HERA: Sources & Cures of Background - Machine Perspective

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Abstract

This report gives an overview about the background sources, measurements and optimisation procedures in the HERA storage ring. After a short introduction into the basic parameters of the machine, the tools are presented that were used to guarantee the beam quality and minimise the particle losses during luminosity runs. Different typical background problems are presented, including their signature and their influence on the data taking of the high energy physics detectors.

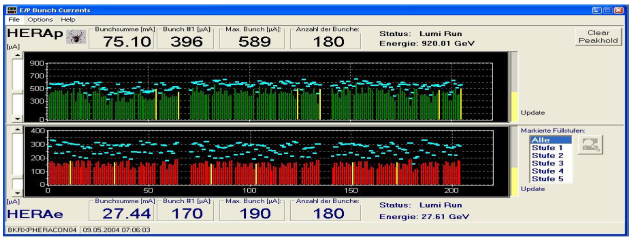
THE HERA STORAGE RING

The HERA machine [1] was a double ring collider for the collision of protons and electrons/positrons at DESY (Deutsches Elektronen Synchrotron) in Hamburg. The 920 GeV protons and the 27.5 GeV leptons were accelerated and stored in two independent rings and brought into collision at the two interaction points “South & North” where the high energy detectors ZEUS and H1 were installed.

Figure 1: The HERA storage ring in Hamburg

According to the nature of the two particle beams in HERA the background characteristics were twofold: Synchrotron light and electromagnetic showers on one side, and hadronic showers related to the proton beam on the other. While the synchrotron light related topics are covered in a dedicated contribution to this workshop [2] the purpose of this document is to concentrate on the details of the HERA proton beam and the related hadronic backgrounds. Detailed analysis of the HERA background situation and its improvement over the past years, as seen by the experiments, can be found in [3,4].

In HERA typical beam intensities for the protons of I_p=100mA and for the electrons of I_e=45mA have been achieved, distributed in routine luminosity runs over 180 bunches.


E/P Bunch Currents

File Options Help

HERAp [μA]
Bunchsumme [mA]: 75.10
Bunch #1 [μA]: 396
Max. Bunch [μA]: 589
Anzahl der Bunche: 180
Status: Lumi Run
Energie: 920.01 GeV

Markierte Füllstufen: Alle, Stufe 1, Stufe 2, Stufe 3, Stufe 4, Stufe 5

HERAe [μA]
Bunchsumme [mA]: 27.44
Bunch #1 [μA]: 170
Max. Bunch [μA]: 190
Anzahl der Bunche: 180
Status: Lumi Run
Energie: 27.61 GeV

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Figure 2: 180 bunches form the HERA standard bunch train for luminosity runs

The resulting single proton bunch population $N_p=7*10^{10}$ therefore differs not much from the foreseen design value for the LHC ($1*10^{11}$). Figure 2 shows the 180 bunches of a standard HERA fill during luminosity operation (upper part for the protons, lower for the lepton beam). As can be deduced from the plot, the intensity distribution of the bunches was constant within approximately 10%. The main parameters of the HERA machine are listed in the table below [5].

	protons	*electrons*
β_x	*2.45m*	*0.6 m*
β_y	*0.18m*	*0.26m*
ε_x	*5.1 nm*	*21nm*
ε_y	*"*	*3.5nm*
σ_x	*112 μm*	*112μm*
σ_y	*30 μm*	*30 μm*
$\Delta\nu_x$	*1.1*10 -3*	*3.0*10 -2*
$\Delta\nu_y$	*3.1*10 -4*	*4.9*10 -2*

The two beams, differing by the nature of the particles in emittance and coupling, were matched in a dedicated way to obtain the same beam size at the interaction points. The beta-function and the tune shift parameter Δν refer to the IP North or South.

Table 1: HERA optical parameters

Machine Aperture:

For luminosity operation an overall aperture in the proton machine of at least 12 sigma of a transverse Gaussian beam distribution has been considered as sufficient. In other words the beta function has been matched in any part of the storage ring according to that requirement. In the super conducting sections of the machine beam losses are much more critical than in the straight sections where conventional magnets are installed. Therefore an aperture of at least 20 σ was guaranteed in the sc. arc. However, unlike to the LHC definition, no additional safety margins has been added for dispersion trajectories and orbit distortions. The luminosity optics of HERA proton ring is plotted in the figure 3.

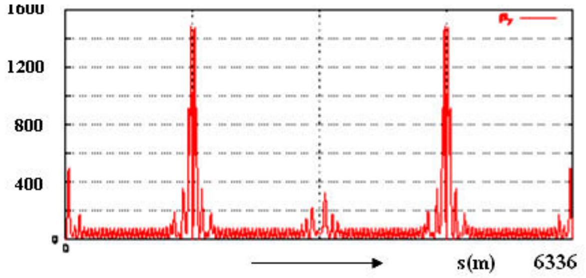


Figure 3: Beta function of the HERA proton ring

According to the mini beta insertions, the highest values of the beta function occur close to the interaction points South and North, where the detectors of the collider experiments are located. At these locations (i.e. inside the mini beta quadrupoles) the free aperture is limited to 12 sigma and - with the exception of the collimators that are put at approximately 7...8 sigma - these regions defined the smallest aperture in the ring. This situation is again reflected in the two plots below: The 12 sigma beam profile for standard luminosity operation is plotted in the cold section of the arc and compared to the free aperture that is obtained inside the horizontal mini beta quadrupole. To enlarge the free space for the beam a special shape of the vacuum chamber has been chosen. The figures show 12 σ of a 920 GeV proton beam inside the cold section (left) and inside the shamrock type vacuum chamber of the warm mini beta quadrupole magnets.

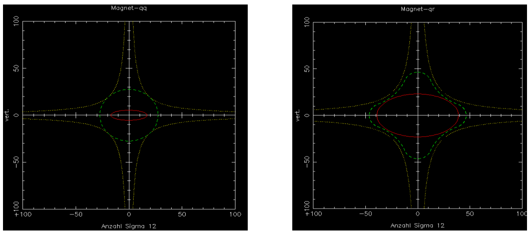


Figure 4: Beam size and aperture in the cold section (left) and in the conventional mini beta quadrupole lens (right). The aperture limitation by design corresponds to 12 σ.

Communication between experiments and machine:
In each big collaboration there is a fundamental problem of how to define and establish the communication flow.

Figure 5: Some members of the ZEUS collaboration

At HERA four high energy detectors had been installed and the number of collaborators easily exceeded 400 per experiment. Very soon therefore it turned out that a well defined information structure and communication flow was needed to avoid misunderstandings and guarantee that the relevant running parameters are known by those to whom they concern. We defined one contact person per experiment and in addition a spokes person that coordinated the wishes and needs of the four different experiments among each other. The basic running conditions were discussed in a weekly meeting. For special problems e.g. commissioning of new detector parts or background tuning a number of experts from the experiment was joining the machine studies in the control room and it turned out to be a very efficient procedure. Direct communication with the experts from the detector and the ability to run specific detector signals in the control room to tune the storage ring turned out to be an ideal solution.

BEAM QUALITY

Proton Injection
It can be considered as a part of the special character of the super conducting HERA ring, that its basic parameters - at low fields - were neither very stable nor reproducible [6]. Instead, they depended on the history of the magnets, i.e. the time and niveau of the preceding run and the way the magnets had been cycled before. Due to eddy / persistent currents [7] the magnetic field at injection was differing from run to run and drifting at the injection plateau. Accordingly a high quality beam in HERA could only be obtained if these fields and the corresponding beam parameters had been measured and corrected properly.
Fig. 6 shows an example of an injection of a pilot bunch train that was routinely used to set up the machine before a complete luminosity fill had been injected. The figure on the left part shows the longitudinal injection oscillations that had typically been observed at the first injection after a magnet cycle. Dipole field mismatches of up to 1 Gauß had been obtained in extreme situations; typical values were measured to be around +/- 0.5 Gauß.
Fitting these longitudinal oscillations and compensating the injection field accordingly led to the situation shown in the right part of the figure, where essentially no further oscillations are observed.

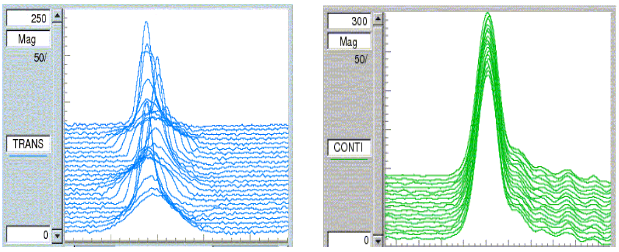


Figure 6: Longitudinal beam oscillations at injection; before and after correction

In a similar way the 10 bunch pilot train was used to measure and optimise the injection energy and phase, the tunes, the coupling and the transverse injection oscillations, the latter with respect to the closed orbit. The key issue of this procedure was to obtain and sustain routinely a high quality beam, i.e. a transverse beam emittance that corresponded to the design values of 20 π mm mrad (normalised and referring to 2 sigma).

Therefore the emittance in both transverse planes had been measured and checked before the start of each acceleration ramp. A typical example is shown in the next figure: The emittance of all 180 bunches is plotted after injection. Values between 15 and 20 π mm mrad were considered as acceptable and the fluctuation between bunches was usually small.

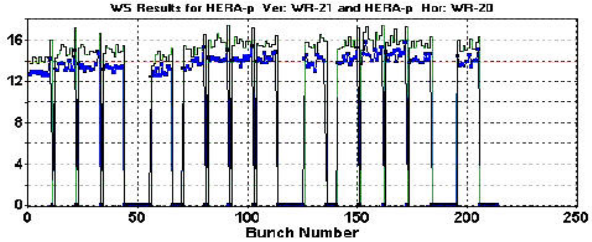


Figure 7: Beam emittance of the 180 HERA proton bunches, measured after injection to check the beam quality before starting the ramp

Proton Ramp:

Problems affecting the beam quality during the acceleration were rare but possible. It turned out that uncompensated coupling of the two transverse planes, orbit distortions and lifetime problems due to aperture or even tune steering had no or only negligible influence on the beam quality. However quite opposite to that chromaticity changes could severely affect the beam quality. Namely the snapback effect in HERA [8], if not compensated accurately, could lead to small or even slightly negative chromaticities and the head tail instability could spoil the beam quality on the first steps of the ramp. For the operators it was visible as a short but strong excitation of the beam in the tune spectrum. A beam quality check at the end of the ramp therefore was indispensable. Fig 8 shows such a measurement at 920 GeV after a head tail instability occurred at the lower part of the ramp. Some bunches in the 180 bunch train show an emittance blow up of nearly a factor of two. Consequently such beams could not been brought into collision and had to be aborted.

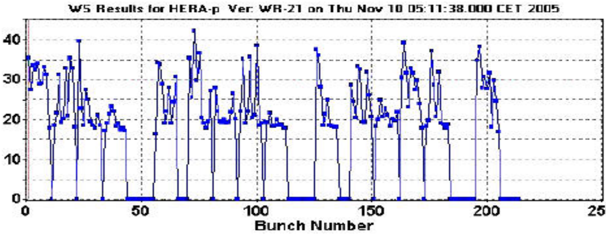


Figure 8: An event that could happen from time to time: A strong beam excitation on the ramp spoiled the bunch quality: some bunches have nearly doubled their transverse emittance; better throw them away.

Luminosity Run:

Once collisions had been established and the ideal machine parameters could be set up, smooth machine running was obtained in general. Similar to the situation at injection however, drifts in tune, coupling, orbit and chromaticity have been observed and had to be compensated. This was usually not a big problem; however a general trend of decaying specific luminosity due to a slow increase of the beam emittance could not be counteracted. After a luminosity run of typically 12 hours duration the emittance increased up to values of 25 ... 30 π mm mrad (fig.9) - limiting in the end the length of a luminosity run.

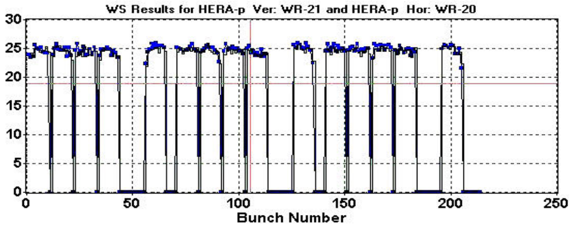


Figure 9: Beam emittance of the 180 bunches after a long luminosity run: still smooth but quite larger than in the beginning of the run (see Fig. 7)

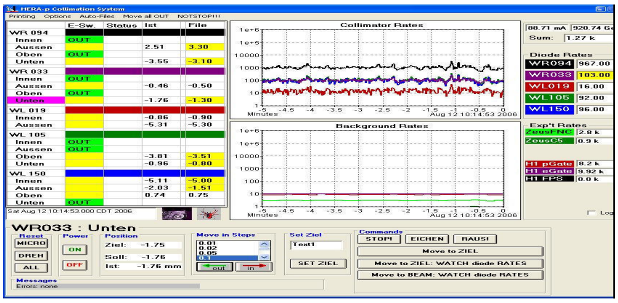
BACKGROUND TUNING

Machine:

In the end this is the topic of the workshop. Once the beams had been brought into collision the main task for the operations group was to optimise the machine parameters, keep them stable and establish reasonable background levels at the high energy detectors. In principle three parameters had been used for that purpose: The beam lifetime, the loss rates at the collimators and signals from different parts of the high energy detectors. In practise it turned out that the HERA lifetime measurement was to slow and not precise enough to be used for fine tuning of the machine.

Figure 10: Beam lifetime measurement: Used mainly for "long term" measurements. For fast and efficient background tuning the significance was limited.

At least it was not trivial to disentangle the fluctuations of the lifetime measurement from real tuning effects, as the indicated lifetime oscillated between 50 and 150 hours (fig. 10). A much better tool for background tuning was the beam loss monitor (BLM) system [9,10]. Originally installed to detect local beam losses and in case of problems dump the proton beam to prevent the machine from quenching, the BLM's also had been installed at the collimator system [11]. And these turned out to be an ideal tool for machine tuning. The BLM diodes measured the beam losses with a period of 5ms and for the display in the control room these values were averaged over one second. Figure 11 shows the BLM signals for each collimator stations: They were used to define the collimator positions with respect to the beam and the relative positions of main and secondary collimators with respect to each other.



HERA-p Collimation System

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WR 094				
Innen	OUT			
Aussen			2.51	3.30
Oben	OUT			
Unten			-3.55	-3.10
WR 033				
Innen	OUT			
Aussen			-0.46	-0.50
Oben	OUT			
Unten			-1.76	-1.30
WL 019				
Innen			-0.86	-0.90
Aussen			-5.31	-5.30
WL 105				
Innen	OUT			
Aussen	OUT			
Oben			-3.81	-3.51
Unten			-0.96	-0.80
WL 150				
Innen			-5.11	-5.00
Aussen			-2.03	-1.51
Oben			0.74	0.75
Unten	OUT			

Sat Aug 12 10:14:53.000 CDT 2006

88.71 mA | 920.74 Ge
Sum: 1.27 k

Diode Rates

WR094	967.00
WR033	103.00
WL019	16.00
WL105	92.00
WL150	96.00

Exp't Rates

ZeusFNC	2.8 k
ZeusC5	0.9 k
H1 pGate	8.2 k
H1 eGate	9.92 k
H1 FPS	0.0 k

WR033 : Unten

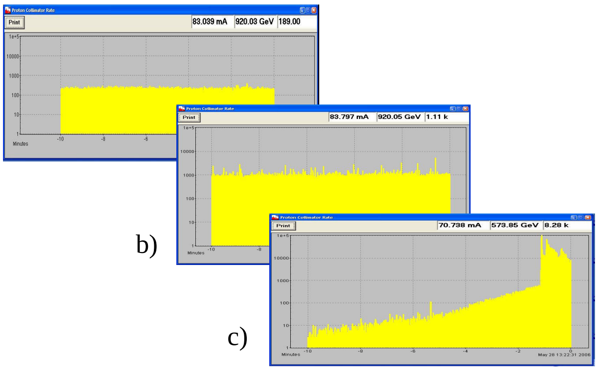
Position
Ziel: -1.75
Soll: -1.76
Ist: -1.76 mm

Set Ziel: Text1

Messages
Errors: none

Figure 11: HERA proton collimators: left positions, right loss rates measured at the corresponding collimator jaws.

For machine optimisation and background tuning the sum signal of these single BLMs turned out to be the ideal tool, and in the following figures (Fig 12 a,b,c) I have plotted the sum signal of theses devices, as used by the operators for three different situations:



a)

b)

c)

Figure 12: A standard tool for background and machine tuning: the sum of the collimator loss rates displayed as a function of time. The three plots correspond to three different machine situations (see text).

a) The beginning of a luminosity run: All parameters had been optimised, the collimators were closed and the data taking of the experiments started. The loss rates as seen in the plot are low and even more important they are smooth.

b) Typical situation towards the end of a luminosity run: The background rates increased, mainly due to the larger beam emittance. Corresponding to that the lifetime is reduced and from time to time spikes occur. The general beam situation however is still acceptable and data taking was possible.

c) The third example shows in contradiction to the smooth behaviour during a routine luminosity run, a problematic situation: The diffusion rate of the beam is much larger than the previous examples and the beam loss rates increase dramatically over several minutes (note the logarithmic scale). At the right part of the plot even a sharp increase of the BLM rates is detected, indicating a sudden change of a beam or machine parameter, such as orbit or tune jumps. Clearly in such a situation data taking by the particle detectors was nor possible and, if after a short while the situation could not be improved, the beam had to be aborted by the operators or by the machine/experiment protection system.

A less dramatic example that demonstrates the way of how the HERA proton beam was tuned is given in the next figure 13: It shows a routine procedure (compensation of the coupling and fine tuning of the chromaticity) during a luminosity run and the corresponding reduction of the beam loss rates as measured by the BLM's.

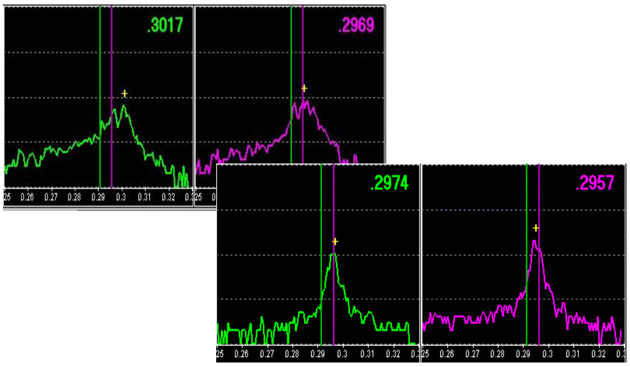


Figure 13: Tune spectrum during fine tuning of the chromaticity and coupling in a luminosity run: The resulting beam loss reduction is displayed in Fig 14.

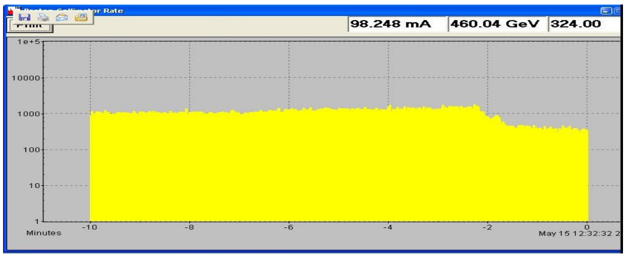


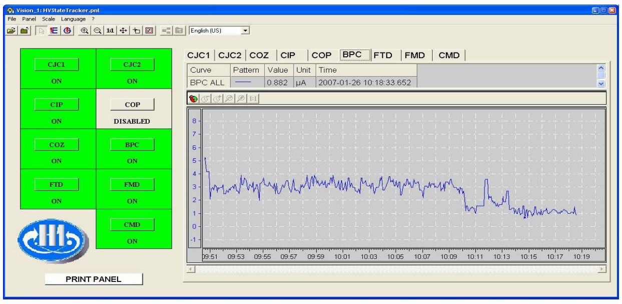
Figure 14: Reduction of the beam loss rates after optimisation of coupling and chromaticy during a luminosity run.

During luminosity runs these fine tuning procedures were repeated several times to keep the beam parameters at optimum values at any time.

Experiment signals

In addition to the global background level, indicated by the beam loss monitor diodes, a successful data taking of the particle detectors required also local beam steering in the straight sections of the machine. Therefore in HERA further background signals were taking into account to get the optimum machine setting and data taking efficiency for the detectors. For this purpose a large number of signals from the high energy detectors could be displayed in the control room.

In the end, for background tuning at the collider experiments H1 and ZEUS, the drift chamber currents turned out to be the most significant devices. Figure 15 shows a typical example from a HERA luminosity run. Out of 9 detector chambers in the experiment H1 we could choose the most appropriate one to tune the machine and get the lowest possible background situation. Background tuning included in this case also the optimisation of the vertex position and the crossing angle of the two beams.



Curve	Pattern	Value	Unit	Time
BPC ALL	——	0.882	μA	2007-01-26 10:18:33.652

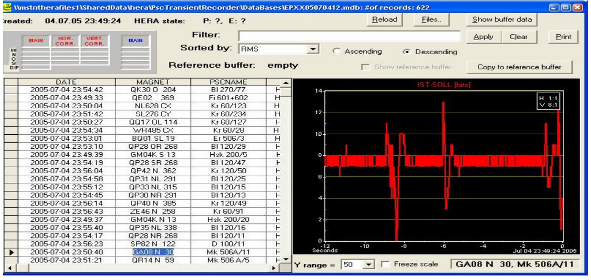
Figure 15: Drift chamber currents from the H1 detector during a HERA luminosity run. The currents were used to perform the fine (and best) background tuning of the machine.

PROBLEMS AND SURPRISES

Sources of Background:

It has already been mentioned that in general once the beams had been prepared carefully, no major background problems occurred. Put in a bit sloppy words: If the proton beam quality is good just leave the beam alone.

With the exception of a slow increase of beam emittance there was no major source of backgrounds. However among the years a number of technical problems occurred that either increased the diffusion rate on the particles or caused spikes in the otherwise smooth back ground level. Examples for typical problems that could cause quite some trouble for the operations crew were: power supply (chopper-) frequencies running on or close to the tune frequency could spoile in a short time the beam emittance, broken power supply electronics leading to ringing or jumping magnet currents, broken filter circuits (that are used to damp jitter), broken (or even burned) magnet coils, bad connections between the rf preamplifier and the main driver tube (causing noise in the rf system) and driving a large dc contribution in the bunch train, faulty power supply electronics etc. Figure 16 shows just one example out of many.



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Reference buffer: empty

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2005-07-04 23:50:04	NL628 CX	Kr 60/123
2005-07-04 23:51:42	SL276 CY	Kr 60/234
2005-07-04 23:50:27	QQ17 OL 114	Kr 60/127
2005-07-04 23:54:34	WR485 CX	Kr 60/28
2005-07-04 23:53:01	BQ01 SL 19	Er 506/3
2005-07-04 23:53:10	QP28 OR 268	Bl 120/29
2005-07-04 23:49:39	GM04K S 13	Hsk 200/5
2005-07-04 23:54:19	QP28 SR 268	Bl 120/47
2005-07-04 23:56:04	QP42 N 362	Kr 120/50
2005-07-04 23:54:58	QP31 NL 291	Bl 120/25
2005-07-04 23:55:12	QP33 NL 315	Bl 120/15
2005-07-04 23:54:45	QP30 NR 291	Bl 120/13
2005-07-04 23:56:14	QP40 N 385	Kr 120/49
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2005-07-04 23:55:40	QP35 NL 338	Bl 120/16
2005-07-04 23:54:17	QP28 NR 268	Bl 120/11
2005-07-04 23:56:23	SP82 N 122	D 100/11
2005-07-04 23:50:40	GA08 N 30	Mk 506A/11
2005-07-04 23:51:21	QR14 N 59	Mk 506 A/5

Y range = 50 ☐ Freeze scale GA08 N 30, Mk 506A/11

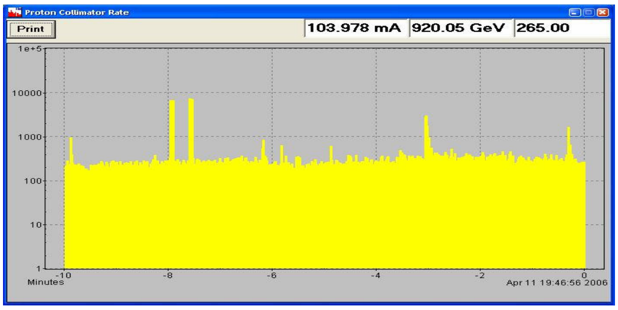
Figure 16: Survey and control of power supply currents.

The example shows the fluctuating current of a mini beta quadrupole as a function of time.

Due to a broken trim potentiometer in the power supply electronics sudden jumps in the magnet current are observed and according to that, strong spikes in the background.

Unfortunately background spikes of that magnitude could not be filtered out by the HERA collimator system. Severe background problems in all experiments therefore led to unacceptable dead-times or even endangered detector components. To overcome the problem a system had been installed to survey the actual magnet current produced by any power supply in the machine [12, 13]. The data were running through a circular buffer and could be stored and analysed at any moment.

The data of any power supply could be plotted and analysed according to the magnitude of the current fluctuations or alternatively according to the rms of the current entries, to localise the problematic device.

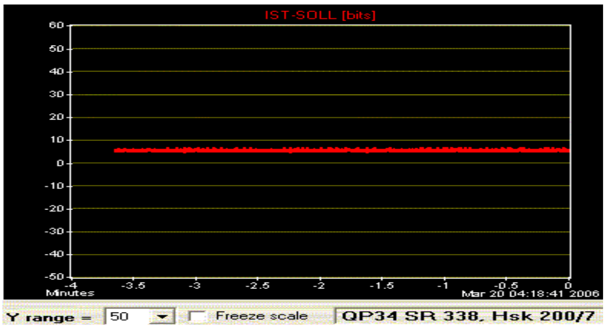


103.978 mA 920.05 GeV 265.00

Figure 17: Spikes observed in the proton background due to unstable power supply currents.

In quite a similar way noise of the rf system could lead to problematic running conditions: Faulty connections or broken electronic parts in a tuner loop could eventually lead to a strong increase of the dc contribution in the beam. There is not much to say about that: The problem had to be detected and repaired.

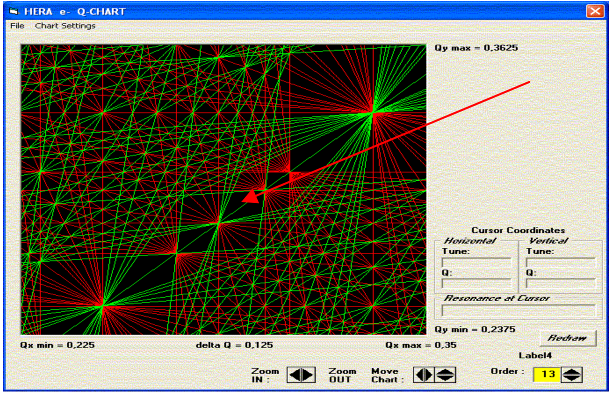
Just for completeness I would like to present the ideal case (which is in the end our goal): The magnet current generated by a well behaving power supply, as a function of time (fig. 18).



Y range = 50 ☐ Freeze scale QP34 SR 338, Hsk 200/7

Figure 18: The ideal case: stable and smooth behaviour of the magnet current - to be compared to Fig. 16 where a problematic situation is displayed.

Beam sensitivity:
By far the most surprising fact was the sensitivity of the proton beam while in collision. Small diffusion rates and good background situation only could be obtained in HERA if the main machine parameters, namely tune, the coupling and the chromaticity had been set to their optimum values and kept constant during the complete luminosity run within a narrow tolerance window. Optimum values in this context means values that had been established empirically during the machine running including the background data from the four experiments. The sensitivity to even small changes in the tune for example was remarkable: The optimum value for the transverse working point was Q_x = 0.292, Q_y = 0.297. These values are located close to the coupling resonance in a small triangle and it turned out that the free space available for machine tuning was as small as 95 Hz (fig 19). Crossing the resonance lines (of 13th order in the figure) could easily increase the beam background by more than an order of magnitude. Even more: to get the real optimum tuning, the trim quadrupoles used for tune control had been changed in bit wise manner, corresponding to a tune variation of $\Delta Q \approx 0.00004$.



Qy max = 0,3625
Qy min = 0,2375
Qx min = 0,225
delta Q = 0,125
Qx max = 0,35
Order : 13

Figure 19: HERA tune in the working diagram

CONCLUSIONS

Helmuts Questions

- Are / were machine backgrounds and issue ?

  The answer is clearly yes. Background problems were always an issue and it took for each of the high energy detectors quite a while (e.g. weeks to find the ideal setting for the vertex, the crossing angle, the up stream and downstream orbit and the collimators.

- Which types of background were most severe?

  DC current contributions of the proton beam and hadronic spikes due to (even small) technical problems caused the main trouble.

- How has the problem been solved?

  Practically in all cases the ideal solution was to detect and localise the origin of the problem and repair or exchange the technical device responsible for it. A big step forward was to survey and control power supply currents, including the use of transient recorders to detect fast and irregular fluctuations of the magnet currents. These recorders were an ideal tool to analyse and localise broken hardware. No solution has been found to avoid external distortions - or "cultural noise" as it is sometimes called. In this sense weekend shifts and mainly night shifts were the ideal conditions to achieve good beam backgrounds.

- The main sources of halo were mostly noise or ripple due to technical problems.
- Is scraping useful ?

  It had been tried several times in HERA to overcome background problems by scraping. Especially in the presence of spikes the idea was to take away the halo population and retain luminosity conditions afterwards. In some cases it worked; the better choice however in our case was to localise the problem and fix the technical component that was creating the trouble. And scraping could even in HERA easily damage the collimator jaws ... and did!

All in all tuning the background in HERA was a tedious, time consuming, never ending story. I may even say that it was also an art of its own as in the end you had to know and take into account the complete machine. And so it was fun for those who liked the beast.

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