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General Overview of Beam Loss Monitoring Systems

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A technical report on

GENERAL OVERVIEW OF BEAM LOSS MONITORING SYSTEMS

by

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Abstract

Beam loss monitors are typically designed to measure the amount and location of beam losses. Also, they are used to tune the accelerator and detect/localize problems in beam steering. Beam loss monitors are a very important part of the machine protection system and therefore need to be accurately designed and reliably constructed. This report briefly describes proton interaction mechanisms with matter, the radiation effects of the interaction and the ways to detect the radiation. The types of radiation detectors that can be used for measuring beam losses are described and analysis for selection is performed (with an emphasis on using the loss monitors for proton linear accelerators). Also the plan on how to optimize the system to precisely detect and distinguish between fast (occurring within microseconds) and slow (occurring within seconds) losses is given.

Contents

Chapter 1

Introduction to Beam Loss Monitors

A number of particle accelerators exist to accelerate charged particles to high speeds for different purposes. The transmission of the charged particles from the source to the target is never 100%. Fraction of the beam is lost during the steering and the losses must be carefully controlled to achive effective transmission. Also, the lost particles cause activation of accelerator components. The radiation as well as heating due to particle's lost energy might damage the accelerator or surrounded instruments. So called Beam Loss Monitors (BLM) are used to detect secondary reaction products and thus control losses. At every high current accelerator facitily these monitors are installed for the protection of accelerator components, environment and personnel. Beam loss monitors are sensitive devices that can detect very low losses, therefore they are also used in machine tunning.

A number of different types of BLMs exist. A careful analysis of the location and time structure of losses has to be performed before choosing suitable detection devices. Beam loss monitors should be able to measure irregular/uncontrolled/fast losses and regular/controlled/slow losses. The irregular losses are usually avoidable and are a result of a misaligned beam or of a faulty condition of accelerator elements, vacuum problems, etc. This type of losses can damage the beam pipe, activate the environment, damage the equipment in the accelerator tunnel, or quench superconducting elements. Thus, a fast response is required. Regular beam losses are not avoidable and are a result of aperture limits on the collimator system, beam size, residual gas scattering, not ideal beam alignment, instabilities in the beam, halo scraping, etc. The regular beam losses need to be monitored constantly and kept low for allowing hands-on maintenance on the machine.

The most common choice for beam loss detection and monitoring, for hadron accelerators, is ionization chamber. We will describe it's working principle, together with other types of detectors in later chapters, but here we will list the main properties of ionization chamber, which make them the best choice for hadron machines (we will as well point out some of their limitations). Ionization chambers are easy to assemble and operate. They are relatively easy to calibrate and are very radiation hard. They also are quite sensitive and a have high dynamic range. All these properties make them robust and easy solution for controlling the losses. The limitations are response time (not fast enough to resolve the micro structure of the beam pulse) and sensitivity for low energy part of the accelerator. Fast scintillators or neutron detectors can replace ionization chambers when faster response is needed or when the low energ losses need to be measured.

Chapter 2

Interaction of Protons with Matter

In this chapter proton–matter interaction processes leading to secondary particle generation is reviewed briefly.

2.1 Overview of the interaction processes

Protons are positively charged particles and interact with matter by **electromagnetic** and **strong interactions**.

- Electromagnetic interaction is the main interaction process taking place for lower energies ($\leq$ 100 MeV). This kind of interaction can occur with the electric field of the nuclei or with the atomic electons of the nuclei.

  Interaction with the electric field is elastic scattering and results in small change in the direction of protons motion. The effect of each small scattering can accumulate and a phenomenon called **multiple coulomb scattering** can occur.

The interaction with atomic electrons are generally inelastic. This means that protons lose some amount of energy by exciting orbital electrons, or by ionizing atoms (kicking electrons out of their orbit). These generally do not change the direction of the motion of a proton, but many scatters do reduse the energy of it. Both, **ionization** process and **excitation** are statistical processes and two identical particles will not create the same number of electron-ion pairs. Because of this, the number of pairs produced does not equal to the energy loss divided by the ionization potential (some energy is lost on excitating electrons), but to the energy loss divided by the mean energy for ion-electron pair creation (W parameter). So, one should distinguish between excitation potential, ionization potential and the W parameter. The excitation potential is the energy needed to excite an atom from it's ground state and there is first, second, third, etc. excitation potentials. The ionization potential is the energy needed to remove electron from an atom to an infitine distance. And the W parameter is the mean energy needed for one electron-ion pair creation. The W parameter for most gases is around 30 eV per electron-ion peir. Once again, these processes, excitation and ionization, account for the most of the change of the proton's energy.

- Stong interaction range is short (of order of fermi) and protons interact with other protons and neutrons in a nucleus by colliding with them. The probability of these colissions is given by the cross section of the interaction. Proton-nucleus interaction via strong interaction can be either elastic or inelastic scattering.

  If the interaction is elastic, the proton scatters at some angle, retaining momentum and identitiy.

  If the interaction is inelastic, the proton get "absorbed" in the interaction. That is most of it's energy is transferred to break up the nucleus, in the process producing subatomic particles called pions. If the energy of protons is sufficient ($\geq$ 100 MeV), spallation happens. Typically spallation process produces large number of neutrons with energy from a few to a few tens of MeV. 1 GeV proton interacting with a heavy matter produces around 30 thermal neutrons, thus about 30 MeV is required to produce one external thermal neutron. It was observed, experimentally, that the neutron yield is proportional to the beam power, independent of the beam energy. For example, a 2 GeV, 1 mA average beam current proton beam produces the same nutron flux as a 1 GeV, 2 mA beam. This is the reason for discussing multi-MW accelerators rather than high-energy machines.

Summary of the interaction processes and some of the secondary particles generated is shown in Figure 2.1. Each process has a certain probability, which is higly dependent on the energy of the incident proton.

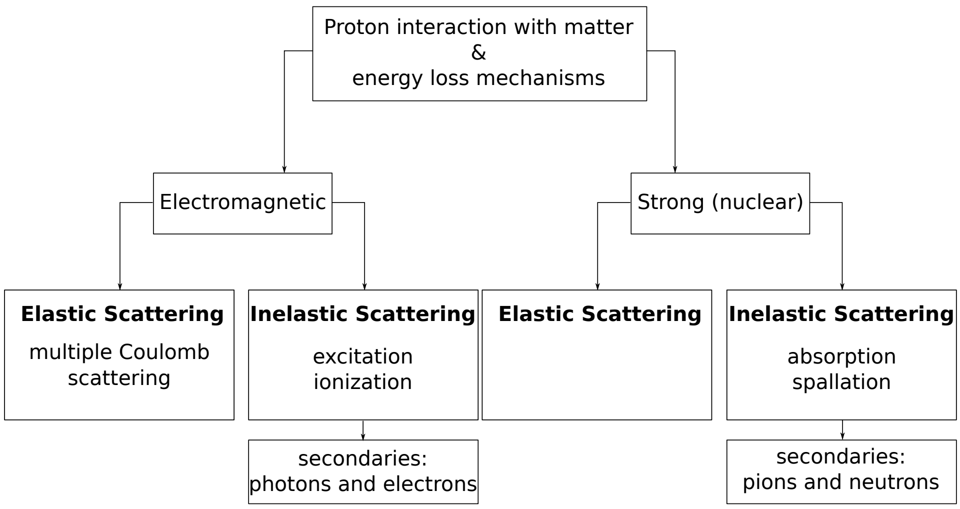

Figure 2.1: The overview of the proton interaction processes with matter and a list of some of the secondary particles produced. The processes are of statistical nature and occur with a certain probability each.

Head-on collisions of protons onto electrons can happen as well, but the percentage of energy loss on this interactions is very low (< 3% for 1 GeV protons), except for some extreme relativistic cases. The maximum energy loss per collision is

$$Q_{max} = \frac{4m_e M_p E_p}{(m_e + M_p)^2}. \tag{2.1}$$

2.1.1 Electromagnetic interactions

The dominant energy loss mechanism, through electromagnetic interactions, is ionization. The average kinetic energy loss per unit distance in the target material (or sometimes refered to as an average stopping power of the medium for the particle of interest), by electromagnetic interactions, with a good approximation is described by the Bethe-Bloch equation:

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\epsilon_0}\right)^2 \left[\ln\left(\frac{2\beta^2 mc^2}{I}\right) - \ln\left(1-\beta^2\right) - \beta^2\right], \tag{2.2}$$

where m_e = electron mass, $Z_p = ze$, $v = \beta c$ and E are projectile charge, velocity and energy respectively, e = electron charge, c = the speed of light, x = distance traveled by the projectile particle, I = the mean ionization potential and $n = \frac{\rho N_A Z}{A M_u}$ is electron density of target; N_A = Avogadro's number, A and Z are mass and atomic numbers of the target and ρ and M_u are density and molar mass of the target.

This is an average linear rate of energy loss and is a quantity of a great importance. With a good approximation $I(Z) = 16$ eV $\cdot Z^{0.9}$ and the stopping range by electro-magnetic processes can be given as:

$$R_{el}(E) = \frac{E^{1.75}}{1.75\ c_R}, \tag{2.3}$$

where $c_R \approx 500\rho\frac{Z}{A} \cdot z \cdot A_p^{0.75}$, and A_p is an atomic number of the projectile. Protons travel a few centimeters to tens of centimeters through matter before they stop by interactions with the object either through strong or electromagnetic forces. These distances are sometimes also called interaction or attenuation length.

Below is shown a total stopping power of a proton in iron together with electromagnetic and nuclear stopping powers and ranges as a function of proton's energy (in the energy range or 0 - 1 GeV).

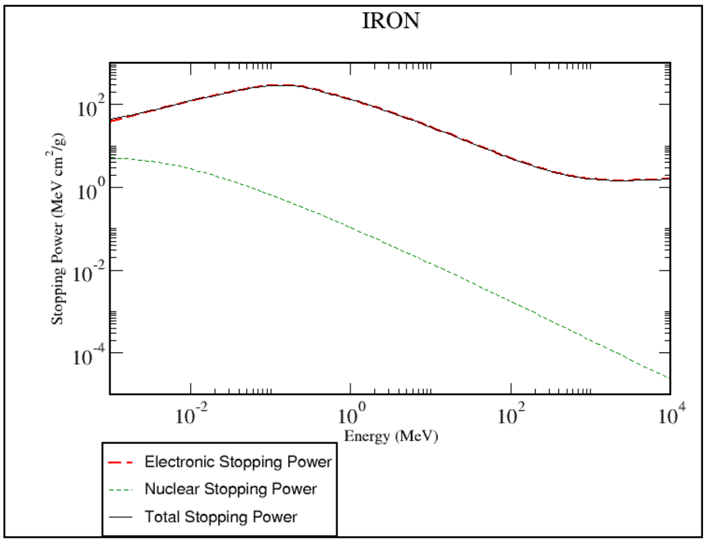

Figure 2.2: Proton stopping power in iron as a function of it's energy

It is convenient to introduce MIP = Minimum Ionizing Particle which is a particle whose mean energy loss rate through matter is close to the minimume. MIP $\approx$ 1 - 2 MeV-cm^2/gram for most materials. We will revisit this concept when describing the ionization chambers in the next chapters.

2.1.2 Strong interactions

Protons may undergo nuclear reactions when travelling through a matter. For protons with energy 100 MeV or more, spallation is the most probably reaction to occur. The process is a source of neutrons. The reaction cross section can be described with:

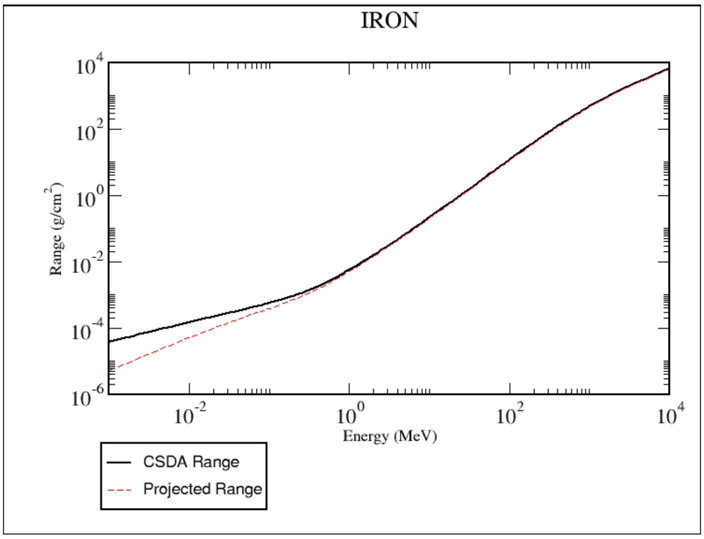

Figure 2.3: Proton range in iron as a function of it's energy

$$\sigma(E) = \sigma_0 \left(1 - \frac{V_c}{E}\right), \tag{2.4}$$

with

$$\sigma_0 = \frac{\pi}{100} \left(1.3\ A^{1/3} + 1\right)^2 barns, \tag{2.5}$$

and V_c coulomb barrier

$$V_c = \frac{1.44\ Z}{1.3\ A^{1/3} + 1} \frac{A + A_p}{A}. \tag{2.6}$$

From above it is possible to derive the nuclear range.

$$R_{nuc}(E) = \frac{A}{0.6\rho\sigma_0} = \frac{31\ A^{1/3}}{\rho}. \tag{2.7}$$

2.2 Secondary particle production

When a high energy proton hits the vacuum beam pipe and other surrounded objects, the processes described in previous sections occur and a number of secondary particles are generated. Some of these secondary particles are electrons, pions, neutrons, and photons. Other elementary particles can be produced via various other (generally less probable) nuclear reactions. For proton energies above 1 GeV, the probability that a nuclear interaction will happen rises to nearly 100% and the neutron yield scales approximately with kinetic energies above 1 GeV (see Figure 2.4). In addition, hadron showers are possible resulting in various species of elementary particles.

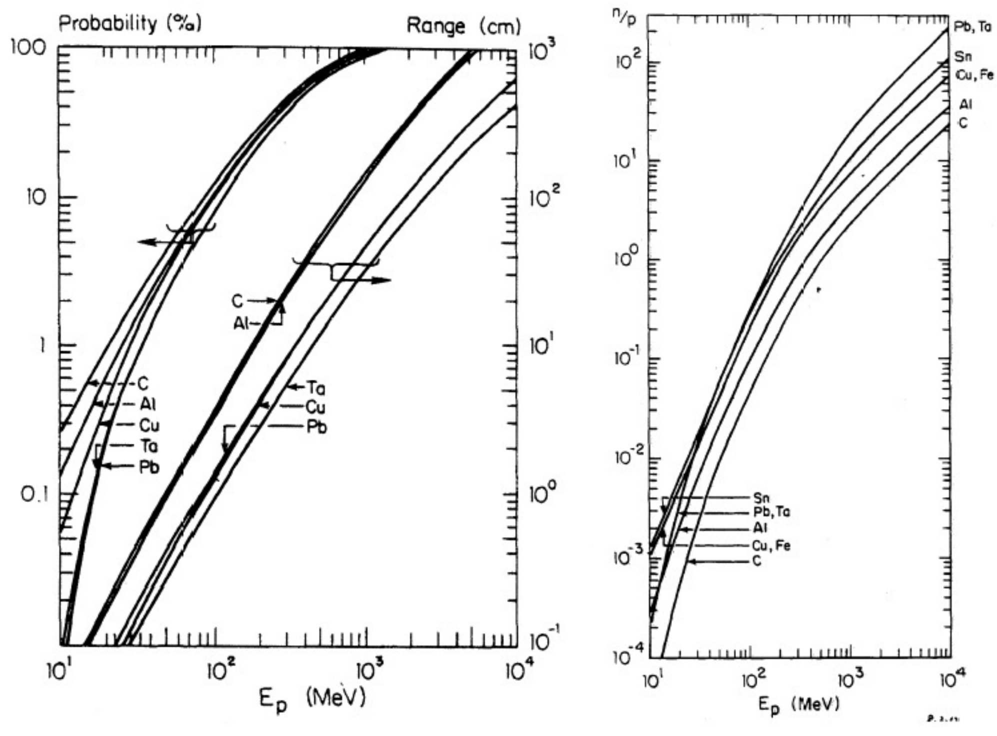

Figure 2.4: Left: probability of proton inelastic nuclear reaction within its range, and proton range as a function of energy. Right: Neutron yield for various metals as a function of proton's energy.

Charged particles are relatively quicly stopped by the surrounded material, but the nuetrons produced can travel long distances. Except the radioactive nuclei production all other processes are fast (faster than 10 ns).

Due to the kinematics of the primary interaction, the secondary particle emission shower is mostly forward peaked (not for low energies). Some of the interaction processes that the secondary particles experience are listed and described briefly in the following section.

2.3 Interactions of secondary particles

Electrons (or positrons):

Electrons, as other charged particles undergo multiple scattering and also electromagnetic stopping when passing through a matter (already described above). However, since they are light particles, there is another stopping mechanism: emission of electromagnetic radiation produced from scattering in the electric field of the nucleus. This is called a bremsstrahlung radiation and is classicaly understood as a braking radiation. At energies of a few MeV, this is still relatively small factor. For these energies, ionization loss dominates, resulting in soft X-rays, which are attenuated within short distances. However, for larger energies energy loss due to bremsstrahlung radiation gets comparable to the losses by collisions/ionization. The total energy loss is a sum of a radiation and a collision/ionization energy losses.

$$\left(\frac{dE}{dx}\right)_{tot} = \left(\frac{dE}{dx}\right)_{brems} + \left(\frac{dE}{dx}\right)_{coll/ion}. \tag{2.8}$$

Photons:

Photons interact completely different way with the matter compared to charged particles. The main interaction processes are: photo-electric effect, compton scattering and pair-production. Also, it is possible, but not as common, to have nuclear reactions (like (γ, n), etc. reactions). In photo-electric effect, the photon gets absorbed by an atom, releasing electron. The two differences compared to charged particle interactions is that photons penetrate much deeper in a matter and the photon beam is not degraded in energy, only attenuated in intensity. This is because the photons get removed from the beam completely (if they get absorbed or scattered) and if they manage to pass through, they usually don't undergo any interactions at all and retain their energy.

Photoelectric effect is a process, in which a photon gets absorbed by an atomic electron and the electron gets ejected with an energy, by binding energy less than the photon energy.

Compton scattering is a scattering of a photon off of a free electron. In matter, of course, electrons are bound, but if the photon energy is high enough, then the binding energy of the electrons can be disregarded and they can be considered free. During the scattering, photon changes energy and direction and is refered to as "different" photon which is not a part of the primary photon beam any more.

The pair-production occurs when the energy of the photon is greated than the rest energy of electron-positron pair (1.022 MeV), then, the electron-positron pair is generated.

Obviously, all the above three processes happen in combined manner. For low energies, the photo-electric effects dominates, in the medium energy range the compton scattering has the highest probability and for higher energies, the pair-production takes over.

Neutrons:

Due to lack of electric charge, neutrons don't experience any Coulomb interactions. Instead, the principal interaction is a strong interaction with the nuclei. Depending on energy, neutrons can experience elastic or inelastic scattering from the nuclei. When inelastically scattered, the nucleus comes to an excitation and then decays emitting gammas, or other form of radiation. The neutron has to have enough energy to cause the excitation. Usually the excitations threshold is of order of 1 MeV or more. Below this threshold, elastic scatterings occur only. Neutron capture is another process that can happen. In general this is led by photon emission and the cross section of the process is inversely proportional to the velocity of the neutron. So, this is most common to happen for slow neutrons. Other nuclear reactions, such as (n, p), (n, d), (n, α), $(n, \alpha p)$, etc. can happen also, in which neutron gets absorbed and charged particle gets emitted. Like the previous capture (radiative neutron capture), the cross section falls with energy as $1/v$. Fission, (n, f) is possible for thermal energies. For high neutron energies ($>$ 100 MeV) hadron showers are produced.

Chapter 3

Beam Loss Detection

When protons interact with matter a shower of diverse secondary particleas are produced. Electrons, positrons, neutrons, photons, pions are some of the possible particles created. All these particles (neutrons are the majority of the secondary particles for high energy incident primary protons), including the primary particles (protons) need ot be detected with approproate radiation detectors. Below is described the types of detectors might be used.

The nature of the losses and secondary particle genetarion is very different along a typical proton linear accelerator, depending on the energy of the protons. There is a number of detectors that can be used for beam loss monitoring. These are: plastic and liquid scintillator detectors, neutron sensitive scintillators, ionization chambers, secondary electron monitors, PIN diodes, diamond detectors, optical fibers, etc. Brief overview of the working mechanism of a few of them is given below.

3.1 Scintillator detectors

Scintillator detectors are one of the type of detectors widely used in nuclear and particle physics. It's working mechanism is based on the fact that when struck by the radiation small flashes of lights are generated, i.e. scintillations happens. Scintillator is usually optically coupled with an amplifier devise, usually a photomultiplier. Coupling is done directly or via a light guide. When the light is transformed to the photomultiplier (PMT) a weak electric signal is generated with the photo-electrons. This signal is then amplified by the electro amplifying mechanism.

Below is shown a schematic diagram of a scintillator detector.

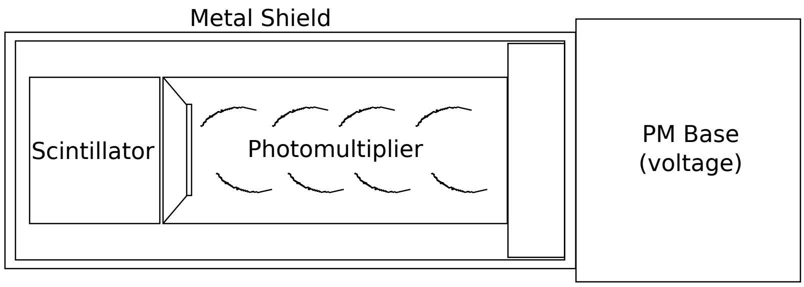

Figure 3.1: Schematic diagram of a scintillator detector.

In principle, scintillator responds to any kind of radiation which can directly or indirectly excite the molecules of it and produce light. However, for a given type of radiation, a proper scintillator has to be chosen to get a useful signal.

Plastic scintillators detect charged particles due to their electronic stopping. They are also sensitive to neutrons due to their scattering on the hydrogen atoms of the polymers. Scintillators are very useful tool for photon detection as well.

3.2 Ionization detectors

Ionization detectors were the first radiation detection devices developed. These instruments are based on collection of the ionization charge, produced in a gas by passing radiation. Because of greater mobility of electrons and ions in gases, gaseous ionization chambers are the most commonly used ones.

The basic principle is demonstrated in Figure 3.2. Ionization chambers are utilised to measure the fluence of charged particles and are very staright forward to use, because the induced current is proportional to the incident particle flux.

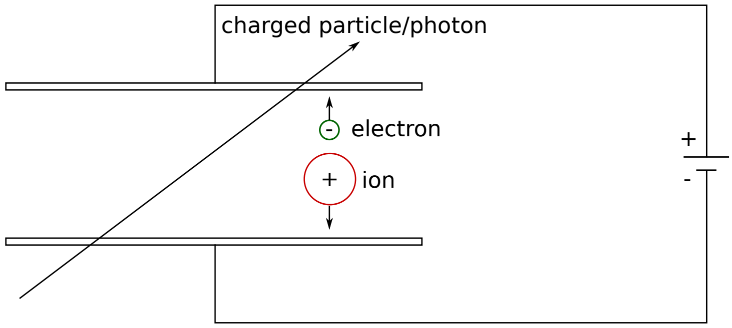

Figure 3.2: Ionization chamber working mechanism.

If there was no voltage applied between the electrodes the produced electron-ion pairs would recombine back and there would be no signal observed. By applying an increasing voltage, the fraction of the charge collected will be increased, reaching the saturation point, at which all the produced charges are collected. The region where ionization charges get completely collected is called an ionization chamber region (see Figure 3.3). For higher voltages, the electrons and ions themselves ionize the gas and more charges get collected than produced by the primary particles of interest. This region is called a proportional region. We need to operate in the ionization chamber region.

For many reasons, ionization chambers are the a primary tool for beam loss detection in hadron accelerators. A cylindrical ionization chamber is of a common use. The cylindrical electrodes inclose a gas with a certain effective volume that determines the detectors sensitivity (see Figure 3.4).

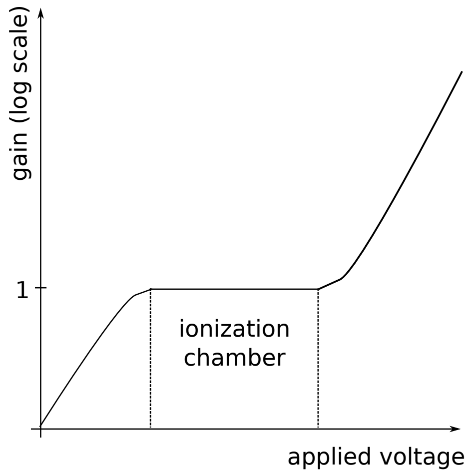

Figure 3.3: Different regions of operation of gas-filles detector.

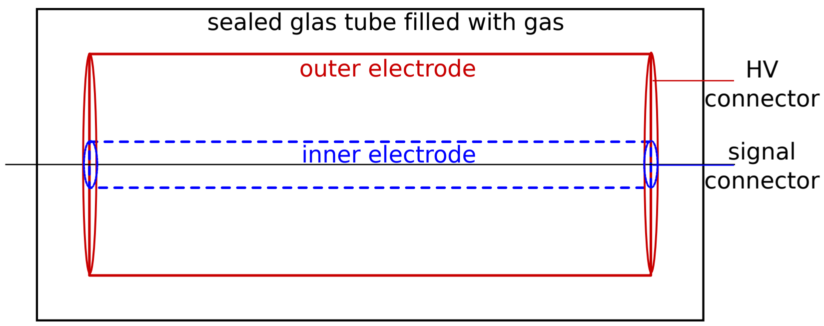

Figure 3.4: Ionization chamber working mechanism.

3.2.1 Response time of ionization chamber

The transit time of the ions through a gap of an ionization chamber is given by:

$$t = \frac{D}{v_{ion}} = \frac{D^2}{\mu_0 V(P_0/P)}, \tag{3.1}$$

where $v_{ion} = \mu_0 E(P_0/P)$, μ_0 is ion mobility, v_{ion} is ion velocity, V is the applied voltage, D is the gap between the electrodes and P/P_0 is the pressure in units of the atmospheric pressure. For cylindrical geometry:

$$D^2 = \frac{a^2 - b^2}{2} \ln\left(\frac{a}{b}\right), \tag{3.2}$$

a and b are inner and outer radii of the cylindrical electrodes.

3.2.2 Dynamic range of ionization chamber

Dynamic range is defined as the ratio of the largest and smallest value of radiation that can be measured with a radiation detector. The upper limit is given by the non-linearity due to the recombination rate at high dose (the typical current in such a case is a few hundred μA). The lower limit is given by the dark current between the two electrodes. Dark currents should be kept at around 10 pA or lower. Careful design to achieve this is needed. This gives a typical dynamic range of 10^6 - 1-^{8}. Such high dynamic range needs special signal treatment (logarithmic amlifiers, high ADC resolutions, current to frequency converters, etc.).

3.2.3 Calibration and sensitivity of ionization chamber

As already mentioned before, MIP is a minimum ionizing partcle. It is a particle whose mean energy loss rate through matter is close to the minimume. MIP $\approx$ 1 - 2 MeV-cm^2/gram for most materials. It is convenient to introduce MIP, because then we can describe the radiation response of a beam loss monitor in terms of either energy deposition (100 ergs/gram), or in terms of a charged particle flux ($3.1 \cdot 10^7$ MIPs/cm^2). This is valid, because:

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

The sensitivity of a beam loss monitor $S_{BLM}[C/rad]$ is calculated for 1 rad dose created by MIPs. The number of electrons n_e produced in the gap D of an ionization chamber by one MIP is

$$n_e = \frac{D \cdot \rho}{W} \cdot \frac{dE}{dx}, \tag{3.3}$$

where $\frac{dE}{dx}$ is given by Bethe-Bloch formula, ρ is a density of the medium and W is the W value (energy needed to create on electron-ion pair).

For example, if we have and Argon-filled chamber, then

$$\rho = 1.661 \cdot 10^{-3} g/cm^2 \ (at\ 20^0 C,\ 1\ atm),$$
$$\frac{dE}{dx} = 1.52\ MeV/(g/cm^2),$$

and thus

$$n_e \approx 100\ cm^{-1} \cdot D[e/MIP].$$

S_{BLM}, normilized to 1 rad depends on it's size. If we assume a 1 liter Ar-filled chamber with 100% charge collection efficiency, then

$$S_{BLM} \approx 638\ \frac{nC}{rad}.$$

3.2.4 PIN diode

PIN diode is essentially a solid state ionization chamber. In the typically 100 μm thick depletion layer of the doped Si-crystal, electron-hole pairs are generated. For one MIP, about 10^4 electron-ion pairs are generated. See Figure 3.5.

3.2.5 Diamond detectors

Diamond detectors, which are solid state ionization chambers are unique for their fast and efficient charge collection and high radiation tolerance. This is a proven technology and are used at many labs around Europe, USA and Japan. The diamond detectors are usually located inside the beam pipe and are mainly used to measure the beam intensity and beam energy spectrum.

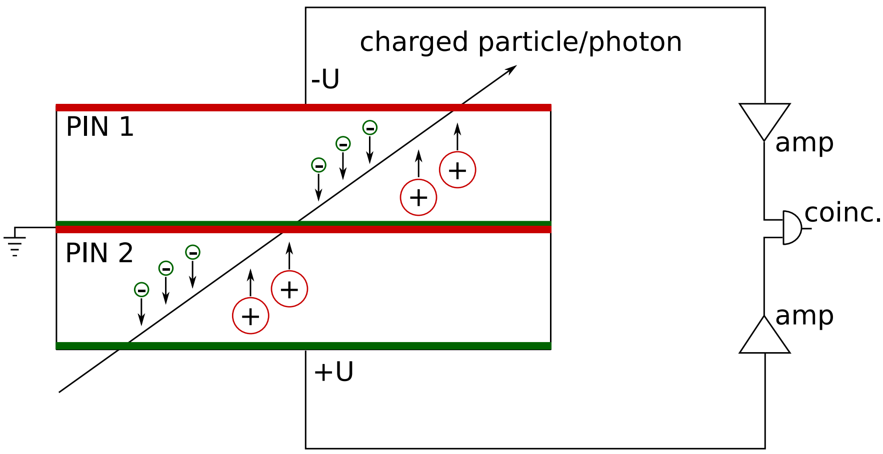

Figure 3.5: Sheme of two PIN diodes driven in coincidence.

The tests for using diamond detectors to measure beam losses using beam halo particles are still ongoing at SPS and LHC.

3.3 Comparison of different beam loss monitors

When choosing the detector, one needs to consider the following properties of it: intrinsic sensitivity, speed, dynamic range, radiation hardness, how easy is it to calibration, calibration uniformity, stability, reliability, size and cost. Obviously, we want something that ideally has a high intrinsic sensitivity, is fast, has a very high dynamic range, is very radiation hard, easy to calibrate, the calibration is uniform from unit to unit, is stable, reliabl, small in size and cheap.

For hadron accelerators, the ion chambers are the best choice. However they have limitations. They are not sensitive enough for low energies, and they are not fast enough to resolve micro-pulse structure (when that is of importance). In both cases scintillator detectors can be used. However, they require excessive recalibration and they degrade in radiation environment rapidly. But their sensitivity can be adjusted highly and they can detect the losses in low energy region of accelerator. Scintillators are faster too (typically they have of about 1 ns responce time compared to typical ionization chamber responce time of about 1 μs) and can record the micro-structure of the pulse. Nuetron sensitive scintillator detectors can also be used for loss detection, but the losses can't be easily localized at all.

Chapter 4

Beam loss monitors as a part of Machine Protection System

A low energy and low intensity beams in accelerators can't cause any damage even if it's all lost in the vacuum chamber. However, in high energy and high intensity accelerators beam losses can be of a great issue. Losses localized in a very small volumes can burn holes in the accelerator components, quench the superconducting magnets, or damage other equipment around the accelerator.

Although, beam loss monitors are instruments that are primarily designed to measure the beam losses, they are also frequently used for machine protection. By proper calibration, BLM signals are used to trigger the beam dump as soon as the energy deposition in the magnets or in the vacuum pipe reaches the levels set to avoid quenches and other possible harms. The thresholds are typicelly set based on experience. They have to be not too low not to prevent continuous operation of a machine.

To set the trigger levels allowed losses must be known. This depends on the perticle energy and the duration of the loss. Thus, the loss signal needs to be integrated over few time periods and the threshold needs to be set for each of them.

BLMs are used to monitor the activation levels due to losses. Losses lead to nuclear reactions, which procude radioactive nucli with lifetime of hours or more. This prevents access to the accelerator tunnel. As a general rule, to allow the maintenance on the accelerator, the power dissipation of the beam losses should be lower than 1 W/m. This corresponds to 0.1 rad/hour at 30 cm from the surface of the accelerator, after 4 hous of cool-down.

The position of beam loss monitors should be well chosen. Simulation tools (FLUKA, Geant4, MARS) are used to calculate the locations of the highest particle fluxes. Of course, an assumption of the primary particle losses is needed. Since the beam is largest at the quadrupole magnets, these are usually the locations where the BLMs need to placed.