TURNAROUND TIME IN MODERN HADRON COLLIDERS & STORE-LENGTH OPTIMIZATION

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Abstract

The paper presents a review of the average accelerator turnaround time in existing superconducting hadron machines (HERA at DESY@, RHIC at BNL§ and the TEVATRON at FNAL&). Based on the past experience with these previous hadron accelerators the paper aims at a best guess estimate for an initial and optimum turnaround time in the LHC during the first year of operation and for routine operation after the machine commissioning.

@: Data on the operational experience with the HERA machine has been kindly made available by Bernhard Holzer from DESY.

$: Data on the operational experience with the RHIC machine has been kindly made available by Wolfram Fischer from BNL.

&: Data on the operational experience with the Tevatron machine has been kindly made available by Vladimir Shiltsev from FNAL and retrieved from the Tevatron operation Internet pages:
http://www-bd.fnal.gov/pplot/index.html.

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1. INTRODUCTION

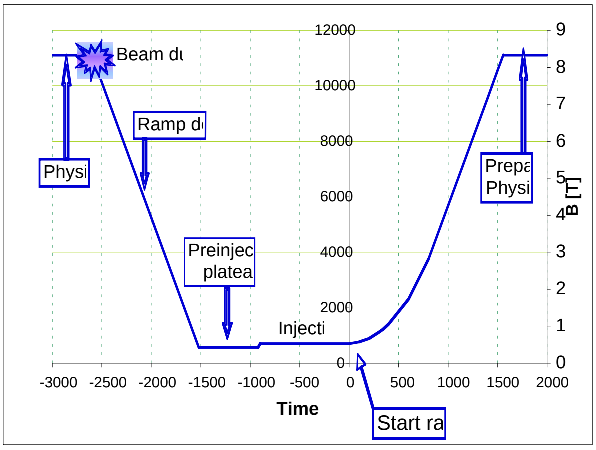
In the following we define the turnaround time of an accelerator storage ring as the time between the end of one and the start of the next physics run. For an accelerator storage ring the measurement of the turnaround time starts with the beam at top energy of the accelerator and comprises the ramp down of the magnet system to the injection energy settings after the beam extraction, the time required for setting up the machine for the next injection, the time required for injecting new beams into the machine, the time required for the beam acceleration (ramp), the optics transition for the physics run (squeeze) and the time required for adjusting the beam conditions so that the detectors can start again data taking. The minimum theoretical turnaround time ($T_{\mathrm{turnaround,min}}$) for the LHC amounts to approximately 70 minutes and is defined by the following contributions [1]:

- Ca. 18 minutes for reducing the magnet strength from the required values during the physics run operation at top energy to the required magnet strength at the pre-injection plateau ('ramp down') assuming a maximum ramp speed of 10A per second in the main LHC magnet circuits. In order to minimize the dynamic magnet field errors during the injection and acceleration process and to assure that the magnetic field does not change the Hysteris branch at the start of the beam acceleration, the magnet current is first reduced to values slightly below the actually required strength for the beam injection ('pre-injection plateau') and then increased again to the values required for the beam injection.
- Ca. 15 minutes steady magnet powering at the 'pre-injection plateau'.
- Ca. 15 minutes for increasing the magnet strength from the 'pre-injection plateau' to the actual injection settings.
- Ca. 8 minutes for machine adjustments with low intensity 'pilot beams' (assuming 6 injection shots per LHC beam).
- Ca. 7 minutes for the actual filling of the LHC with nominal beams.
- Ca. 28 minutes for increasing the magnet current from the strength required for beam injection to the required values required for physics operation at top energy ('ramp up'). The 'ramp-up' of the magnet current takes slightly longer than the 'ramp down' because the ramp rate is optimized at each acceleration stage for minimizing the dynamic field errors in the main magnets. At the beginning of the ramp the magnet current follows a parabolic current variation with time, followed first by an exponential and then a linear variation with time and a final parabolic round off at top energy. The ramp down without beam features on the other hand only a linear variation of the magnet current with time.
- Ca. 15 minutes for the optics transition to the physics configuration ('optics squeeze'). Due to aperture limitations inside the magnets next to the Interaction Point (IP) the optics configuration for physics operation can only be adjusted at top energy when the beam size has shrunk due to the acceleration damping.

Some of the above estimates are only best guesses for the minimum required time. For example, the time required for adjusting the machine with pilot beams at injection energy and the optics squeeze at top energy depend a lot on the machine reproducibility, which can only be quantified with machine operation.

The actual required time for larger in real operation due to required additional adjustments (e.g. beam based fine tuning of the collimator jaws). Figure 1 shows basic magnet cycle for the LHC [1].

Figure 1: The LHC magnet cycle during nominal operation.



The minimum machine turnaround time defines an important input parameter for calculating the maximum attainable integrated luminosity of a collider complex. Equation 1 yields the total integrated luminosity in a collider as a function of the collider turnaround time and the luminosity lifetime [2].

$$\hat{L}=R\cdot M\cdot(24\cdot 60^2)\cdot L_0\cdot\frac{\tau_{L,tot}[h]}{T_{run}[h]+T_{turnaround}[h]}\cdot\left[1-e^{-T/\tau_{L,tot}}\right] \tag{1}$$

$$\hat{L}=R\cdot M\cdot(24\cdot 60^2)\cdot L_0\cdot f(T,\tau) \tag{2}$$

T_{run} specifies the run time for physics data taking, $T_{turnaround}$ the collider turnaround time, L_0 the initial luminosity (expressed in cm-2 sec-1), and $t_{L,tot}$ the luminosity lifetime, M the number of scheduled days of physics operation and 'R' the overall collider efficiency. Using an exponential approximation for the luminosity decay, the luminosity lifetime is approximately 15h for the nominal LHC beam parameters and reduces to approximately 10h for the ultimate beam parameters [2]. In both cases, the luminosity lifetime is dominated by the beam losses due to the beam collisions at the IP. Increasing the initial luminosity beyond the nominal and 'ultimate' luminosity values ($L_{nominal}$ = 1.0 1034 cm-2 sec-1 and $L_{ultimate}$ = 2.3 1034 cm-2 sec-1) results therefore in a rapidly decreasing luminosity lifetime. Depending on the upgrade solution, it decreases to 2.2h or 4.5h for the two Phase 2 upgrade scenarios under study for the LHC [3]. Table 1 summarizes the main LHC machine parameters for the nominal and ultimate performance as well as for the two upgrade options that are currently studied for pushing the LHC machine peak luminosity above 10^{35} cm^{-2} sec^{-1}. Table 2 shows the ratio of average to peak luminosity as a function of luminosity lifetime and turnaround time assuming an optimum run length for each fill (function 'f' in Equation (2)). One clearly recognizes that the ratio of integrated to peak luminosity decreases significantly if the machine turnaround time becomes significantly longer than the luminosity lifetime. Transforming an increase in peak luminosity into a gain in integrated luminosity therefore requires a machine turnaround time, which is comparable or shorter to the luminosity lifetime.

Table 1: The nominal, ultimate and Phase 2 upgrade machine parameters for the LHC [3].

parameter	nominal	ultimate	25ns	50ns
Protons per bunch	1.15 10^{11}	1.7 10^{11}	1.7 10^{11}	4.9 10^{11}
Total beam current	0.58 A	0.86 A	0.86 A	1.22 A
Longitudinal bunch profile	Gauss	Gauss	Gauss	Flat
β^* at the IPs	0.55m	0.5m	0.08m	0.25m
Full crossing angle at the IPs	285μrad	315μrad	0μrad	381μrad
Peak luminosity [cm^{-2} sec^{-1}]	1 10^{34}	2.3 10^{34}	15.5 10^{34}	10.7 10^{34}
Peak events per crossing	19	44	294	403
Initial luminosity lifetime	25h	14h	2.2h	4.5h
Stored beam energy	370MJ	550MJ	550MJ	780MJ
Additional requirements	-	-	Large aperture triplet magnets	Large aperture triplet magnets
			Efficient / radiation hard absorbers	Efficient / radiation hard absorbers
			D0	Wire compensators
			Crab cavities	

Table 2: The ratio of average to peak luminosity as a function of luminosity lifetime and machine turnaround time (function 'f' in Equation (2)).

$T_{turnaround}$ [h] τ_{lumi} [h]	1	6	10	20
2.5	**0.46**	**0.20**	**0.14**	**0.09**
10	**0.66**	**0.39**	**0.32**	**0.22**
15	**0.70**	**0.46**	**0.38**	**0.28**
19	**0.73**	**0.5**	**0.42**	**0.31**

The assumption of an optimum run length clearly provides an optimistic estimate as the optimum run length depends on the machine turnaround time which is only precisely known once the machine starts the next physics run. Table 3 shows the optimum run lengths for various luminosity lifetimes and machine turnaround times.

Table 3: The optimum run length for various luminosity lifetimes and machine turnaround times.

T_{turn} τ_{lumi}	1h	6h	10h	20h
2.5h	**2h**	**4h**	**5h**	**6h**
10h	**4h**	**9h**	**11.5h**	**15h**
15h	**5h**	**12h**	**15h**	**20h**
19h	**5.5h**	**13h**	**16.5h**	**22h**

Figure 2 shows the integrated luminosity for a turnaround time of 10h and a luminosity lifetime of 10h as a function of the run length. One recognizes how the integrated luminosity decreases if the run length becomes too short, e.g. due to an unscheduled run abort due to a technical fault in the collider equipment, or too long, e.g. if there is a fault in the injector complex and a new fill cannot be prepared at the requested moment or if a too large value had been assumed for the turnaround time.

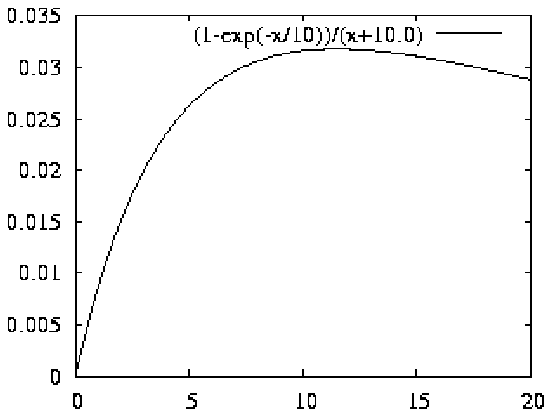


Figure 2: The integrated luminosity as a function of the run length for a luminosity lifetime of 10h and a turnaround time of 10h in arbitrary units.

2. OPERATIONAL MACHINE TURNAROUND TIME VERSUS MINIMUM THEORETICAL MACHINE TURNAROUND TIME

The average machine turnaround time can be significantly larger than the theoretical minimal turnaround time of a collider storage ring. This is particularly true if the machine performance is pushed to its maximum and the operating margins are reduced. An estimate for the operational machine turnaround time during routine operation is therefore the prerequisite for estimating the potential performance reach of the LHC in terms of integrated luminosity for various luminosity values. Faults generating a long interruption time (long compared to the optimum run length) essentially reduce the scheduled operation time and can be accounted for by an overall collider efficiency 'R'.

$$\hat{L} = R \cdot M \cdot (24 \cdot 60^2) \cdot L_0 \cdot f(T, \tau) \tag{3}$$

In the following we will therefore discard all interruptions of the machine operation that are longer than a given threshold value. This cut depends on the machine under investigation and will be specified separately for each studied case.

Faults creating a short interruption time result either in a non-optimum run length if the fault occurs during a physics run, or in prolonged effective machine turnaround times if the fault occurs during the preparation of a new fill.

3. EXPERIENCE FROM EXISTING HADRON COLLIDER STORAGE RINGS

In the following we will look at the operational experience from existing hadron storage rings and compare their operational average and minimum turnaround times to their theoretical values. We will look at three machines (RHIC at BNL, Tevatron at FNAL and HERA at DESY) and discuss the main reasons for operation failures.

3.1 Tevatron at FNAL

Table 4 shows the planned Tevatron machine parameters for RunII from the technical design report [4] and Table 5 shows the main beam parameters from the operational experience with RunII [5]. The operational minimum turnaround time and average store length are approximately twice as long as the planned parameters.

Table 4: The planned Tevatron machine parameters for RunII [4].

Planned RunII parameters	**Value**
Minimum theoretical turnaround time	1 hour
Nominal proton beam intensity	36 x 27 10^{10} ppb
Nominal anti-proton intensity	36 x 3.1 10^{10} ppb
Nominal initial luminosity	86 10^{30} cm^{-2} sec^{-1}
Theoretical beam lifetime	$\tau > 13$ hours
Store length	12 hours

Table 5: The operational Tevatron machine parameters for the 2007 RunII [5].

RunII parameters in operation	**Value**
Minimum operational turnaround time [6]	2.5 hours
Proton beam intensity	36 x 26 10^{10} ppb
Anti-proton intensity	36 x 6.1 10^{10} ppb
Average initial luminosity	186 10^{30} cm^{-2} sec^{-1}
Average Store length	21.3 hours
Average set-up time	2.4 hours

The Tevatron featured a total of 1292 stores during its first 6 years of operation. 932 of these 1292 stores were intentionally terminated with an average store length of 22.4 hours. 360 stores ended due to failures with an average store length of 10.23 hours. The top 10 causes for unintentional run terminations were:

- Problems related to the cryogenic system: 49 cases ➔ 13%
- Lightening and thunder storms: 40 cases ➔ 11%
- Problems with the quench protection system: 33 cases ➔ 9%
- Problems with the controls: 29 cases ➔ 8%
- Problems with the beam separators: 25 cases ➔ 7%
- RF problems: 25 cases ➔ 7%
- Problems related to the low b quadrupoles: 24 cases ➔ 7%
- Corrector magnet problems: 20 cases ➔ 5.5%
- Human errors: 20 cases ➔ 5.5%
- Power converter problems: 20 cases ➔ 5.5%

One can expect most of the above failure causes also for the operation of the LHC. Figures 3 and 4 show the efficiency of the machine expressed in time spend in physics and average store hours per week averaged of the full fiscal year respectively for the 2007 run [5]. The above statistics is compatible with M = 365 and R = 0.6 in Equations (1) and (2) and corresponds well to the experience from the RHIC operation. Figure 5 shows the occurrence of various turnaround times between two consecutive fills [6] in form of a histogram. Figures 6 and 7 show the average turnaround time as a function of store umber without and with the application of a 36h cut respectively. The minimum operational turnaround time is approximately 2.5 hours and is therefore, after 6 years of Run II operation, ca. 2.5 times larger than the minimum theoretical turnaround time. The average operational turnaround time is ca. 8 hours and approximately 8 times larger than the minimum theoretical turnaround time. The average store length in 2007 operation was 21 hours and the average machine setup time amounted to ca. 2.4 hours.

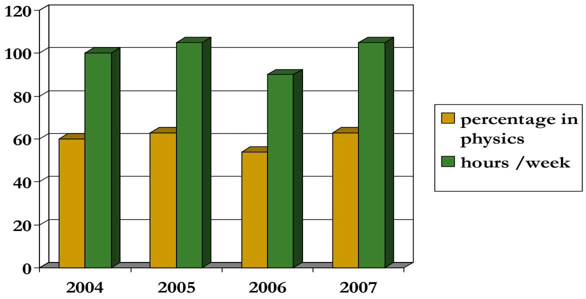


Figure 3: Machine efficiency expressed in time spent in physics operation in hours per week and percentage per calendar time.

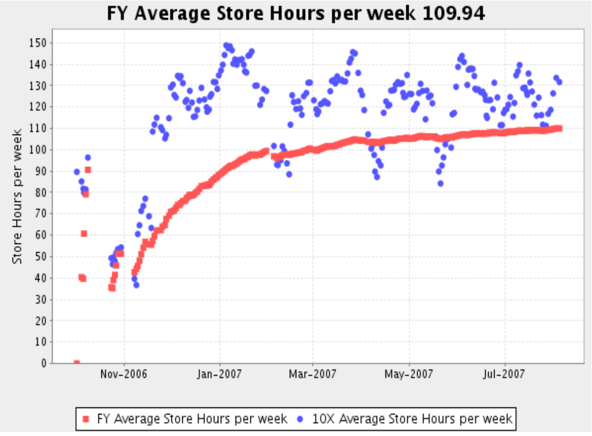


Figure 4: Average store hours per week averaged over the full fiscal year [5].

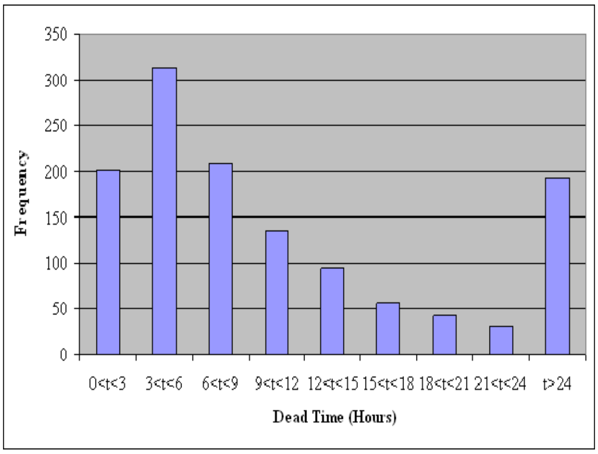


Figure 5: Time between two consecutive fills of the Tevatron [6].

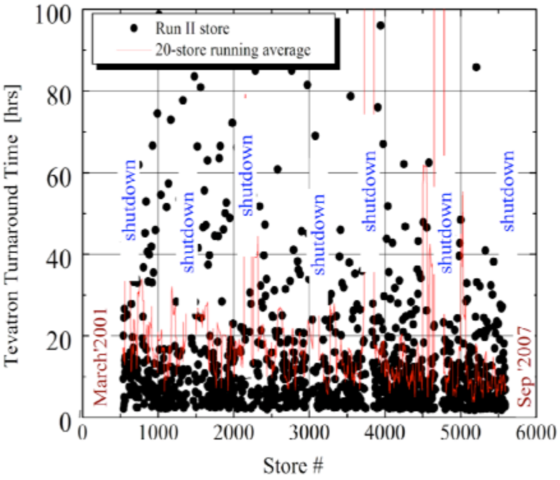


Figure 6: The Tevatron turnaround time as a function of store number.

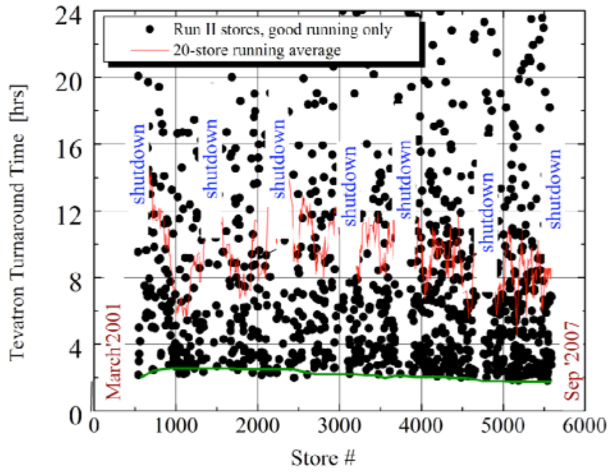


Figure 7: The Tevatron turnaround time as a function of store number with a cut of 36h

Table 6: Summary of the key observations from the Tevatron operation.

Parameter	Value
Minimum theoretical turnaround time	1 hours
Minimum operational turnaround time	2.5 hours
Average operational turnaround time	8 hours
Machine efficiency in percent of calendar time spent in physics operation.	60%
Average Store length	21 hours

Table 6 summarizes the main observations from the Tevatron operational experience.

3.2 HERA AT DESY

Table 7 and 8 show the main machine parameters for the HERA I and HERA II run periods [7]. The minimum theoretical turnaround time consists of 35 minutes filling time (defined by the cycle of the PETRA machine) plus 2 times 30 minutes for ramping the magnets up and down.

Table 7: The main HERA machine parameters for HERA I operation.

HERA I parameters	Value
Minimum theoretical turnaround time	1.5 hour
Nominal proton beam intensity	180 x 7.3 10^{10} ppb
Nominal electron beam intensity	180 x 3.7 10^{10} ppb
Nominal initial luminosity	17.8 10^{30} cm^{-2} sec^{-1}
Theoretical beam lifetime	t > 1000 hours
Store length	Ca. 10 hours

Table 8: The main HERA machine parameters for HERA II operation.

HERA II parameters	Value
Minimum theoretical turnaround time	1.5 hour
Nominal proton beam intensity	180 x 10.3 10^{10} ppb
Nominal electron beam intensity	180 x 4.3 10^{10} ppb
Nominal initial luminosity	75.8 10^{30} cm^{-2} sec^{-1}
Theoretical beam lifetime	t > 340 hours
Store length	Ca. 14 hours

Figures 8 and 9 show examples for the machine reliability from the 2006 operation. The left-hand side of Figure 8 shows a series of unscheduled proton beam losses that were caused by a variety of unforeseen beam losses (e.g. beam showers in the collimation sections and fast (ms time scale) beam losses. The right-hand side of Figure 8 shows fills of a regular operation period. The left-hand side of Figure 9 shows a series of operation failures due to technical problems (cryogenic problems, power failure and quench alarms during beam injection). The right-hand side of Figure 9 shows again regular fills corresponding to a normal operation period. Figure 10 shows the overall machine efficiency during the 2000 operation. The average machine efficiency of ca. 55% corresponds well to the operational experience from RHIC and Tevatron. Figure 11 gives a statistics of the most frequent reasons for an interruption of the HERA operation and Figure 12 shows the corresponding failure time in operation days [7]. In total HERA featured 115 physics stores in the 2006 operation requiring 164 proton and 185 electron injections. During the 2006 operation period HERA featured a total of 230 faults. The average store length amounted to 7.4 hours with a minimum store time of 0.16 hours and a maximum sore length of 14 hours. Figure 13 shows the distribution of various operation modes for HERA during the 2006 run. Ca. 50% of the operation time was spent in luminosity operation and ca. 25% of the operation time was lost due to faults. Ca. 13% of the operation time was required for filling the HERA machine with new beams.

The most frequent interruptions are caused by:

- Problems with operation ('Bedienung'): 40 cases ➔ 17%.
- Problems with the electron RF ('eHF'): 35 cases ➔ 15%.
- Problems with power supplies: 29 cases ➔ 13%.
- Problems created by beam losses ('Strahlverlust'): 19 cases ➔ 8%.
- Problems related to controls ('MSK'): 18 cases ➔ 8%.
- Problems related to the injector complex: 13 cases ➔ 6%.
- Problems related to the proton RF: 9 cases ➔ 4%.
- Problems related to super conducting cavities: 7 cases ➔ 3%.
- Problems related to the quench protection system: 7 cases ➔ 3%.
- Problems related to beam instrumentation: 7 cases ➔ 3%.

Most of the above fault types can also be expected for the LHC operation (except for problems related to the electron RF system).

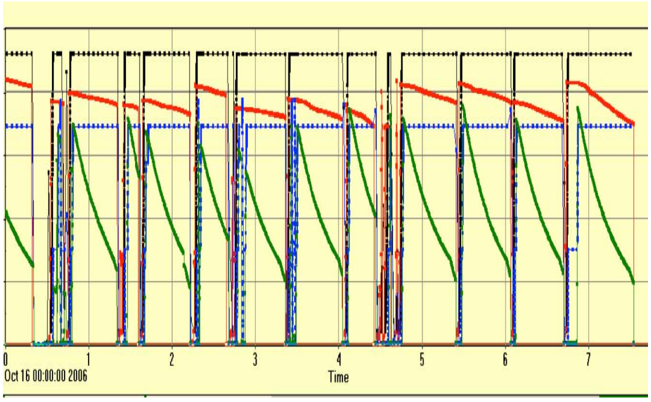


Figure 8: HERA operation in week 46 in 2006 [7].

The left-hand side shows a series of unscheduled proton beam losses that were caused by unforeseen beam losses (e.g. beam showers in the collimation sections and fast (ms time scale) beam losses). The right-hand side shows fills of a regular operation period.

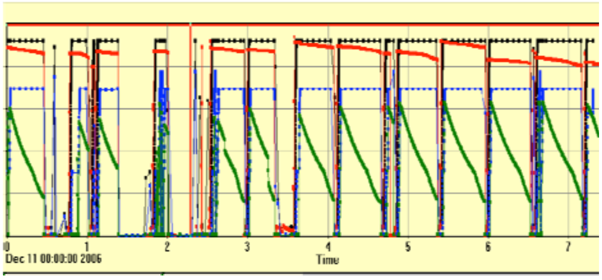


Figure 9: HERA operation in week 50 in 2006 [7].

The left-hand side shows a series of operation failures due to technical problems (cryogenic problems, power failure and quench alarms during beam injection). The right-hand shows regular fills corresponding to a normal operation period.

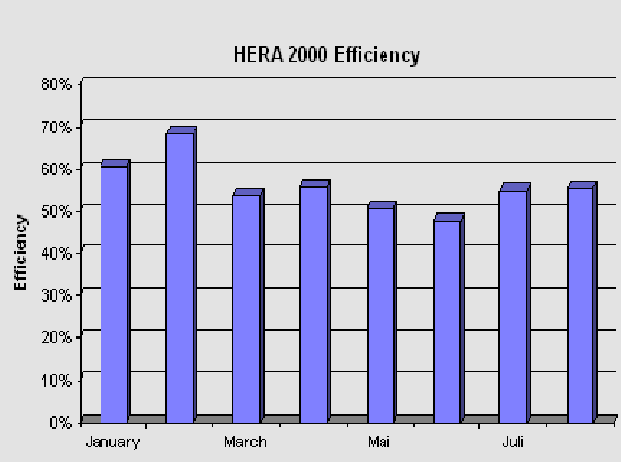


Figure 10: The HERA machine efficiency during the 2000 operation.

In addition to the loss of total operation time, the faults and beam aborts result in a significant increase of the average machine turnaround time. For example, the operational experience from the 2005 run showed that, even after 10 years of experience, the HERA operation featured on average 2.5 faults per luminosity run and required 1.8 proton injections and 1.6 electron injections per successful luminosity fill [8]. Taking further into account that a fault in the 2005 operation lasted on average 2.5 hours and that the preparation of the proton and electron fills required on average 1.43 hours and 0.83 hours for the proton and electron beams respectively, one obtains an average machine turnaround time of 10.2 hours for the 2005 run [9].

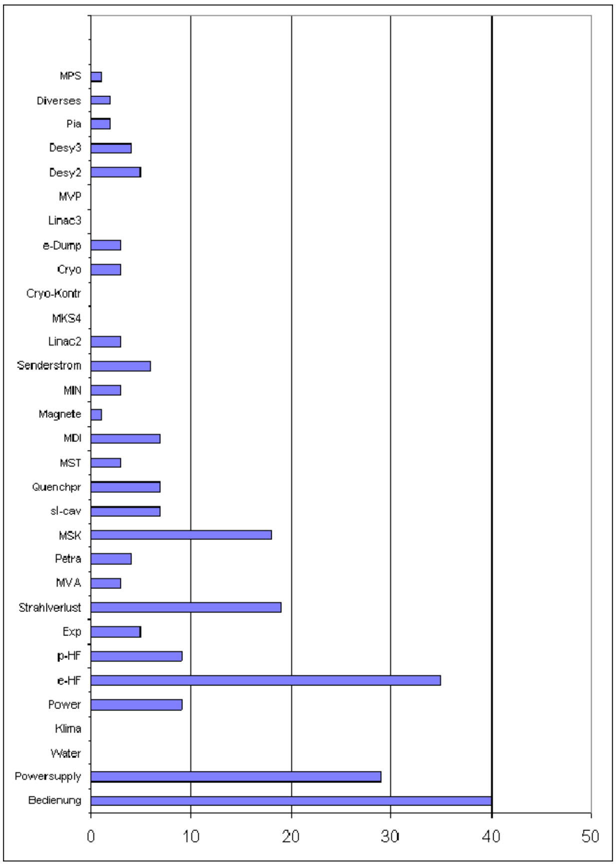


Figure 11: The most frequent reasons for an interruption of the HERA operation in the 2006 run period.

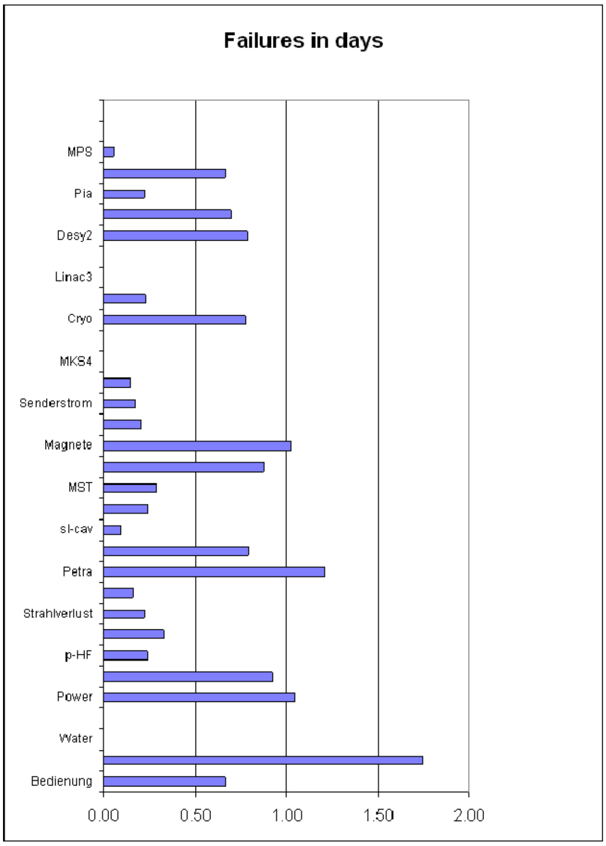


Figure 12: The total machine down time for various causes of for an interruption of the HERA operation in the 2006 run period.

This average machine turnaround time is approximately 6 times larger than the minimum theoretical turnaround time. The minimum operational turnaround time amounts to ca. 2.5 hours and is therefore ca. 1.7 times the theoretical minimum time.

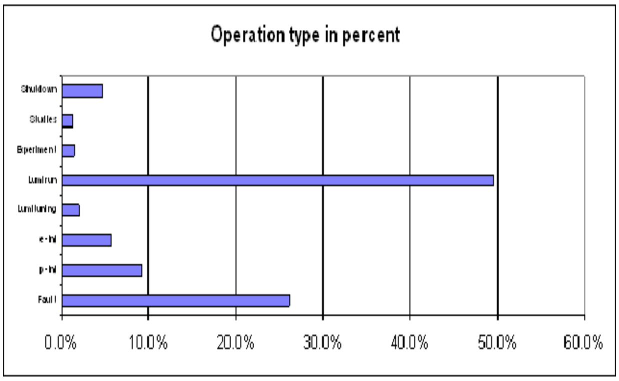


Figure 13: The distribution of various operation modes for HERA during the 2006 run.

Ca. 50% of the 2006 operation time was spent in luminosity operation and ca. 25% of the operation time was lost due to faults. Ca. 13% of the operation time was required for filling the HERA machine with new beams.

Table 9 summarizes the main observations from the HERA operational experience.

Table 9: Summary of the key observations from the HERA operation.

Parameter	Value
Minimum theoretical turnaround time	1.5 hours
Minimum operational turnaround time	2.5 hours
Average operational turnaround time	10.2 hours
Machine efficiency in percent of calendar time spent in physics operation.	55%
Average Store length	10 to 14 hours

3.3 RHIC at BNL

The RHIC collider operates in two different modes: operation with polarized proton collisions and operation with ion-ion collisions. The beam parameters are different for the two operation modes and we list the relevant values separately for both modes.

Table 10 lists the main parameters of the RHIC collider as given in [9]. The commissioning assumption for RHIC was a store length of 10h and a turnaround time of much less than 1h. Figure 14 shows the operational time in physics operation (store time) in RHIC for various calendar years and operation modes as a fraction of the full calendar time. The machine operation improved over the first 4 years from ca. 25% of the calendar year to ca. 50% in the following years. The above statistics is compatible with M = 365 and R = 0.5 in Equations (1) and (2). Figure 15 shows the operational machine turnaround time in RHIC for various runs.

The average turnaround time was ca. 23 times the theoretical minimum value and ca. 5 times the operational minimum value after 4 years of operation. Figure 15 shows the data without and with a cut of 5h where at cut of 5h implies that all machine turnaround times larger than 5h have been discarded for the calculation of the average operational turnaround time (resulting only in a reduction of the time the machine spend in physics operation). The average turnaround time was approximately 1.9h in the Run4 and Run6 operation assuming a 5h cut for the data and 8h for the first years of operation without a cut. The minimum operational turnaround time was ca 1h for Run2 and Run3 and ca. 0.4h for the last 4 years

Table 10: The minimum theoretical and operational machine turnaround times and key beam parameters for the two main RHIC operation modes as defined in [9] before RHIC was commissioned. The luminosity values of the 2006 and 2007 runs exceed the above luminosity values by a factor 2 (p-p) to 5 (Au-Au). The average store length refers to the experience from the 2007 / 2008 operation.

Parameter	p-p	Au-Au
Minimum theoretical turnaround time	5min	5min
Minimum operational turnaround time	24min	24min
Nominal beam intensity	60 x 10^{11} ppb	60 x 10^{9}ipb
Nominal initial luminosity	1.5 10^{31} cm^{-2} sec^{-1}	8 10^{26} cm^{-2} sec^{-1}
Theoretical beam lifetime (2 experiments)	t = 1000h	t = 20h
Operational beam lifetime	t = 50h	t = 30h (stoch. cooling)
Ion luminosity lifetime (dominated by IBS)	-	t= 2h
Average store length	7.2h	4.6h

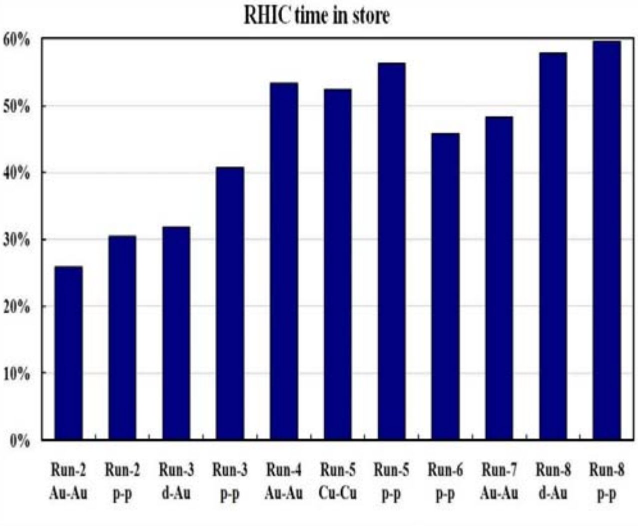


Figure 14: The operational store time in RHIC for various runs from 2002 to 2008 in percentage of the full calendar year. The above statistics is compatible with M = 365 and R = 0.3 and R = 0.6 in Equations (1) and (2) during the first and last years of operation respectively.

Both values are significantly larger than the theoretical minimum turnaround time of 5 minutes. The minimum operational turnaround time was approximately 12 times the theoretical value during the first 4 years of operation and ca. 5 times the theoretical value during the last years of operation.

Among other things, the longer operational turnaround times are mainly caused by aborted ramps due to beam loss monitor readings during the optics squeeze, equipment failure and injection tuning. One can expect all the above problems also for the LHC operation. The machine operation uses the average operational turnaround time for calculating the optimum store length. Table 11 summarizes the main observations from the RHIC operational experience.

Table 11: Summary of the key observations from the RHIC operation

Parameter	**Value**
Minimum theoretical turnaround time	5 minutes
Minimum operational turnaround time	24 minutes
Average operational turnaround time	114 minutes
Machine efficiency in percent of calendar time spent in physics operation	60%
Average Store length (p-p / Au-Au) [10]	7.2 hours/ 4.6 hours

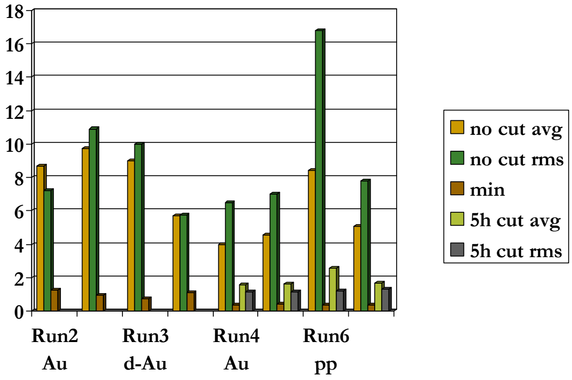


Figure 15: The operational machine turnaround time in RHIC in hours for various runs.

4. SUMMARY

4.1 Findings from the operational experience in existing Hadron colliders

Table 12 summarizes the main observations from the Tevatron, HERA and RHIC operation.

All analyzed hadron colliders have, after several years of operation, an operational efficiency (time in physics / calendar time) of ca. 60%. It therefore seems reasonable to assume for the nominal LHC operation well after the commissioning a similar figure:

$$\hat{L} = R \cdot M \cdot (24 \cdot 60^2) \cdot L_0 \cdot f(T,\tau) \tag{6}$$

with M = 365 and R = 0.6 and 'f' given in Table (2). During the first years of operation the collider efficiency can be significantly lower. For example, RHIC featured an efficiency of R = 0.3 during its first three years of operation. It seems therefore reasonable to assume also for the LHC for the first year of operation M = 365 and R = 0.3.

All analyzed hadron colliders did not reach their minimum theoretical turnaround time. The main reasons for the required longer minimum operational turnaround times are the need for injection tuning:

- The Tevatron achieved a minimum operational turnaround time that is 2.5 times the minimum theoretical value.
- HERA achieved a minimum operational turnaround time that is 1.5 times the minimum theoretical value.
- RHIC achieved a minimum operational turnaround time that is 12 times the minimum theoretical value.

The case of the RHIC collider is a bit special as the theoretical machine turnaround time (ca. 5min) is much shorter than the minimum theoretical turnaround time in the other colliders and much shorter than the average run length. Reducing the minimum operational turnaround time in RHIC further below the achieved value of 24 minutes will not have a large impact on the overall integrated luminosity and has therefore not been pursued with high priority in the RHIC operation. We will therefore use for RHIC the ratio between average and minimum turnaround time when we compare in the following it's performance with that of the other hadron colliders.

Table 12: Summary of the key observations from the Tevatron, HERA and RHIC operation

Parameter	Tevatron	HERA	RHIC
Minimum theoretical turnaround time	60 minutes	90 minutes	5 minutes
Minimum operational turnaround time	150 minutes	150 minutes	24 minutes
Average operational turnaround time	480 minutes	612 minutes	114 minutes
Machine efficiency in percent of calendar time spent in physics operation	60%	55%	60%
Average Store length (from last years of proton operation)	21 hours	14 hours	7.2 hours

Due to beam aborts during the store preparation, all analyzed hadron colliders feature on average turnaround times, which are significantly larger than the minimum operational turnaround times:

- The Tevatron achieved on average an operational turnaround time that is 8 times it's minimum theoretical and 3 times it's operational minimum turnaround time.
- HERA achieved on average an operational turnaround time that is 7 times it's minimum theoretical and 4 times it's operational minimum turnaround time.
- RHIC achieved on average an operational turnaround time that is 23 times it's minimum theoretical value and 5 times it's minimum operational turnaround time.

The LHC has a minimum theoretical turnaround time of 1.2 hours and, based on the operational experience of HERA, it seems reasonable to assume an average operational turnaround time of seven times it's minimum theoretical value ($T_{turnaround}$ = 10 hours) during the first years of operation. Using the experience from the Tevatron (an average turnaround time that is 20 times the theoretical minimum value) or RHIC (an average turnaround time that is 23 times the theoretical minimum value) would lead to even longer average turnaround times for the LHC.

4.2 Implications for the LHC performance during the first year of operation

During the first years of operation the collider efficiency can be significantly lower (e.g. R = 0.3 in the case of RHIC). Assuming a peak luminosity of $L = 2\ 10^{33}$ $cm^{-2}\ sec^{-1}$ for the LHC during the first year of operation (limit for the operation without Phase II collimation system and dump dilution kickers [11]), using M = 365, R = 0.3 and assuming an average turnaround time of 10 hours with a beam lifetime of 20 hours one obtains from Table 2: *f = 0.42.* Inserting this value into Equation (6) yields a total integrated luminosity of

$$4.6\, fbarn^{-1} \tag{7}$$

per year.

4.3 Implications for Nominal LHC Performance

Inserting the nominal peak luminosity of the LHC, R = 0.6 and assuming again an average turnaround time of 10 hours and a beam lifetime of 20 hours one obtains an integrated luminosity of

$$46\, fbarn^{-1} \tag{8}$$

per year of operation.

4.4 Implications for the nominal performance with a fully commissioned machine

Each transition from one accelerator generation to the next achieved a reduction of the ratio between minimum theoretical and average operational machine turnaround time (for RHIC we use the minimum operational turnaround time instead of the minimum theoretical value). For the transition from the Tevatron to HERA the ratio improved from 8 to 6 and from HERA to RHIC from 6 to 5. After several years of operation one might hope to obtain a similar improvement in the ratio between theoretical minimum and average turnaround time as has been achieved between the last two accelerator generations. An improvement of the ratio by approximately 20% with respect to the RHIC experience implies a factor 4 between the theoretical minimum and operational average turnaround times of a fully commissioned LHC machine. In other words, one could hope for an average machine turnaround time of 5 hours after several years of machine operation. Table 2 yields for a luminosity lifetime of 20 hours and a machine turnaround time of 5 hours: *f = 0.5* and therefore an integrated luminosity of:

$$55\, fbarn^{-1} \tag{9}$$

per year of operation.

However, this assumption neglects the fact that all colliders discussed in this paper are much smaller and less complex than the LHC machine. It is therefore far from obvious that one can hope to actually obtain the same level of improvement from RHIC to the LHC as has been achieved from the Tevatron to HERA for example. On the contrary, given the much smaller operational margins and larger machine complexity of the LHC compared to HERA, one might even question if one can actually achieve a similarly good performance of the LHC in terms of ratio between average operational to minimum theoretical machine turnaround time as has been achieved in the Tevatron and HERA operation.

4.5 Implications for the upgraded LHC performance with a tenfold increase in the peak luminosity

Looking at the ratio of integrated to peak luminosity given in Table 2, it becomes clear that an operation with luminosity lifetimes below 3 hours, as required for the Phase 2 luminosity upgrade scenarios of the LHC [3], becomes only efficient if the average machine turnaround time can be clearly kept below 6 hours. For example, Table 2 yields for a luminosity lifetime of 2.5 hours and an average machine turnaround time of 6 hours: f = 0.2. Inserting this value into Equation (6) and assuming again M = 365 and R = 0.6 yields a total integrated luminosity of

$$378\, fbarn^{-1} \tag{10}$$

per year.

Using instead a machine turnaround time of 10 hours, Table (2) yields: $f = 0.14$.which implies a luminosity loss of 30% with respect to the value given in (10). Efforts for minimizing the machine turnaround time (renovation and upgrade of the LHC injector complex and an efficient beam collimation system) are therefore the prerequisites for an LHC luminosity upgrade that aims at a ten fold increase of the integrated.

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