Solutions: Beam Loss Monitors

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Discuss why irregular losses should be avoided?

- 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.

Discuss which effects are theoretical beam lifetime limitations ?

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.

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?

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* $I = 16 \cdot eV \cdot Z^{0.9}$

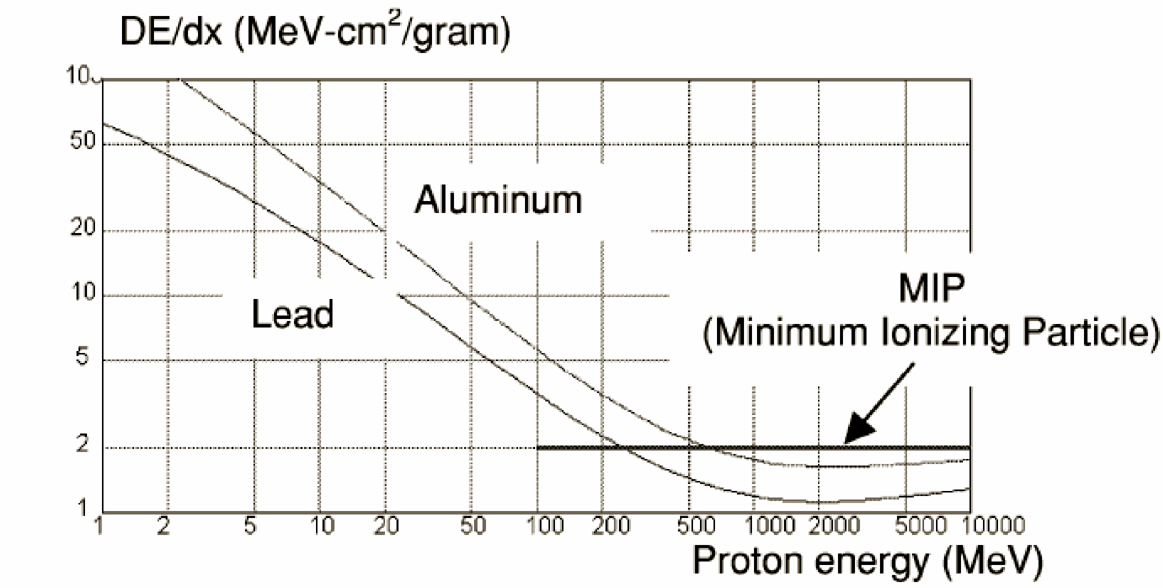

Figure 1. Plot of energy loss dE/dx vs. energy of incident proton.

$dE/dx_{Minimum}$ 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.

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*	*$\approx 10^5$ (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

Regular losses

<u>Exercise BLM 2a:</u>

<u>HERAp is a proton storage ring (920 GeV/c) with 6.3 km circumference.</u>

<u>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?</u>

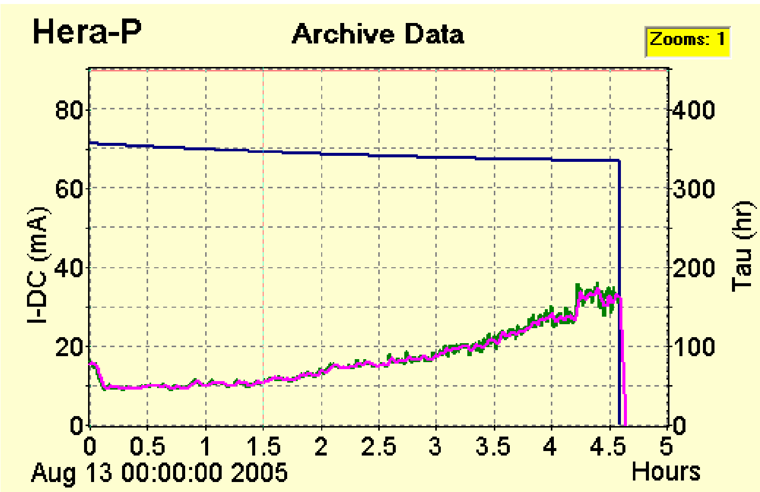

Fig. 1: Beam current [mA] vs time

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!!!)*

$N_{Lost} = (I_0 - I)/ I_p = 5.1 \cdot 10^7$ 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 $P = N_{Lost} \cdot dE/dx \cdot L = 5.9 \cdot 10^8\ MeV/s = 0.095\ mW$

Where to put the BLMs to measure beam losses?

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

Exercise BLM 2c:

At a certain location of a BLM in HERA (collimator), the efficiency to beam losses is about ε= 0.1 MIP / (cm^2 · 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 or* $N_{pair} = 10^5$ *e/ltr.*

Depending on the HV polarity one can measure either electrons or ions of charge e.

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

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).

Quench Protection

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.*

What is a "critical loss rate"? How to define it
Discussion in plenum. Derived from quench limits for superconducting cables of the magnets.

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

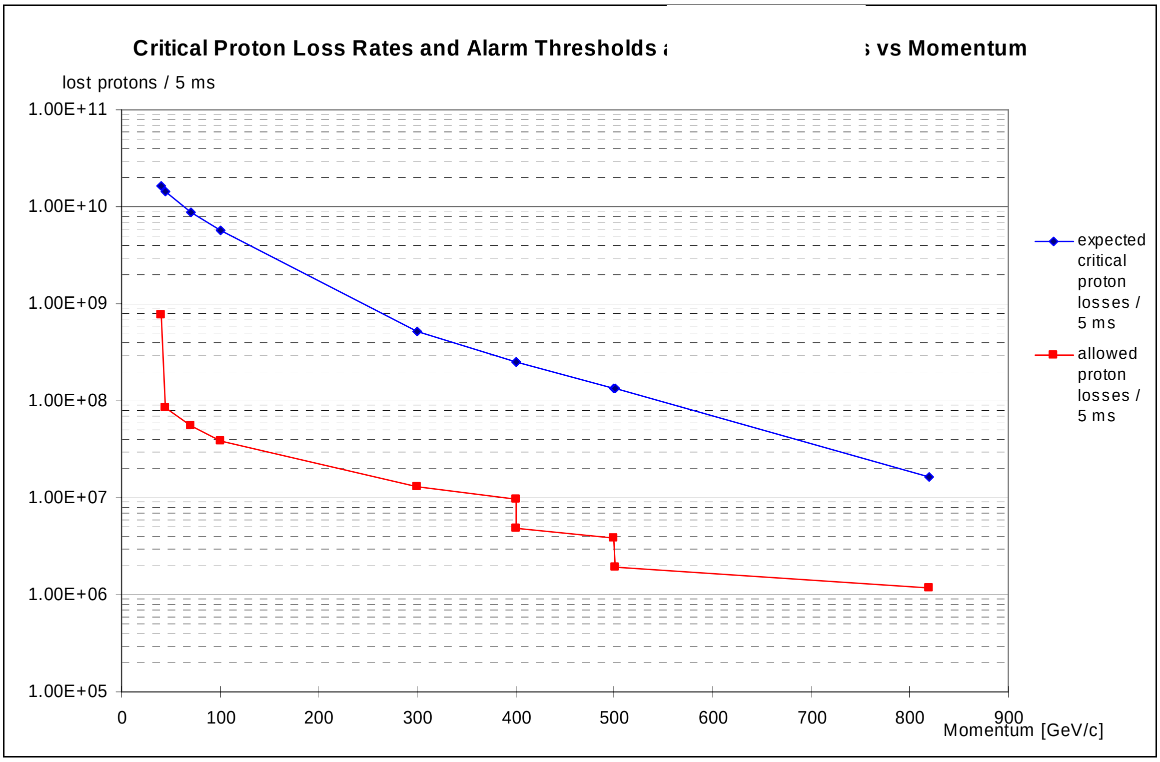

Fig. 2: Critical proton loss rate (above a quench occur) vs. momentum for the superconducting magnets in HERAp

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 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_{ion} (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 $\approx 1.5 \cdot 10^2$

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.***

See R. Jones talk (CAS: Beam Instrumentation) or Ref. [4] for the LHC solution to cover the whole range: => counting technique

Exercise BLM 3a:
Calulate electron loss rate/bunch of 60pA/m at a bunch rate of 1 MHz

$1.6*10^{-19}C/s = 1$ e
$60 * 10^{-15}$ C/s/m = $3.7*10^{5}$ e/m
with 10^{6} bunches/s
Rate = 0.37 e/(bunch m)

Exercise BLM 3b:
Calculate electron loss rate/bunch of 1W/m at a bunch rate of 1 MHz

1 W/m = $6.24 * 10^{18}$ eV/(s m) **(to be given by tutor)**
with a 5 GeV electron every bunch (1 MHz) =>
Rate = $6.24 * 10^{18}$ eV/(s m) / (5 GeV * 10^{6} bunch/s) = 1248 e/(bunch m)

Exercise BLM 3c:
What's the required dynamic range?

1248 e/(bunch m)/0.37 e/(bunch m)= $3 * 10^{3}$
but: see slide 35 : 20 mGy/h reduces to 1 mGy/h (positioning of BLM)

- ⇨ range $20 * 3 * 10^{3}$
- ⇨ detect ± factor 10 => * 100

=> range: $100 * 20 * 3 * 10^{3} = 6 * 10^{6} \approx 10^{7}$

or 1 mGy/h vs. 60 Gy/h * 100 (from detect ± factor 10) = > $\approx 10^{7}$

Exercise BLM 3c:
Which type of BLM for LINACs
Discussion in Plenum