Beam Loss Monitoring and Control

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The use of Beam Loss Monitors (BLMs) as sensitive tools for various beam diagnostic applications will be discussed as well as their tasks of machine protection and loss location detection. Examples will illustrate that an appropriate design of a BLM system and a proper understanding of loss events can improve machine performance.

Contents

You do not need a BLM System as long as you have a perfect machine without any problems. However, you probably do not have such a nice machine, therefore you better install one.

Loss Types

Irregular (uncontrolled, fast) losses: These losses may distributed around the machine and not obviously on the collector system. Can be avoided and should be kept to low levels

- to keep activation low enough for hands-on maintenance, personal safety and environmental protection.
- to protect machine parts from beam related (radiation) damage (incl. Quench protection and protection of the detector components)
- to achieve long beam lifetimes/efficient beam transport to get high integrated luminosity for the related experiments.

These higher levels losses are very often a result of a misaligned beam or a fault condition, e.g. operation failure, trip of the HF-system or of a magnet power supply. Sometimes such losses have to be tolerated even at a high level at low repetition rates during machine studies. A beam loss monitor system should define the allowed level of those losses. The better <u>protection</u> there is against these losses, the less likely is down time due to machine damage. A post mortem event analysis is most helpful to understand and analyze the faulty condition.

Regular (controlled, slow) loss: Those losses are typically not avoidable and are localized on the collimator system or on other (hopefully known) aperture limits. They might occur continuously during operational running and correspond to the lifetime/transport efficiency of the beam in the accelerator. The lowest possible loss rate is defined by the theoretical beam lifetime limitation due to various effects, like residual gas, Touschek effect, etc. Suitable for machine <u>diagnostic</u> with a BLM System.

<u>It is clearly advantageous to design a BLM System which is able to deal with both loss modes.</u>

Common aspects (1):

There are some common aspects, which are valid for every beam loss monitor system:

a) Type of loss monitor
b) Positioning of the loss monitor

a) Type: Typical beam loss monitors detect beam losses by measurement of ionising radiation produced by lost beam in real-time and with a certain position resolution. Other systems, like differential beam current measurements, have a very rough position resolution, or have a very long time constant (e.g. dose measurements or activation) and are not the subject of this talk.

The produced radiation consists mainly of electromagnetic particles (electron-, positron- and gamma- shower), while the loss of a hadron (proton, ion) produces hadronic particles (protons, neutrons), too. The signal source of beam loss monitors is mainly the ionizing capability of the charged shower particles.

Considerations in Selecting a Beam Loss Monitor

By R.E.Shafer; BIW 2002

- Sensitivity
- Type of output (current or pulse)
- Ease of calibration (online)
- System end-to-end online tests
- Uniformity of calibration (unit to unit)
- Calibration drift due to aging, radiation damage, outgassing, etc.
- Radiation hardness (material)
- Reliability, Availability, Maintainability, Inspect ability, Robustness
- Cost (incl. Electronics)
- Shieldability from unwanted radiation (Synchrotron Radiation)
- Physical size
- Spatial uniformity of coverage (e.g. in long tunnel, directionality)
- Dynamic range (rads/sec and rads)
- Bandwidth (temporal resolution)
- Response to low duty cycle (pulsed) radiation
- Instantaneous dynamic range (vs. switched gain dynamic range)
- Response to excessively high radiation levels (graceful degradation)

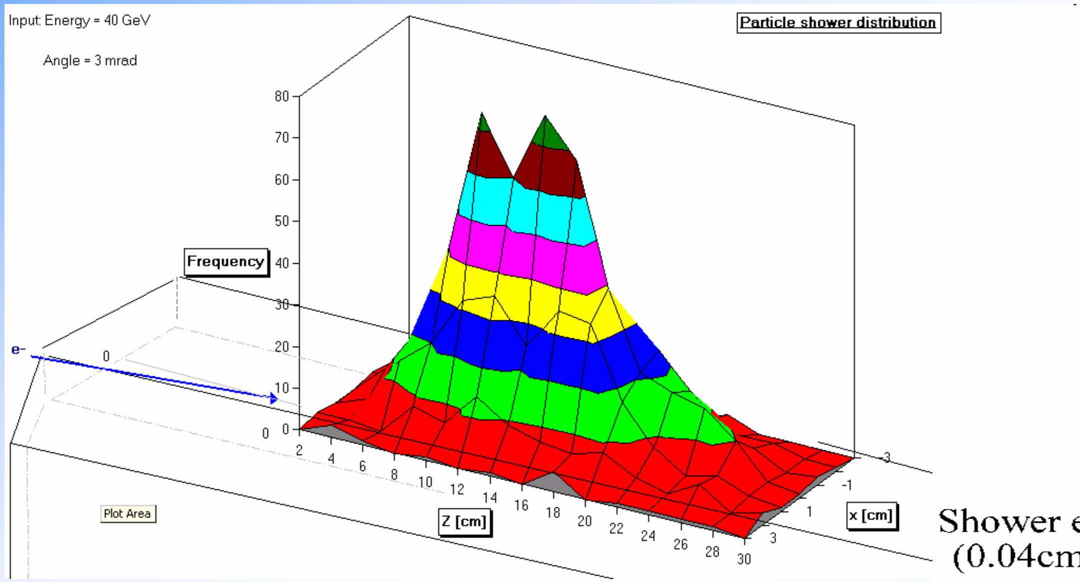
Consideration of these parameters gives a good guide to find (or design) the best monitor type for a particular beam loss application.

Options: long and short Ion Chambers, PMT with scintillators (incl. Optical Fibers), PIN Diodes, SEM-PMT, Microcalorimeters, Compton Diodes, …

Common aspect (2):

Monte Carlo Calculation to define BML positions and calibrations (1):

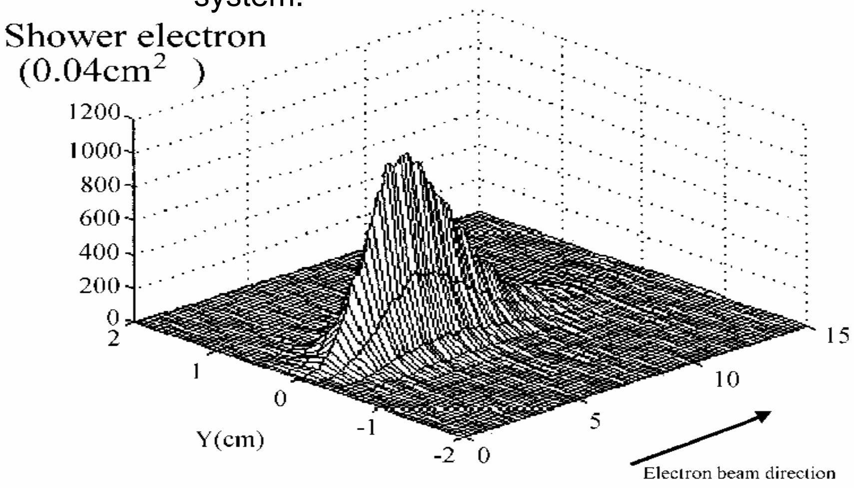
HERAe



The loss of a high-energy particle in the wall of a beam pipe results in a shower of particles, which leak out of the pipe*. The signal of a loss detector will be highest, if it is located at the maximum of the shower. Use Monte Carlo simulations to find the optimum locations for the monitors, as well as to calibrate the monitors in terms of 'lost particles/signal'

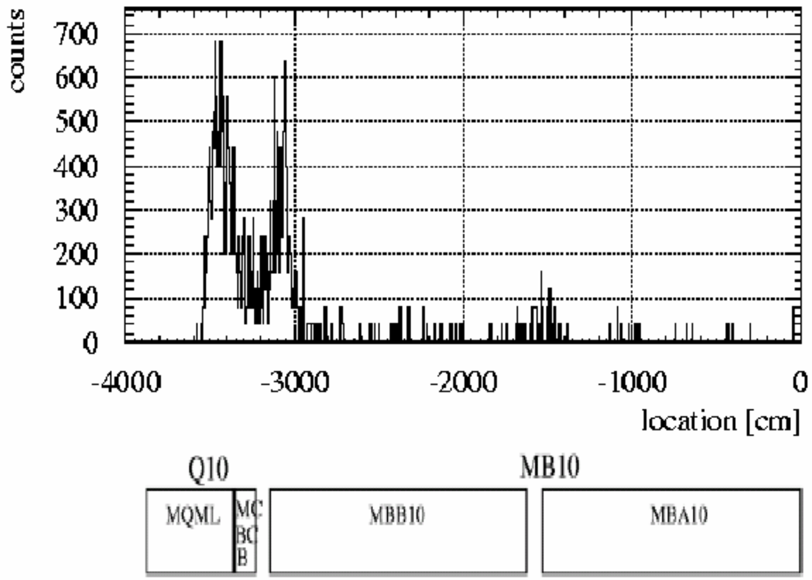
* Low energy particles which do not create a shower leakage outside the vacuum pipe wall are hardly detectable by a loss monitor system.

HLS Storage ring



Location of Beam Loss Monitors (2):

Monte Carlo Calculation to define BML positions and calibrations (2):



- impact of the protons at the centre of Q10
- first maximum due to shower in the cold mass
- second maximum due to gap between MQ and MB magnet
- third maximum due to gap between two MB magnets
- reduction of shower particles by a factor of over 100 after a few meters

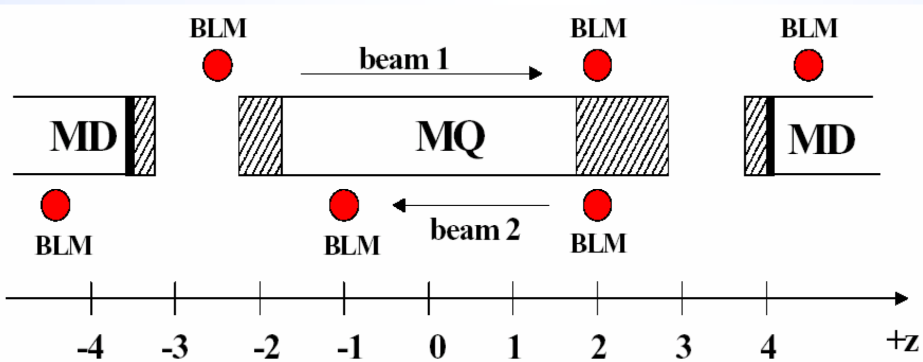


Figure 2: Proposed beam loss monitor locations around the quadrupoles.

β-function is max. in Quad

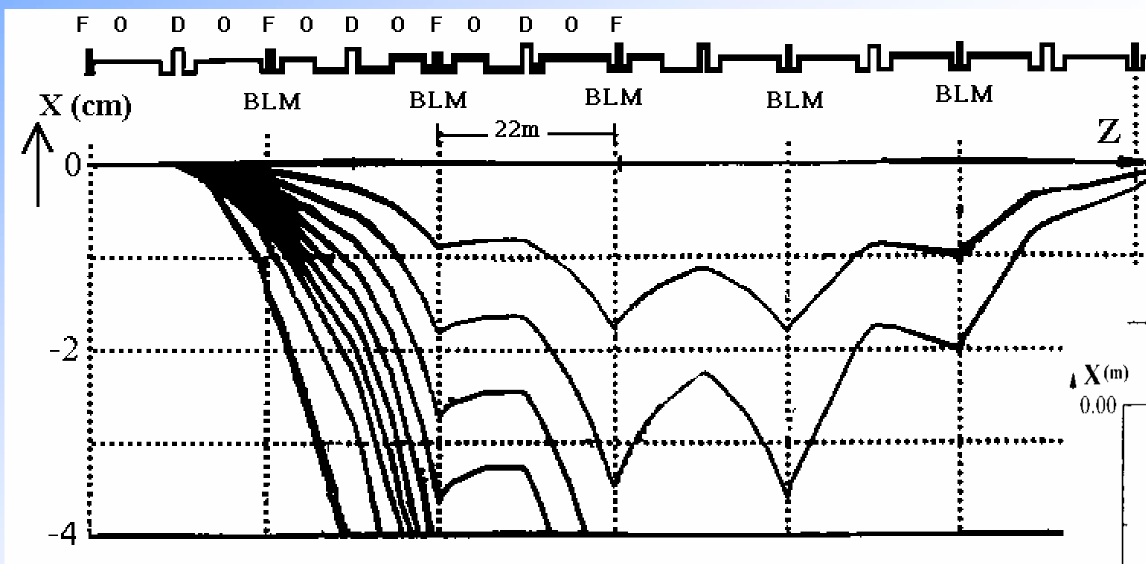
LHC example:
B. Dehning et al., BIW2002

b) Location of Beam Loss Monitors (3):

Understanding the loss dynamics:

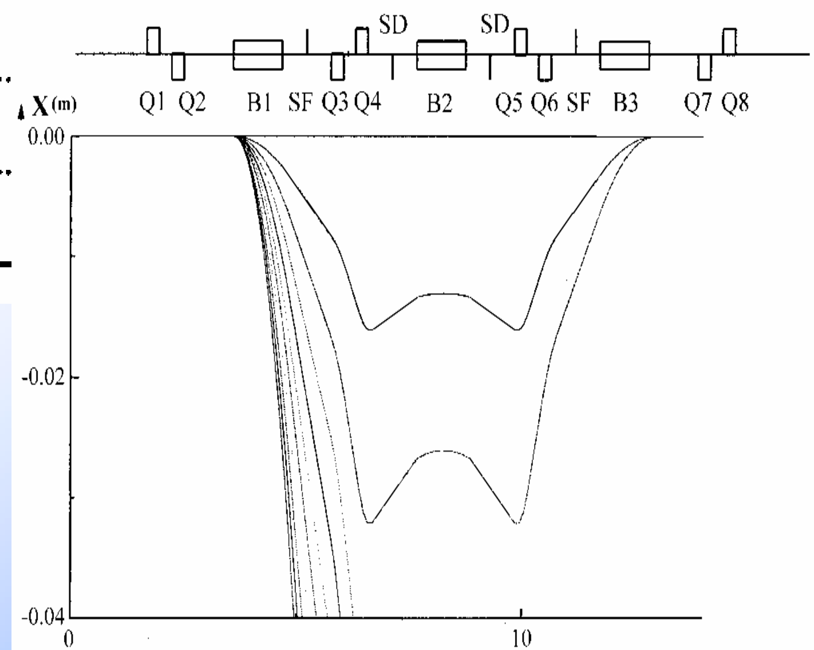
Losses due to: Touschek- or Coulomb scattering, Failures, Microparticles, Obstacle, …

HERAe



Trajectory of electrons due to energy loss (Coulomb scattering)

HLS Storage ring



The Loss Mechanism; inelastic scattering

Electrons lose energy ΔE due to inelastic scattering (Bremsstrahlung) mainly on the nuclei of the residual gas molecules. The deviation of the electron orbit from the nominal orbit depends on the dispersion function in the accelerator and on ΔE. Therefore the electrons may be lost behind the following bending magnet on the inside wall of the vacuum chamber.

Some Examples for irregular (uncontrolled, fast) losses

- Activation of environment due to losses
- Commissioning: Obstacle
- Vacuum Problems (Coulomb Scattering)
- Microparticles (reported in HERAe and TRISTAN)
- Superconducting machines: Quench protection
- High current/brilliance machines (Ring or Linac): Destruction of Vacuum-Components

There must be sufficient monitor coverage in the accelerator!

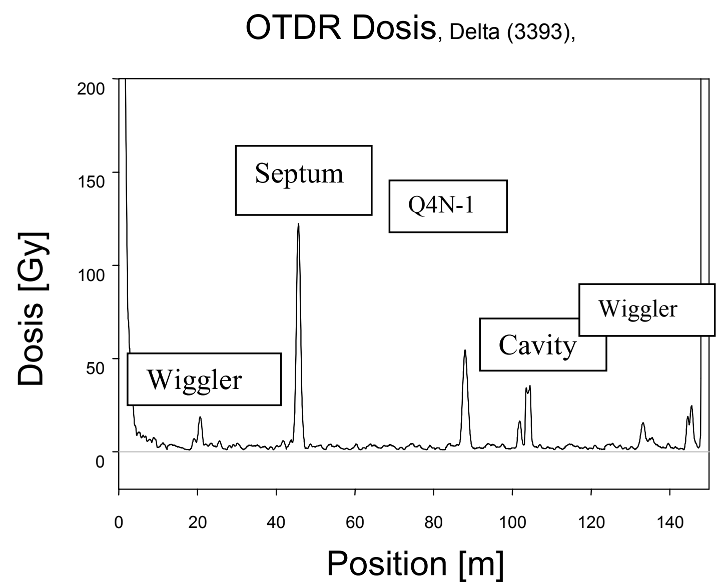
No BLM

Activation of components/environment

KEK

DESY

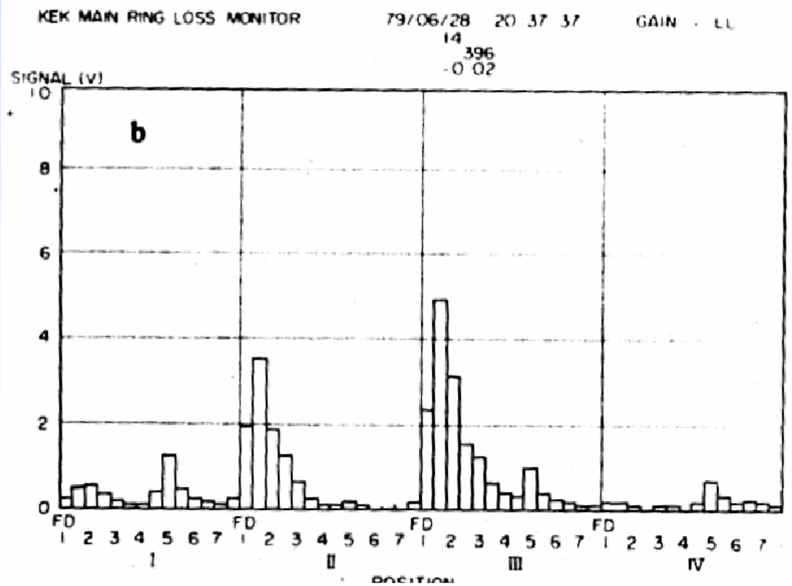
Activation is strongly correlated with beam losses. Very important issue for high energy/high current machines to shield components (e.g. maintenance, radiation damage) and the environment (e.g. ground water and air activation, personal safety)



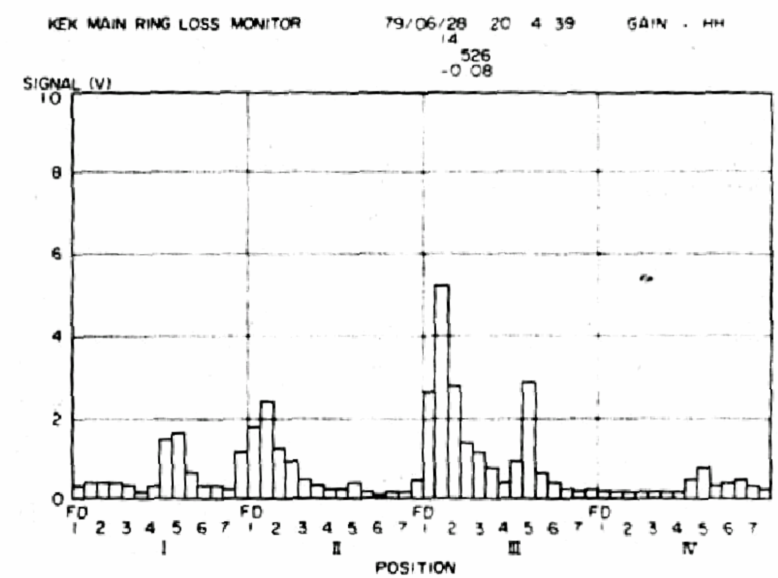
Accumulated dose deposited along the optical fibre placed at the DELTA storage ring vacuum chamber

Delta, Dortmund, this conference

opt. fiber



Beam Loss distribution around the main ring up to flat top end; Gain 2

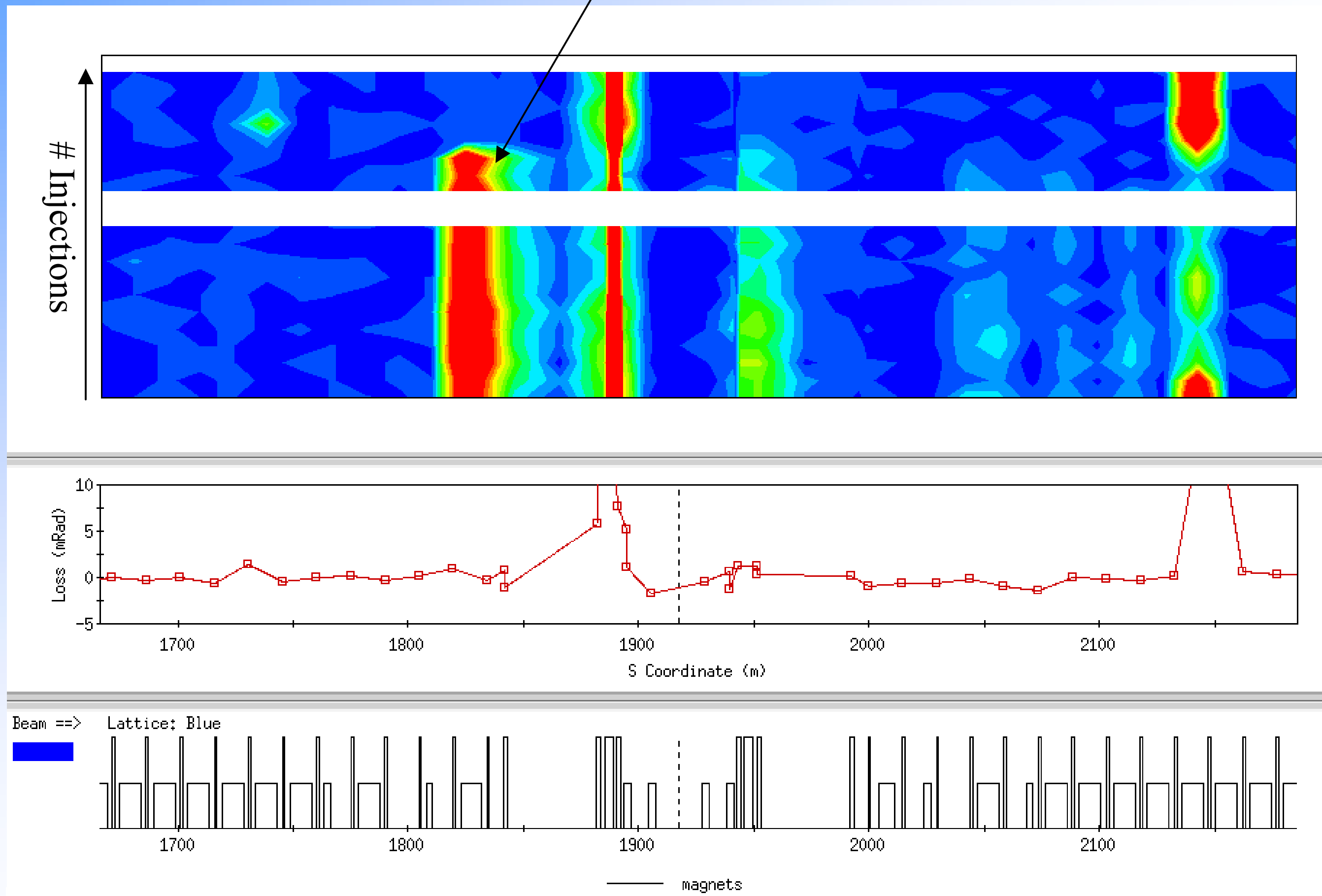


Activation distribution around the main ring; Gain 200

Ion Chambers

Beam Loss Monitoring System with free-air Ionisation Chambers, H. Nakagawa et al; NIM 174 (1980)

RHIC Commissioning: Obstacle (RF Finger) detected by BLMs



Loss pattern evolution as beam was steered locally around an apparent obstacle at s ~= 1820 meters (sector 11, quad 6) in the BLUE ring. When the losses there went away, beam began circulating for thousands of turns.

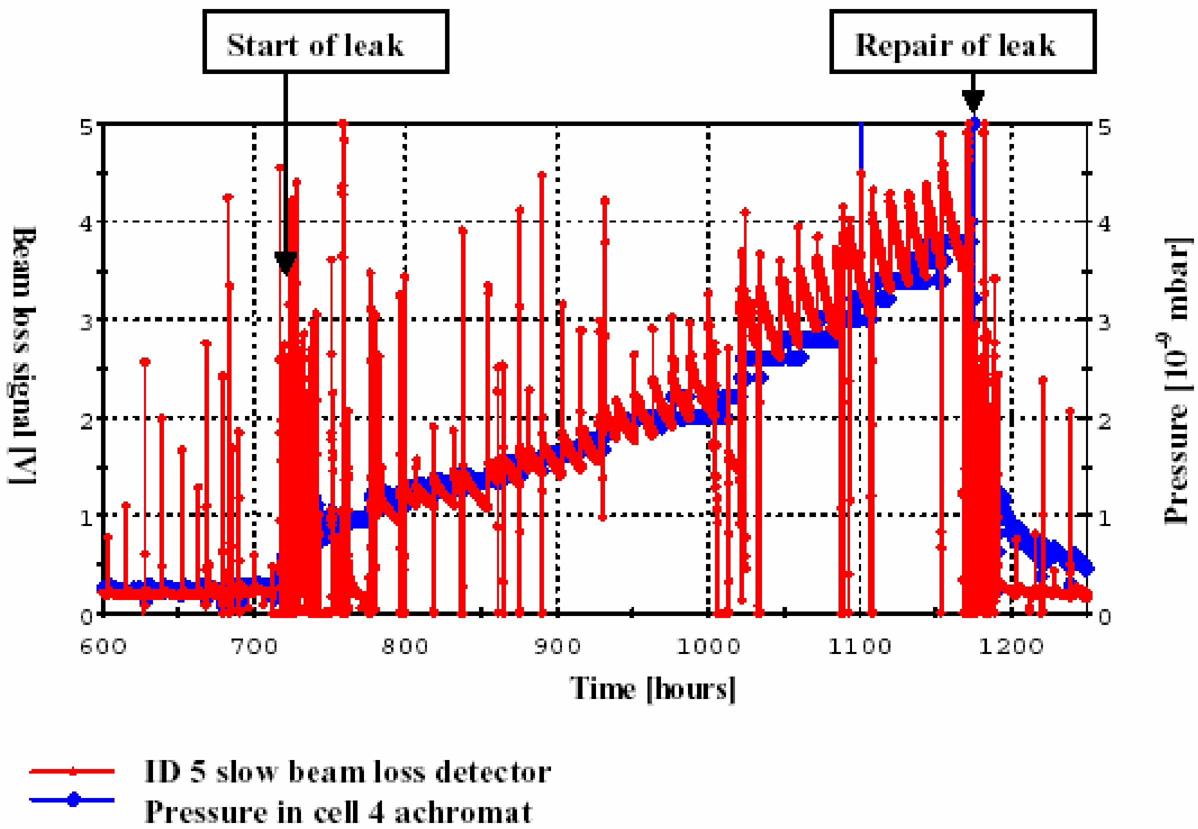
Ion Chambers

http://www.rhichome.bnl.gov/RHIC/YearZero/early_beam.html

Vacuum Problems (1)

ESRF

There is a nice correlation of the beam loss detection and the vacuum pressure. The saw teeth behavior of the BLM signal results from the beam intensity variation.

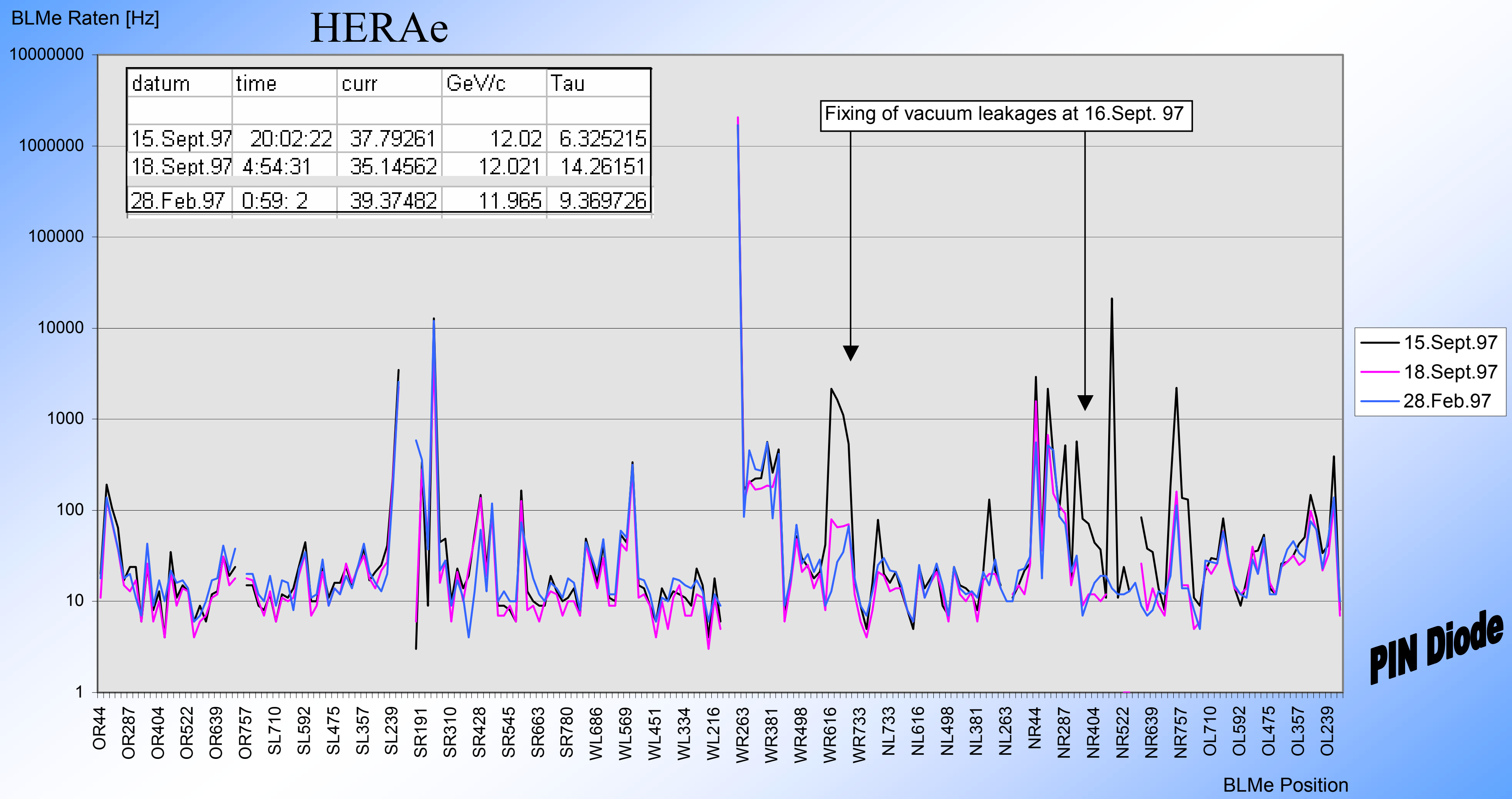


Detection of a vacuum leak with a beam loss detector

PMT

Weinrich, Udo : Mastering beam losses on small gap vacuum chambers in synchrotron light sources;ESRF 1999, Dortmund, Univ., Diss., 2000
http://eldorado.uni-dortmund.de:8080/FB2/ls6/forschung/2000/Weinrich

Vacuum Problems (2)

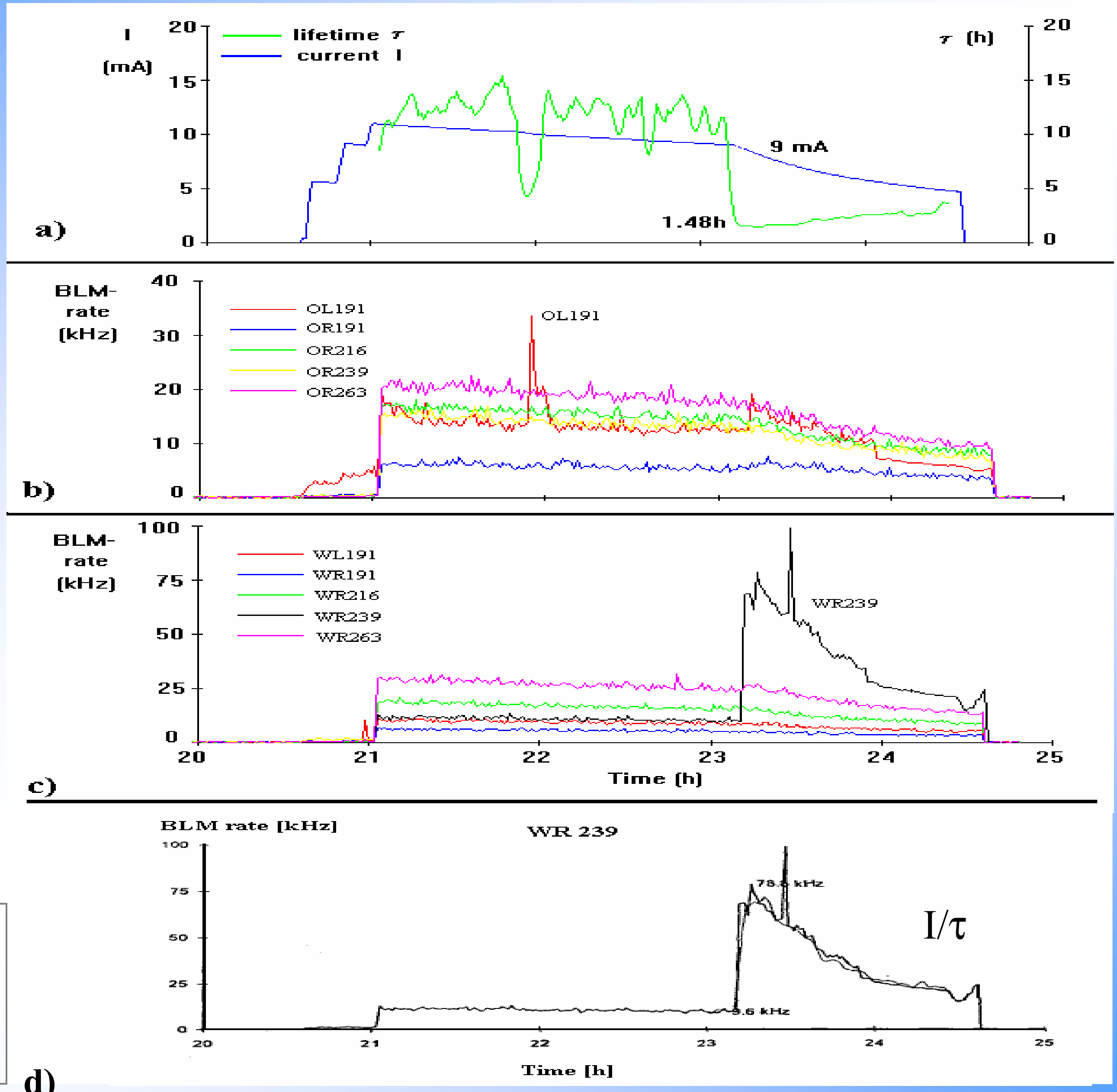


datum	time	curr	GeV/c	Tau
15.Sept.97	20:02:22	37.79261	12.02	6.325215
18.Sept.97	4:54:31	35.14562	12.021	14.26151
28.Feb.97	0:59: 2	39.37482	11.965	9.369726

Microparticles (1)

HERAe

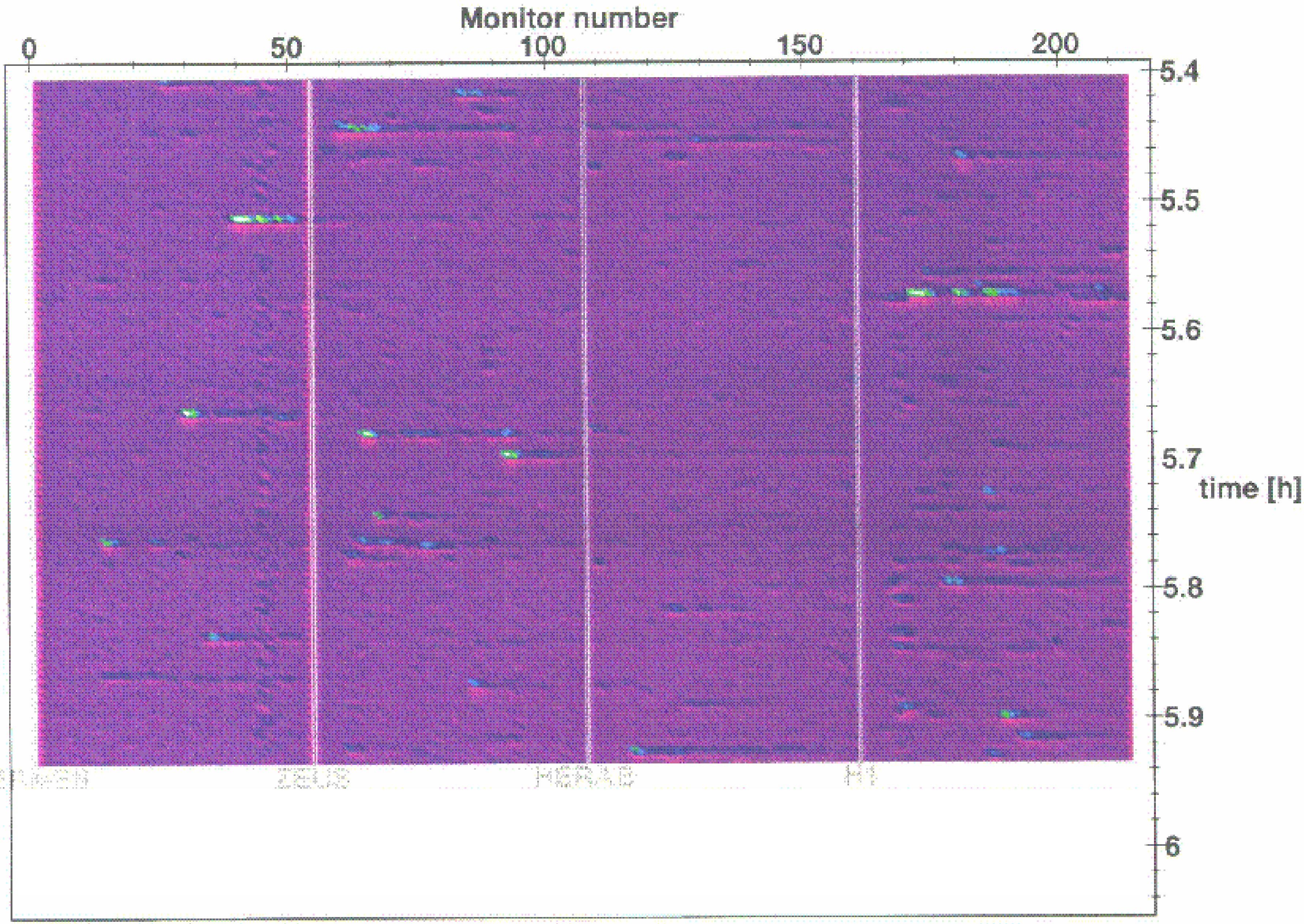
Lifetime reduction events correlate well with losses seen in the HERA electron loss monitors. In this example the brief disruption of lifetime is seen in the loss monitor SL191, and the irreversible disruption is seen in the monitor WR239



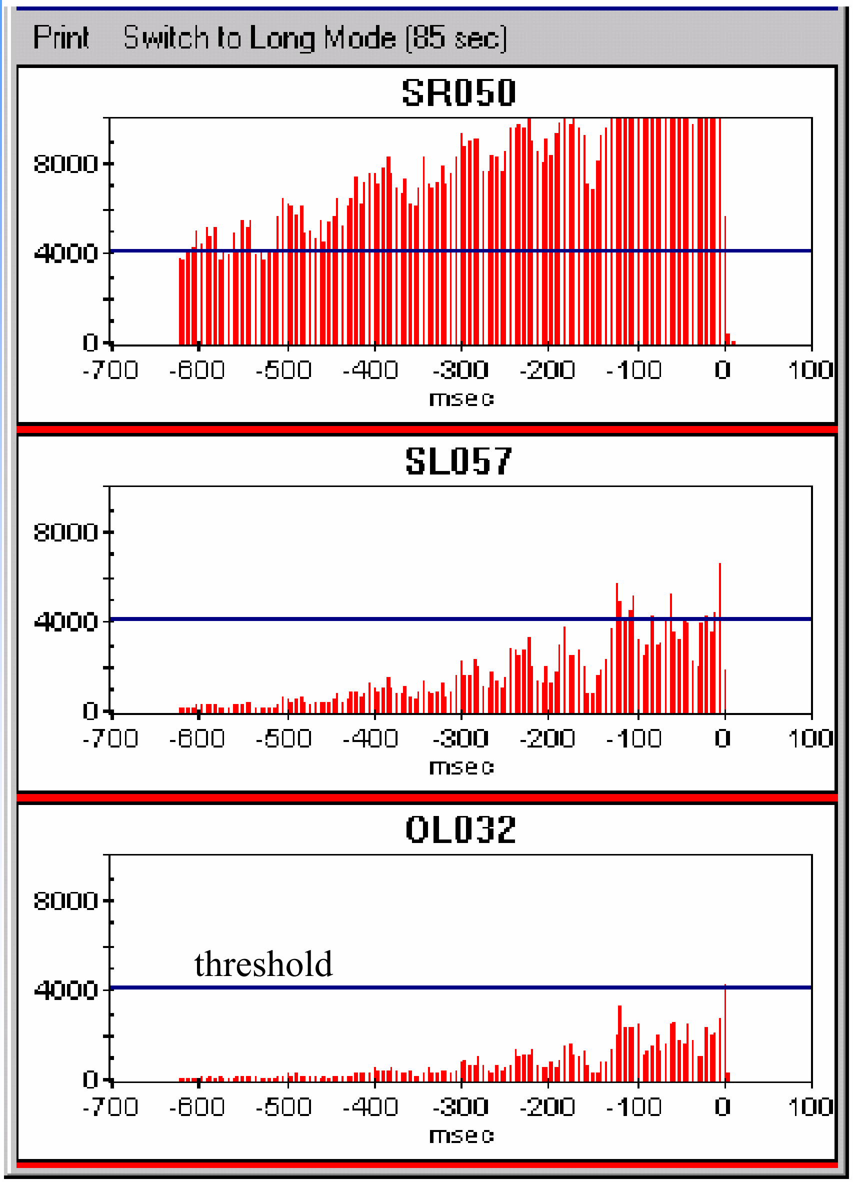
PIN Diodes

The Electron beam Lifetime Problem in HERA.
By D.R.C. Kelly et al., PAC 1995

Moving Microparticles (2) in HERAe

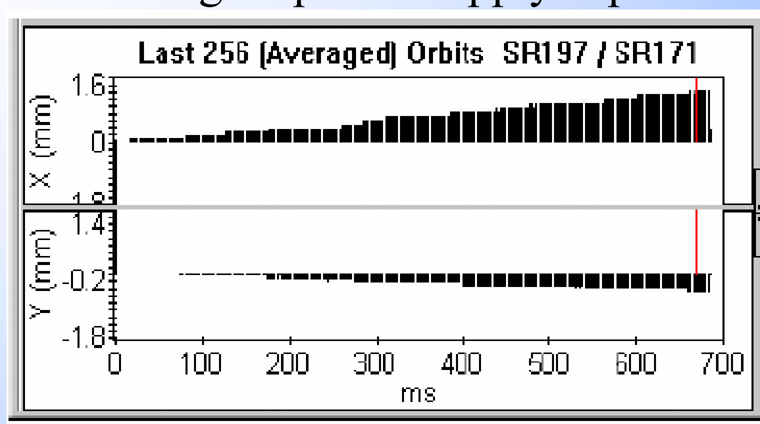


Quench Protection at HERAp



An event archive is most helpful for a post mortem analysis of the data to understand the reason of the beam loss.

Reason: Orbit excursion due to magnet power supply trip

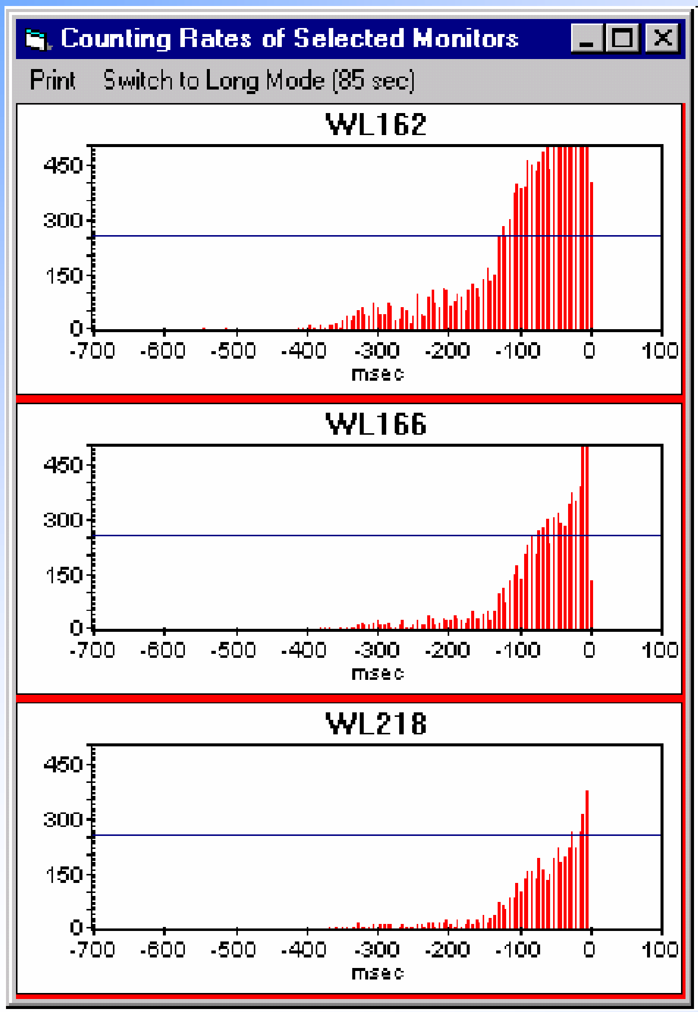


PIN Diodes

M. Lomperski: 11th Chamonix workshop http://cern.web.cern.ch/CERN/Divisions/SL/publications/chamx2001/PAPERS/8-2-ml.p

Reason: Head tail instability => emittance blow up:

No effect on Orbit!



Archive Alarm Analysis

Print 3-D Chart Help!?

Which BLMs Triggered The Alarm?

Start Search

BLMs Found: 8

Search/Test Criteria

Start+Stop Bins:
- Before Dump: 4
- After Dump: 1

Threshold:
- Ratio of Test to ALRM Threshold: 1.00

Archive: 10-Mar-1999 00:48:16 142 GeV

BLM	ALRM	-4	-3	-2	-1	Dump?	1
WL58	1024	77	62	77	102	211	4872
WL91	1024	268	228	298	310	2962	11974
WL123	1024	96	81	104	98	1393	761
WL162	256	837	876	1361	1268	404	0
WL166	256	349	392	503	595	130	0
WL195	256	179	220	243	297	48	0
WL218	256	225	263	313	379	0	0
WL250	256	252	218	340	363	158	0

Some examples for regular (controlled, slow) Losses

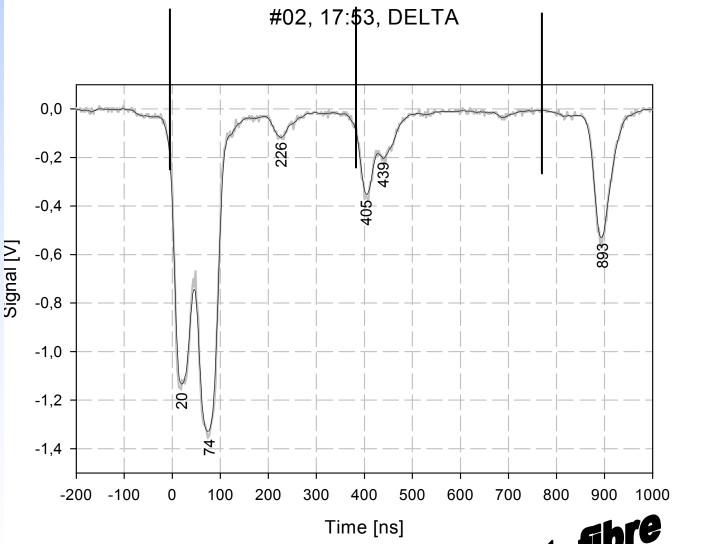
- Injection studies
- Lifetime limitations (Touschek effect, etc.)
- Tail scans (Compton scattering)
- Tune scans
- Ground motion
- Diffusion

Injection studies

Useful to improve injection efficiency, even at low injection current (radiation safety issue). BLMs are more sensitive than current transformers and they can distinguish between transversal mismatch (betatron oscillations) and energy mismatch (dispersion).

DELTA

Cerenkov light signal from one photomultiplier connected to one fibre around the ring. Three turns in DELTA (one turn = 380 ns). Several peaks per turn result from different centres of beam loss. An online optimisation of the injection chain was possible

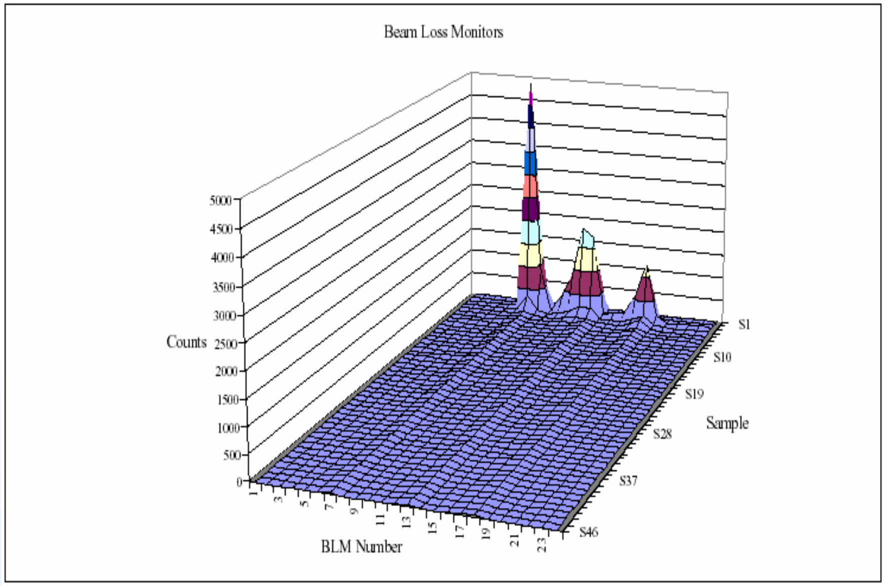


opt. fibre

DELTA, this conference

ALS

Several BPMs report high count rates at injection. After injection the loss rate is low which is commensurate with beam liftime of about 4 hours. From this graph one can identify the sites of highest beam loss.

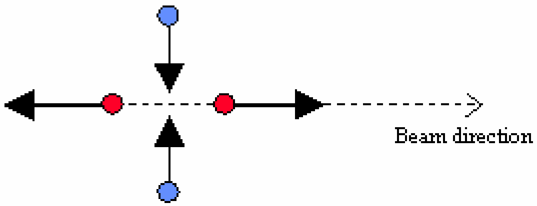


Surface plot of beam loss at injection.

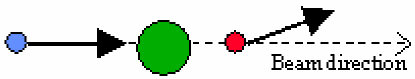
PIN Diode

ALS Beam Instrumentation; Beam Loss Monitoring, Jim Hinkson, February 1999

Lifetime limitations (1)



Touschek effect: Particles inside a bunch perform transverse oscillations around the closed orbit. If two particles scatter they can transform their transverse momenta into longitudinal momenta. If the new momenta are outside the momentum aperture the particles are lost. Good locations for the detection of Touschek scattered particles are in high dispersion sections following sections where a high particle density is reached. Since the two colliding particles loose and gain an equal amount of momentum, they will hit the in- and outside walls of the vacuum chamber. In principle the selectivity of the detection to Touschek events can be improved by counting losses at these locations in coincidence.

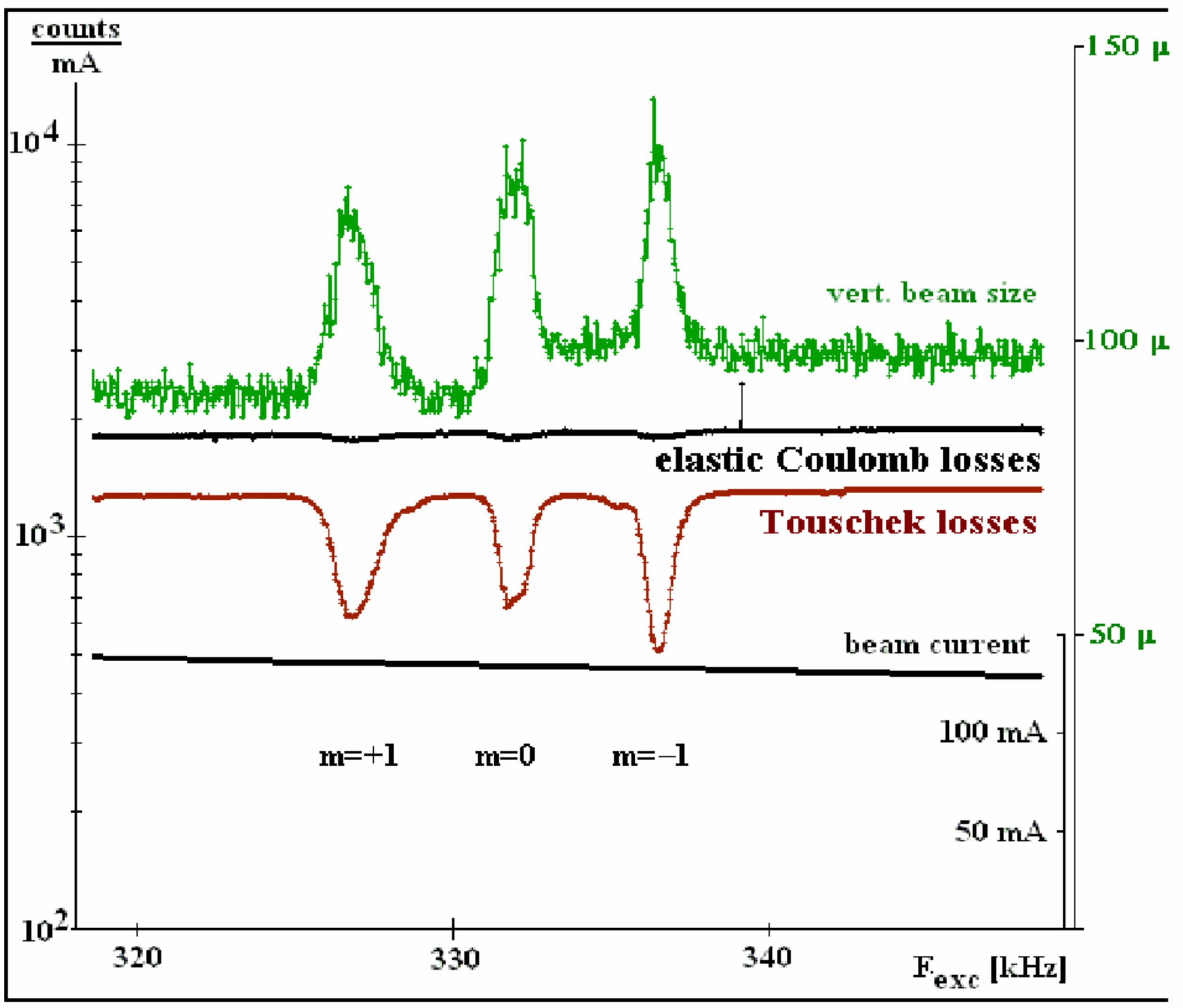


Coulomb scattering: Particles scatter elastically or inelastically with residual gas atoms or photons or emit a high energy photon (SR). This leads to betatron or synchrotron oscillations and increases the population of the tails of the beam. If the amplitudes are outside the aperture the particles are lost. Losses from elastic scattering occur at aperture limits (small gap insertions, septum magnet, mechanical scrapers and other obstructions). If, in an inelastic Coulomb collision, the energy carried away by the emitted photon is too large, the particle gets lost after the following bending magnet on the inside wall of the vacuum chamber.

Lifetime limitations (2)

Bessy

Vertical beam size, Touschek and Coulomb loss rates during excitation of a vertical headtail mode in Bessy.



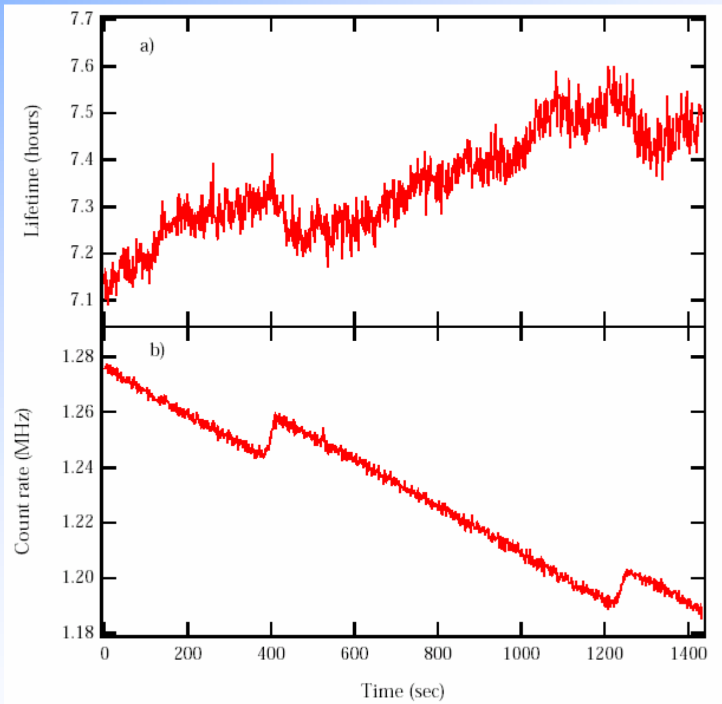
P. Kuske, DIPAC2001, Accelerator Physics Experiments with Beam Loss Monitors at Bessy

PMT

Lifetime limitation (3)

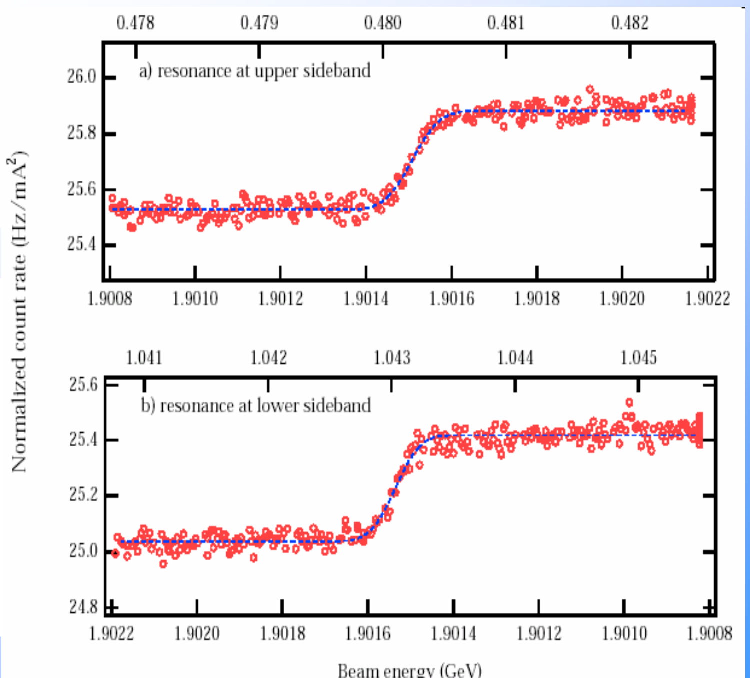
Bessy, ALS

The cross section for the Touschek scattering process is lower for electrons with parallel spins than for antiparallel spins. Therefore, a polarized beam will have fewer scattering events and a longer lifetime than an unpolarized beam. Thus one can use the beam lifetime, or equivalently a BLM, as a measure for changes in the polarization.



Beam lifetime derived from current monitor and count rate from beam loss detector showing two partial spin depolarizations over a 25 minute period.

PIN Diodes



Normalized loss detector rate during excitation sweep of spin resonances. a) Sweep through upper sideband and b) lower sideband of a spin resonance.

<u>Useful for Beam Energy Calibration and measurement of Momentum Compaction Factor</u>

ENERGY CALIBRATION OF THE ELECTRON BEAM OF THE ALS USING RESONANT DEPOLARISATION* C. Steier, J. Byrd, P. Kuske
http://accelconf.web.cern.ch/accelconf/e00/PAPERS/MOP5B03.pdf

Lifetime limitation (4)

ESRF

The measurement was done with a 16 bunch filling at 30 mA. The coupling was reduced in steps by separation of the horizontal and the vertical tune. The vertical emittance was measured to decrease from about 35 pm to 14 pm. As the consequence the lifetime decreases from 7.6 hours to 5 hours due to the increase of the Touschek scattering. One can see the dose rate measured by the ionisation chambers of ID8 and ID23 increasing. Since Touschek scattering only creates horizontal oscillations and the losses on ID8 and ID23 are vertical losses this is a prove of the coupling from horizontal betatron motion into the vertical plane. In the discussion of the beam loss positions this was explained to come from the energy acceptance limitation due to the vertical integer resonance.

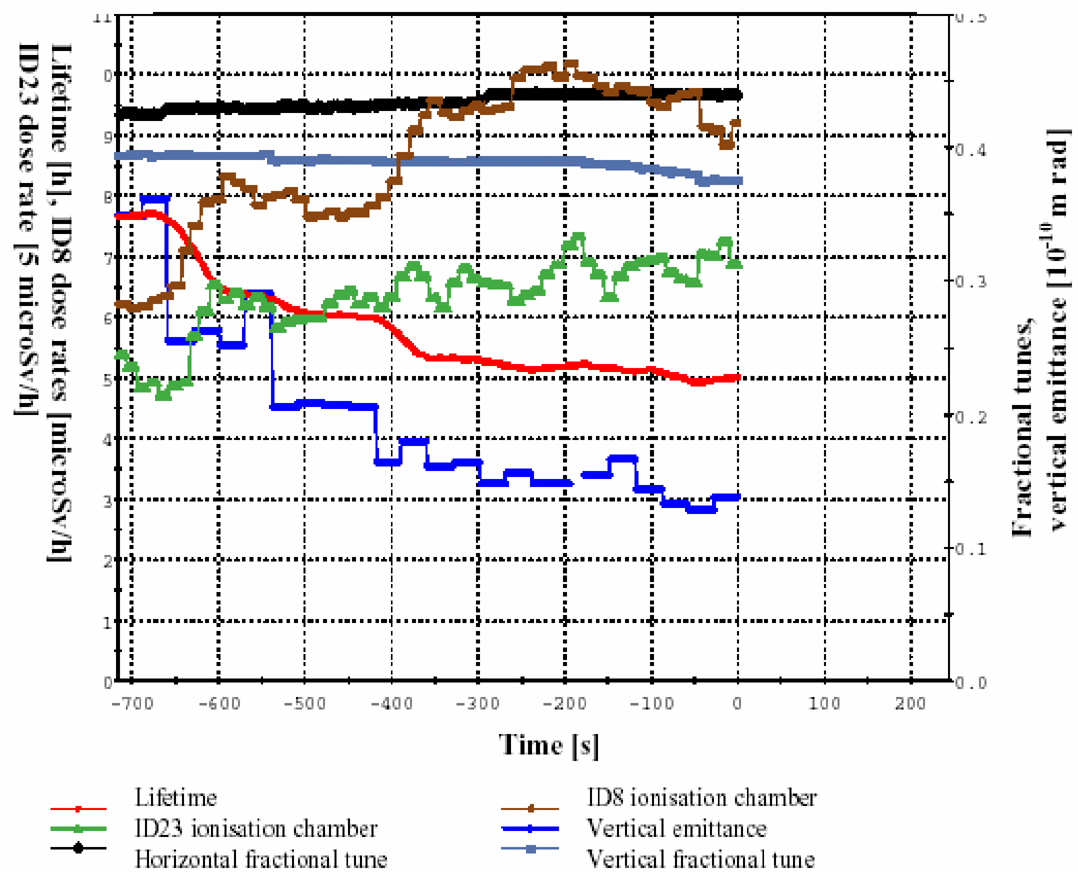


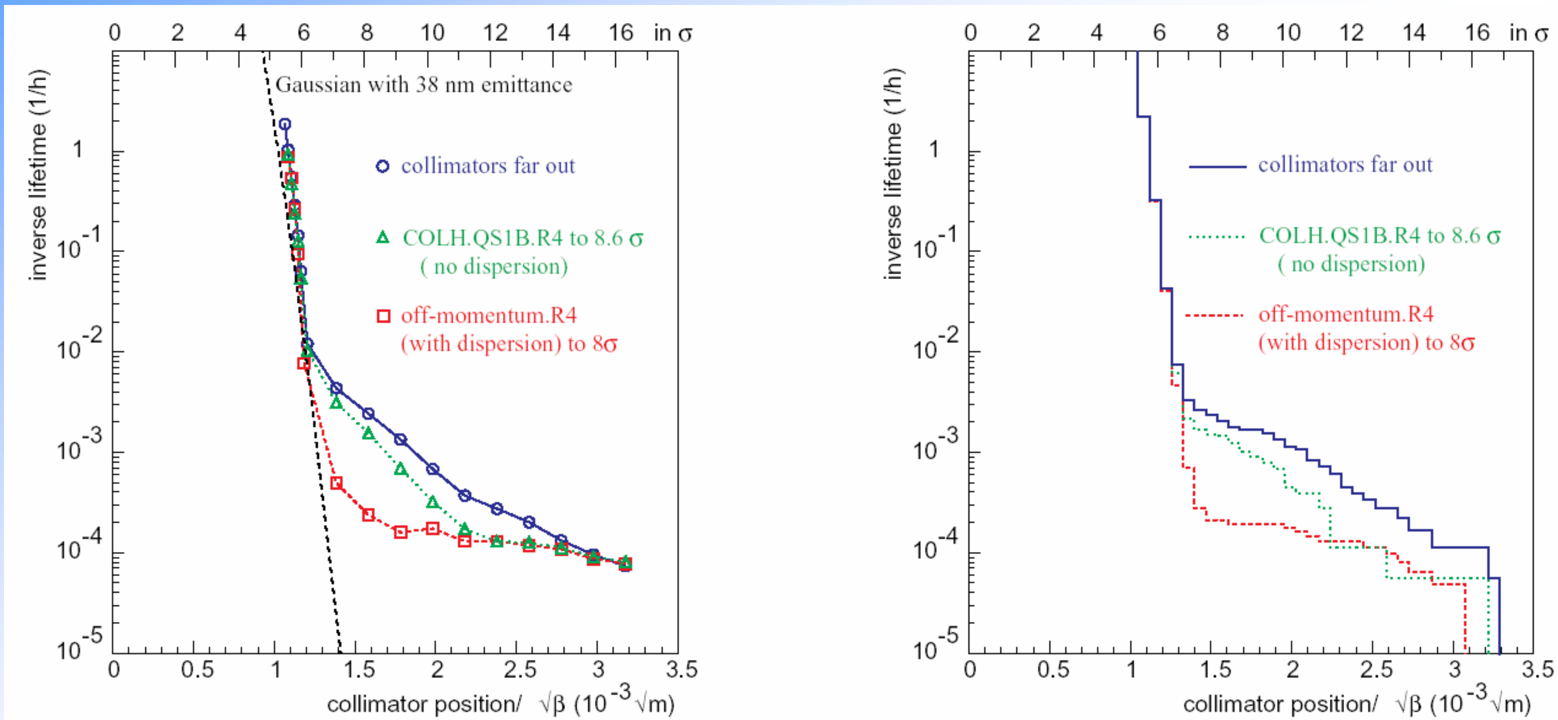
Figure 5-12 Touschek losses identification by variation of the coupling.

Ion chamber

Weinrich, Udo **:** Mastering beam losses on small gap vacuum chambers in synchrotron light sources;ESRF 1999, Dortmund, Univ., Diss., 2000
http://eldorado.uni-dortmund.de:8080/FB2/ls6/forschung/2000/Weinrich

Tail scans

LEP



Measurement (left) and simulation (right) of the horizontal beam tails for a beam energy of 80.5 GeV and for different collimator settings at LEP. The simulation is the result of tracking particles after Compton scattering on thermal photons (black body radiation of vacuum chamber).

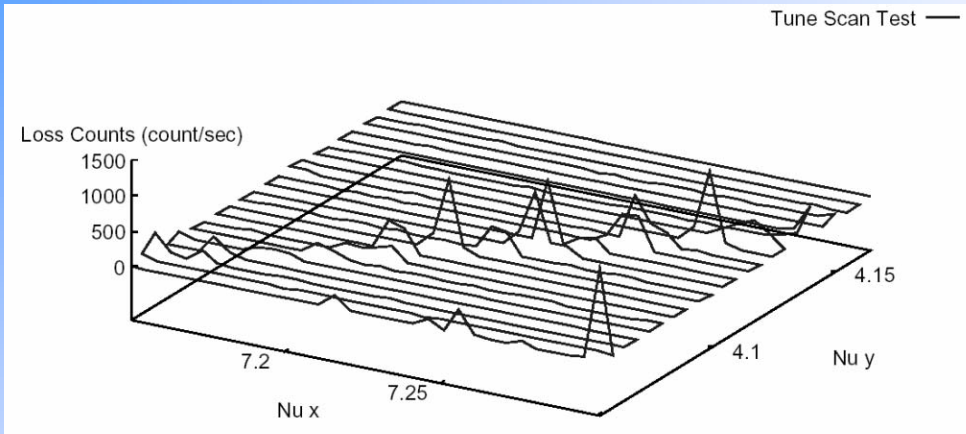
PIN Diodes

PMT

Transverse Beam tails Due To Inelastic Scattering, H. Burkhardt, I. Reichel, G. Roy, CERN-SL-99-068

Tune Scans

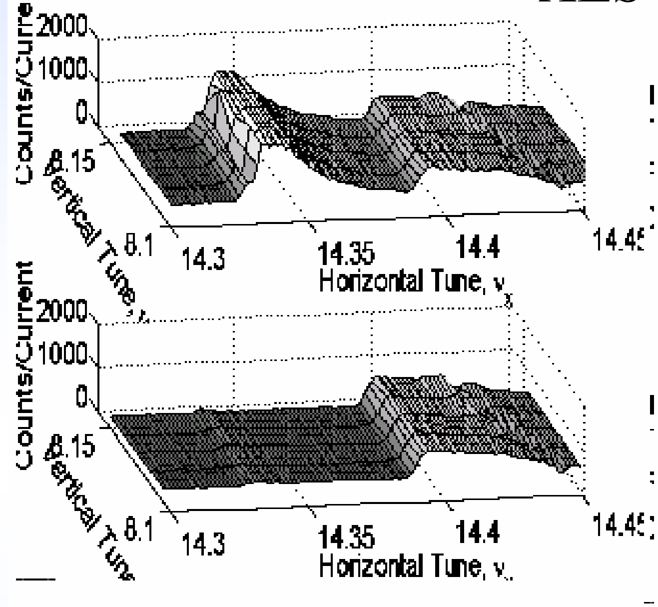
SRRC



First tune scan test at the Taiwan Light Source

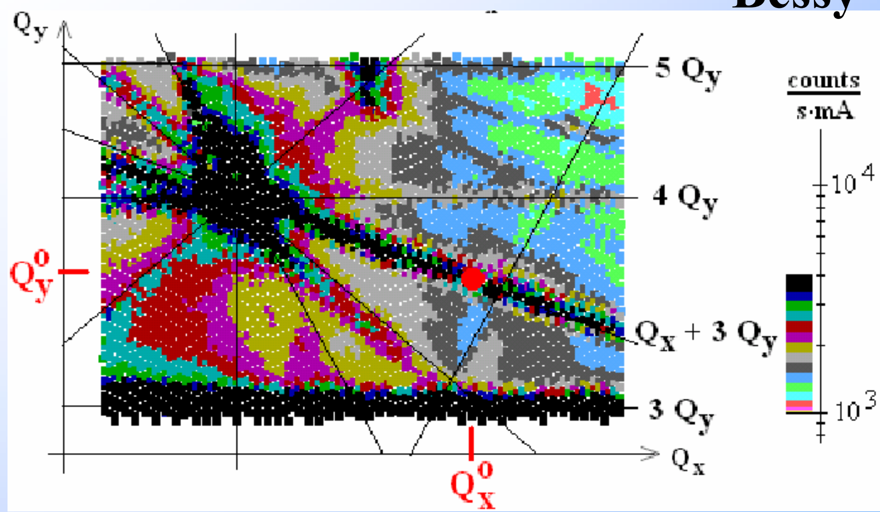
Optimizing machine lattice requires systematic studying of its corresponding tune space. Tune scans are useful for studying insertion devices caused nonlinear resonance. Interpretation of the results is simplified if a good selectivity of the beam loss monitors to the different loss mechanisms can be achieved.

ALS



PIN Diodes

Bessy



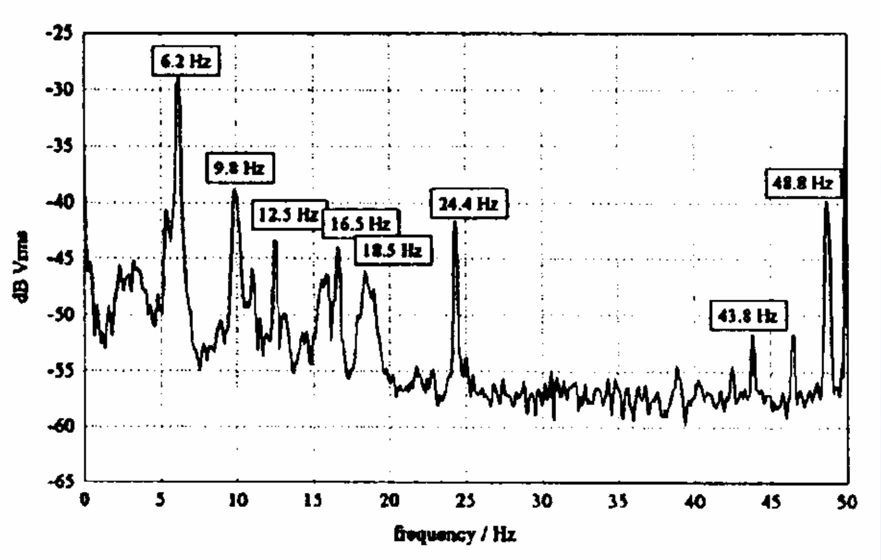
PMT

REAL-TIME BEAM LOSS MONITORING SYSTEM AND ITS APPLICATIONS IN SRRC, K. T. Hsu,
http://accelconf.web.cern.ch/accelconf/pac97/papers/pdf/8P068.PDF

Ground Motion

HERAp

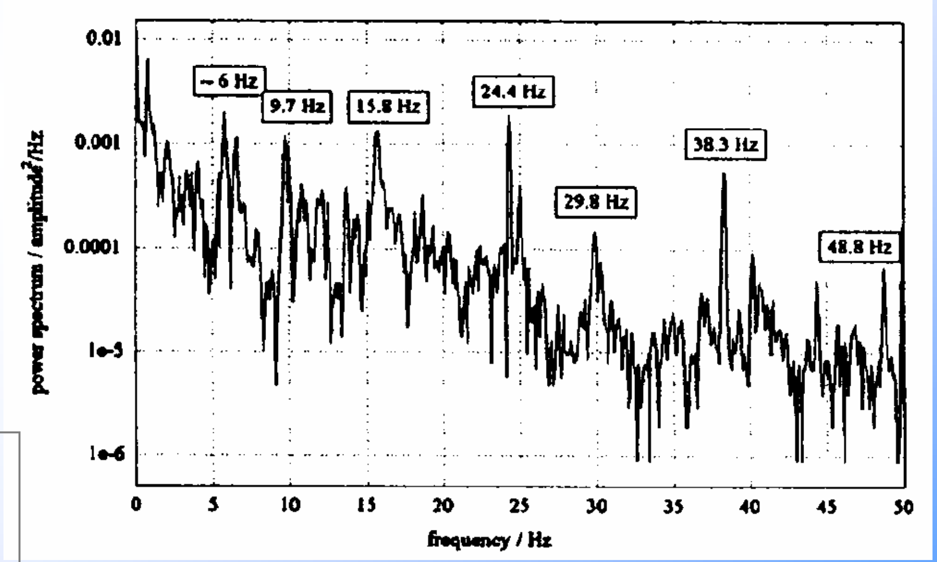
Frequency spectrum of BLM at collimator



PIN Diodes

Ground motion => Tune modulation
+
Beam beam
=
Proton diffusion

Frequency spectrum of ground motion



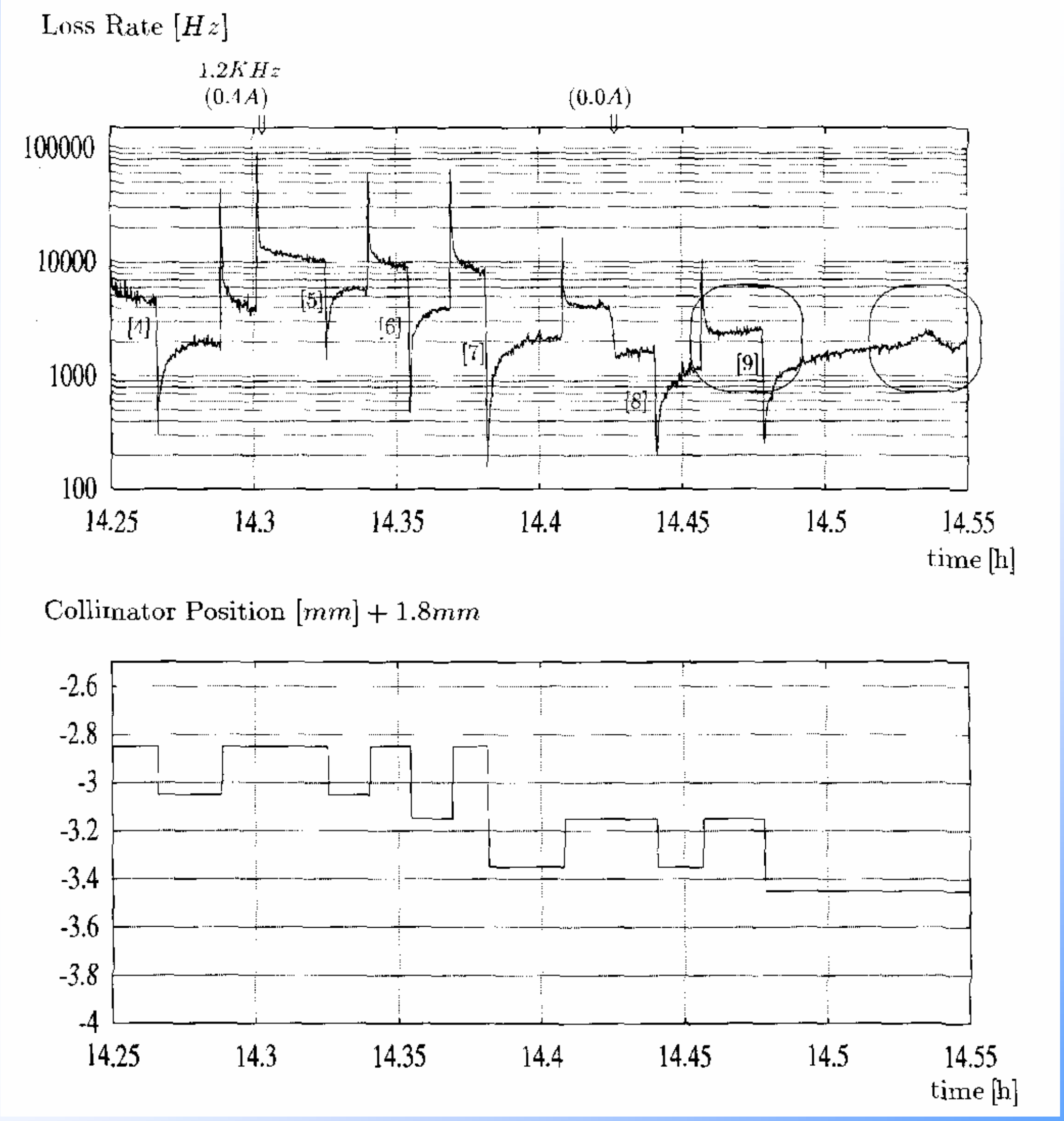
MEASUREMENT OF PROTON BEAM OSCILLATIONS AT LOW FREQUENCIES.

By K.H. Mess, M. Seidel (DESY). 1994. London 1994, Proceedings, EPAC 94

Proton Diffusion

HERAp

The diffusion parameters at different tune modulation settings are measured by retracting a scraper from the beam tail and observing the adjacent loss rate decrease and slow increase afterwards.



PIN Diodes

Brüning, O , et al., "Measuring the effect of an external tune modulation on the particle diffusion in the proton storage ring of HERA"DESY-HERA-94-01, 1994,

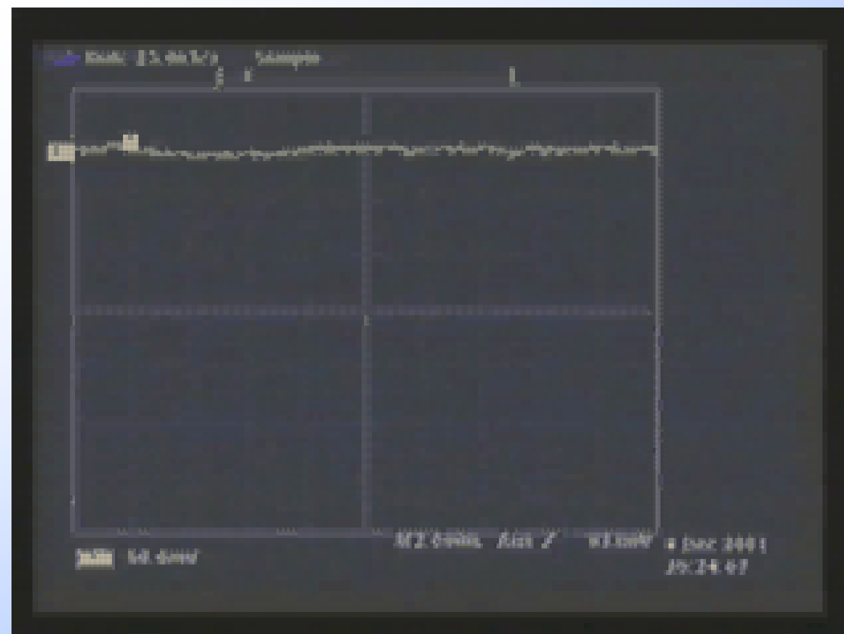
Conclusions

BLM-systems are multi-faceted beam instrumentation tools, which opens a wide field of applications. A precondition is a proper understanding of the physics of the beam loss to place the monitors at their adequate positions.

BLM

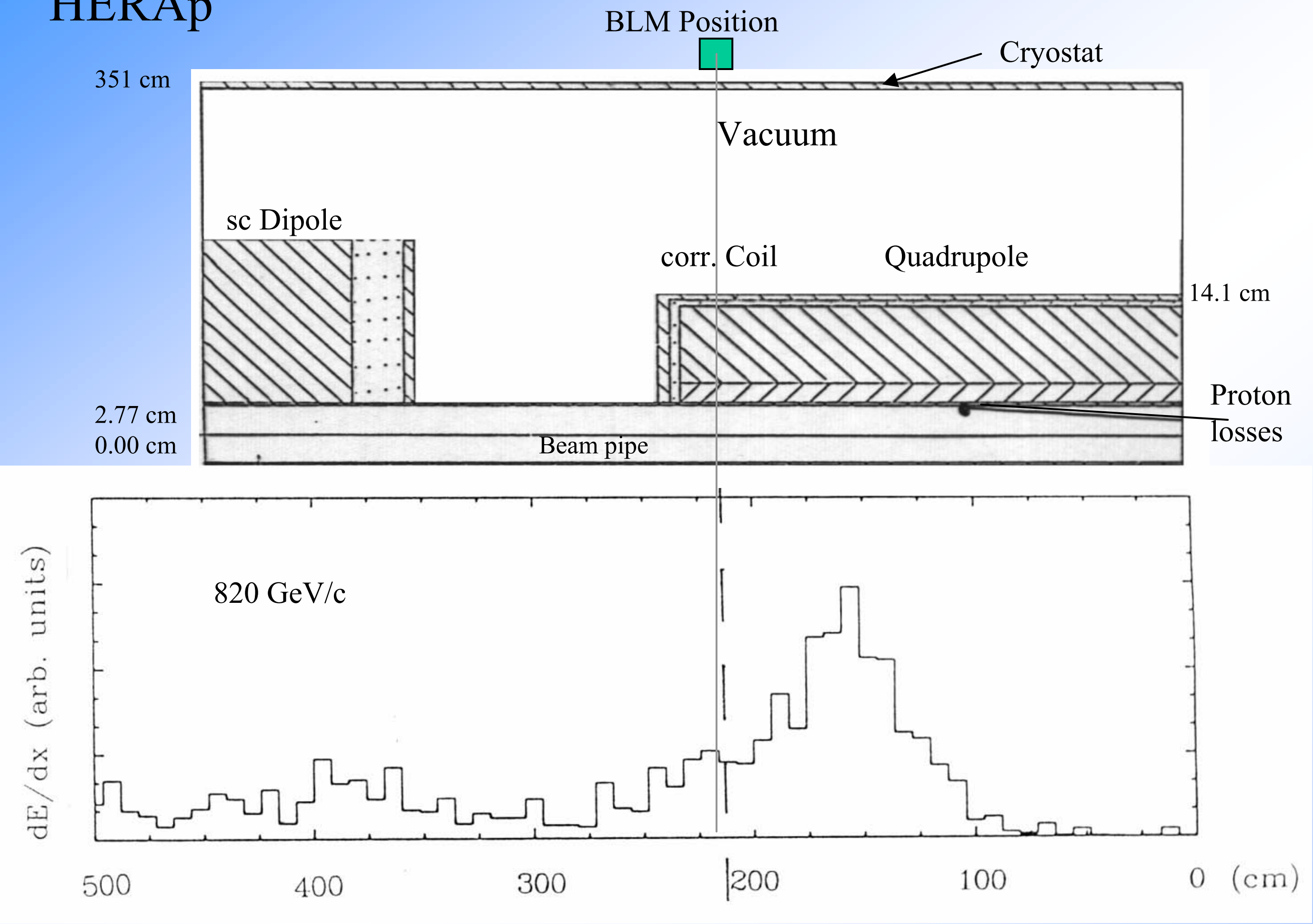
Beam Loss

Strahlungsquelle ELBE
http://www.fz-rossendorf.de/FWQ/
ELBE-Palaver u.a.
P. Michel: Strahlverlustmonitore für ELBE

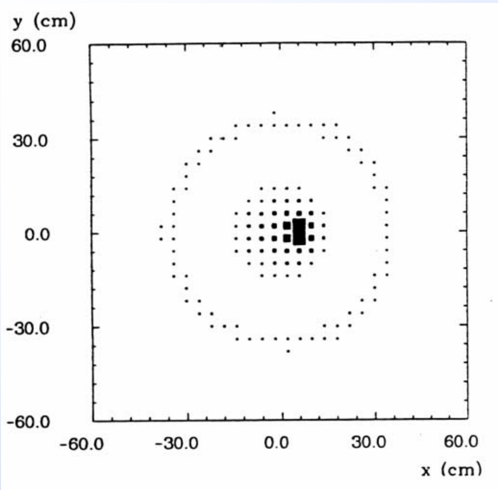


Monte Carlo calculations for positioning and calibration (2)

HERAp

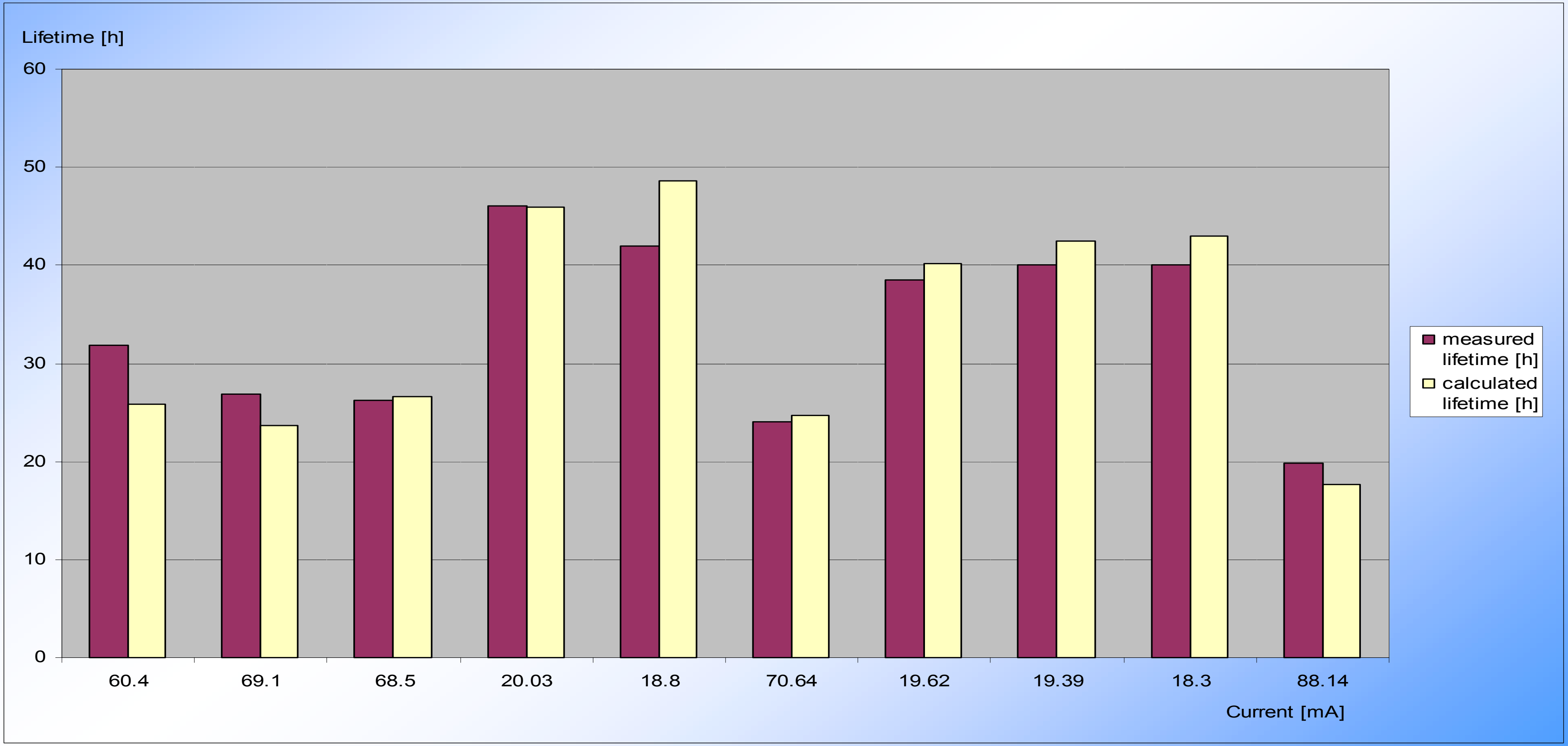


Longitudinal and radial energy/MIP distribution in the surface of the cryostat after proton losses in the middle of the sc-quadrupole



Symmetrical particle (MIP)and energy (dE/dx) distribution (radial) distributed over a few meters (longitudinal)
=> Efficiency is almost position independent

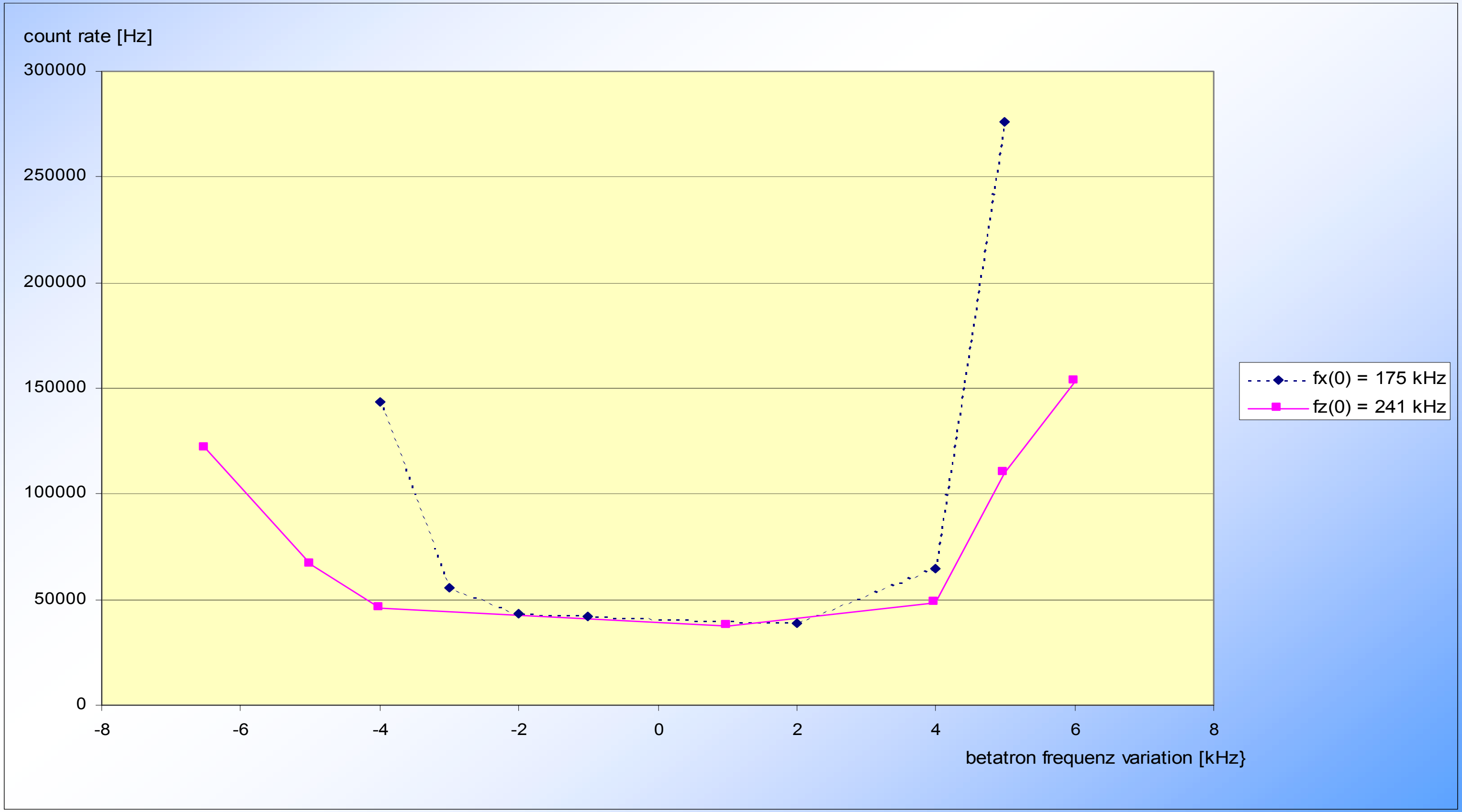
It is expected that the vacuum determines the lifetime at the normal working point of DORIS. The main loss process is the Bremsstrahlung at the residual gas in the beam pipe. The monitor is sensitive to the Bremsstrahlungs-photons emitted in the whole straight section. The total length of the section is 6.019 m or 2.1 % of the circumference. Assuming a homogeneous residual gas distribution around the ring, about 2.1 % of the losses take place in the straight section. From the measured lifetime the loss rate is calculated and compared with the measured rate of the monitor. An efficiency of (75 ± 8.6) % over a current range from 18 mA < I < 88 mA is determined by this method. A result which agrees with the previous method.



Comparison of measured and calculated lifetimes. The factor 75% is already taken into account. The measured lifetime has an uncertainty of about ± 10%. Note that the x-values are not in order.

Tune Scans (2)

Tune scan: Measurements are done at I ≈ 20 mA, τ ≈ 35 h and at the normal working point of DORIS. The collimator yaw on the inside of the ring is set close to the beam, without changing the lifetime. First the horizontal tune, then the vertical tune is moved slightly upwards and downwards as far as the monitor shows a large change in the count rates. We always proofed that the beam position is not changed during the scans. The results show that the monitor is a very sensitive tool to make <u>fast</u> tune scans of the area around the working point even at very long lifetimes.



Count rates versus horizontal f_x and vertical f_z betatron frequency

PMT