Beam Loss Monitors

1 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.
Beam losses can be divided into two different classes:

1) Irregular losses, sometimes called “fast or uncontrolled losses”: These losses may be distributed around the accelerator and not obviously on a collimation system. They 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. Losses should 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. This includes quench protection of superconducting magnets and acceleration structures and protection of detector components, Accidental beam losses of high energy, high brilliance or high intense beams can cause serious problems in accelerators including vacuum leaks, melting of material, activation, quenches of superconductors, etc. A beam loss monitor system should measure all losses and should prevent dangerous beam loss rates in the machine. However, it can only take action, if already losses happened and therefore it stands in the very last position in a machine protection system.
- to achieve long beam lifetimes or an efficient beam transport to get high integrated luminosity for the related experiments.

Sometimes such losses have to be tolerated even at a high level at low repetition rates during machine studies. However, 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 damage of components. A post mortem event analysis is most helpful to understand and analyse the faulty condition.

2) Regular losses, sometimes called “slow” or “controlled” losses: 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.

It is clearly advantageous to design a BLM-System which is able to deal with both loss modes.
In addition measurements of injection-, ejection- or collimator- efficiencies can be performed using BLMs or beam current monitors, as well as background measurements

in the detectors. This survey concentrates on BLM systems which cover the entire accelerator.

1.1 Principles of loss detection

In case of a beam loss, the BLM system has to establish the number of lost particles in a certain position and time interval[1]. All BLM systems discussed here are mounted outside of the vacuum chamber, so that the detector 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?

Solution:

The signal source of beam loss monitors is mainly the ionizing capability of the charged shower particles. The Ionization Loss is 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* $I = 16 \cdot eV \cdot Z^{0.9}$

---

[1] I exclude from this exercise beam current monitors, which give the amount of losses but not the position

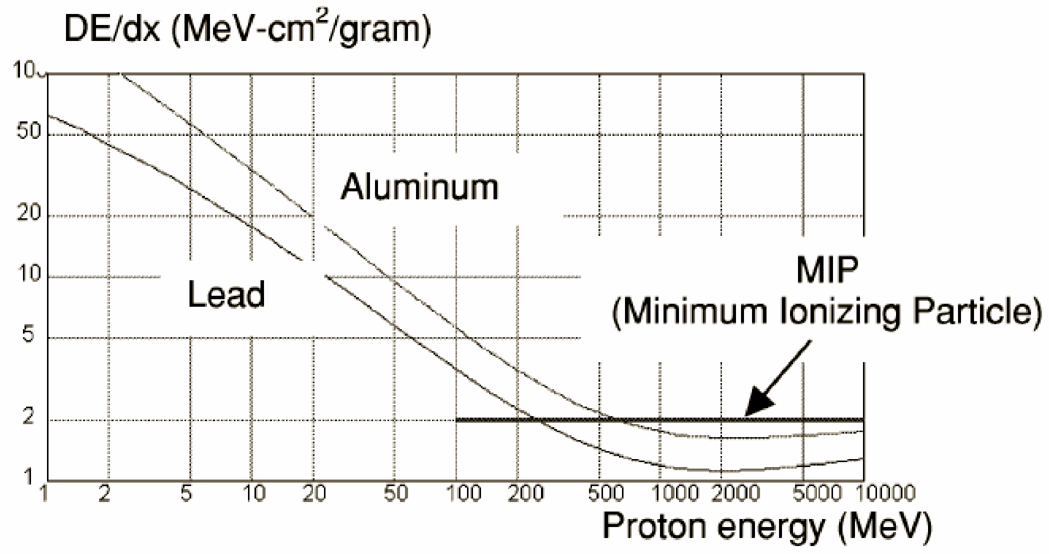


Figure 1. Plot of energy loss dE/dx vs. energy of incident proton.

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

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

A nice list of "considerations in selecting a beam loss monitor" is discussed in [2]:

- 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.

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)

Solution:
Different types of loss monitors exist and detailed descriptions of most types can be found in [1, 2]. Options for beam loss monitors might be: ***long and short Ion chambers, Photomultipliers with scintillators (incl. Optical Fibers), PIN Diodes (Semiconductors), Secondary Emission Multiplier-Tubes, Microcalorimeters, Compton Diodes, etc***

Interesting to know:
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)]*
Plastic Scintillators:	*250 – 2500*	10^3 - 10^4
Inorganic Scint.	*50 - 250*	10^4 - 10^5
Gas Ionization:	*22 – 95*	$\approx 10^2$ *(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)*

2 Measuring Beam Losses

2.1 Regular 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?

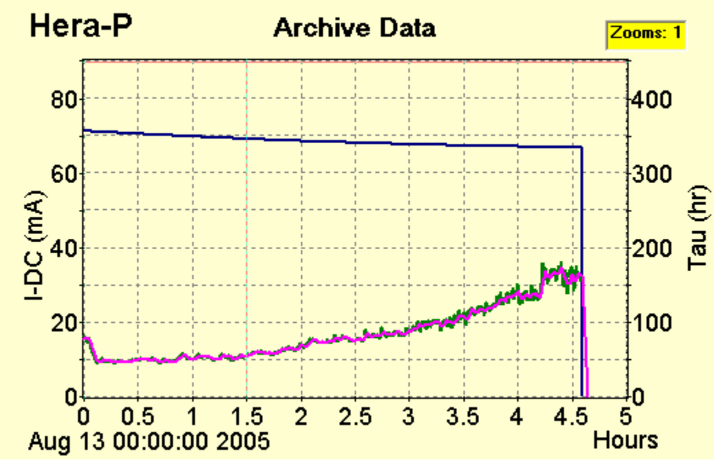


Fig. 1: Beam current [mA] vs time

Solution

$I = I_0 \cdot exp(-t/\tau)$

$I_0 = 70\ mA = 0.07\ C/s$

$\tau = 50\ h = 1.8 \cdot 10^5\ s$

$t = 1\ s$

$I = 0.07\ C/s \cdot exp(-1 / 1.8 \cdot 10^5) = 0.069996\ C/s$

$I_0 - I = 3.9 \cdot 10^{-7}\ C/s$

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!!!)*

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

Exercise BLM 2b:

Assuming all protons are lost in a 1 cm^3 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):

Solution:

$dE/dx = 11.6$ MeV/cm for Fe

Power $P = N_{Lost} \cdot dE/dx \cdot L = 5.9 \cdot 10^8$ MeV/s = 0.095 mW

This number gives a macroscopic feeling of the measurable power due to beam losses during a bad luminosity run in HERAp with worse lifetime. 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 e.g. Ref. 3). But note that typically losses might not be concentrated at one location only!

Preferred locations for beam losses and therefore for BLMs might be Collimators, scraper, aperture limits, high β-functions, …

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.

Exercise BLM 2c:

At a certain location of a BLM in HERA (collimator), the efficiency to beam losses is about $\varepsilon = 0.1$ MIP / ($\mathrm{cm}^2 \cdot$ lost proton) (at 300 GeV/c) at the BLM location.

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

Solution:

$dE/dx_{air} = 2.2\cdot 10^{-3}$ *MeV/cm (from attached data sheet)*

$N_{pair} = dE/dx_{air} / E_{pair} = 100$ *e/cm. Depending on the HV polarity one can measure either electrons or ions of charge e.*

$I_{ion} = N_{Lost}/10 \cdot N_{pair} \cdot \varepsilon \cdot 1000\ \mathrm{cm}^3 = 5.1 \cdot 10^{10}\ \mathrm{e/s} = 8.16\ \mathrm{nA}$

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).*

2.2 Quench Protection

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.

Exercise BLM 2d:
Which design criteria are important for a BLM system to prevent beam loss induced quenches (Discussion in plenum)?
Solution:

- *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.*

Exercise BLM 2e:

Calculate from the following table and figure (note the time scale of the losses) the current I_{ion} in a 1 liter air filled ionization chamber at the critical loss rate at 40 and 820 GeV/c (at that particular location):

Momentum [GeV/c]	efficiency ε [MIP/cm^2/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 ε vs beam momentum for the BLMs at the superconducting magnets in HERA

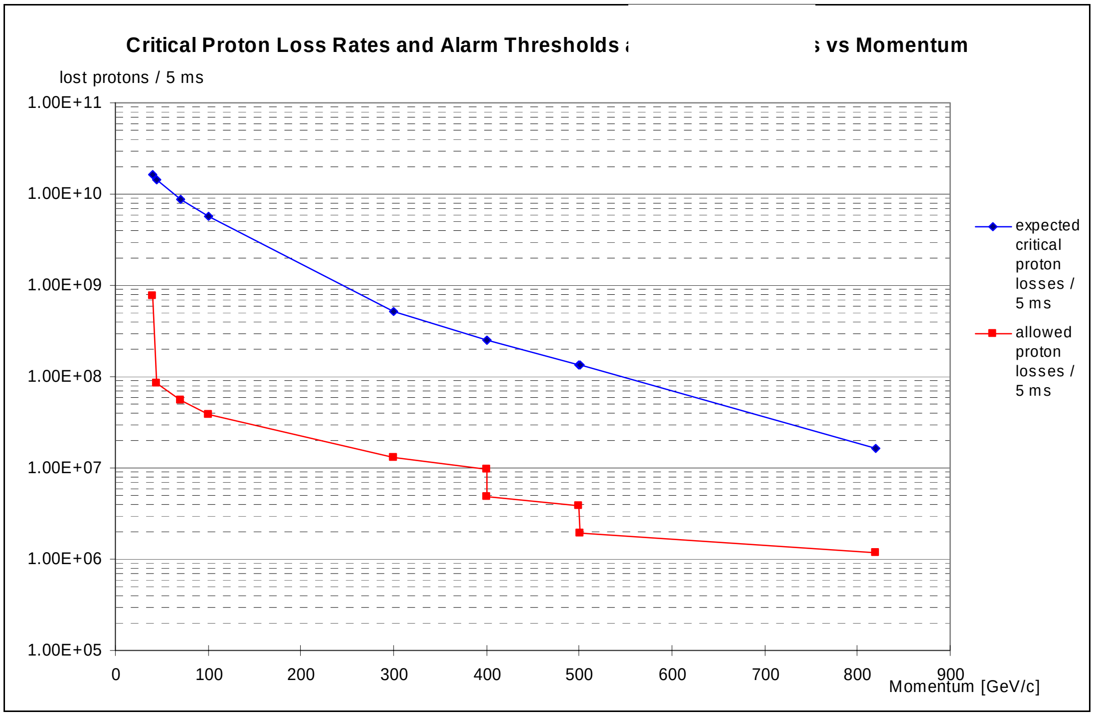


Fig. 2: Critical proton loss rate (above a quench occur) vs. momentum for the superconducting magnets in HERAp

Solution:
$dE/dx_{air} = 2.2 \cdot 10^{-3}$ *MeV/cm (from attached data sheet)*

$N_{pair} = dE/dx_{air} / E_{pair} = 100$ *e/cm. Depending on the HV polarity one can measure either electrons or ions of charge e.*

At 40 GeV/c: $N_{lost} = 1.1 \cdot 10^{10}$ *MIPS/5 ms,* $\varepsilon = 3.25 \cdot 10^{-4}$

I_{ion} (40 GeV) = $N_{Lost} \cdot N_{pair} \cdot \varepsilon \cdot 1000\ \mathrm{cm}^3 = 7.15 \cdot 10^{13}$ e/s = 11.4 μA (within 5 ms)

At 820 GeV/c: $N_{lost} = 1.1 \cdot 10^{7}$ *MIPS/5 ms,* $\varepsilon = 2.2 \cdot 10^{-3}$

I_{ion} (820 GeV) = $N_{Lost} \cdot N_{pair} \cdot \varepsilon \cdot 1000\ \mathrm{cm}^3 = 4.8 \cdot 10^{11}$ e/s = 77.4 nA (within 5 ms)

=> dynamic range $\approx 1.5 \cdot 10^{2}$

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 a BLM system should exceed*** **10^{6}** ***to measure regular losses (diagnostic) as well as dangerous losses.***

3 References

[1] K. Wittenburg, “**Beam Loss Detection**”, 1st European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators, Montreux, Switzerland, 3-5.5.1993, CERN PS/93-35 (BD)
http://desyntwww.desy.de/mdi/downloads/BLM-DET.pdf

[2] R. E. Shafer, “**A tutorial on Beam Loss Monitoring**,” 10th Beam Instrumentation Workshop 2002, Brookhaven, Mai 2002.
http://beamdocs.fnal.gov/DocDB/0010/001068/001/A%20tutorial%20on%20beam%20loss%20monitoring.pdf

[3] Kay Wittenburg. “**Beam Loss Monitoring and Control**” Proc. Eighth European Particle Accelerator Conference La Villette – PARIS, 3 - 7 June 2002
http://accelconf.web.cern.ch/AccelConf/e02/PAPERS/THYGB001.pdf

6. ATOMIC AND NUCLEAR PROPERTIES OF MATERIALS

Table 6.1. Revised May 2002 by D.E. Groom (LBNL). Gases are evaluated at 20°C and 1 atm (in parentheses) or at STP [square brackets]. Densities and refractive indices without parentheses or brackets are for solids or liquids, or are for cryogenic liquids at the indicated boiling point (BP) at 1 atm. Refractive indices are evaluated at the sodium D line. Data for compounds and mixtures are from Refs. 1 and 2. Futher materials and properties are given in Ref. 3 and at `http://pdg.lbl.gov/AtomicNuclearProperties.`

Material	Z	A	$\langle Z/A\rangle$	Nuclear [a] collision length λ_T {g/cm^2}	Nuclear [a] interaction length λ_I {g/cm^2}	$dE/dx\vert_{\rm min}$ [b] $\left\{\frac{\rm MeV}{\rm g/cm^2}\right\}$	Radiation length [c] X_0 {g/cm^2}	{cm}	Density {g/cm^3} ({g/ℓ} for gas)	Liquid boiling point at 1 atm(K)	Refractive index n (($n-1$)×10^6 for gas)
H_2 gas	1	1.00794	0.99212	43.3	50.8	(4.103)	61.28 [d]	(731000)	(0.0838)[0.0899]		[139.2]
H_2 liquid	1	1.00794	0.99212	43.3	50.8	4.034	61.28 [d]	866	0.0708	20.39	1.112
D_2	1	2.0140	0.49652	45.7	54.7	(2.052)	122.4	724	0.169[0.179]	23.65	1.128 [138]
He	2	4.002602	0.49968	49.9	65.1	(1.937)	94.32	756	0.1249[0.1786]	4.224	1.024 [34.9]
Li	3	6.941	0.43221	54.6	73.4	1.639	82.76	155	0.534		—
Be	4	9.012182	0.44384	55.8	75.2	1.594	65.19	35.28	1.848		—
C	6	12.011	0.49954	60.2	86.3	1.745	42.70	18.8	2.265 [e]		—
N_2	7	14.00674	0.49976	61.4	87.8	(1.825)	37.99	47.1	0.8073[1.250]	77.36	1.205 [298]
O_2	8	15.9994	0.50002	63.2	91.0	(1.801)	34.24	30.0	1.141[1.428]	90.18	1.22 [296]
F_2	9	18.9984032	0.47372	65.5	95.3	(1.675)	32.93	21.85	1.507[1.696]	85.24	[195]
Ne	10	20.1797	0.49555	66.1	96.6	(1.724)	28.94	24.0	1.204[0.9005]	27.09	1.092 [67.1]
Al	13	26.981539	0.48181	70.6	106.4	1.615	24.01	8.9	2.70		—
Si	14	28.0855	0.49848	70.6	106.0	1.664	21.82	9.36	2.33		3.95
Ar	18	39.948	0.45059	76.4	117.2	(1.519)	19.55	14.0	1.396[1.782]	87.28	1.233 [283]
Ti	22	47.867	0.45948	79.9	124.9	1.476	16.17	3.56	4.54		—
Fe	26	55.845	0.46556	82.8	131.9	1.451	13.84	1.76	7.87		—
Cu	29	63.546	0.45636	85.6	134.9	1.403	12.86	1.43	8.96		—
Ge	32	72.61	0.44071	88.3	140.5	1.371	12.25	2.30	5.323		—
Sn	50	118.710	0.42120	100.2	163	1.264	8.82	1.21	7.31		—
Xe	54	131.29	0.41130	102.8	169	(1.255)	8.48	2.87	2.953[5.858]	165.1	[701]
W	74	183.84	0.40250	110.3	185	1.145	6.76	0.35	19.3		—
Pt	78	195.08	0.39984	113.3	189.7	1.129	6.54	0.305	21.45		—
Pb	82	207.2	0.39575	116.2	194	1.123	6.37	0.56	11.35		—
U	92	238.0289	0.38651	117.0	199	1.082	6.00	≈0.32	≈18.95		—
Air, (20°C, 1 atm.), [STP]			0.49919	62.0	90.0	(1.815)	36.66	[30420]	(1.205)[1.2931]	78.8	(273) [293]
H_2O			0.55509	60.1	83.6	1.991	36.08	36.1	1.00	373.15	1.33
CO_2 gas			0.49989	62.4	89.7	(1.819)	36.2	[18310]	[1.977]		[410]
CO_2 solid (dry ice)			0.49989	62.4	89.7	1.787	36.2	23.2	1.563	sublimes	—
Shielding concrete [f]			0.50274	67.4	99.9	1.711	26.7	10.7	2.5		—
SiO_2 (fused quartz)			0.49926	66.5	97.4	1.699	27.05	12.3	2.20 [g]		1.458
Dimethyl ether, $(CH_3)_2O$			0.54778	59.4	82.9	—	38.89	—	—	248.7	—
Methane, CH_4			0.62333	54.8	73.4	(2.417)	46.22	[64850]	0.4224[0.717]	111.7	[444]
Ethane, C_2H_6			0.59861	55.8	75.7	(2.304)	45.47	[34035]	0.509(1.356) [h]	184.5	(1.038) [h]
Propane, C_3H_8			0.58962	56.2	76.5	(2.262)	45.20	—	(1.879)	231.1	—
Isobutane, $(CH_3)_2CHCH_3$			0.58496	56.4	77.0	(2.239)	45.07	[16930]	[2.67]	261.42	[1900]
Octane, liquid, $CH_3(CH_2)_6CH_3$			0.57778	56.7	77.7	2.123	44.86	63.8	0.703	398.8	1.397
Paraffin wax, $CH_3(CH_2)_{n\approx23}CH_3$			0.57275	56.9	78.2	2.087	44.71	48.1	0.93		—
Nylon, type 6 [i]			0.54790	58.5	81.5	1.974	41.84	36.7	1.14		—
Polycarbonate (Lexan) [j]			0.52697	59.5	83.9	1.886	41.46	34.6	1.20		—
Polyethylene terephthlate (Mylar) [k]			0.52037	60.2	85.7	1.848	39.95	28.7	1.39		—
Polyethylene [l]			0.57034	57.0	78.4	2.076	44.64	≈47.9	0.92–0.95		—
Polyimide film (Kapton) [m]			0.51264	60.3	85.8	1.820	40.56	28.6	1.42		—
Lucite, Plexiglas [n]			0.53937	59.3	83.0	1.929	40.49	≈34.4	1.16–1.20		≈1.49
Polystyrene, scintillator [o]			0.53768	58.5	81.9	1.936	43.72	42.4	1.032		1.581
Polytetrafluoroethylene (Teflon) [p]			0.47992	64.2	93.0	1.671	34.84	15.8	2.20		—
Polyvinyltolulene, scintillator [q]			0.54155	58.3	81.5	1.956	43.83	42.5	1.032		—
Aluminum oxide (Al_2O_3)			0.49038	67.0	98.9	1.647	27.94	7.04	3.97		1.761
Barium fluoride (BaF_2)			0.42207	92.0	145	1.303	9.91	2.05	4.89		1.56
Bismuth germanate (BGO) [r]			0.42065	98.2	157	1.251	7.97	1.12	7.1		2.15
Cesium iodide (CsI)			0.41569	102	167	1.243	8.39	1.85	4.53		1.80
Lithium fluoride (LiF)			0.46262	62.2	88.2	1.614	39.25	14.91	2.632		1.392
Sodium fluoride (NaF)			0.47632	66.9	98.3	1.69	29.87	11.68	2.558		1.336
Sodium iodide (NaI)			0.42697	94.6	151	1.305	9.49	2.59	3.67		1.775
Silica Aerogel [s]			0.50093	66.3	96.9	1.740	27.25	136@ρ=0.2	0.04–0.6		1.0+0.21ρ
NEMA G10 plate [t]				62.6	90.2	1.87	33.0	19.4	1.7		—

Beam Loss Detection

K. Wittenburg
Deutsches Elektronen Synchrotron, DESY; Hamburg

1 Abstract

A review of Beam Loss Monitor Systems (BLM systems) used in accelerators since about 1960 is given, with emphasis on systems suitable for measuring and localizing beam losses over an entire accelerator. Techniques presented include: Long and Short Ionization Chambers, Scintillation Counters, Electron Multipliers, Cryogenic Calorimeters and PIN Photodiodes.

2 Introduction

2.1 Uses of BLM systems

The usual goal of particle accelerators is to deliver high luminosity to experiments. The information from BLMs helps in the tuning of the machines for the high beam currents and long lifetimes necessary for improved luminosity.

Beam loss may result in damage to accelerator components or the experimental detectors. A task of the BLM system is to avoid such damage; in some accelerators it is an integral part of the protection system, signaling a beam abort system to fire if a certain loss rate is exceed (Ref. 1, 2, 3). This is of vital importance to the Generation of superconducting accelerators, for which beam losses in the superconducting components may lead to a quench, resulting in a shut-down of accelerator operation during the quench recovery procedure, as well as possible damage to the components. Another task of BLM systems is to identify of the position (and time) of unacceptable losses. This often indicates the source of the problem in the machine. A BLM system provides a fast way to determine the position of aperture restrictions and semitransparent obstacles in the accelerator, and helps to keep the radiation level in the accelerator and its surroundings as low as possible.

2.2 Principles of loss detection

In case of a beam loss, the BLM system has to establish the number of lost particles in a certain position and time interval[1]. All BLM systems discussed here are mounted outside of the vacuum chamber, so that the detector 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 extend the utility of the system for diagnostic work.

One has to distinguish between two types of losses:

FAST LOSSES:

Total beam loss during one or very few turns. In most cases there is no need of a BLM system to localize the error in the machine. Often it is a easily detectable error like a closed vacuum valve, a broken power supply, a

---

[1] I exclude from my talk beam current monitors, which give the amount of losses but not the position

fired (or not fired) kicker, etc. Nevertheless it could be dangerous for accelerator components (especially superconducting components) and a BLM system may warn if an intolerable dose occurs.

SLOW LOSSES:

Partial beam loss over a time (circular machines) or distance (LINAC, transport lines) interval. In storage-rings, the lifetime is defined by slow losses. There are many reasons for these losses and a BLM system is very helpful for finding out what is happening in the machine. In superconducting accelerators a BLM system may prevent from beam loss induced quenches caused by slow losses.

In addition measurements of injection-, ejection- or collimator- efficiencies can be performed using BLMs (e.g. Ref. 4), as well as background measurements in the detectors (e.g. Ref. 27, 28). This survey concentrates on BLM systems which cover the entire accelerator.

3 Long Ionization-Chambers

In 1963, Panowsky (Ref. 5) proposed for SLAC a BLM system consisting of one long (3.5 km) hollow coaxial cable. It is an industrial RG-319/U cable with a diameter of 4.1 cm, filled with Ar (95%) + CO_2 (5%) and used as an ionization-chamber (Panowski's long ionisation chamber, PLIC). It is mounted on the ceiling along the LINAC, about 2 m from the beam.

Position sensitivity is achieved by reading out at one end the time delay between the direct pulse and the reflected pulse from the other end. The time resolution is about 30 ns (≈ 8 m), for shorter PLICs about 5 ns are achieved. This BLM system has been working for more than 20 years and was upgraded for the SLC (Ref. 6). Nearly the entire SLC is covered with a few PLICs

This principle of space resolution works for one-shot (-turn) accelerators (and transport lines) with a bunch train much shorter than the machine and with relativistic particles. For particles travelling significantly slower than the signal in the cable (≈0.92c) the resolution of multiple hits in the cable becomes difficult. In this case and for circular machines it is necessary to split the cable. Each segment has to be read out separately, with spatial resolution approximately equal to the length of the unit. This was done in the BNL 200 MeV LINAC, where 30 cables, each 7-9 m long, are used (Ref. 7). They are installed at 1.5 - 3 m from the beam.

In the AGS ring, Booster and transport lines about 200 monitors with a length of about 5 m are installed (Ref. 8, 9). To improve the sensitivity of the BLM system in the AGS ring for ion acceleration the cables were moved from a position below the magnets to the median plane on the open side of the magnets (Ref. 10). The dynamic range of the BLMs is about 10^3.

In the KEK-PS 56 air-filled cables with a length of about 6 m are installed. Using amplifiers with a variable gain, a dynamic range of 10^4 is archived (Ref. 11).

4 Short Ionisation Chambers

Short ionization chambers are used in many accelerators. They are more or less equally spaced along the accelerator with additional units at special positions such as aperture restrictions, targets, collimators, etc. An early example of an Air filled Ionisation Chamber is the AIC proposed in 1966 in Ref. 12 (Fig. 1). 100 AICs were installed in the CERN-PS. Each chamber had a volume of about 8000 cm^3 and used a multi-electrode layout to reduce the drift path, and hence the recombination probability, of the ions and electrons, with the goal of improved linearity. A dynamic range of 10^3 was obtained.

The idea of AIC was renewed in 1992 in Ref. 14. The authors propose an AIC with a 2π geometry around the beam pipe. The goal is to measure the loss in the vacuum wall independent of azimuth angle and with high sensitivity.

The TEVATRON relies on 216 Argon filled glass sealed coaxial ionization chambers to protect the superconducting magnets from beam loss induced quenches (Ref. 1). The volume of each chamber is 190 cm^3 (Fig. 2). Most are positioned adjacent to each superconducting quadrupole. An Ar-filled chamber has the advantage of a better linearity because of a lower recombination rate than in AICs. A dynamic range of 10^4 has been reached.

A new idea is proposed in Ref. 15 for the UNK superconducting magnets. The ionization chamber is an integral part of the magnet and uses the liquid Helium as an ionization medium. A 2π geometry close to the beam pipe is foreseen, with predicted dynamic range of 10^5, but additional investigations are necessary to determine the linearity in this range, which may be restricted by the recombination rate.

5 Scintillation counters

In case of losses in a machine without a, BLM system, a temporary installation of plastic scintillator with photomultiplier readout is often made. This counters have a well known behavior but the strong radiation damage of the plastic scintillator restricts their long term use. Liquid scintillators avoid this damage and were installed in some accelerators, e.g. Ref. 16, 17. Fig. 3 shows the device at LAMPF with a dimension of 500 cm^3. A photomultiplier (PM) inside a oil filled paint can detects the scintillation light from the oil. This BLM is very fast, the pulse rise time is about 10 ns and a dynamic range of 10^5 was obtained. The gain of the photomultipliers varies within a factor of 10. Therefore a careful intercalibration of the BLM sensitivities was necessary by adjusting the high voltage (HV). The drift of the gain is a well known behavior of PMs. A stabilized HV-source and continuous monitoring of the photomultiplier gain over the run period keep the calibration error small.

6 Aluminum Cathode Electron Multipliers

An enhanced sensitivity of photomultipliers to ionized radiation is archived by replacing the photocathode by an aluminum foil. This foil works as secondary electron emitter when irradiated. A BLM system consisting of this Aluminum Cathode Electron Multipliers (ACEM) was proposed in Ref. 18 and installed in the CERN-PS (100 units) and in the PS-Booster (48 units). They are located on top of the magnets behind each straight section plus 32 additional positions for specific applications (PS).The dimensions of the tube are 4 cm in diameter and 9 cm length plus the adjacent HV-divider (Fig. 4). This BLM is very fast; the rise time of the signal is about 10 ns. For the dynamic range a value of 10^6 was exceeded by adjusting the HV. An careful selection of the ACEMs had led to gain variations of 10 %, but intercalibration and gain monitoring was performed nevertheless. This BLM system is rather expensive because the ACEM is not a standard tube of PM-suppliers (Ref. 20).

7 Cryogenic Microcalorimeters

A new system called the Cryogenic Microcalorimeter was proposed and tested in 1992 for LEP (Ref. 21). It is designed to detect beam loss induced quenches in the superconducting quadrupoles of LEP. This detector is different from all the other BLMs presented here because it does not make use of the charge created by the lost particles. A carbon resistor thermometer measures the temperature rise of the liquid Helium in the cryostat produced by beam losses. It is a very small device with dimensions of about 3 x 3 x 1.5 mm (see Fig. 5). Its position is restricted to the cryostat of superconducting magnets.

No values for the linearity and the dynamic range are available up to now but first measurements indicate an easily detectable signal with a rise time of about 20 ms in case of a beam induced quench. The signal occurs well before the quench and it should give enough time for the quench protection system to take action. The dynamic range is limited by the critical (quench-) temperature of the liquid Helium and by the noise of the monitor. One can expect that, with a known correlation between losses and temperature, this detector will work in a BLM system for superconducting accelerators. For quantitative loss measurements the temperature increase due to synchrotron radiation has to taken into account.

8 PIN Photodiodes

Most of the existing BLM systems are installed in hadron accelerators or in Linacs. Circular electron accelerators emit hard synchrotron - radiation (SR). The radiation interacts with the BLMs and a separation between SR-background and the beam loss distributions using the traditional BLM techniques is practically impossible. HERA is an accelerator with an electron and a proton ring in the same tunnel, operating at the same time. Protection of the superconducting proton magnets from beam loss induced quenches must rely on a BLM system which sees only the proton beam losses and not the SR-background. The (hadronic) shower created by beam losses includes a large number of charged particles, in contrast to the photons of the SR. The HERA BLM system consists of two PIN Photodiodes, mounted close together (face to face) and read out in coincidence (Ref. 22). Thus charged particles crossing through the diodes give a coincidence signal, while photons interact in only one diode do not.

In contrast to the charge detection of most other BLM systems, coincidences are counted, with the count rate is proportional to the loss rate so long as the number of overlapping coincidences is small.

The Photodiodes (2 x 2.5 x 2.5 mm^3) and the preamplifier (5 x 5 x 5 cm^3) are shielded by a hat of 3 cm of lead (Fig. 6). The overall reduction of SR signals is about 10^4, resulting in a count rate of $\approx$ 1 Hz with 25 mA current at 30 GeV/c in the electron ring (Ref. 23). The system has very low noise, with a dark count rate of less than 0.01 Hz. The pulse length is adapted to the 96 ns bunch spacing in HERA, so that the maximum count rate is 10.4 MHz. Therefore a. dynamic range of more than 10^9 is available.

The radiation resistance of the BLMs is adequate for long term use in HERA. A dose of 5 x 10^5 rad leads to a small and tolerable reduction in gain (Ref. 24, 25), while the dose reaching the monitor below the lead shield will be about 10^4 rads/year. BLMs are mounted on top of each of the superconducting quadrupoles. At this position the showering of the lost protons give a count rate which is independent of the radial position of the loss, and, within 5 m, also of the longitudinal position (Ref. 23). Additional BLMs are mounted on collimators, and on some of the warm quadrupole magnets, for a total of 250 units.

The BLM system has been operating since the 1992 running period and their good performance is indicated by some measurements:

1) The loss rotes calculated from lifetime and measured by the BLMs agree to within 25 % (Ref. 26)[2].

2) The counts are integrated over a time period of 5.2 ms to match the cryogenic time constant of the superconducting magnets (>20 ms). The predicted coincidence rate corresponding to the critical loss rate for a quench at 820 GeV/c is about 860 counts/5.2 ms. The only beam induced quench of a HERA quadrupole in 1992 showed a count rate of 1258 counts/5.2 ms for the quenched quadrupole. A nearby quadrupole which did not quench showed a rate of 893 counts/5.2 ms. The critical rate must be somewhere in between and is not far away from the predicted one. The critical rate was detected about 100 ms before the magnet quenched.

3) A lifetime problem in the HERA electron ring was solved using the BLMs. All monitors were moved from the proton ring to the electron ring to find the problematic section. A high count rate, inversely proportional to the beam lifetime, was measured in one of the straight sections. The problem vanished after a part of the vacuum-chamber in this section was replaced. This result demonstrates that the BLM system is also useful in high energy electron rings. It is planned to install about 250 additional monitors in the HERA electron ring.

9 Summary

Some Beam Loss Monitors techniques for measuring losses along an entire accelerator have been presented.

A long ionization chambers using a single coaxial cable works well for one-shot accelerators or transport lines. To achieve spatial resolution of losses along an entire accelerator two conditions must be fulfilled: 1) The machine must be much longer than the bunch train, and 2), the particles must be relativistic.

The most common BLM now in use is a short ionization chamber. Whether a simple air filled chamber is adequate, or an Argon or Helium filled chamber, with superior higher dynamic range, must be used, depends on the conditions of the particular accelerator. Ionisation chambers are radiation resistant but respond to synchrotron radiation.

A very sensitive system for measuring beam losses is an electron multiplier in combination with a photocathode and scintillator or with an Aluminum cathode acting as secondary electron emitter. Because of the adjustable gain the dynamic range can be large, but the calibration of each device must be adjusted and monitored over time. These systems are also sensitive to synchrotron radiation and relatively expensive.

The Cryogenic microcalorimeter measures the temperature rise of the liquid Helium in superconducting magnets resulting from beam loss. The temperature rise corresponding to beam loss sufficient to cause a quench

---

[2] Please note that the efficiency of the BLM to charged particles is about 20 time higher than previously assumed (Ref. 27). Correct the loss-rate in Ref. 26 by 1/20.

is readily observed. Some additional investigations must be made of the dynamic range and the linearity of this device but first measurements indicate its suitability for quench prevention and loss measurements. The temperature rise due to synchrotron radiation must be taken into account when using Cryogenic Microcalorimeters for loss diagnostics in electron machines. The application of the calorimeter is limited to superconducting magnets.

The combination of two PIN-Photodiodes in a coincidence counting results in a detector with very large dynamic range and extremely effective rejection of synchrotron radiation. The small dimensions permit simple shielding and easy installation at any position. The measured radiation resistance permits long term use also in high energy electron machines with a high radiation background. The monitor with its simple accompanying electronic is inexpensive, which may be of great importance in very big machines with a large number of loss monitors. A (present) limitation is the inability to distinguish overlapping counts, so that the response is linear only for losses for which there is significantly less than one count per coincidence interval.

Acknowledgements

Many thanks to Steve Herb, who made some very useful comments on the manuscript.

10 References

Ref. 1: R.E. Shafer et al.; The TEVATRON Beam Position and Beam Loss Monitoring System. Int. Conf. on High Energy Accelerators, Fermilab, (1983)

Ref. 2: M. Fishman, D. Reagan; The SLAC Long Ion Chamber System for Machine Protection. IEEE Trans. on Nucl. Science Vol. 14 (1967), p.1096 - 1098

Ref. 3: SSC Central Design Group; Conceptual Design of the Superconducting Super Coillider. SSC-SR-2020, (1986)

Ref. 4: F. Hornstra; The System for precise Measurement of Accelerator Extraction Efficiency. Nucl. Instr. & Methodes 128, (1975), p. 435 - 440

Ref. 5: W.K.H. Panofsky; SLAC Internal Report TN-63-57, (1963)

Ref. 6: J. Rolfe et al.; Long Ion Chamber System for the SLC. SLAC-PUB-4925, (1989)

Ref. 7: J. Balsamo et al.; Long Radiation Detector System for Beam Loss Monitoring. IEEE Trans. on Nucl. Science Vol.NS-24, No. 3, (1977), p. 1807-1809

Ref. 8: R.L. Witkover; Microprocessor Based Beam Loss Monitor System for the AGS. IEEE Trans. on Nucl. Science, Vol. NS-26, No. 3, (1979), p. 3313-3315

Ref. 9: E.R. Beadle et al.; The AGS Beam Loss Monitor System. Proc. Part. Accel. Conf., San Francisco, (1991), p. 1231-1233

Ref. 10: G.W. Bennett et al.; The Upgraded Ring Loss Radiation Monitoring System at the AGS. Proc. Part. Accel. Conf., Chicago, (1989); BNL-41824

Ref. 11: N. Nahagawa et al.; Beam Loss Monitoring System with Free - Air Ionisation Chambers. Nucl, Instr. & Meth. 174, (1980), p. 401 - 409

Ref. 12: V. Agoritsas; Air Ionisation Chamber as Detector of the Beam Losses in the CPS Ring. Internal Report CERN MPS/Int.CO 66-23, (1966)

Ref. 13: J.J. Merminod; Le System d'Obversation des Pertes du Fraisceau Interne du PS.
CERN MPS/Int. CO 68-6, (1968)

Ref. 14: S.N. Lapitsky et al.; The Concept of Beam Loss Monitors Design and their Implementation at IHEP.
Proc. 15th Int. Conf. on high Energy Accel., Hamburg, (1992), p.242-244

Ref. 15: I.A. Kurochkin et al.; Beam Loss Monitor for Superconducting Accelerators.
IHEP 91-168, (1991), Protvino

Ref. 16: J.R. Parker et al.; A Beam-Spill Monitor for LAMPF.
IEEE Trans. on Nucl. Science Vol. 18 No. 3, (1971), p. 825-826

Ref. 17: R.A. Lundy and D.F. Sutter; A System for Monitoring Proton Losses from the NAL Main Accelerator.
IEEE Trans. on Nucl. Science Vol. 20 No. 3, (1973), p. 596-598

Ref. 18: V. Agoritsas and C. Johnson; EMI Aluminum Cathode Electron Multipliers: CERN TESTS.
CERN MPS/CO Note 71-51, (1971)

Ref. 19: V. Agoritsas et al.; A Microprocessor-Based System for Continuous Monitoring of Radiation Levels around the CERN PS and PSB Accelerators.
CERN PS/ 85-60 (CO), (1985)

Ref. 20: Thorn EMI, Technical Data sheet; Nuclear Radiation Detector Type 9841 (Aluminum Cathode Electron Multiplier), (1989)

Ref. 21: Ph. Lebrun et al.; Cryogenic Microcalorimeters for Measurement of Energy Deposition by Beam Losses in Superconducting Accelerator Magnets.
15th Int. Conf. on high Energy Accel., Hamburg, (1992), p. 592-595

Ref. 22: K. Wittenburg; Strahlverlustmonitore für den HERA Protonen-Ring.
DESY HERA 89-23, (1989)

Ref. 23: S. Schlögl; Einsatz von PIN-Photodioden als Protonen-Strahlverlustmonitore bei HERA.
DESY HERA 92-03, (1992)

Ref. 24: K. Wittenburg; Radiation Damage in PIN - Photodiodes.
Nucl. Instr. & Meth. A270, (1988), p. 56 - 61

Ref. 25: K. Wittenburg; Strahlenschäden am Photodioden Verstärker.
Interner Bericht, PKTR note No. 9, (1987)

Ref. 26: S. Schlögl and K. Wittenburg; A Beam Loss Monitor System for HERA.
Proc. 15th Int. Conf. on high Energy Accel., Hamburg, (1992), p. 254-256

Ref. 27: E. Morre; Ein Untergrundmonitor für das ZEUS-Experiment.
Diploma Thesis, (1992), University Hamburg

Ref. 28: J. Wear; The ALEPH Rapid Beam Loss Interlock- System.
This proceedings

11 Figures

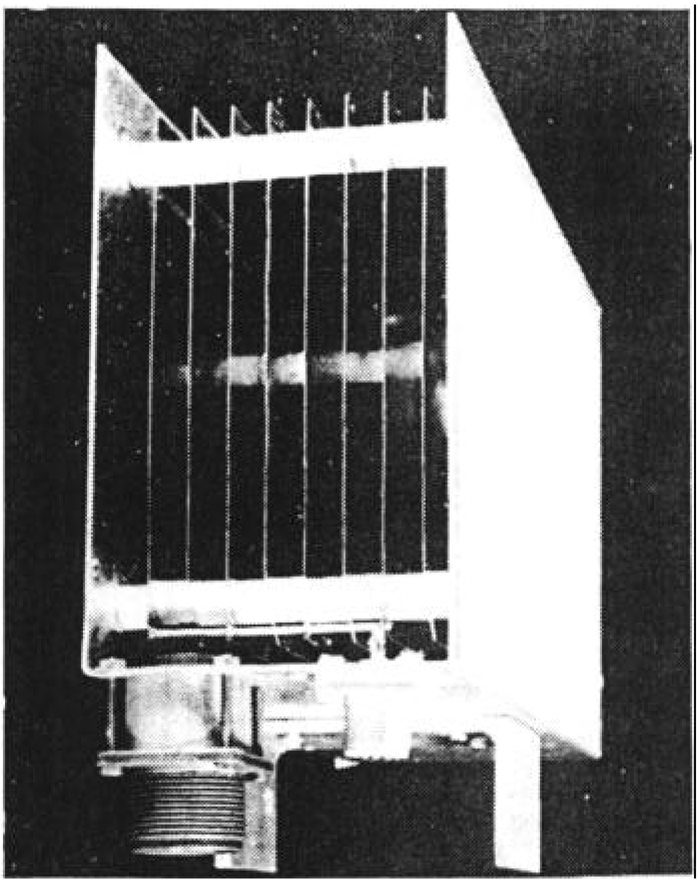


Figure 1: Air Ionisation Chamber at the PS (1968). The cover is removed (from Ref. 13).

Figure 2: The TEVATRON Argon filled Ionization Chamber (1983)

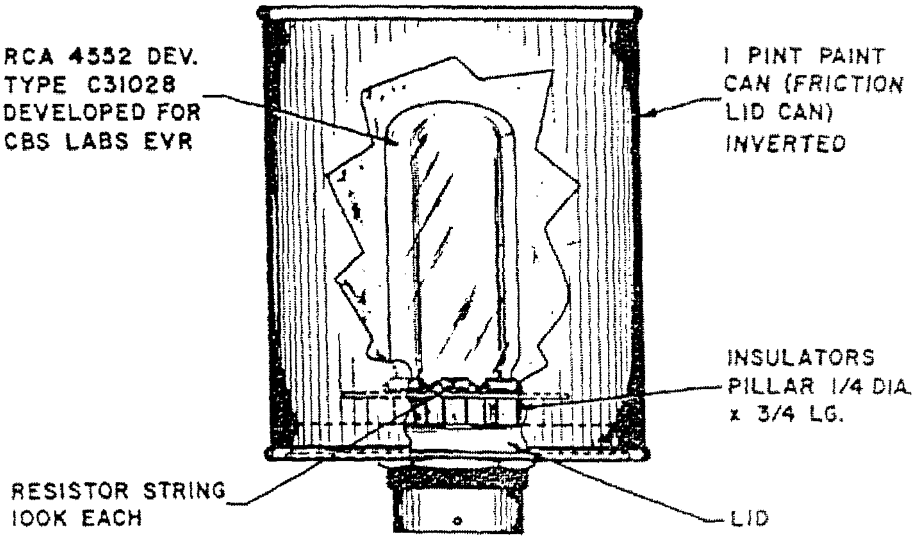


Figure 3: The Liquid Scintillator BLM at LAMPF (1971), (from Ref. 16)

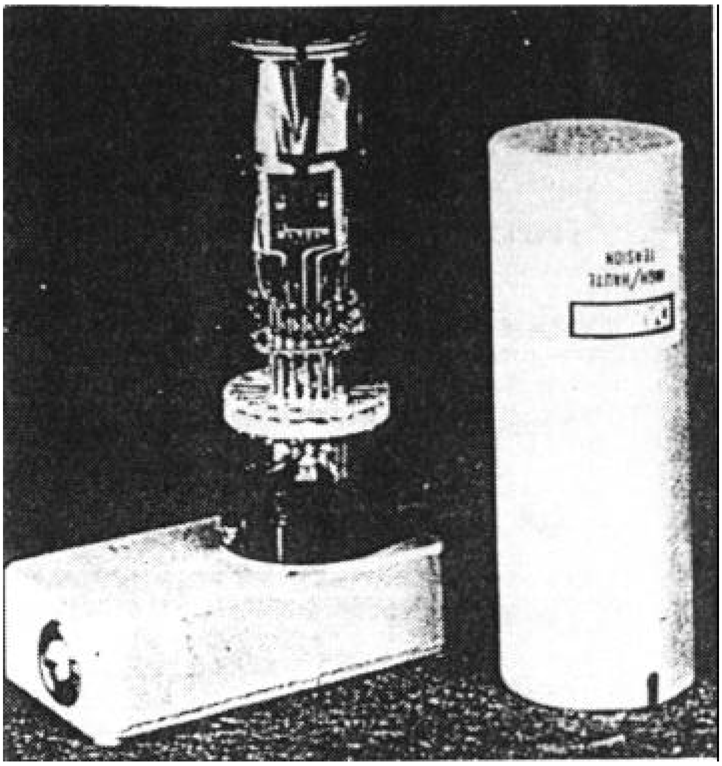


Figure 4: The Aluminum Electron Multiplier at CERN PS (1985), (from Ref. 19).

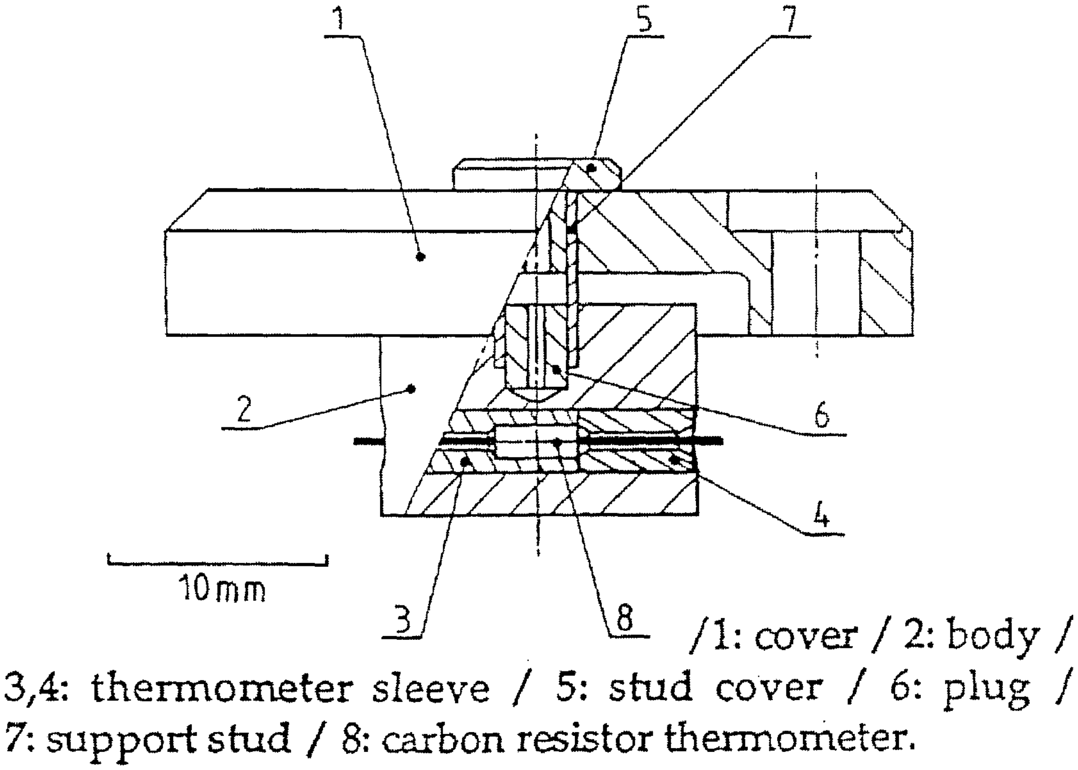


Figure 5: Cut-away view of the microcalorimeter (1992), (from Ref. 21).

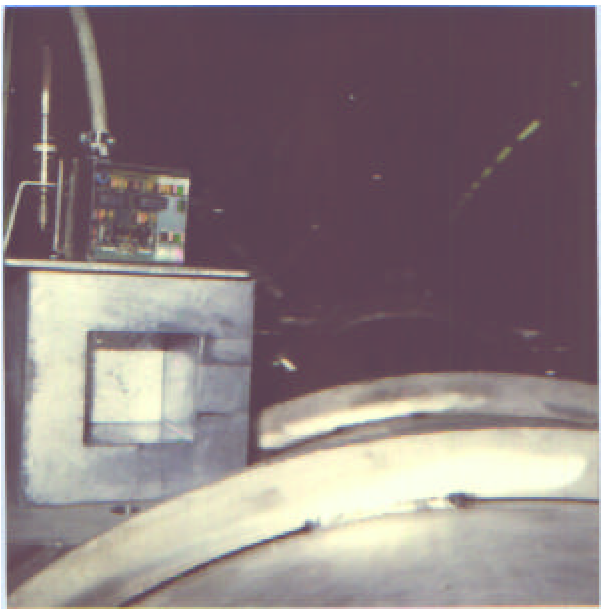
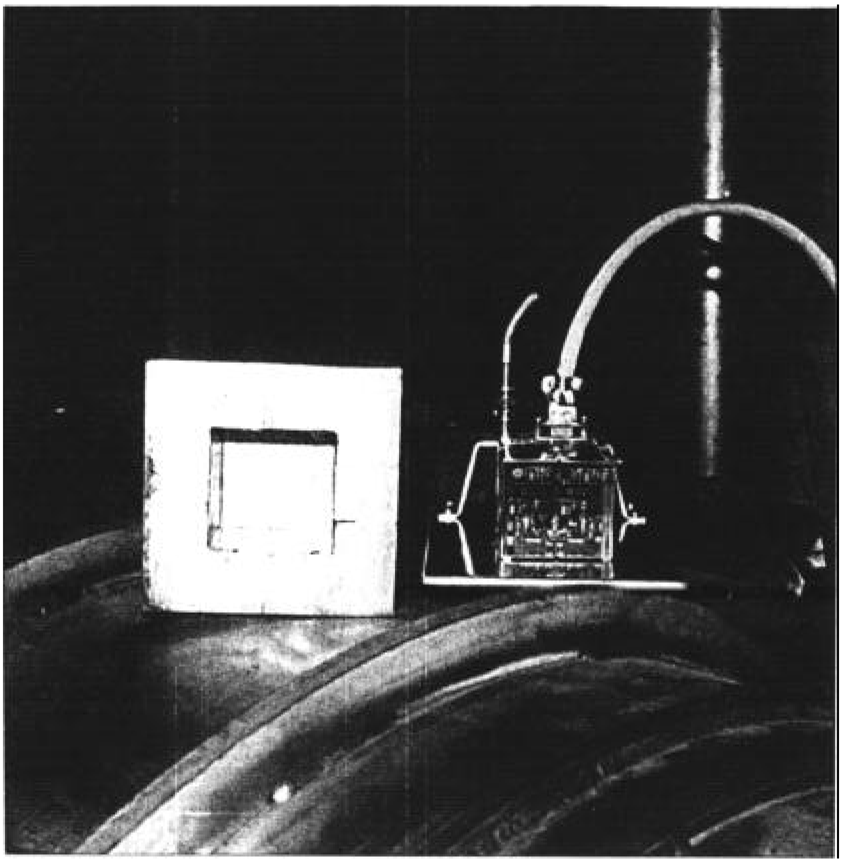


Figure 6: The PIN Photodiode BLM on top of a HERA magnet (1991). The lead hat is removed



BEAM LOSS MONITORING AND CONTROL

Kay Wittenburg, Deutsches Elektronen Synchrotron DESY, Hamburg, Germany

Abstract

The use of Beam Loss Monitors (BLMs) as sensitive tools for various beam diagnostic applications will be discussed as well as their tasks in 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.

1 INTROCUCTION

"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."

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.

Beam losses can be divided into two different classes:

1) **Irregular losses**, sometimes called "fast or uncontrolled losses": These losses may be distributed around the accelerator and not obviously on a collimation system. They 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. Losses should 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. This includes quench protection of superconducting magnets and acceleration structures and protection of detector components,
- to achieve long beam lifetimes or an efficient beam transport to get high integrated luminosity for the related experiments.

Sometimes such losses have to be tolerated even at a high level at low repetition rates during machine studies. However, 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 damage of components. A post mortem event analysis is most helpful to understand and analyse the faulty condition.

Some examples of such a functionality of beam loss monitor systems will be given in this paper.

2) **Regular losses**, sometimes called "slow" or "controlled" losses: 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.

Some examples will be discussed, where, with the help of a beam loss monitor system, the measurement of losses can be used for machine diagnostic purposes.

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

2 SOME COMMON ASPECTS

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

2.1 Type of Loss Monitor

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 some hadronic particles (protons, neutrons), too. However, the signal source of beam loss monitors is mainly the ionizing capability of the charged shower particles.

Different types of such loss monitors exist and detailed descriptions of most types can be found in [1, 2]. Options for beam loss monitors might be: long and short Ion chambers, Photomultipliers with scintillators (incl. Optical Fibers), PIN Diodes, Secondary Emission Multiplier-Tubes, Microcalorimeters, Compton Diodes, etc. A nice list of "considerations in selecting a beam loss monitor" is discussed in [2]:

- 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.

2.2 Positioning of the Loss Monitor

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 (Low energy beam particles, which do not create a shower leakage outside the vacuum pipe wall, will be hardly detectable by a loss monitor system). The signal of a loss detector will be highest, if it is located at the maximum of the shower. Refs. [3, 4, 5] are using Monte Carlo simulations to find the optimum locations for the monitors, as well as to calibrate the monitors in terms of ‘lost particles/signal’. The length of the shower depends on the energy of the lost particle and ranges from some meters for very high proton energies [4] to a few cm for medium electron energies [5]. Therefore the expected location of lost particles has to be studied in advance to locate the monitors at the right location, especially at electron accelerators. But this means, that an understanding of the loss mechanism and dynamics in the accelerator is necessary to predict the typical positions of losses. For example, Refs [5, 6] had done detailed particle tracking studies to follow the trajectory of an electron in the accelerator after an energy loss due to scattering on a residual gas molecule or on a microparticle.

There are many different reasons for beam losses and a complete beam loss system has to be carefully designed for a detection of a specific loss mechanism.

In the following, some examples for different loss mechanisms, their detection and their use for beam control and diagnoses will be presented.

3 SOME EXAMPLES FOR IRREGULAR, UNCONTROLLED LOSSES

3.1 Radiation Damage

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. Such a system must have enough sensitivity and dynamic range to measure low-level losses at low current (test-) beams, as well as high local losses of short duration. Together with well-designed collimation and machine interlock systems, the BLM-System should prevent harmful accidents by switching off the beam in time in case that the loss rate exceeds a certain threshold at any position. But it should also serve as a sensitive diagnostic tool during the set-up periods of the accelerator to prevent high losses at nominal currents [7, 8]. This will help to prevent excessive activation of the environment and equipment damage. Especially for high-current proton and ion accelerators, this became a very important for hands-on maintenance as well as for ground water and air activation [9].

3.2 Obstructions

The set-up periods of a new accelerator or after a reconstruction of an existing machine are always associated with beam losses, before the machine goes into normal operation. Unexpected losses can be caused by a various number of reasons, and a BLM-System may help to find them. A ‘beautiful’ example is discussed in [10], where an RF-finger pointing in the beam line prevented the beam from circulating in Rhic. The loss pattern showed an apparent obstacle in the ring at a certain location. The losses there went away as the beam was steered locally around an obstacle after which the beam began circulating for thousands of turns.

Other obstacle-like obstructions are vacuum-crashes and trapped microparticles [11]. They caused in more or less sudden drops in the lifetime due to scattering of the electrons on the additional particles in the beam pipe. The lifetime is reduced because beam particles lose energy by bremsstrahlung both in the field of the atomic nuclei and in the macroscopic field of the highly charged microparticle or ‘dust’. The deviation of the electron orbit from the nominal orbit depends on the dispersion function in the accelerator and on the energy loss. Therefore the electrons may be lost behind the following bending magnet on the inside wall of the vacuum chamber. Beam loss monitors located at this location are sensitive to these effects and therefore can measure the vacuum-distribution, vacuum leaks (Fig. 1) and the existence, location and even the movement of microparticles [6, 12].

3.3 Quench Protection

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. A time constant of a few ms is adequate for the main loss system. 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 [3, 13]. Care has to be taken, to set-up

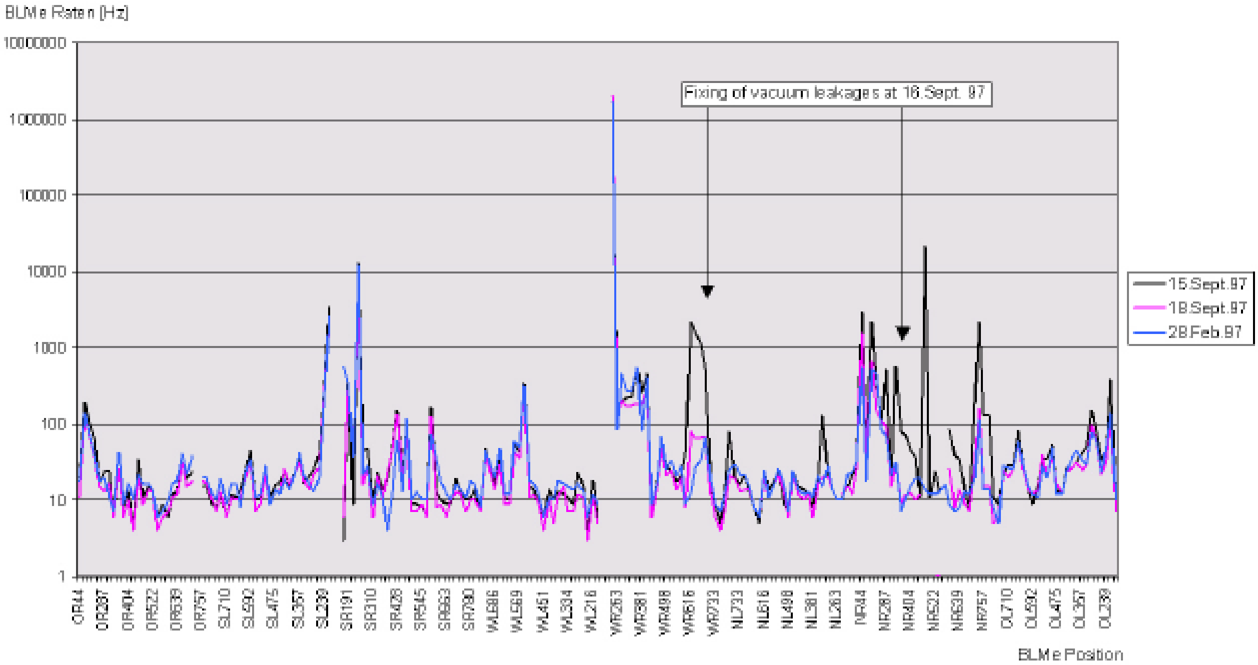


Figure 1: Beam loss monitor signals versus their location along HERAe at different dates during 1997. The two vacuum leaks on the 15.Sept. are clearly visible, as well as their reparation on the next day. Note the reproducibility of the rates.

such a system properly, so that it is not overly active (dumping too often) and also not too relaxed, allowing dangerous loss rates. 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. It might turn out, that 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 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.

4 SOME EXAMPLES FOR REGULAR, CONTROLLED LOSSES

4.1 Injection Studies

The injection of beam into the next accelerator of a chain should work with the highest possible efficiency. Keeping the loss rate of adjacent BLMs as low as possible is a very simple way of tuning the injection schema. BLMs measure the loss directly and with better sensitivity and resolution than the differential beam current measurement. This became important, if low injection (test-) currents are required as a result of radiation safety issues. Additional, a distributed BLM-system shows the areas of losses during the injection process as well as the loss timing behaviour (Fig. 2). By placing BLMs at betatron and dispersion aperture limits, one can distinguish between transversal mismatch (betatron oscillations) and energy mismatch (dispersion) at injection [15].

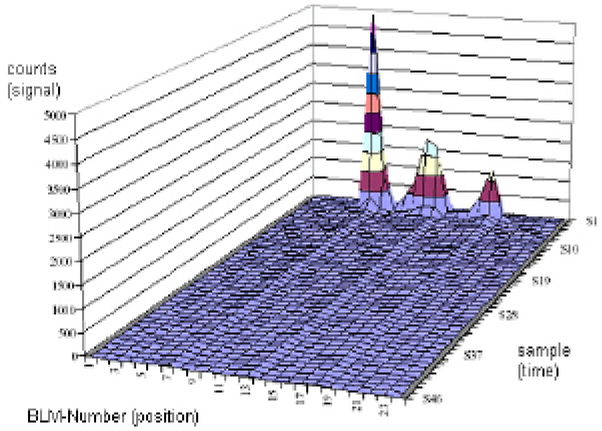


Figure 2: Surface plot of beam loss at injection and afterwards (from [14]).

4.2 Lifetime Limitations

Beside of unwanted conditions, there are unavoidable effects which limit the beam lifetime in an accelerator, e.g. vacuum lifetime (Coulomb scattering), Touschek effect, quantum lifetime, etc.:

<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 lose 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 etc.: Particles scatter elastically or inelastically with residual gas atoms or photons (Compton) or emit a high energy synchrotron radiation photon (Quantum). 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 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.

A BLM-System with good selectivity to the different loss mechanisms is a very useful tool for various kinds of beam diagnostics, especially in Touschek limited (electron-) accelerators: The Touschek loss rate depends on the 3-dimensional electron density and on the spin of the scattering particles. Therefore any change of one or more of these parameters has an influence on the loss rates at the selected monitors. The BLM-System at BESSY was used to determine the (desired) vertical beam blow up due to a resonant head-tail mode excitation [16]. At ESRF the BLM-System was used to study the beam coupling between the transversal planes [17]. At ALS and BESSY the BLM-System was used to calibrate precisely the beam energy and observing its variation in time by using resonant depolarization of the beam [16, 18].

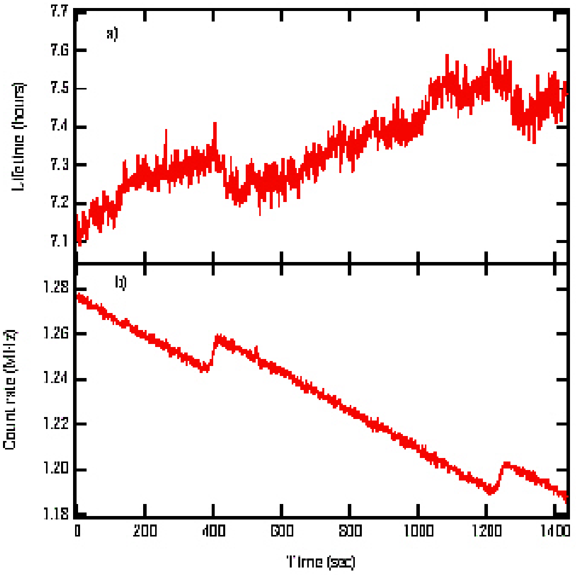


Figure 3: Beam lifetime derived from current monitor and count rate from beam loss monitor showing two partial spin depolarizations over a 25 minute period (from [18]). Note the much clearer signal from the BLM.

One useful applications of the energy measurement is the precise determination of the momentum compaction factor [18].

4.3 Tail Scans

Non-Gaussian tails in the transverse and longitudinal beam distribution produce lower beam lifetimes and background in experimental detectors. With beam profile monitoring, these tails are difficult to detect because of their small population in respect to the core of the beam. A combination of scrapers and BLMs is a good choice to measure the tail population and to get rid of it. Transverse tails are best measured at scraper positions with a large β-function and with no dispersion, while for longitudinal tail scraping scraper positions at small β -function and large dispersion are best. The measurement and scraping can be done by moving the scraper in small steps closer to the beam core measuring at each step the response of the adjacent BLM. This procedure does not affect the lifetime because the particles in the tails will get lost anyhow (as long as the scraper doesn't reach the beam core). Coulomb or Touschek scattering are the dominant processes for creating tails in lower energy electron rings, while at the very high energy ring LEP the dominant processes are Compton scattering on thermal photons (horizontal) and beam-beam bremsstrahlung (vertical) [19].

In the high-energy proton accelerator HERAp, the lifetime limitation arises from proton diffusion due to beam-beam interaction and tune modulation due to ground motion. The ground motion frequencies can be measured with BLMs at the scrapers [20, 21]. The loss spectrum of a very stable machine corresponds very well with the ground motion spectrum. The diffusion parameters at different tune modulation settings are measured by retracting the scraper from the beam tail and observing the time constants of the adjacent loss rate decrease and slow increase afterwards [20].

4.4 Tune Scans

Any change of the 3-dimansional phase space of a particle beam will effect the loss rates. By observing these losses as a function of the tune, the phase space area of the lattice can be investigated, as well as the influence of insertion devices that may cause non-linearities [16, 22]. The examination of the tune area might be somewhat lengthy, when only measuring the small changes of the beam lifetime. With the help a BLM-System, this procedure can be done very fast because the change of the loss rate can be measured immediately. [23] had shown, that a combination of a collimator and a BLM is a very sensitive tool to make fast tune scans of the area around the working point even at very long lifetimes and very small lifetime-changes.

5 CONCUSIONS

It has been shown, that a beam loss monitor system is a multi-faceted beam instrumentation tool, 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-systems are frequently used to minimise irregular, uncontrolled losses to protect the environment and equipment of the accelerator from radiation damage; in superconducting accelerators also from beam loss induced quenches. They also serve as a sensitive tool to localise and study any kind of physical obstruction in the accelerator, from abominably RF-fingers down to different vacuum problems. Also a BLM-system helps to study and optimise the injection scheme of an accelerator. BLM-systems play an important role in investigating and optimising the beam lifetime, which is defined by different, but regular losses. A BLM-System with a good selectivity to the different loss mechanisms is a very useful tool for various kinds of beam diagnostics and beam control, e.g. controlled beam blow-up, coupling studies and tune scans. Even a precise energy calibration of the beam can be done with signals from a BLM-system. The combination of a scraper and a BLM offers additional useful applications for lifetime studies, e.g. ground motion observation, beam diffusion measurements and tail scans.

6 REFERENCES

[1] K. Wittenburg, “Beam Loss Detection**”,** 1st European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators, Montreux, Switzerland, 3-5.5.1993, CERN PS/93-35 (BD)

[2] R. E. Shafer, “A tutorial on Beam Loss Monitoring,” 10th Beam Instrumentation Workshop 2002, Brookhaven, Mai 2002.

[3] K. Wittenburg, “The PIN-Diode Beam Loss Monitor System At HERA” Beam Instrumentation Workshop 2000, Boston, USA, Mai 2000

[4] A. Arauzo et al., “LHC Beam Loss Monitors”, DIPAC2001, Grenoble

[5] L. Yuxion et al., „The beam loss monitoring system for the HLS storage ring”, Nucl. Instr. & Meth. A467-468, 2001

[6] F. Ridoutt, K. Wittenburg, “Experience with the Electron and Proton Beam Loss monitor System at HERA”, EPAC 1996, Stiges

[7] D. Gassner et al., „Spallation Neutron Source Beam Loss Monitor System”; 9th Beam Instrumentation Workshop, Boston, USA; May 2000

[8] M. C. Ross, D. McCormick, “A Coaxial Cable Beam Loss Monitor Ion Chamber System for High Power Multi-Bunch Beams”, 19th International Linear Accelerator Conference (Linac 98), Chicago, IL, Aug 1998.

[9] O. E. Krivosheev, N. V. Mokhov, “Tolerable Beam Loss at High-Intensity Proton Machines”, Proce ICFA Beam Halo and Scraping Workshop, Lake Como, WI, 1999

[10] P. Thompson et al., “RHIC Beam Loss Monitor System Commissioning in RHIC Year 00 Run”, 9th Beam Instrumentation Workshop (BIW 2000), Cambridge, Massachusetts, May 2000. and: http://www.rhichome.bnl.gov/RHIC/YearZero/early_beam.html

[11] Zimmermann, F. et al., “Trapped macroparticles in electron storage rings”, 16th Particle Accelerator Conference : PAC '95, Dallas, TX, USA, May 1995

[12] B. Joly, U. Weinrich, G. A. Naylor, “Beam Loss Monitors at the ESRF”, 4th DIPAC, 1999, Chester, UK, May 1999.

[13] M. Lomperski: “Beam losses at HERA - is everything understood?”, 11th Chamonix workshop 2001 http://cern.web.cern.ch/CERN/Divisions/SL/publications/chamx2001/PAPERS/8-2-ml.pdf

[14] J. Hinkson, “ALS Beam Instrumentation, Beam Loss Monitoring”, not published, Feb. 1999

[15] A. Pietryla, W. Berg, “A Cerenkov Radiation Detection System for the Advanced Photon Source Storage Ring”, PAC 2001, Chicago, USA, 2001

[16] P. Kuske “Accelerator Physics Experiments with Beam Loss Monitors at BESSY”, 5th DIPAC2001, Grenoble, 2001

[17] Weinrich, Udo, “Mastering beam losses on small gap vacuum chambers in synchrotron light sources”, ESRF 1999, Dortmund, Univ., thesis, 2000

[18] C. Steier, J. Byrd, P. Kuske, “Energy Calibration of the Electron Beam of the ALS Using Resonant Depolarisation”, EPAC2000, Vienna, Austria, 2000

[19] H. Burkhardt, I. Reichel, G. Roy, “Transverse Beam Tails due to Inelastic Scattering”, Phys. Rev. Spec. Top. Accel. Beams : 3 (2000)

[20] Brüning, O ; Mess, K H ; Seidel, M ; Willeke, F , “Measuring the effect of an external tune modulation on the particle diffusion in the proton storage ring of HERA”DESY-HERA-94-01,DESY, Jan 1994.

[21] K.H. Mess, M. Seidel, “Measurement of Proton Beam Oscillations at low Frequencies”, EPAC 94, Vol. 2, London 1994

[22] K.T. Hsu et al. „Real-Time Beam Loss Monitoring and its Applications in SRRC” Particle Accelerator Conference, Vancouver, B.C., Canada, May 1997

[23] O. Kaul, B. Sarau, K. Wittenburg , “Fast Measurement of Lifetime Changes and Beam Losses in DORIS by the use of Bremsstrahlung from a Collimator”, DIPAC 97, Frascati, Italy, 1997