# 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 <u>any</u> 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.

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

## 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

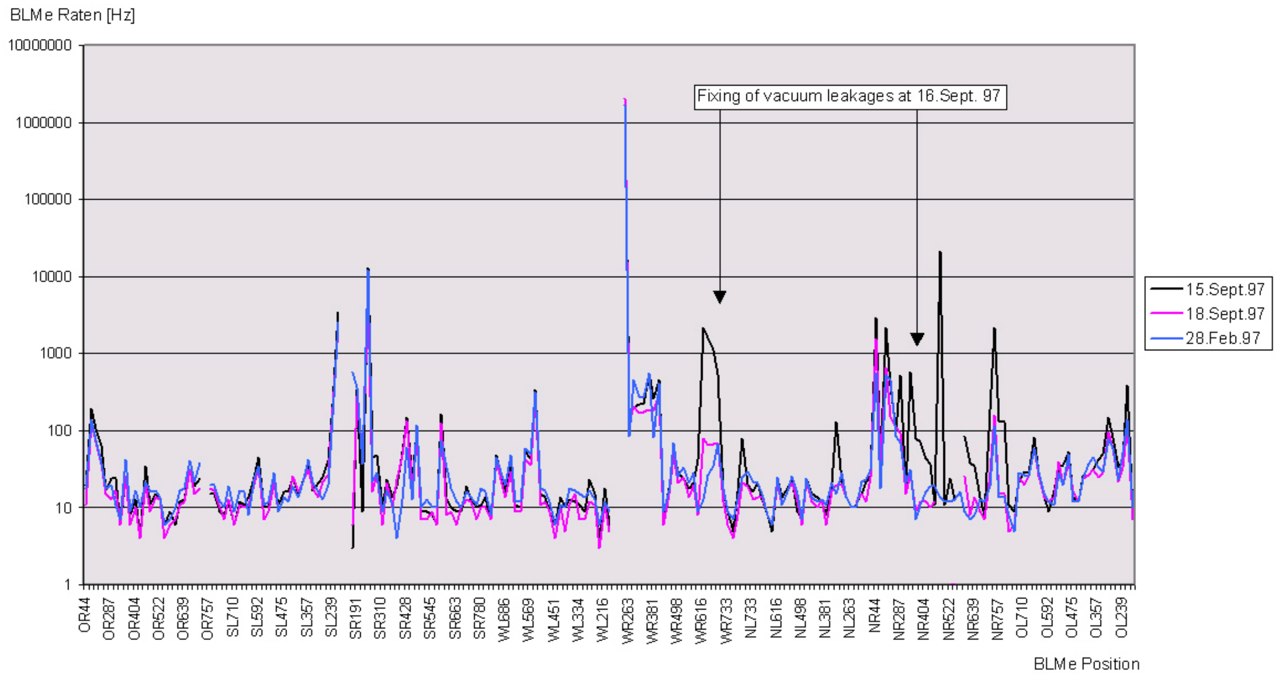


Figure 1: Beam loss monitor signals versus their location along HERAe at different dates during 1997. The two vacuum leaks on the 15.Sept. are clearly visible, as well as their reparation on the next day. Note the reproducibility of the rates.

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].

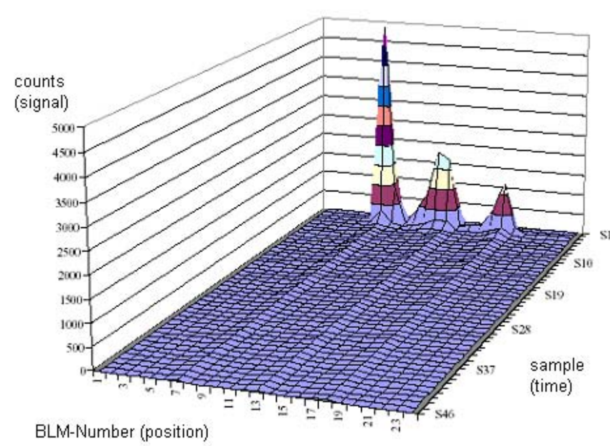


Figure 2: Surface plot of beam loss at injection and afterwards (from [14]).

### *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.:

Touschek Effect: Particles inside a bunch perform transverse oscillations around the closed orbit. If two particles scatter, they can transform their transverse momenta into longitudinal momenta. If the new momenta are outside the momentum aperture the particles are lost.

Good locations for the detection of Touschek scattered particles are in high dispersion sections following sections where a high particle density is reached. Since the two colliding particles 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].

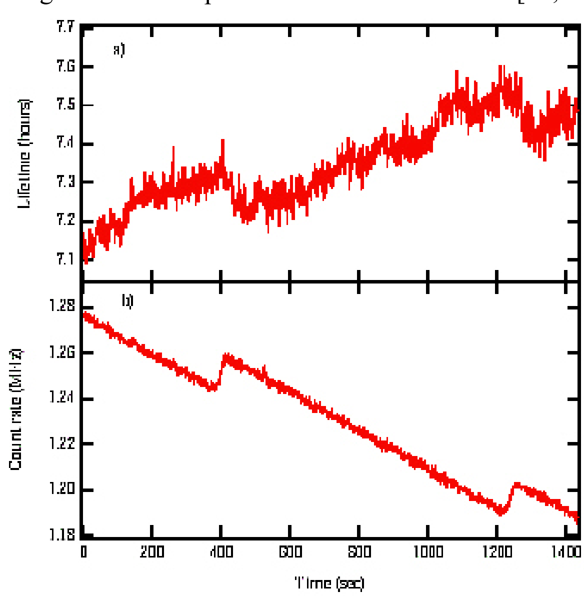

Figure 3: Beam lifetime derived from current monitor and count rate from beam loss monitor showing two partial spin depolarizations over a 25 minute period (from [18]). Note the much clearer signal from the BLM.

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