Turnaround time in modern hadron colliders & store-length optimization

- acknowledgments:

Wolfram Fischer for RHIC

Bernhard Holzer for DESY & 2005 Arcidosso presentation by M. Bieler

Vladimir Shiltsev for Tevatron & http://www-bd.fnal.gov/pplot/index.html

Turnaround time in modern hadron colliders & store-length optimization

- Luminosity lifetime: summary of different contributions
- Integrated Luminosity Optimization: turnaround time and run length
- Minimum turnaround time for the LHC
- Impact on operation failures on integrated luminosity:
  effective operation and turnaround time
- Experience from existing superconducting machines: Tevatron
  HERA
  RHIC

Luminosity Lifetime

- Nuclear reactions at the IP: $$\frac{dN}{dt} = -k_{IP} \cdot \sigma_{nuc} \cdot L(t)$$

➔ $$\frac{dN}{dt} = -k_{IP} \cdot \sigma_{nuc} \cdot \frac{L_0}{N_0^2} \cdot N^2(t) \Rightarrow N(t) = \frac{N_0}{1 + t/\tau}$$ with $$\tau = \frac{N_0}{\sigma_{nuc} \cdot k_{IP} \cdot L_0}$$

$\sigma_{nuc} = 10^{-25}\ \mathrm{cm}^2$

- Nominal LHC parameters:

$$L_0 = 10^{34} cm^{-2} \sec^{-1}; N_0 = 2808 \cdot 1.15 \cdot 10^{11} \Rightarrow \tau_{nom} = 44.85h$$

- Ultimate LHC parameters:

$$L_0 = 2.3 \cdot 10^{34} cm^{-2} \sec^{-1}; N_0 = 2808 \cdot 1.7 \cdot 10^{11} \Rightarrow \tau_{nom} = 28.8h$$

- Phase II Lumi upgrade 25ns option:

$$L_0 = 15.5 \cdot 10^{34} cm^{-2} \sec^{-1}; N_0 = 2808 \cdot 1.7 \cdot 10^{11} \Rightarrow \tau_{nom} = 4.3h$$

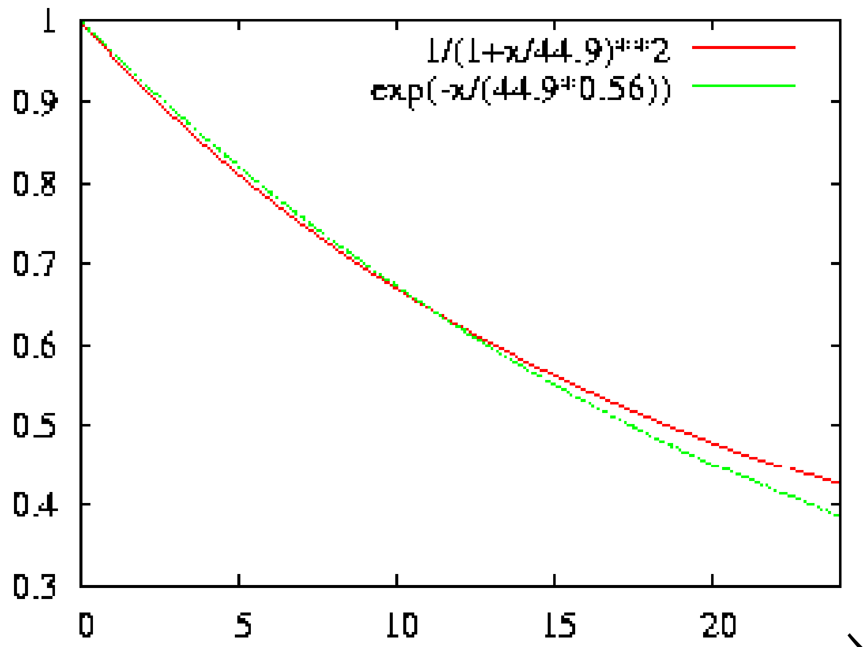
Luminosity Lifetime

- Luminosity lifetime:

$$N(t) = \frac{N_0}{1 + t/\tau} \Rightarrow L(t) = \frac{L_0}{(1 + t/\tau)^2}$$

- Exponential approximation:

$$L(t) \approx N_0 \cdot e^{-t/\tau_{\exp}}$$



$\rightarrow t$

- LHC parameters:

nominal: $\Rightarrow \tau_{\exp,nom} = 25h$ ultimate: $\Rightarrow \tau_{\exp,ult} = 16h$ PhaseII: $\Rightarrow \tau_{\exp,ult} = 2.5h$

Luminosity Lifetime

- additional sources for luminosity decay: (without noise & rad damping)

  -restgas collisions $\tau_{gas} = 100h$

  -IBS $\tau_{IBS} = 80h$

  -emittance growth due to beam-beam (difficult to predict ➔ HERA)

  -particle losses due to beam-beam (difficult to predict ➔ Tevatron: 16%)

➔ $$\frac{1}{\tau_{L,tot}} \approx \frac{1}{\tau_{\exp}} + \frac{1}{\tau_{IBS}} + \frac{2}{\tau_{gas}} + \frac{1}{\tau_{emit,bb}} + \frac{2}{\tau_{N,bb}}$$

- nominal LHC parameters: $\Rightarrow \tau_{L,tot-nom} \approx 15h$

- ultimate LHC parameters: $\Rightarrow \tau_{L,tot-ult} \approx 10h$

- LHC PhaseII upgrade parameters: $\Rightarrow \tau_{L,tot-PhaseII} \approx 2.3h$

(LHC with IBS & rest-gas only)

Integrated Luminosity

- Integrated luminosity over one run:

$$\hat{L} = \int_0^T L(t)dt$$

$$\rightarrow \quad = L_0 \cdot \tau_{L,tot} \cdot \left[1 - e^{-T/\tau_{L,tot}}\right]$$

- M operation days per year:

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

- Optimum run time:

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

Integrated Luminosity

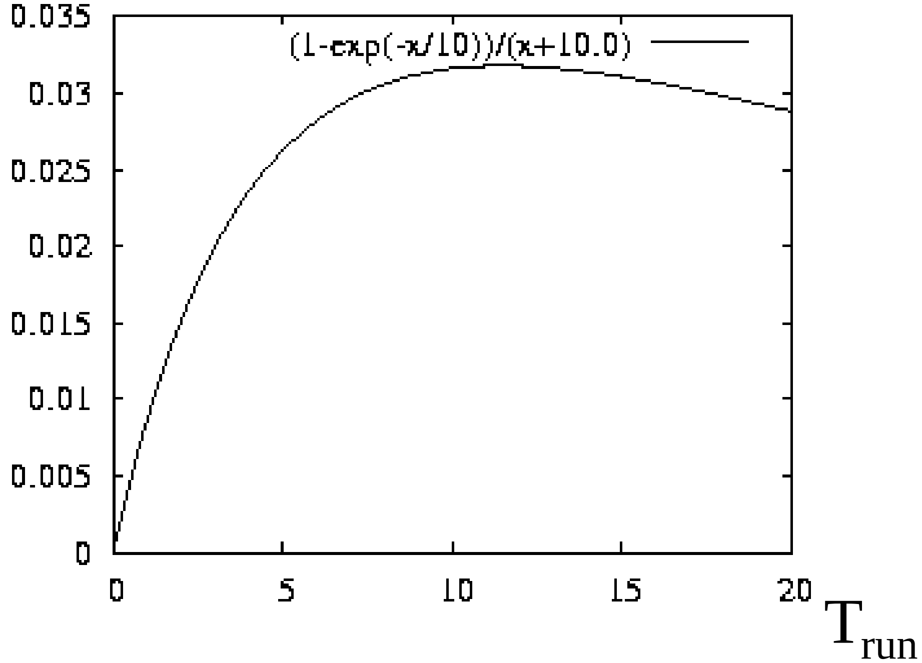
- Integrated luminosity over one year:

example: $\tau_{lumi} = 10h$

$T_{turnaround} = 10h$

➔ broad peak

➔ not very sensitive to slight variations in the run time



- Optimum run time:

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

Integrated Luminosity

Integrated luminosity versus turnaround time:

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

with: $$f(T,\tau) = \frac{\tau_{L,tot}[h]}{T_{run}[h] + T_{turnaround}[h]} \cdot \left[1 - e^{-T/\tau_{L,tot}}\right]$$

➔ f(T,τ) for different scenarios:

τ_{lumi} \ T_{turn}	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

➔ variation by 130% for τ = 2.5h and T_{turn} 1h ➔ 6h! (PhaseII)

➔ variation of only 70% for τ = 10h for T_{turn} 1h ➔ 6h (ultimate)

➔ variation of only 20% for τ = 15h for T_{turn} 6h ➔ 10h (nominal)

Integrated Luminosity: Failure Scenarios

- Faults creating a long interruption of the operation ($t >> T_{run}$)

  ➔ this essentially reduces the scheduled operation time M and can be accounted for by an overall accelerator efficiency R:

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

- Faults creating a short interruption of the operation ($t < T_{run}$)

  ➔ this results either in non-optimal run length (too early termination) or long effective turn-around times if the faults occur during the preparation of a new fill

  ➔ this affects the function:

$$f(T, \tau) = \frac{\tau_{L,tot}}{T_{run}[h] + T_{turnaround}[h]} \cdot \left[1 - e^{-T/\tau_{L,tot}}\right]$$

Experience from other Machines: RHIC

- RHIC design: (S. Peggs in RHIC AP 115)

minimum theoretical design report Turnaround time → 5min (0.4h oper)

nominal beam intensity (protons) → 60 bunches; 10^{11} ppb

nominal beam intensity gold → 60 bunches; 10^{9} ipb

nominal initial luminosity (protons) → 1.5 10^{31} cm^{-2} sec^{-1} (p)

nominal initial luminosity (gold) → 8 10^{26} cm^{-2} sec^{-1}

theoretical beam lifetime (2 exp.) → $\tau > 100$h

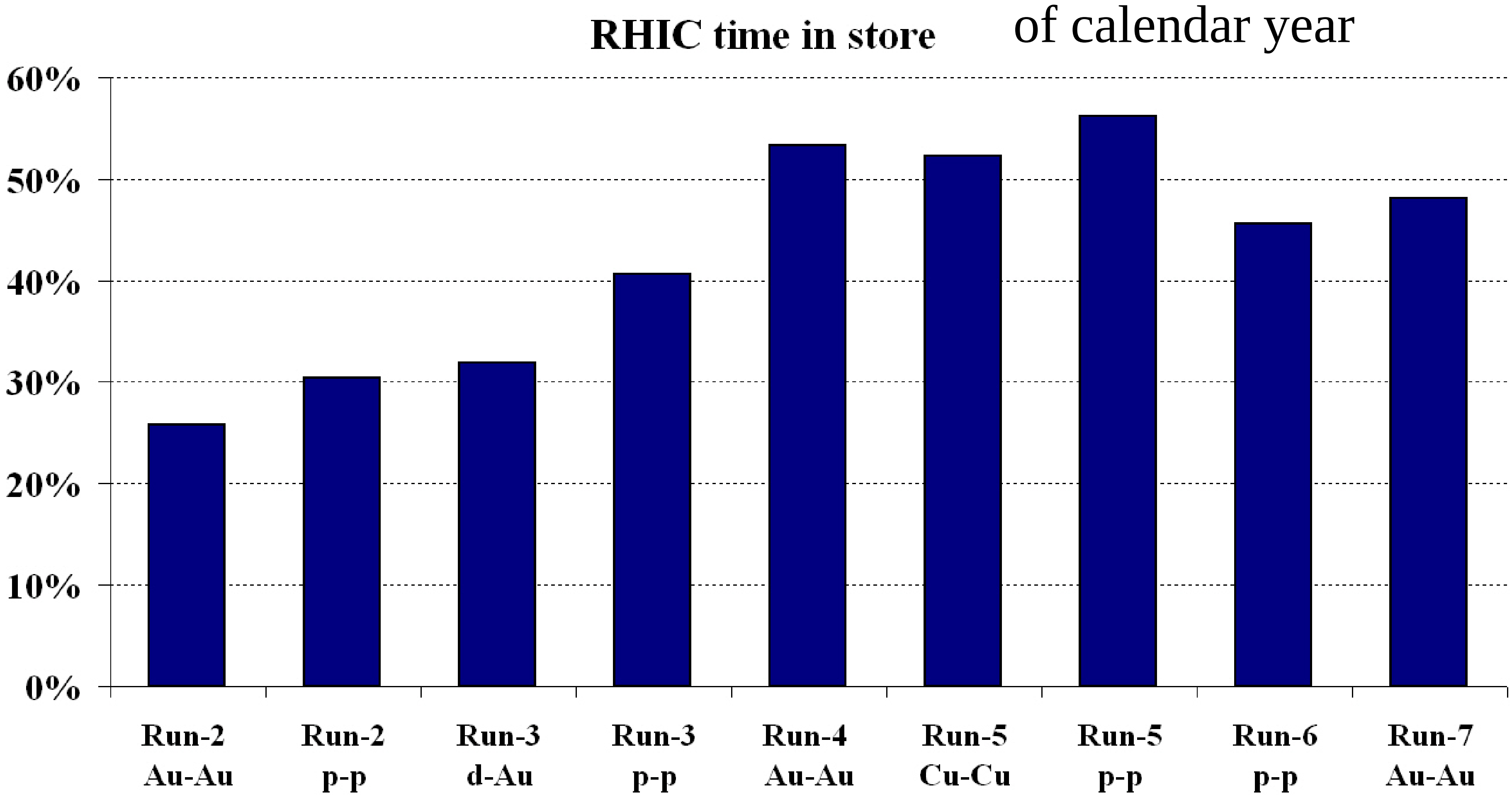
theoretical beam lifetime (2 exp.) → $\tau > 49$h

Luminosity lifetime (dominated by IBS) → τ_{lumi} ca. 2h

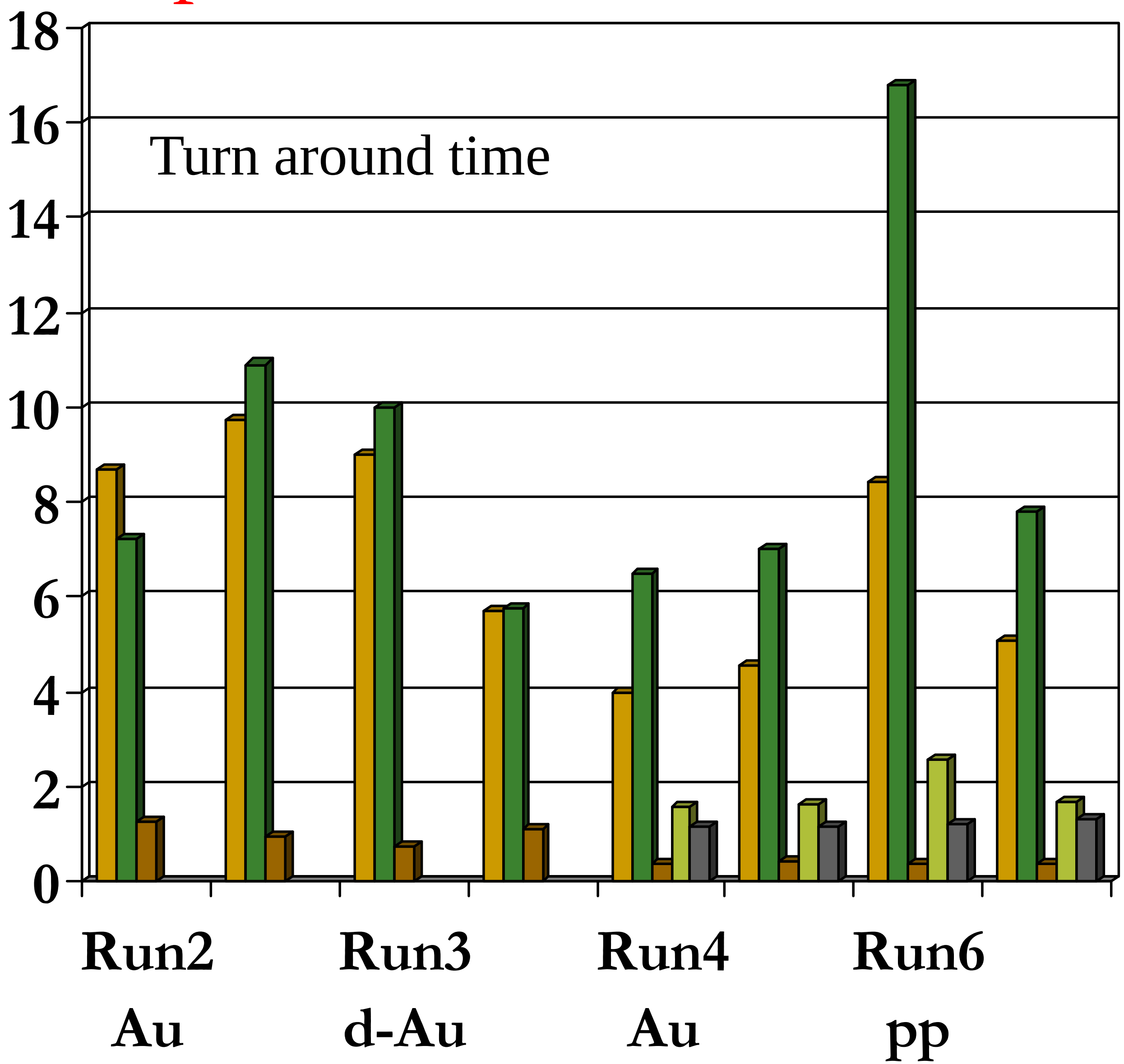
- commissioning assumptions: $T = 10h$ & $T_{turn\text{-}around} << 1h$

Experience from other Machines: RHIC

- operational experience: (curtsey of W. Fischer BNL)



Experience from other Machines: RHIC@



average $T_{turn\text{-}around}$:
ca. 1.9h for 5h cut

min $T_{turn\text{-}around}$:
ca. 1h for 2nd & 3rd run
ca. 0.4h for last 4 years

@(curtsey of W. Fischer BNL)

Experience from other Machines: RHIC

- operational experience: (curtsey of W. Fischer BNL)

  -RHIC had a min T_{turn} = 12 * theoretical limit in first 4 years operation

  -RHIC manages a min T_{turn} = 5 * theoretical limit after 4 years operation

  -RHIC has average T_{turn} = 23 * theoretical limit after 4 years operation

  = 5 * operational minimum

  Among other things, the long turn around times are mainly caused by aborted ramps due to beam loss monitor readings during optics squeeze (bad orbit, tune or enlarged beam sizes after instabilities) & equipment failure and due to injection tuning ➔ we can expect this also for the LHC!

- operation application: the average turn around time is used for calculating the optimum store length.

Experience from other Machines: Tevatron

- Tevatron design: (Plans for RunII; 2001[@])

minimum theoretical design report Turnaround time → 1 h

nominal proton beam intensity	→ 36 bunches; 27 10^{10} ppb
nominal b-par beam intensity	→ 36 bunches; 3.1 10^{10} ppb
nominal initial luminosity	→ 86 10^{30} cm^{-2} sec^{-1}
theoretical beam lifetime	→ $\tau > 13h$
Store length	→ $T_{run} = 12$ h

[@](http://www-bd.fnal.gov/doereview02/RunIIBTDR.pdf)

Experience from other Machines: Tevatron

Tevatron operation[@]:

minimum operational Turnaround time[&] → 2.5 h

average proton beam intensity → 36 bunches; 24 10^{10} ppb

nominal b-par beam intensity → 36 bunches; 3.9 10^{10} ppb

average initial luminosity (2007) → 163 10^{30} cm^{-2} sec^{-1}

average store length (2007) → T_{run} = 21 h

average set-up time (2007) → t = 2.4h

[@](http://www-bd.fnal.gov/pplot/index.html)

[&](Cons Gattuso)

Experience from other Machines: Tevatron

- Tevatron operation first 6 years of RunII[&]: [&](Cons Gattuso)

1292 stores in total

932 stores were terminated intentionally; average store length: 22.4h

360 stores ended due to failures; average store length: 10.23h

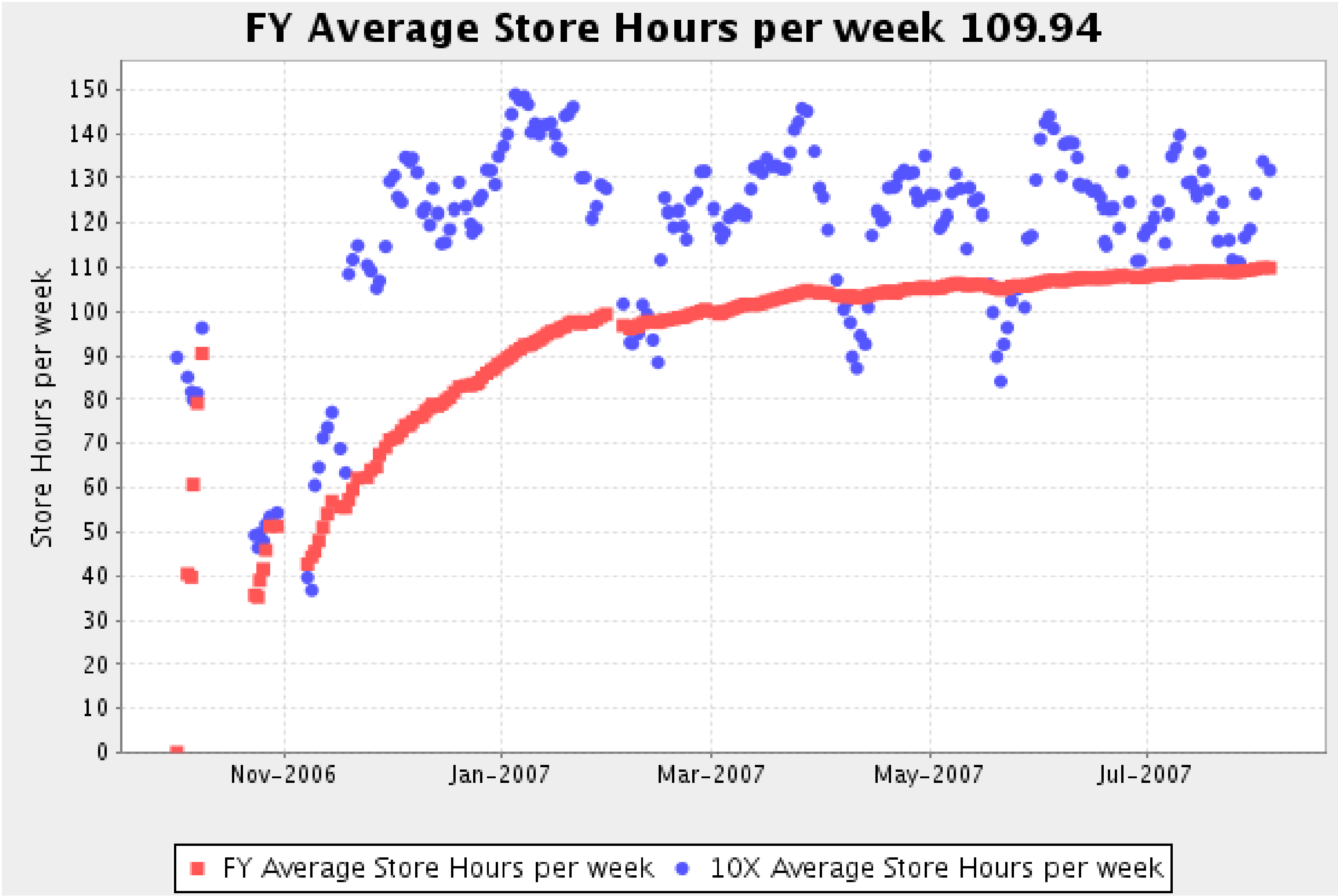
Top 10 causes:

-cryogenics	49 →	13%
-lightening	40 →	11%
-quench protection	33 →	9%
-controls	29 →	8%
-separators	25 →	7%
-RF	25 →	7%
-low β quadrupoles	24 →	7%
-corrector magnets	20 →	5.5%
-human error	20 →	5.5%
-PC	20 →	5.5%

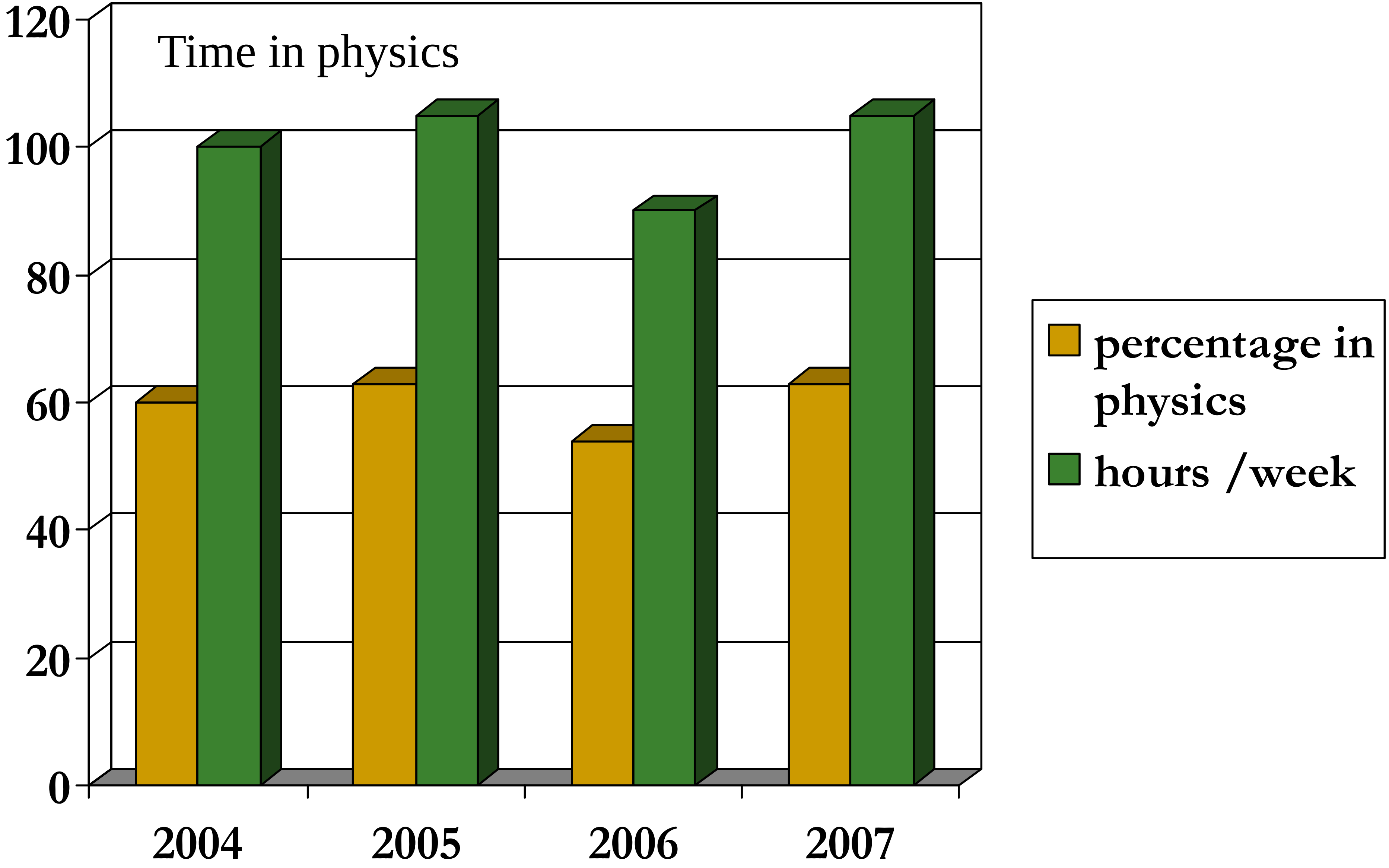
one can expect most of them also for the LHC operation!

Experience from other Machines: Tevatron

- operational experience: (http://www-bd.fnal.gov/pplot/index.html)



Experience from other Machines: Tevatron

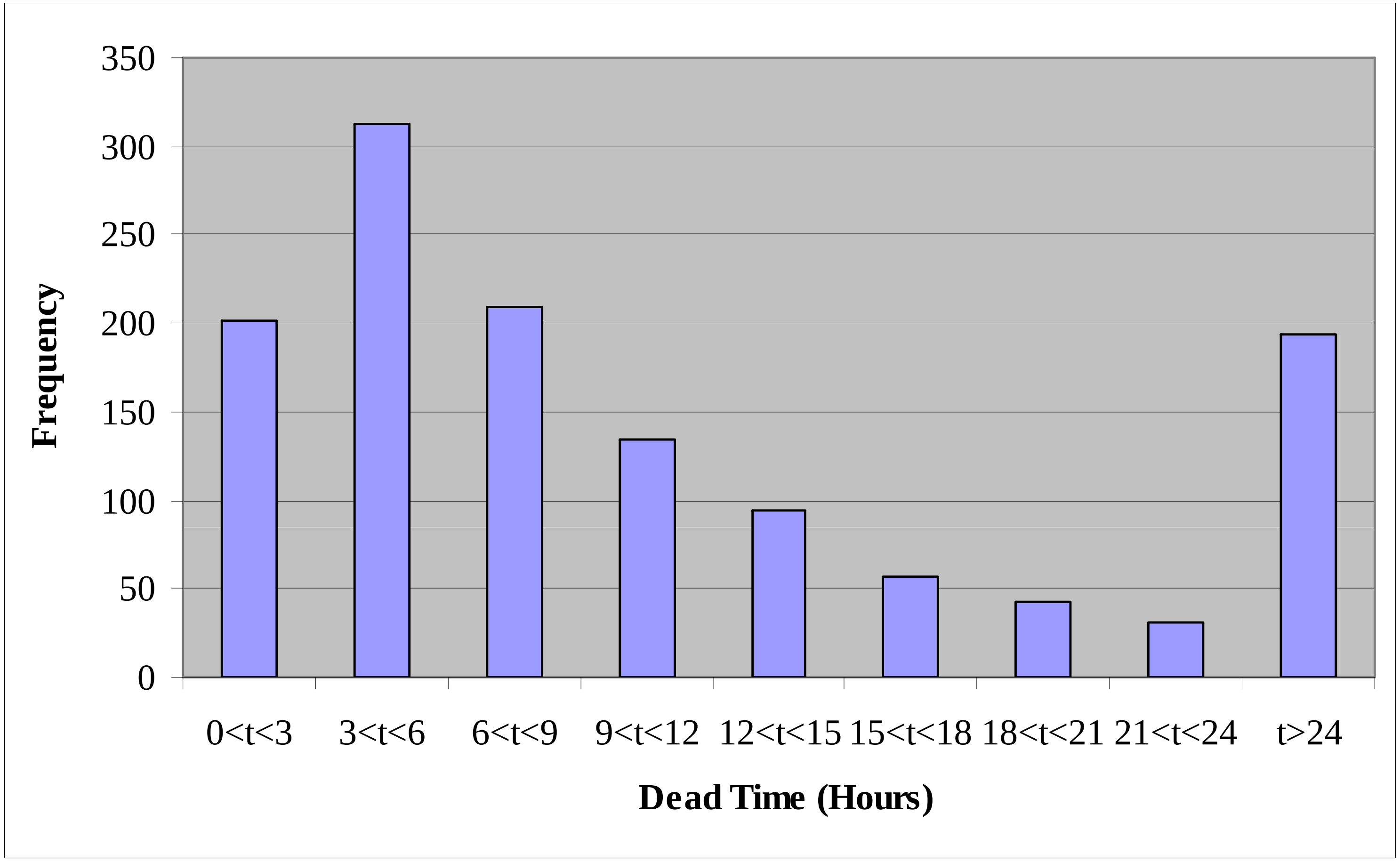


@(http://www-bd.fnal.gov/pplot/index.html)

Experience from other Machines: Tevatron

Time between shots

[&](Cons Gattuso)

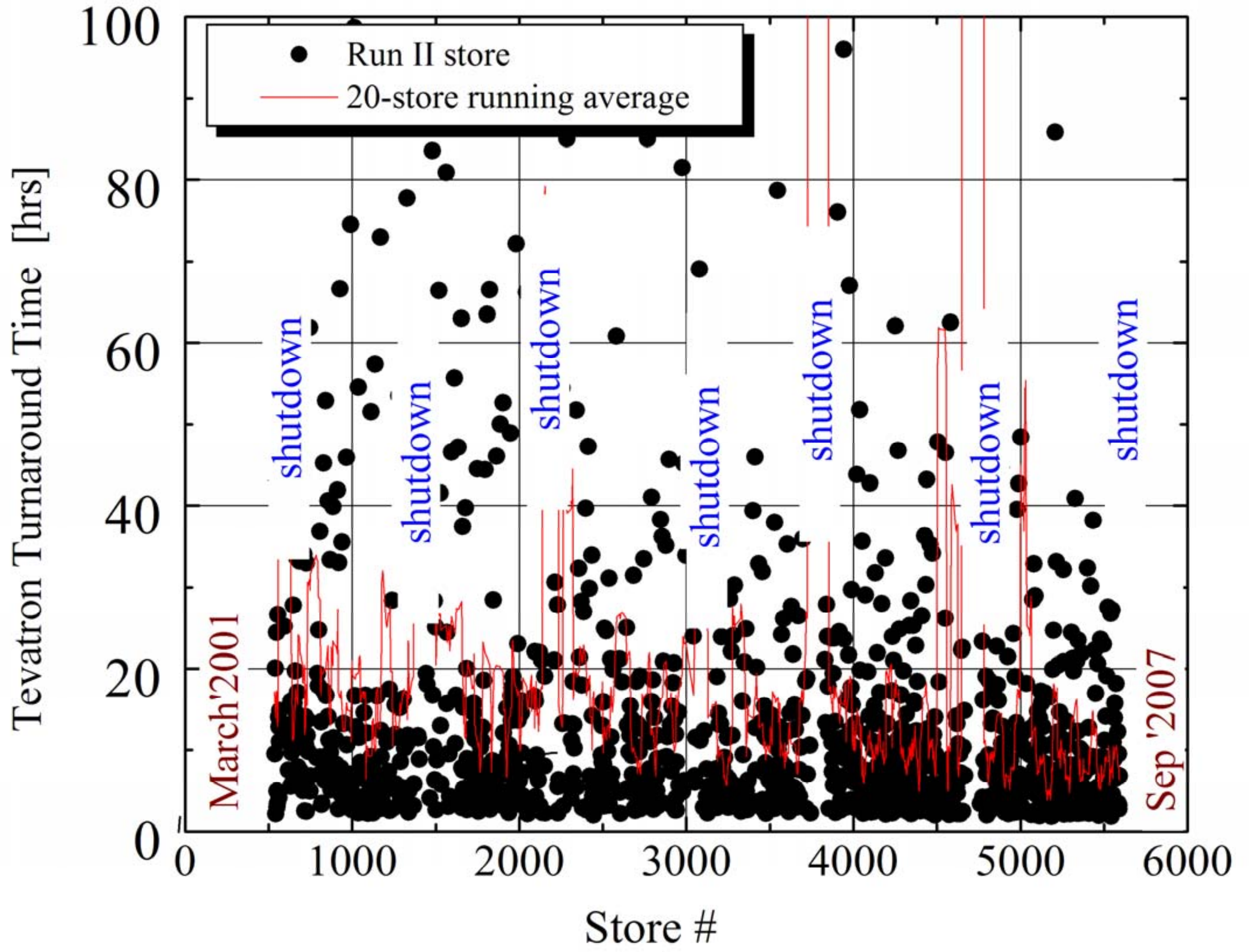


[@](http://www-bd.fnal.gov/pplot/index.html)

Experience from other Machines: Tevatron

- average turn-around time: (V. Shiltsec)

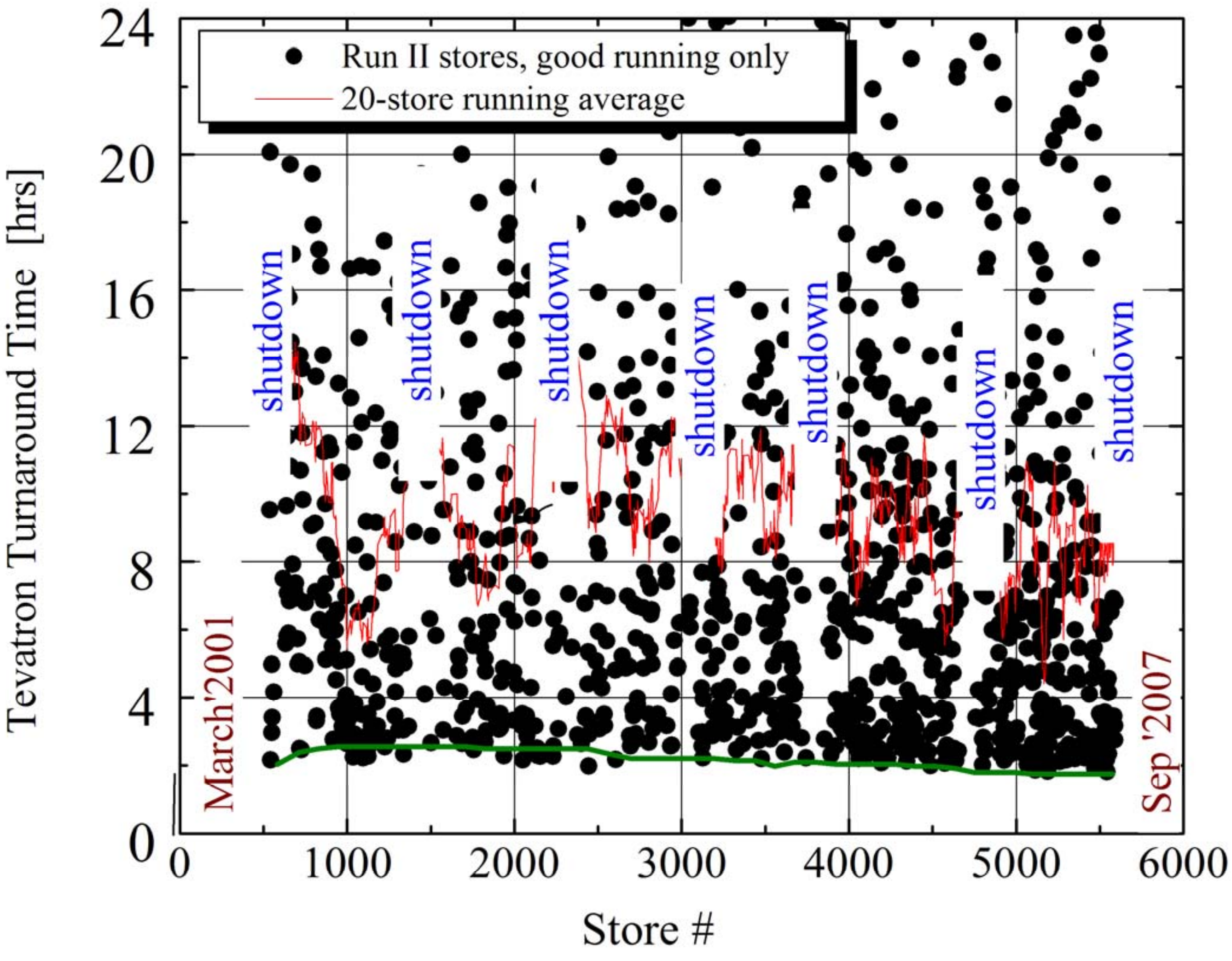
without cut



Experience from other Machines: Tevatron

- average turn-around time: (V. Shiltsec)

with 36h cut



Experience from other Machines: Tevatron

Tevatron operation@: @(V. Shiltsev)

minimum operational Turnaround time → 2.5 h

→ 2.5 * minimum after 6y RunII

average operational Turnaround time → 8 h

→ 8 * minimum after 6y RunII

average store length (2007) → T_{run} = 21 h

average set-up time (2007) → t = 2.4h

Experience from other Machines: HERA

- HERA design:

minimum theoretical Turnaround time → 1.5h

(35min filling plus 2*30min ramp up and down)

HERA I:

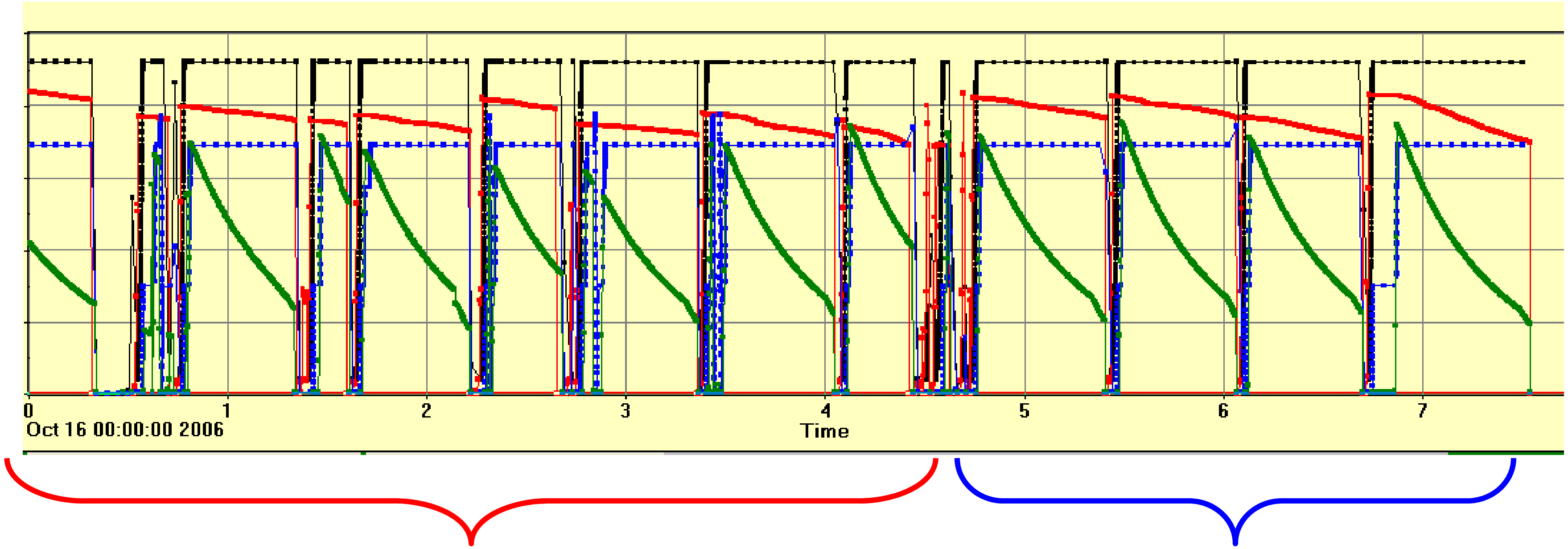
nominal beam intensity (protons) → 180 bunches; 7.3 10^{10} ppb
nominal beam intensity (electrons) → 180 bunches; 3.7 10^{10} ppb
nominal initial luminosity (protons) → 1.78 10^{31} cm^{-2} sec^{-1}
theoretical proton beam lifetime (2 exp.) → $\tau > 1025$h

HERA II:

nominal beam intensity (protons) → 180 bunches; 10.3 10^{10} ppb
nominal beam intensity (electrons) → 180 bunches; 4.3 10^{10} ppb
nominal initial luminosity (protons) → 7.57 10^{31} cm^{-2} sec^{-1}
theoretical proton beam lifetime (2 exp.) → $\tau > 340$h

Experience from other Machines: HERA

- HERA operation week 46 2006: (B. Holzer)

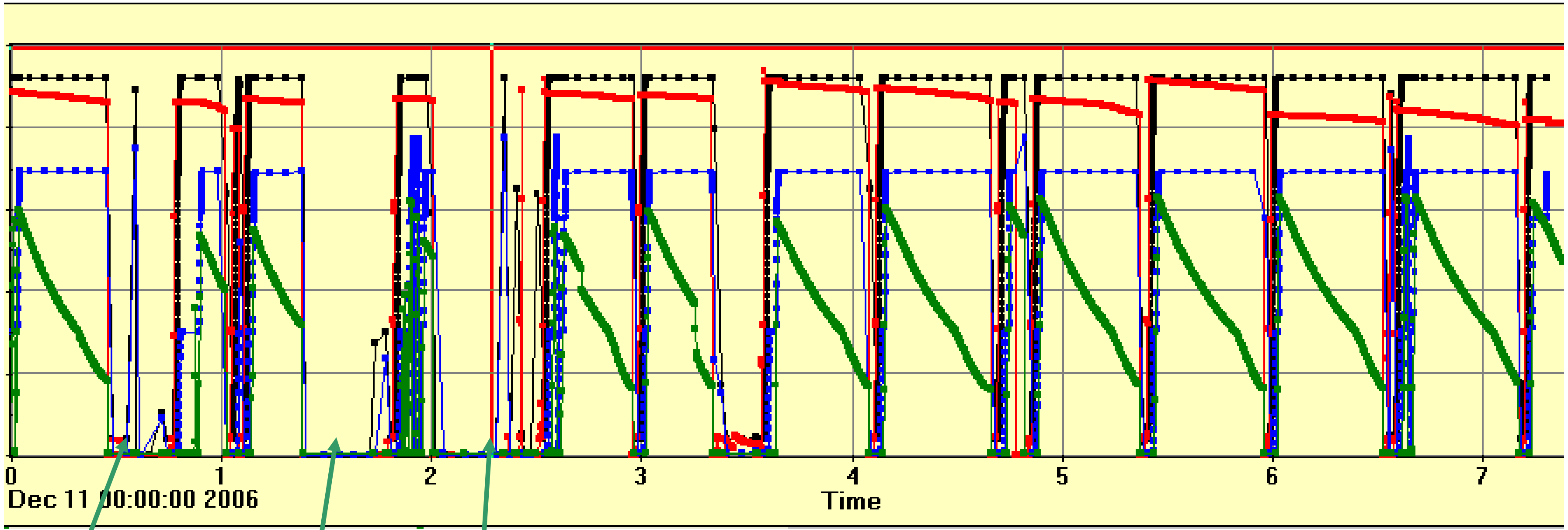


exclusively unscheduled p beam losses
unexplained proton beam losses
beam shower in collimation section
fast losses: ms

regular operation

Experience from other Machines: HERA

HERA operation week 50; 2006: (B. Holzer)

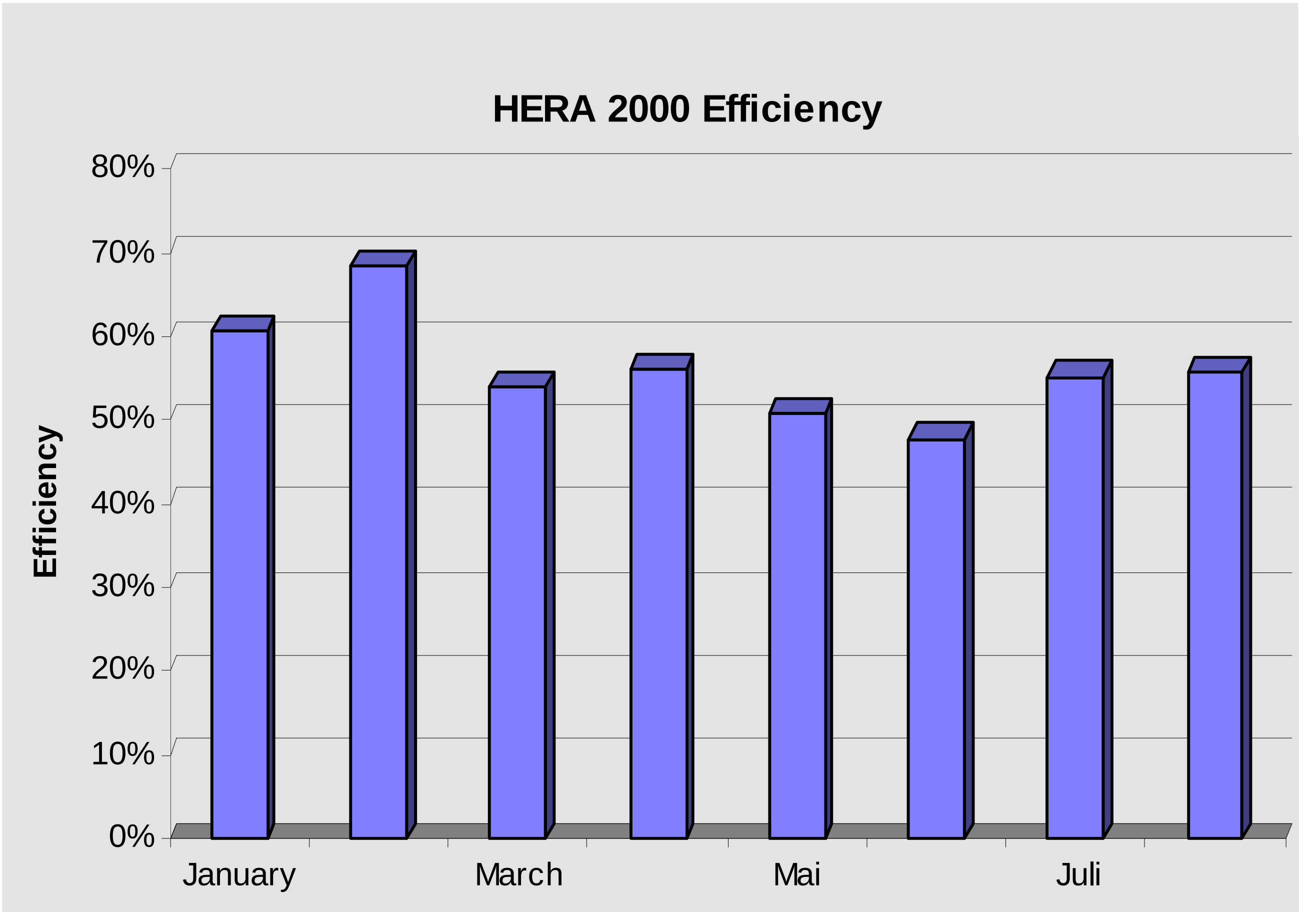


technical problems:
cryogenics
power failure
Quench at injection

regular operation

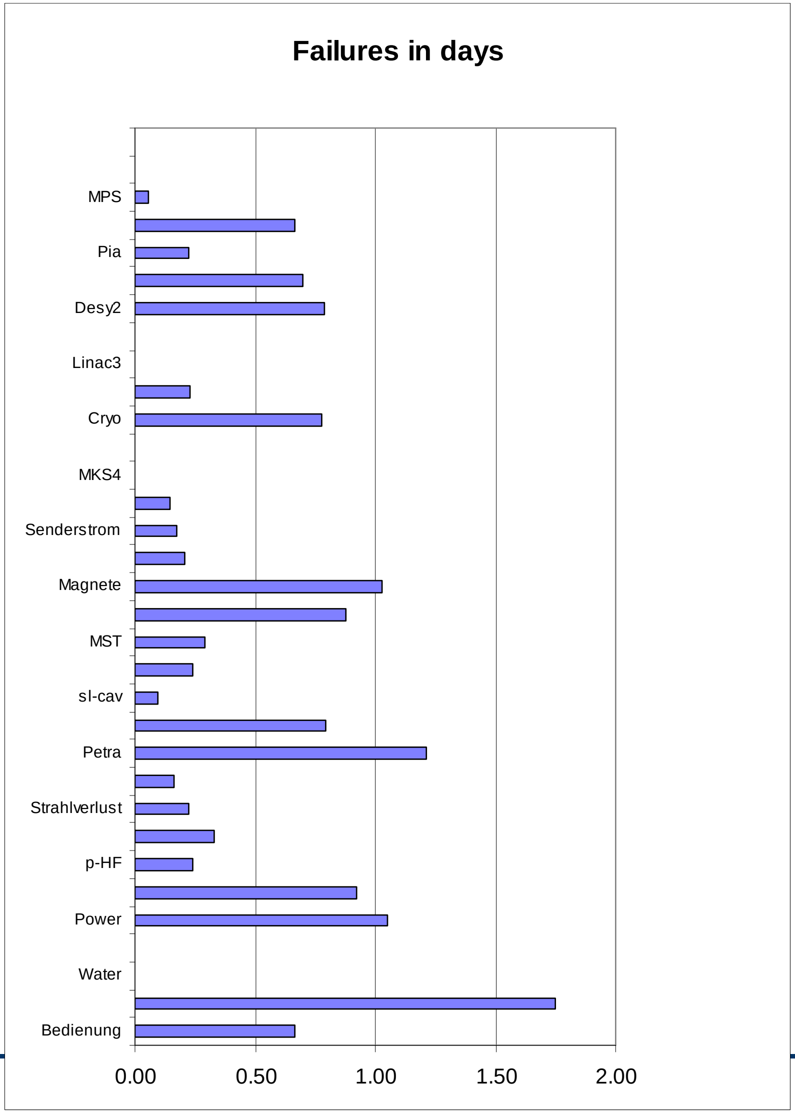
Experience from other Machines: HERA

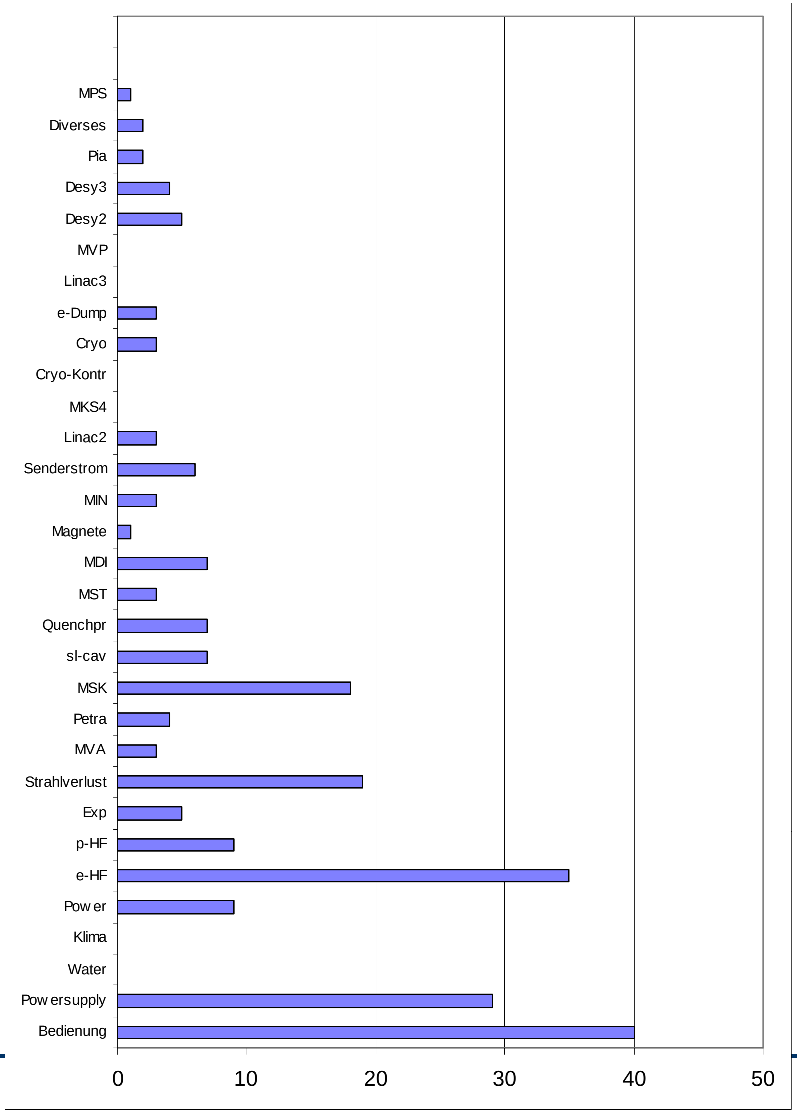
- operational experience 2000: (curtsey of B. Holzer DESY)



Experience from other Machines: HERA

- operational experience 2006: (curtsey of B. Holzer DESY)





Experience from other Machines: HERA

- HERA 2006 operation statistics[&]: [&](B. Holzer; DESY)

  115 stores in total

  230 faults; average store length: 7.4h; (min = 0.16h; max = 14.3h)

  # of p-injections = 164; number of e-injections = 185

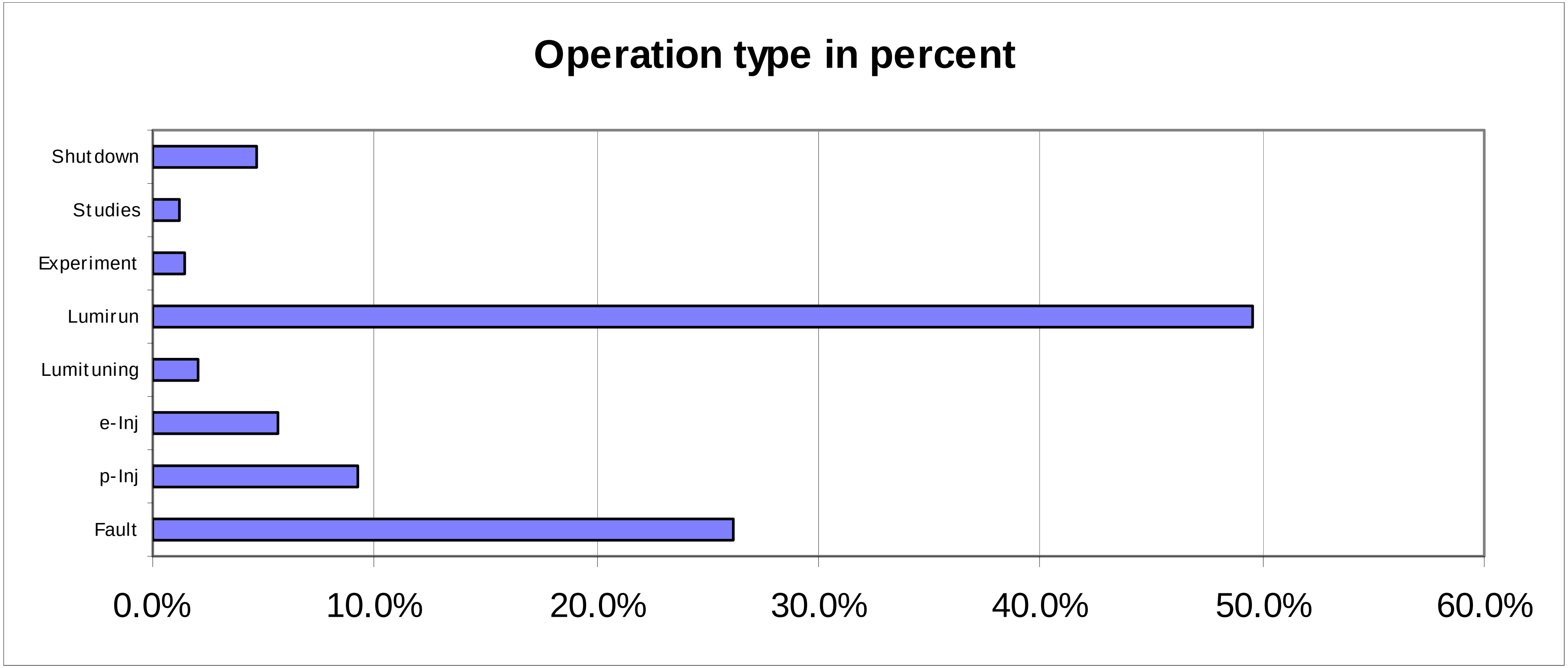
Top 10 causes: (frequency)

-operation	40 →	17%
-e-RF	35 →	15%
-power supplies	29 →	13%
-beam loss	19 →	8%
-controls	18 →	8%
-injector complex	13 →	6%
-proton RF	9 →	4%
-SC cavities	7 →	3%
-quench protection	7 →	3%
-beam instrumentation	7 →	3%

one can expect most of them also for the LHC operation!

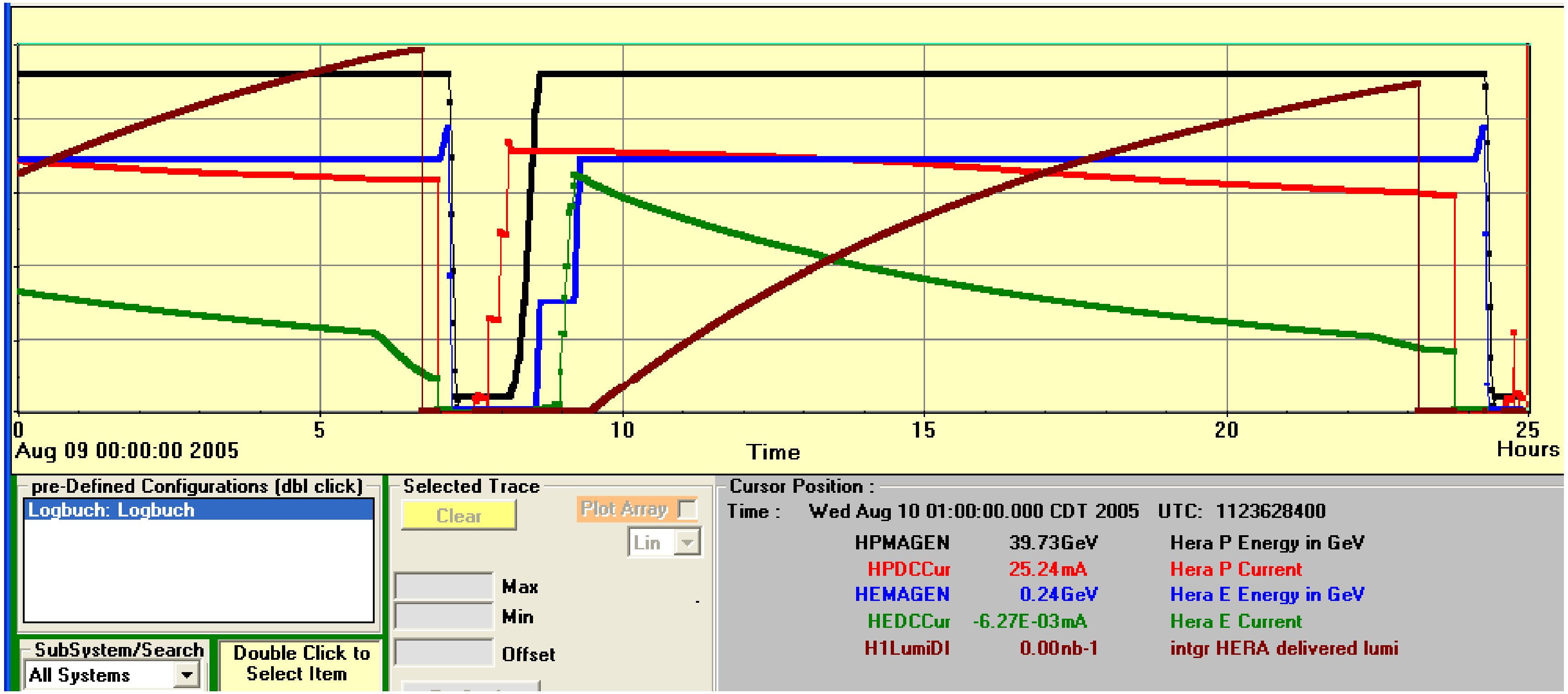
Experience from other Machines: HERA

- operational experience 2006: (curtsey of B. Holzer DESY)



Experience from other Machines: HERA

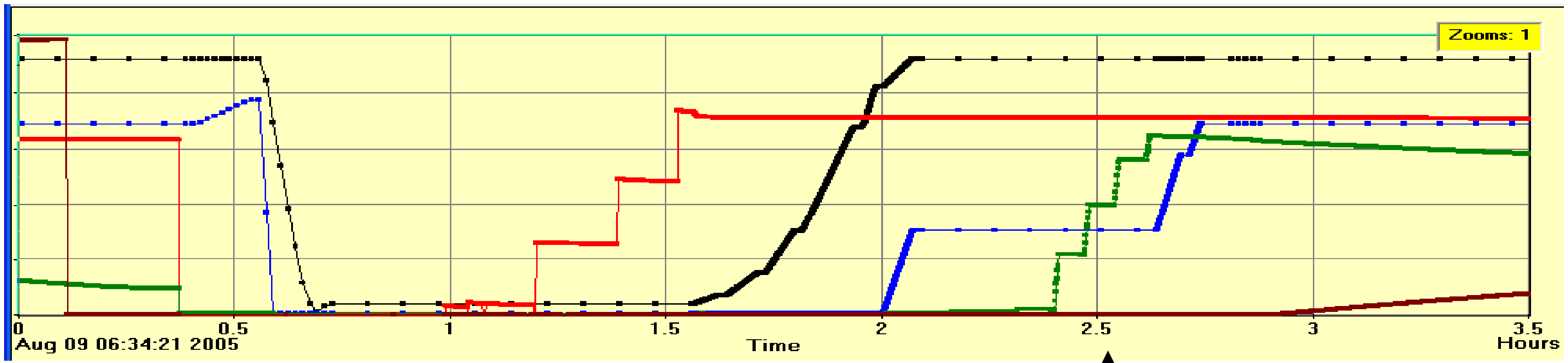
- optimum operation cycle: (M. Bieler DESY; Arcidosso 2005)



2.5 h turn around time and ca. 15h run time

Experience from other Machines: HERA

- Optimum operation cycle: (M. Bieler DESY; Arcidosso 2005)



Beam Dump

HERA Magnet Cycle

Setup p-Injection

3 PETRA Cycles

40 GeV to 920 GeV

Setup e-Injection

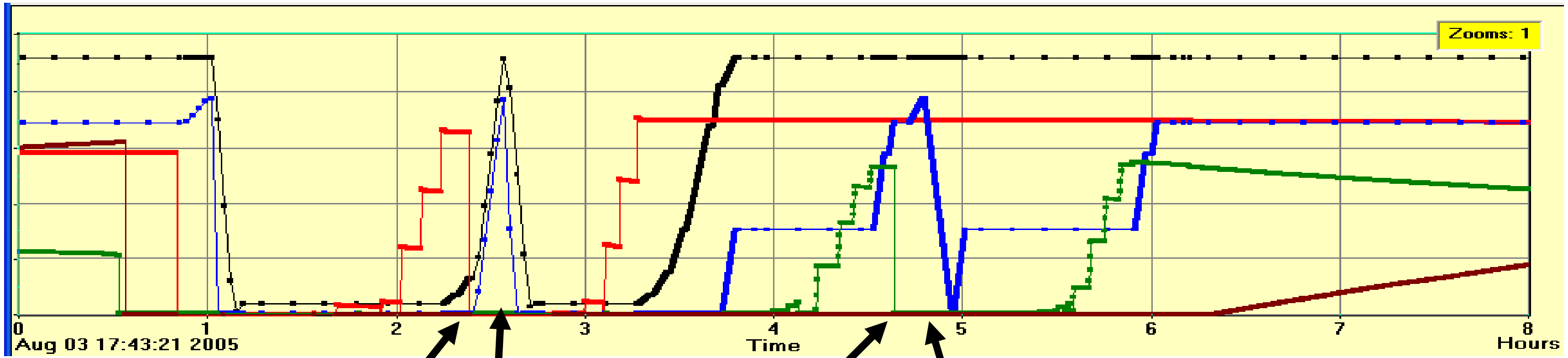
4 PETRA Cycles

12 GeV to 27.5 GeV

Lumi

Experience from other Machines: HERA

- real life: (M. Bieler DESY; Arcidosso 2005)



p Beam Loss on the Ramp

HERA Magnet Cycle

e Beam Loss on the Ramp

Electron Magnet Cycle

➔ 5.5 hours from beam dump to luminosity

Experience from other Machines: HERA

Operational experience 2005[@]: (10 years after HERA operation)

HERA 2005:

2.6 faults per luminosity run	*	2.5	hours per fault	= 6.5 h
1.8 p injection attempts per luminosity run	*	1.43	hours per p inj.	= 2.6 h
1.6 e injection attempts per luminosity run	*	0.83	hours per e inj.	= 1.3 h
				10.2 h from dump to lumi

→ average turn around time = 6 * minimum turn around time

[@](M. Bieler; Arcidosso, September 2005)

Summary

- operation efficiency: all analyzed colliders have ca. 50% efficiency (time in physics / allocated operation time)
  ➔ seems to be a reasonable assumption for LHC operation

- minimum turnaround time: all analyzed colliders could not reach their theoretical minimum turn around time (injection tuning!)
  RHIC: 12 * min_{theor}; Tevatron: 2.5 * min_{theor}; HERA: 1.5 * min_{theor}

- average turnaround time: all analyzed colliders have a significantly larger average turn around time even after several years of operation (failures)
  RHIC: 23 * min_{theor} (5 * min_{oper}); Tevatron: 8 * min_{theor}; HERA: 6 * min_{theor}

Summary

- LHC: assuming a minimum turn around time of 1.2h for the LHC it seems to be reasonable to assume:

  T_{turn} = 10h during first years (8 * theoretical minimum [like Tevatron])

  T_{turn} = 5h during operation with ultimate parameters

  ➔ apply the same ratio as Tevatron -> HERA improvement

  (average $T_{turnaround} = 8 * T_{theo\text{-}min} \rightarrow 6 * T_{theo\text{-}min}$)

  However: HERA and Tevatron have the same size and similar complexity while LHC is much larger than Tevatron

  ➔ can this improvement be extrapolated to the LHC?

- LHC Phase II luminosity upgrade is only efficient if $T_{turnaround} < 5$h:

  ➔ ½ of potential L gain is lost if $T_{turnaround}$ is 6h instead of 1.2h

  ➔ need consolidation efforts for minimizing fault rate!

Phase 2 Beam Parameter Options[@]

Summary of the nominal, ‘ultimate’ and Phase2 upgrade beam parameters

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 absorbers / radiation hard	Efficient absorbers / radiation hard
			D0	Wire compensators
			Crab cavities	

[@]LUMI’06 workshop proceedings