Beam Loss Monitors

By Kay Wittenburg,
Deutsches Elektronen Synchrotron DESY, Hamburg, Germany

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.

Discussing Wire Scanner heat load:

$$T_h = C \cdot dE/dx \cdot n_{bunch} \cdot \frac{f_{bunch}}{v} \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_v} \cdot \alpha \quad [^0C]$$

3. Wire heat load

According to Bethe-Blochs formula, a fraction of energy dE/dx of high energy particles crossing the wire is deposit in the wire. Each beam particle which crosses the wire deposits energy inside the wire. The energy loss is defined by dE/dx (minimum ionization loss) and is taken to be that for a minimum ionizing particle. In this case the temperature increase of the wire can be calculated by:

$$T = C \cdot dE/dx_m \cdot d' \cdot \boxed{N} \cdot \frac{1}{c_p \cdot \boxed{G}} \quad [^0C]$$

unknown

where N is the number of particles hitting the wire during one scan, d' is the thickness of a quadratic wire with the same area as a round one and G [g] is the mass of the part of the wire interacting with the beam. The mass G is defined by the beam dimension in the direction of the wire (perpendicular to the measuring direction):

Therefore, the temperature increase of the wire after one scan becomes:

$$T = C \cdot dE/dx_m \cdot d' \cdot N \cdot \frac{1}{c_p \cdot G} \quad [^0C]$$

$$Mass\,G = wire\ volume \cdot \rho = 2 \cdot \sigma_v \cdot d'^2 \cdot \rho \quad [g]$$

$$N = \frac{d' \cdot f_{rev}}{v} \cdot (NB \cdot n_{bunch})$$

In MeV/cm

$$T_h = C \cdot dE/dx_m \cdot \cancel{d'} \cdot \frac{\cancel{d'} \cdot f_{rev}}{v} \cdot (NB \cdot n_{bunch}) \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_v \cdot \cancel{d'^2} \cdot \rho} \cdot \alpha \quad [^0C]$$

$$with \quad \frac{dE/dx_m}{\rho} = dE/dx \left[\frac{MeV \cdot cm^2}{g}\right] \quad and \quad f_{rev} \cdot NB = f_{bunch}$$

$$\Downarrow$$

$$T_h = C \cdot dE/dx \cdot n_{bunch} \cdot \frac{f_{bunch}}{v} \cdot \frac{1}{c_p \cdot 2 \cdot \sigma_v} \cdot \alpha \quad [^0C]$$

Parameter table

Where h, denotes the horizontal (h) scanning direction. The cooling factor 'α' is described in the next section. **Note that the temperature does not depend on the wire diameter and that it depends on the beam dimension perpendicular to the measuring direction. The temperature increase is inverse proportional to the scanning speed**, therefore a faster scanner has a correspondingly smaller temperature increase.

Emittance growth due to a wire scan:

$$\delta\,\varepsilon_{rms} = \boxed{\sqrt{2\pi}} \cdot \delta\,\Theta^2 \cdot \Psi^2 \cdot \beta = 5.1 \cdot 10^{-2}\,\pi\,mm\,mrad$$

$\sqrt{2\pi}$ from Literature

D. Möhl, Sources of emittance growth (also P. Bryant; CAS, Beam transfer lines):

$$\delta\,\varepsilon = \pi \frac{1}{2} \cdot \Theta_{rms}{}^2 \cdot \beta$$

Averaging over all Betatron-phases

Unit of phase space emittance

M. Giovannozzi (CAS 2005)

$$\delta\,\varepsilon = \pi \frac{1}{4} \cdot \Theta_{rms}{}^2 \cdot \beta$$

D. Möhl, Sources of emittance growth, 2007:

$$\delta\,\varepsilon_\sigma = \frac{1}{2} \cdot \Theta_{rms}{}^2 \cdot \beta_x$$

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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.

Introduction

Beam loss monitor systems are designed for measuring beam losses around an accelerator or storage ring. A detailed understanding of the loss mechanism, together with an appropriate design of the BLM-System and an appropriate location of the monitors enable a wide field of very useful beam diagnostics and machine protection possibilities.

Contents

Loss Classes
Common aspects for a sufficient Beam Loss Monitor Systems
(Lets try to design a BLM system for a superconducting accelerator)
Examples for irregular losses
Examples for regular losses used for beam diagnostic

Loss Classes

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:

Why???

✓ 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 protection 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.**

Loss Classes

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:

Which???

Residual gas, Touschek effect, beam beam interactions, collisions, diffusion, transversal and longitudinal dispersion, residual gas scattering, halo scraping, instabilities etc. Suitable for machine diagnostic with a BLM System.

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

Principles of loss detection:

What should a Beam Loss Monitor monitor?

- In case of a beam loss, the BLM system has to establish the **number of lost particles** in a certain position and time interval.
- A typical BLM is mounted outside of the vacuum chamber, so that the monitor normally **observes the shower** caused by the lost particles interacting in the vacuum chamber walls or in the material of the magnets.
- The number of detected particles (amount of radiation, dose) and the signal from the BLM should be **proportional to the number of lost particles**. This proportionality depends on the position of the BLM in respect to the beam, type of the lost particles and the intervening material, but also on the momentum of the lost particles, which may vary by a large ratio during the acceleration cycle.
- Together with the specification for acceptable beam losses as a function of beam momentum, this defines a **minimum required sensitivity and dynamic range** for BLMs.
- Additional sensitivity combined with a larger dynamic range extends the utility of the system for **diagnostic work.**

Exercise BLM 1a:

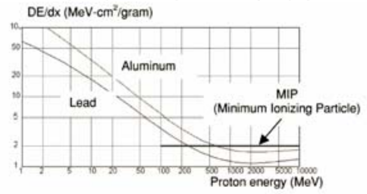
Assuming a high energy accelerator, what is the main physical process in a BLM-detector to produce a useful signal?

The signal source of beam loss monitors is mainly the ionizing capability of the charged shower particles. Ionization Loss described by Bethe-Bloch Formular:

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)}\right) - \beta^2\right]$$

with

$\beta = v/c$ and $I = 16 \cdot eV \cdot Z^{0.9}$



(from Ref [2])

Figure 1. Plot of energy loss dE/dx vs. energy of incident proton.

$dE/dx_{Minimum}$ at ≈ 1-2 MeV/(g/cm2) = so called: minimum ionizing particle (MIP), valid for many materials.

The energy can be used to create electron / ion pairs or photons in the BLM-detector material.

Useful:

Using the definition of a rad radiation dose as 100 ergs per gram leads to another definition, in terms of *MIPs*.

$$1\,rad = \frac{100\,ergs}{gram} \cdot \frac{MeV}{1.6 \cdot 10^{-6}\,ergs} \cdot \frac{MIP \cdot gram}{2\,MeV \cdot cm^2} = 3.1 \cdot 10^7\ MIPs\ per\ cm^2$$

So now we can describe the response of a beam loss monitor in terms of either energy deposition (100 ergs/gram), or in terms of a charged particle (MIPs) flux (3.1-10^7 MIPs/cm^2). (from Ref. [2])

Exercise BLM 1b:

Which type of particle detection / detector do you propose for beam loss detection? Why? How the signal creation works? (Discussion in auditorium)

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)

Exercise BLM 1b:

Mostly used devices:
Short ion chambers,
Long ion chambers,
Photomultipliers with scintillators (incl. Optical Fibers),
PIN Diodes (Semiconductors),
Secondary Emission Multiplier-Tubes,
…

More exotic:
Microcalorimeters,
Compton Diodes,
Optical fibers,
…

Dosimetrie is excluded here. Typically interest in long time scales (days-years), BLMs in short time scales (few turns to 10 ms)

Useful (2)

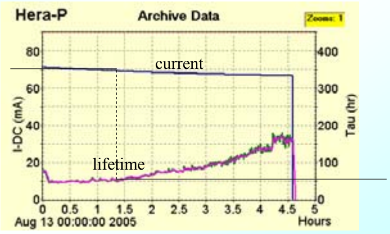
Energy needed to create an electron in the detector (**without (tube-) amplification**):

Detector Material	energy to create one electron [eV/e]	number of e / (cm MIP) [e/(cm MIP)] **(depends on dE/dx)**
Plastic Scintillator:	250 – 2500	10^3 - 10^4
Inorganic Scint.	50 - 250	10^4 - 10^5
Gas Ionization:	22 – 95	≈10^5 (N_2,1 atm.)
Semiconductor (Si):	3.6	10^6
Secondary emission:	2%/MIP (surface only)	0.02 e/MIP
Cherenkov light	10^5 - 10^6	≈10 (H_2O, dep. on energy)

Measuring beam losses

Exercise BLM 2a:

HERAp is a proton storage ring (920 GeV/c) with 6.3 km circumference. How many beam particles are lost within a second (N_{Lost}), assuming a proton beam current of I_0 = 70 mA and a lifetime of τ = 50 hours (=$1.8 \cdot 10^5$s)?



$I = I_0 \cdot \exp(-t/\tau)$
I_0 = 70 mA = 0.07 C/s
τ = 50 h = $1.8 \cdot 10^5$ s
t = 1 s
$I = 0.07 \cdot \exp(-1 / 1.8 \cdot 10^5) = 0.069996$ C/s
$I_0 - I = 3.9 \cdot 10^{-7}$ C/s
But 1 lost proton ($1.6 \cdot 10^{-19}$ C) reduces the current in the ring I_p (6.3 km => 21 µs/turn or f_{rev} = 47.6 kHz) by:

$I_p = 1.6 \cdot 10^{-19} \cdot 47.6 \cdot 10^3 = 7.6 \cdot 10^{-15}$ C/s/lost proton
(Note: NOT by $1.6 \cdot 10^{-19}$ C/s/proton only!!!)

$N_{Lost} = (I_0 - I) / I_p = 5.1 \cdot 10^7$ lost Protons /s

Exercise BLM 2b:

Assuming all protons are lost in a 1 cm³ block of iron (penetration length L = 1 cm). Calculate the deposit power P [W] in the block (1 J = $6.241 \cdot 10^{18}$ eV):

dE/dx = 11.6 MeV/cm for Fe
Power $P = N_{Lost}$ [1/s]· dE/dx [MeV/cm] · L [cm] = $5.9 \cdot 10^8$ MeV /s = **0.095 mW**

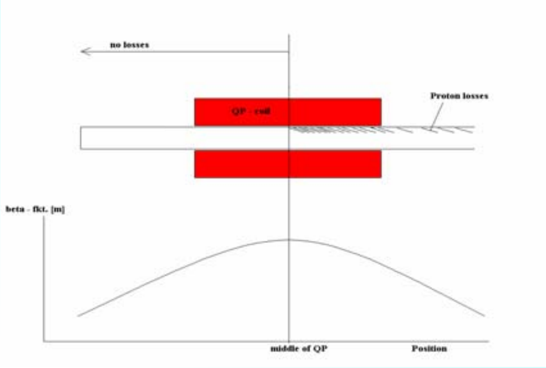
This number gives a macroscopic feeling of the measurable power due to beam losses during a worse luminosity run in HERAp. Possible reasons for these losses are: Beam-beam kicks, transversal and longitudinal dispersion, residual gas scattering, halo scraping, instabilities… These losses can be used for beam diagnostics (see later)

But note that typically losses will not be concentrated at one location only! Note also, that at LHC such losses has to be concentrated at the collimators!

Each BLM at different locations needs its special efficiency-calibration in terms of signal/lost particle. This calibration can be calculated by use of a Monte Carlo Program with the (more or less) exact geometry and materials between the beam and the BLM. For the simulation it might be important to understand the (beam-) dynamics of the losses and the loss mechanism.

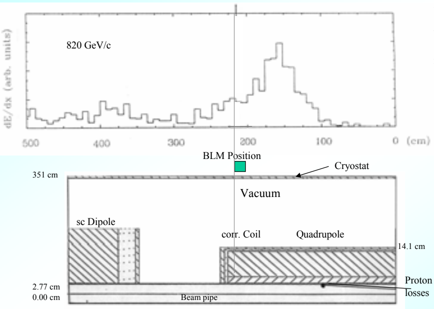
Where to put the BLMs to measure beam losses?

Preferred locations for beam losses and therefore for BLMs might be Collimators, scraper, aperture limits, and high β-functions…, therefore also the superconducting quadrupoles
(By the way, why the middle of a quad is a preferred location for a loss of a beam particle?)

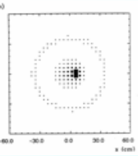


Monte Carlo calculations for positioning and calibration (2)

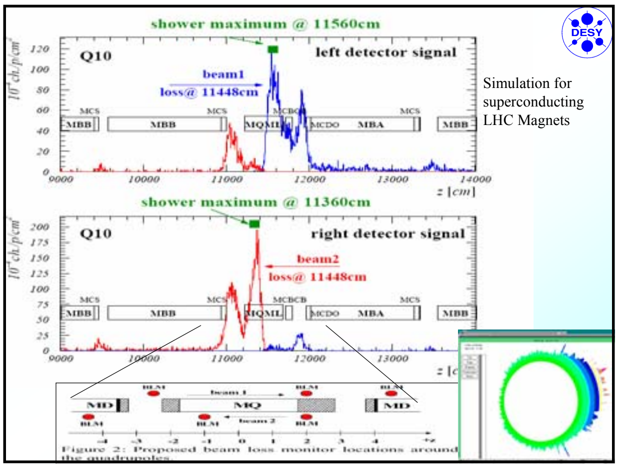
HERAp



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



Simulation for superconducting LHC Magnets

Exercise BLM 2c:

At a certain location of a BLM in HERA (collimator), the efficiency to beam losses is about ε= 0.1 minimum ionizing particles / (cm2 · lost proton) (at 300 GeV/c) at the BLM location.

Calculate the resulting current of a 1 litre air filled ionization chamber BLM. Assume that 1/10 of the losses above (exercise 2a: 5.1·107 lost Protons /s) occur here. About E_{pair} = 22 eV/pair is needed to create an electron / ion pair in air.

$dE/dx_{air} = 2.2\cdot10^{-3}$ MeV/cm (from attached data sheet) →
$N_{pair} = dE/dx_{air} / E_{pair}$ = 100 e/cm or $N_{pair} = 10^5$ e/ltr.
Depending on the HV polarity one can measure either electrons or ions of charge e.
$N_{tot} = N_{Lost} /10 \cdot N_{pair} \cdot \varepsilon = 5.1 \cdot 10^{10}$ e/s/ltr = 8.16 nA/ltr

Note that at other locations the efficiency of loss detection might be orders of magnitude less (HERA magnets $\varepsilon = 10^{-3}$) and that losses might occur also at other locations. But note also, that these are regular losses, dangerous losses are orders of magnitude higher (see 2.2).

Irregular Losses:

A serious problem for high current and high brilliance accelerators is the high power density of the beam. A misaligned beam is able to destroy the beam pipe or collimators and may break the vacuum. This fact makes the BLM-System one of the primary diagnostic tools for beam tuning and equipment protection in these machines.
Superconducting accelerators need a dedicated BLM-system to prevent beam loss induced quenches. Such a system has to detect losses fast enough before they lead to a high energy deposition in the superconducting material.

Some Examples for irregular (uncontrolled, fast) losses

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

nor this

Don't do this again!!!

Exercise BLM 2d:

Which design criteria are important for a BLM system to prevent beam loss induced quenches? (Discussion in Plenum)

✓Typical locations for the protection system monitors are the quadrupoles of the accelerator, were the beam has its largest dimensions. The quadrupoles act as local aperture limits and therefore the chance for a loss is larger there.
✓Adequate dynamic range to cover all beam parameters (e.g. current, energy, …)
✓A time constant of a few ms is adequate for the main loss system.
✓Some special locations are more sensitive to losses than others, e.g. global aperture limits and collimators. For such locations a special treatment of the alarm-threshold, timing constant (faster) and sensitivity is applicable. Even an additional type of monitor and/or faster measurement might be the right choice.
✓In all cases of fast beam losses, an event archive is most helpful for a post mortem analysis of the data, to find out the reason for the loss. Certainly this will improve the operational efficiency of the accelerator.
✓Care has to be taken, to set-up such a system properly, so that it is not overly active (dumping too often) and also not too relaxed, allowing dangerous loss rates.

In the following we want to calculate the current (signal) in a 1 liter air filled ionization chamber at the *critical loss rate* at 40 and 820 GeV/c. At that particular location the following values should be assumed

Exercise BLM 2e:

What is a “critical loss rate”? How to define it

Insertion: Energy deposition in magnets

a) quench level of a cable (820 GeV/c)

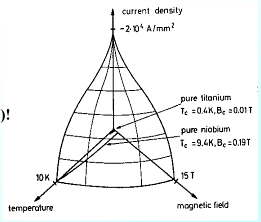
For NbTi cables (HERA):	B=5T (at coil, 4.7 T in gap), T_b = He bath temp = 4.4 K
critical values:	T_c (B=0, I=0) = 9.2 K; B_c = 14.5 T; $T_c (B, I=0) = T_c (0) \cdot (1- (B/ B_c))^{0.59}$
current sharing temp.:	$T_{cs} (B,I) = T_b + (T_c(B, I=0) - T_b) \cdot (1 - J_{op}/J_c)$
critical current:	$J_c = J_c(B, T)$

With

J_{op} = HERA operating current ≈ $0.7 \cdot J_c$ = 5025 A

=> $T_{cs}(B, J_{op})$ = 5.2 K

⇒ΔT_c = 0.8 K
between He-bath-temp. (T_b) and quench-temp (T_{cs})!



Critical surface of NbTi

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a) quench level of a cable *cont.*

Heat capacity c_p of Copper-NbTi composite cable:
$c_p = 10^{-3}\ \varepsilon\ \{(6.8/\varepsilon + 43.8) \cdot T^3 + (97.4 + 69.8 \cdot B) \cdot T\}$ [mJ/cm³ · K]   Ref 2a
ε is the superconductor fraction of the cable: ε = 0.36 for HERA Type cable

=> c_p = 2.63 mJ/cm³ · K⁻¹

=> E_{dep} = 2.1 mJ/cm³ is needed for a temperature increase of ΔT_c = 0.8 K (at 820 GeV/c)

- We performed Monte Carlo calculations to simulate the beam loss and the energy deposition in the coils. The critical losses were determined from the critical energy deposition in 1 cm³ coil volume (hot spot)
- BLMs cannot protect against instantaneous losses!
- At Tevatron (Ref. 6) they observe beam loss induced quenches at a continuous loss rate (dose) (/s) 16 times higher than instantaneous losses.
- Decisions: Measure loss rates in ≈5 ms intervals = alarm time binning.
  Definition: critical loss rate/5.2 ms = cont. loss rate · 5.2 · 10^{-3}
  Threshold: Accepted loss rate ≤ 1/10 critical loss rate
  BLMs on superconducting Quads (+ warm Quads)

All information to calculate a response of a BLM:

From Monte Carlo calculations:

Momentum [GeV/c]	efficiency ε [MIP/cm²/proton]
40	$3.25 \cdot 10^{-4}$
100	$4.47 \cdot 10^{-4}$
400	$1.53 \cdot 10^{-3}$
820	$2.20 \cdot 10^{-3}$

Tab. 1: Efficiency e vs beam momentum for the BLMs at the superconducting magnets in HERA

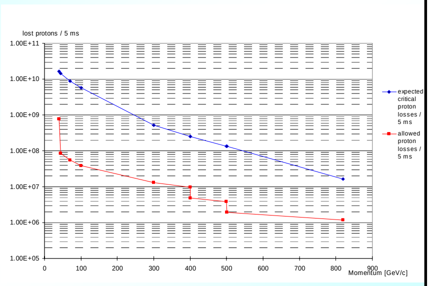

Fig. 2: Critical proton loss rate vs. momentum for the superconducting magnets in HERAp

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In the following the current (signal) in a 1 liter air filled ionization chamber at the critical loss rate at 40 and 820 GeV/c is calculated.

Signal calculation:
$dE/dx_{air} = 2.2 \cdot 10^{-3}$ MeV/cm (from attached data sheet), 1 ltr = 1000 cm³
$N_{pair} = dE/dx_{air} / E_{pair}$ = 100 e/cm or $N_{pair} = 10^5$ e/ltr.
Depending on the HV polarity one can measure either electrons or ions of charge e.

At 40 GeV/c: $N_{lost} = 1.1 \cdot 10^{10}$ protons/5 ms, $\varepsilon = 3.25 \cdot 10^{-4}$
I_{ion} (40 GeV) = $N_{Lost} \cdot N_{pair} \cdot \varepsilon = 7.15 \cdot 10^{13}$ e/s/ltr = 11.4 µA (within 5 ms)/ltr

At 820 GeV/c: $N_{lost} = 1.1 \cdot 10^7$ protons/5 ms, $\varepsilon = 2.2 \cdot 10^{-3}$
I_{tot} (820 GeV) = $N_{Lost} \cdot N_{pair} \cdot \varepsilon = 4.8 \cdot 10^{11}$ e/s/ltr = 77.4 nA (within 5 ms)/ltr

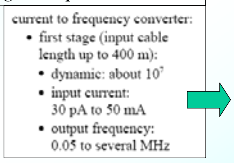
=> dynamic range ≈$1.5 \cdot 10^2$

Note that regular losses at this location ($\varepsilon \approx 1 \cdot 10^{-3}$) give an ion-chamber current of $8.16 \cdot 10^{-2}$ nA (exercise 2c). **Therefore the dynamic range of this BLM system should exceed 10^6 to measure regular losses (diagnostic) as well as dangerous losses (protection).**
How to design a readout system with such a huge dynamic range?

---

bit	value
0	1.00E+00
1	2.00E+00
2	4.00E+00
3	8.00E+00
4	1.60E+01
5	3.20E+01
6	6.40E+01
7	1.28E+02
8	2.56E+02
9	5.12E+02
10	1.02E+03
11	2.05E+03
12	4.10E+03
13	8.19E+03
14	1.64E+04
15	3.28E+04
16	6.55E+04
17	1.31E+05
18	2.62E+05
19	5.24E+05
20	1.05E+06
21	2.10E+06
22	4.19E+06
23	8.39E+06
24	1.68E+07

See R. Jones talk for the LHC solution to cover the whole range: => counting technique

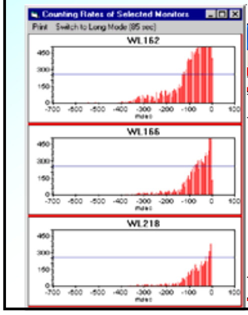


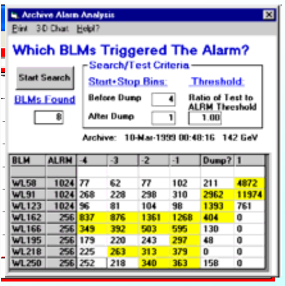
current to frequency converter:
- first stage (input cable length up to 400 m):
  - dynamic: about 10^7
  - input current: 30 pA to 50 mA
  - output frequency: 0.05 to several MHz

Tevatron upgraded BLM System:
Dual Charge Integrator (Burr Brown ACF2101)
Alternately integrating or being readout and reset
Provides continuous measurement
50 kHz maximum sample rate
16-Bit SAR ADC
DAC to give analog scope output

Quench Protection at HERAp

HERA has shown, that the BLM-system is very often the last chance to recognize a doomed beam and to dump it before it is lost uncontrollably, possibly quenching magnets. An event archive is most helpful for **a post mortem analysis** of the data to understand the reason of the beam loss
Reason here: Head tail instability => emittance blow up: No effect on Orbit!





Which BLMs Triggered The Alarm?

Search/Test Criteria

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

Threshold:
Ratio of Test to ALRM Threshold: 1.00

BLMs Found: 8

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

PIN Diodes

Some examples for regular (controlled, slow) Losses.
Examples to make diagnostics with BLMs

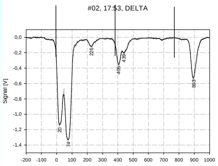
- Injection studies
- Vacuum Problems
- Lifetime limitations (Touschek effect, etc.)
- Tail scans
- Tune scans
- Ground motion
- Diffusion

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

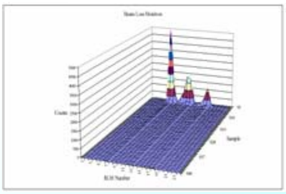


opt. fibre

DELTA, EPAC 2002

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.

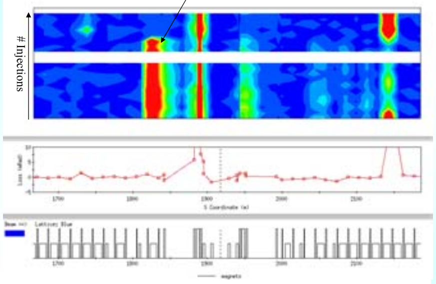


Surface plot of beam loss at injection.

PIN Diode

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

RHIC Commissioning: Obstacle (RF Finger) detected by BLMs



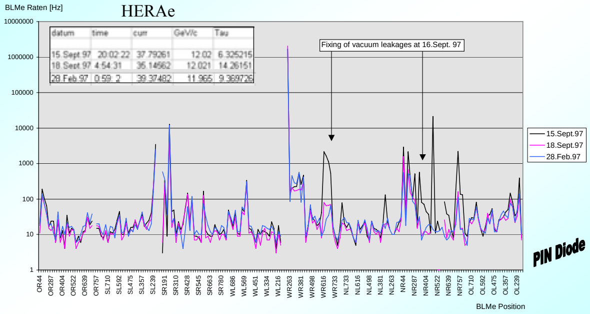
Loss pattern evolution as beam was steered locally around an apparent obstacle at s ~= 1820 meters (sector 11, quad 6) in the BLUE ring. When the losses there went away, beam began circulating for thousands of turns.

Ion Chambers

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

Vacuum Problems

HERAe



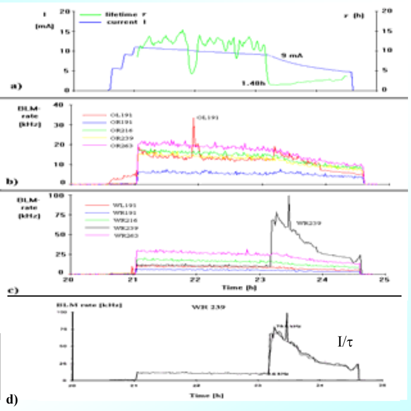
datum	time	curr	GeV/c	Tau
15.Sept.97	20:02:22	37.79261	12.02	6.325215
18.Sept.97	4:54:31	35.14562	12.021	14.26151
28.Feb.97	0:59: 2	39.37482	11.965	9.369726

PIN Diode

Microparticles (1)

HERAe

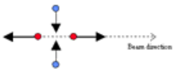
Lifetime reduction events correlate well with losses seen in the HERA electron loss monitors. In this example the brief disruption of lifetime is seen in the loss monitor SL191, and the irreversible disruption is seen in the monitor WR239



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

PIN Diodes

Lifetime limitations (1)



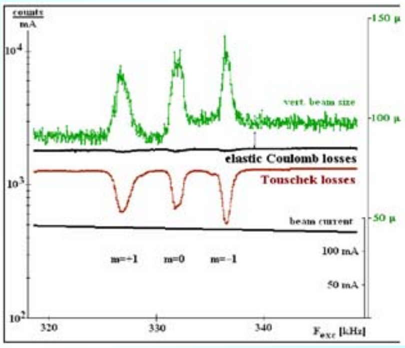
<u>Touschek effect</u>: Particles inside a bunch perform transverse oscillations around the closed orbit. **If two particles scatter they can transform their transverse momenta into longitudinal momenta**. If the new momenta are outside the momentum aperture the particles are lost. Good locations for 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 <u>outside</u> 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.

<u>Coulomb scattering:</u> 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 **<u>inside</u> 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.



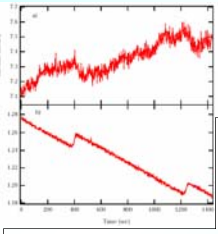
P. Kuske, DIPAC2001, Accelerator Physics Experiments with Beam Loss Monitors at Bessy

PMT

Lifetime limitation (3)

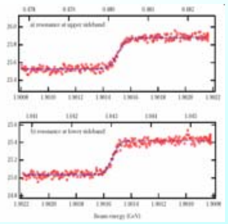
Bessy, ALS

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

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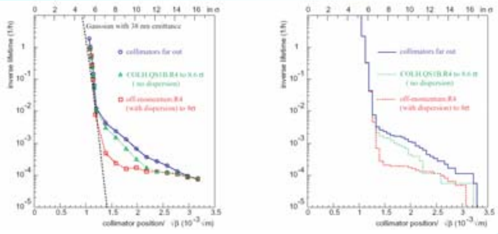
Tail scans

LEP



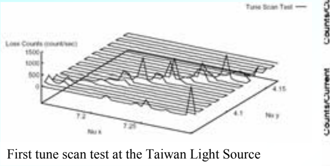
Measurement (left) and simulation (right) of the horizontal beam tails for a beam energy of 80.5 GeV and for different collimator settings at LEP. The simulation is the result of tracking particles after Compton scattering on thermal photons (**black body radiation of vacuum chamber).**

PIN Diodes
PMT

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

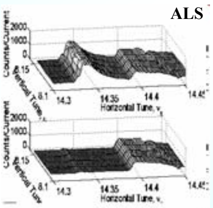
Tune Scans

SRRC



First tune scan test at the Taiwan Light Source

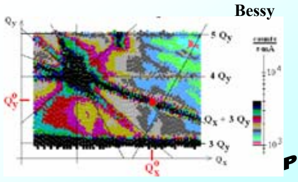
ALS



PIN Diodes

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.

Bessy



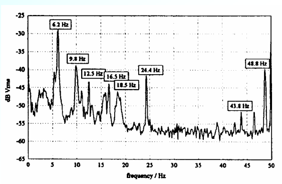
PMT

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

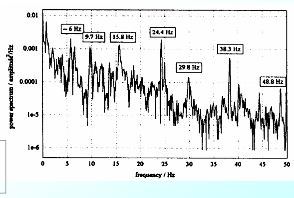
Frequency spectrum of BLM at collimator



PIN Diodes

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

Frequency spectrum of ground motion



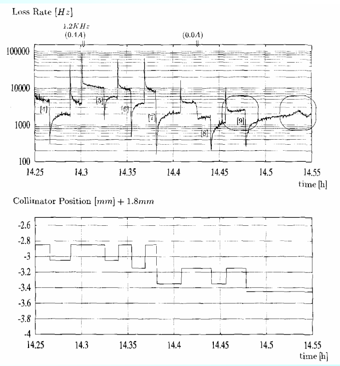
MEASUREMENT OF PROTON BEAM OSCILLATIONS AT LOW FREQUENCIES.

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,

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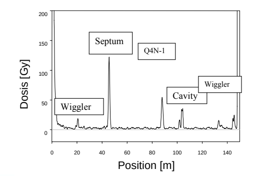
Activation of components/environment

KEK

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)

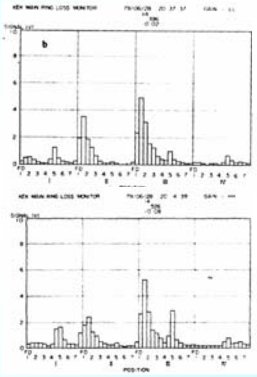
OTDR Dosis, Delta (3393),



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

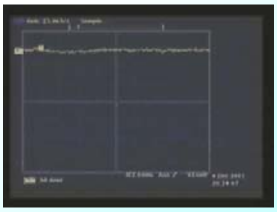
Ion Chambers

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

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.

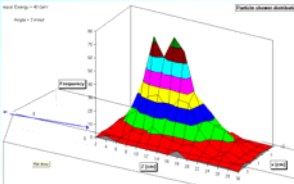
Strahlungsquelle ELBE
http://www.fz-rossendorf.de/FWQ/
ELBE-Palaver u.a.
P. Michel: Strahlverlustmonitore für ELBE



The End

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

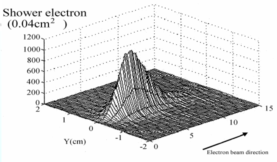
HERAe



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'

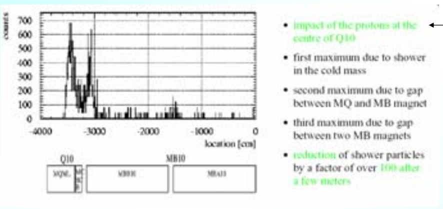
* Low energy particles which do not create a shower leakage outside the vacuum pipe wall are hardly detectable by a loss monitor system.

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

β-function is max. in Quad

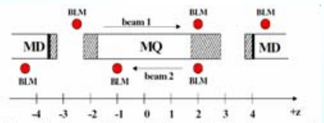
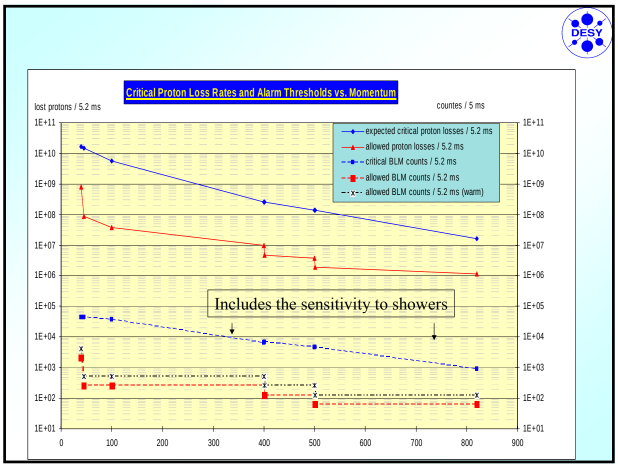
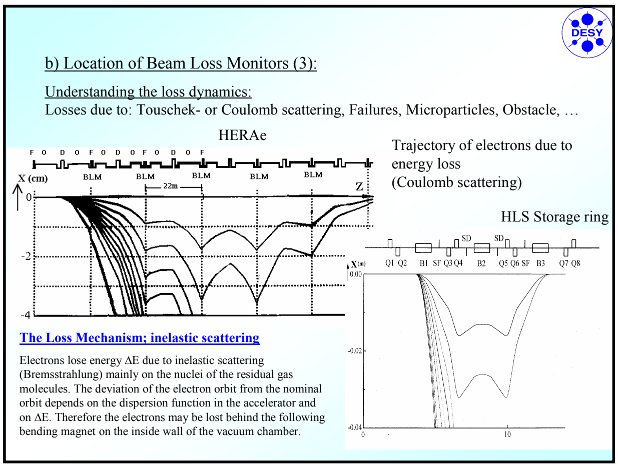


Figure 2: Proposed beam loss monitor locations around the quadrupoles.

LHC example:
B. Dehning et al., BIW2002



Includes the sensitivity to showers



b) Location of Beam Loss Monitors (3):

Understanding the loss dynamics:

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

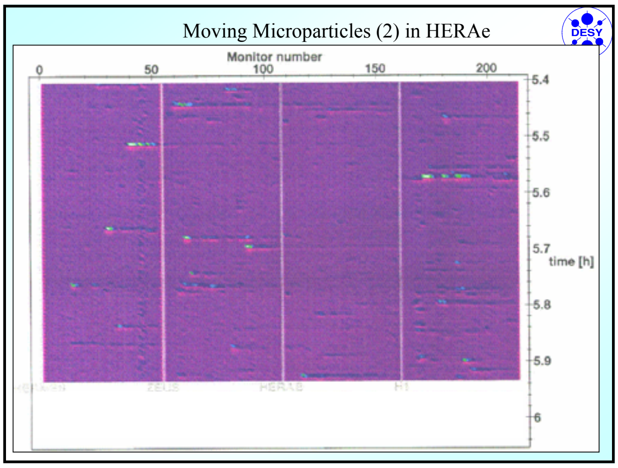
HERAe

Trajectory of electrons due to energy loss (Coulomb scattering)

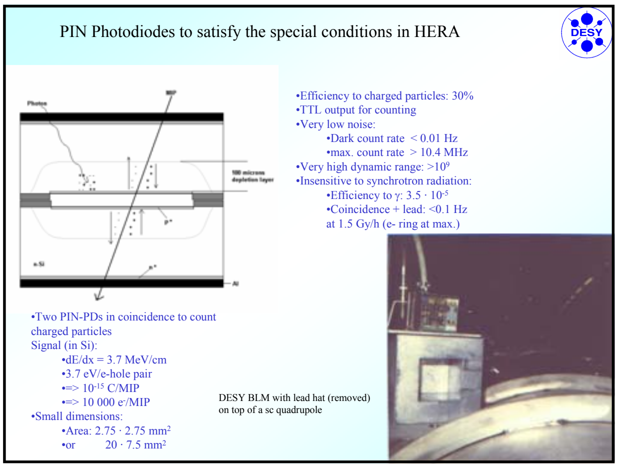
HLS Storage ring

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.



Moving Microparticles (2) in HERAe



PIN Photodiodes to satisfy the special conditions in HERA

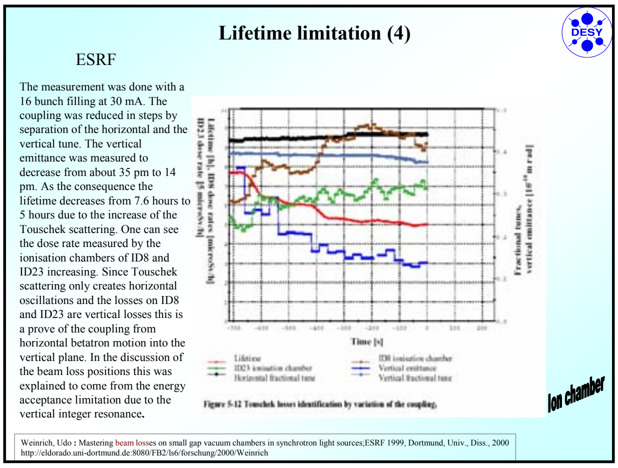
- Efficiency to charged particles: 30%
- TTL output for counting
- Very low noise:
    - Dark count rate < 0.01 Hz
    - max. count rate > 10.4 MHz
- Very high dynamic range: >10^9
- Insensitive to synchrotron radiation:
    - Efficiency to γ: $3.5 \cdot 10^{-5}$
    - Coincidence + lead: <0.1 Hz at 1.5 Gy/h (e- ring at max.)

- Two PIN-PDs in coincidence to count charged particles

Signal (in Si):
- dE/dx = 3.7 MeV/cm
- 3.7 eV/e-hole pair
- => 10^{-15} C/MIP
- => 10 000 e^-/MIP

- Small dimensions:
    - Area: $2.75 \cdot 2.75$ mm^2
    - or $20 \cdot 7.5$ mm^2

DESY BLM with lead hat (removed) on top of a sc quadrupole



Lifetime limitation (4)

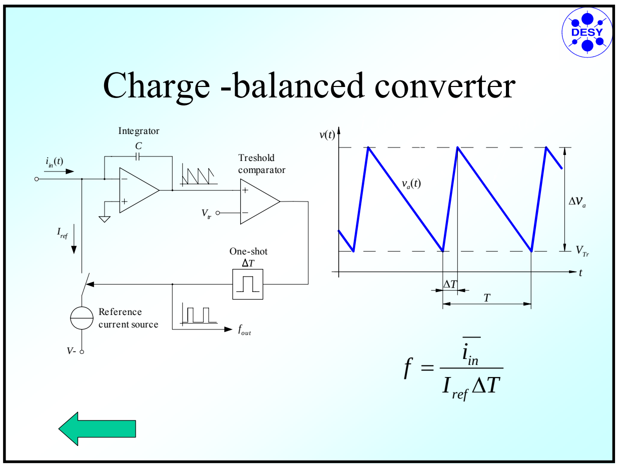
ESRF

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.

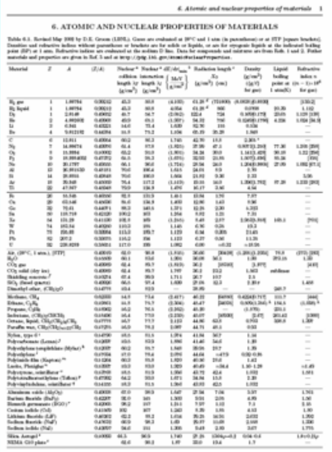
Ion chamber

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



Charge -balanced converter

$$f = \frac{\overline{i_{in}}}{I_{ref}\,\Delta T}$$



6. Atomic and nuclear properties of materials 1

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Wire Parameters

Parameter	Symbol	Unit	wire material				
			AL	W	Carbon	Beryllium	Quartz (SiO_2)
wire diameter	d $= 7 \cdot 10^{-4}$	cm					
mean wire diameter	$d' = d/2 \cdot \sqrt{\pi}$ $= 5.5 \cdot 10^{-4}$	cm					
Conversion	0.239	cal/Joule					
Conversion factor	$C = 3.8 \cdot 10^{-14}$	MeV / cal					
Speed of wire	v = 100	cm/s					
specific heat capacity*	c_p	cal / g / ^{0}C	0.21	0.036	0.42 (>400^{0}C) 0.17 (< 400^{0}C)	0.43	0.18
Energy loss of min. ion. part. (MIPs)	dE/dx dE/dx_m	MeV cm^2 / g MeV/cm	1.62 4.37	1.82 35.13	2.3 5.3	1.78 3.3	2.33 5.3
density	ρ	g/cm^3	2.7	19.3	2.3	1.85	2.29
melting temp.	T_m	^{0}C	650	3400	ca. 3500	1200	1700
Heat conductivity	1	W/(m K)	230	100-160	30-3000	200	1.2-1.4
Radiation length	l_{rad}	cm	8.9	0.35	18.8	34.7	12.3
Nuclear coll length	lnuc	cm	26	9.6	34	30	25.4

Table WIRE1: Parameters of wire materials. *> 500 ^{0}C

The beam parameters used in this exercise are shown in the following table:

Parameter	Symbol	Unit	Value
circumference of accel.	circ.	m	300
particle		Proton	
Beam particle momentum	p	GeV/c	0.3-7
Beta function	$\beta_h = \beta_v$	m	11.8
Emittance	$\varepsilon_h = \varepsilon_v$	π mm mrad	15
revolution Frequency	f_{rev}	MHz	0.93
Bunch spacing	t_{bunch} f_{bunch}	ns MHz	98 10.2
Number of bunches in accel.	NB		11
Bunch charge	n_{bunch}	1/e	$1.1 \cdot 10^{11}$
Beam width measurement [1]	σ_h	mm	1.5
Beam width perpendicular to meas. [1]	σ_v	mm	1

Table WIRE2: Parameters of Beam