/hour)**
SETUP	10	221.6
INJECTION	40	75
PREPARE RAMP	5	10
RAMP-SQUEEZE-FLAT TOP	20+5+3	27.7+14.1+5.9
ADJUST	5	13.7
RAMP DOWN	20	40
TOTAL	108±10 **(1.8±0.2) h**)	408±10 (6.8±0.2)

Table 2: Estimated time spent in each of the FCC-hh operational cycle steps. The third column illustrates the average time spent in the different LHC phases using data from October 2015, while the theoretical turn-around time in LHC is very similar to the one of FCC-hh.

6. Conclusions

A nominal FCC-hh operation cycle has been proposed based on the LHC cycle motivated by the similarities of both machines. Based on the LHC experience and on theoretical studies performed on the injection systems into FCC-hh and the layout of the FCC-hh powering, the theoretical turn-around time for FCC-hh is (1.8 ± 0.2) hours, a remarkable result for a machine that is four time larger than LHC.

Real machines, however, behave different and some of the cycle phases are more complex than foreseen in the design phase. For example, the injection into FCC-hh will be more complex than just the beam production in the injectors and the transfer into FCC-hh, as illustrated with the LHC case in Section 3.2. In the case of LHC, with a similar theoretical turn-around time as FCC-hh, the measured turn-around time based on fills produced in October 2015 is 6.8 hours (without including turn-around time greater than 15 hours), a factor 3.8 larger than the theoretical one.

The optimization of the turn-around time is a crucial input to the reliability and availability studies of FCC-hh [12] and to the calculation of the optimal time in stable beams as discussed in [13].

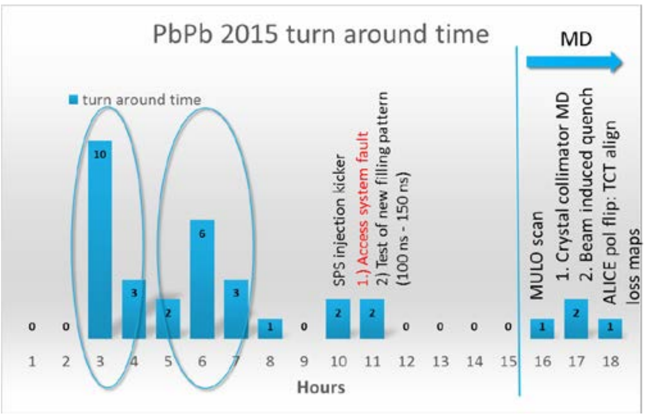

Figure 3: Distribution of the turn-around time of all the fills during the PbPb operation at the end of 2015.

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