Beam Loss Monitors

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You do not need a BLM System as long as you have a perfect machine without any problems. However, you probably do not have such a nice machine, therefore you better install one.

Introduction

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

Contents

- Loss Classes (with some examples)
- Principles of Loss Detection
- Beam Loss Monitors (BLMs)
  - Ion chambers
  - PLIC
  - PIN Diodes
  - LWL
  - Scintillators
  - SEM

Focus: Sensitivity

Loss Classes (I)

• **Regular (controlled, slow) loss**

• **Irregular (uncontrolled, fast) losses**:

The irregular losses may be distributed around the machine and not obviously on the collector system. Can 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 (incl. Quench protection and protection of the detector components)

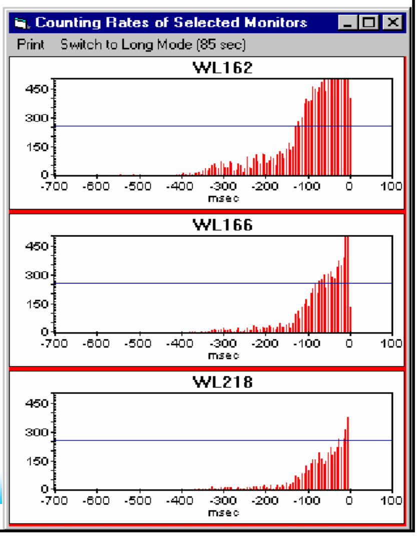
✓ to achieve long beam **lifetimes/efficient beam transport** to get high integrated luminosity for the related experiments.

These higher levels losses are very often a result of a **misaligned beam or a fault condition**, e.g. operation failure, trip of the HF-system or of a magnet power supply. Sometimes such losses have to be tolerated even at a high level at low repetition rates during machine studies. **A beam loss monitor system should define the allowed level of those losses**. The better protection there is against these losses, the less likely is down time due to machine damage.

A post mortem event analysis is most helpful to understand and analyze the faulty condition.

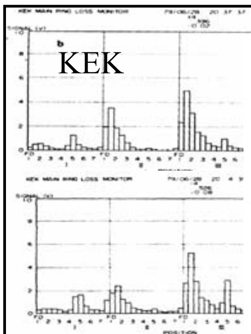
Irregular Losses

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



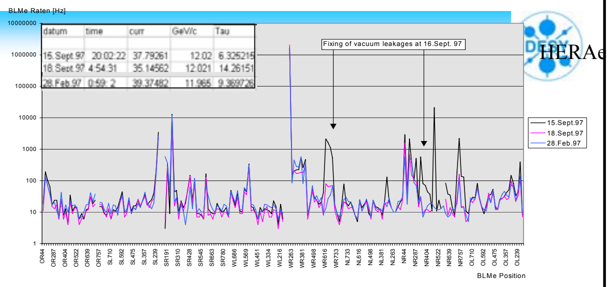
Irregular (uncontrolled, fast) losses may result in:

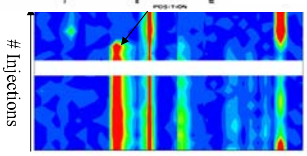
- Superconducting machines: Quench protection
- Activation of environment due to losses
- Commissioning: Obstacle
- Vacuum Problems (Coulomb Scattering)
- Microparticles
- High current/brilliance machines (Ring or Linac): Destruction of Vacuum-Components

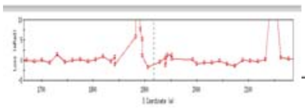


Beam Loss distributio n around the main ring up to flat top end (Gain 2)

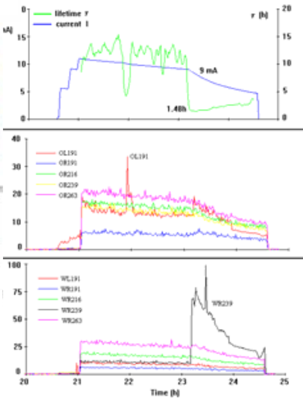
Activation distributio n around the main ring; Gain 200

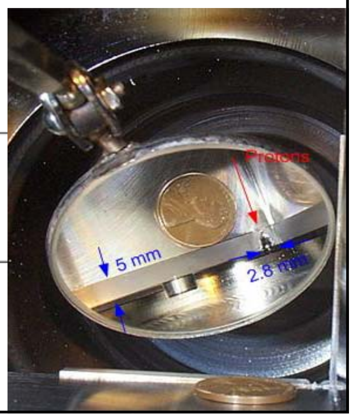






Loss pattern evolution as beam was steered locally around an apparent obstacle. When the losses there went away, beam began circulating for thousands of turns.





Loss Classes (II)

Regular (controlled, slow) loss:
Those losses are **typically not avoidable** and are localized on the collimator system or on other (hopefully known) aperture limits. They might occur continuously during operational running and correspond to the lifetime/transport efficiency of the beam in the accelerator. **The lowest possible loss rate** is defined by the theoretical beam lifetime limitation due to various effects:

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

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

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

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

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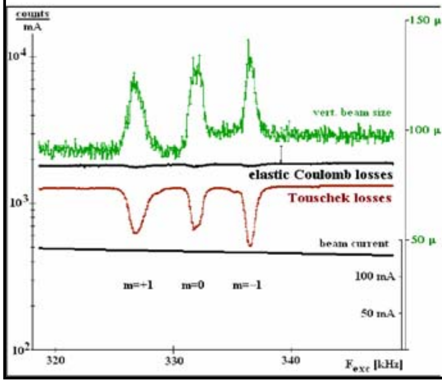
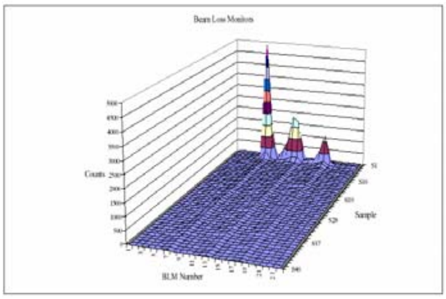
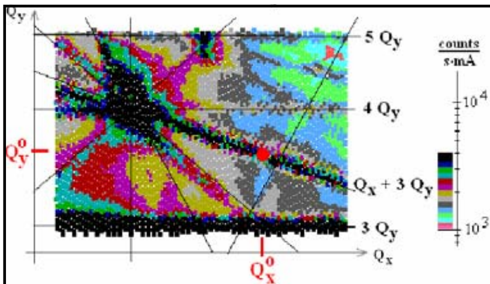
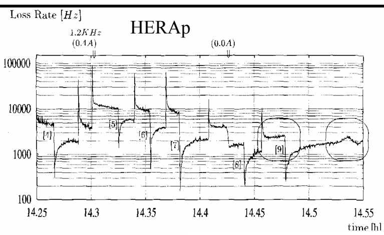
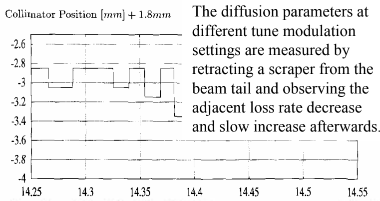
Several BPMs report high count rates at injection. After injection the loss rate is low which is commensurate with beam liftime of about 4 hours. From this graph one can identify the sites of highest beam loss.











The diffusion parameters at different tune modulation settings are measured by retracting a scraper from the beam tail and observing the adjacent loss rate decrease and slow increase afterwards.

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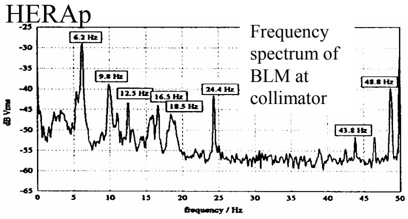
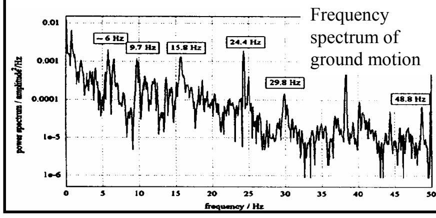
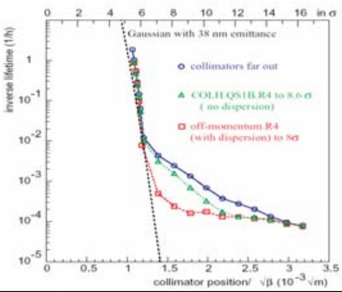


Frequency spectrum of BLM at collimator



Frequency spectrum of ground motion



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

Principles of loss detection (I):

Considerations in selecting a Beam Loss Monitor (common aspects):

By R.E.Shafer; BIW 2002

- **Sensitivity**
- **Type of output (current or pulse)**
- **Ease of calibration (online)**
- **System end-to-end online tests**
- **Uniformity of calibration (unit to unit)**
- **Calibration drift due to aging, radiation damage, outgassing, etc.**
- **Radiation hardness (material)**
- **Reliability, Availability, Maintainability, Inspect ability, Robustness**
- **Cost (incl. Electronics)**
- **Shieldability from unwanted radiation (Synchrotron Radiation)**
- **Physical size**
- **Spatial uniformity of coverage (e.g. in long tunnel, directionality)**
- **Dynamic range (rads/sec and rads)**
- **Bandwidth (temporal resolution)**
- **Response to low duty cycle (pulsed) radiation**
- **Instantaneous dynamic range (vs. switched gain dynamic range)**
- **Response to excessively high radiation levels (graceful degradation)**
- **Signal source** →
- **Positioning**

Systems, like differential **beam current** measurements, have a very rough position resolution. **Dose measurements** (or activation) have a very long time constant and are **not the subject of this session**.

Principles of loss detection (III):

Signal Source or 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.**
- The **signal source of beam loss monitors** is mainly …

Signal source:

… is mainly the ionizing capability of the charged shower particles.

Ionization Loss described by Bethe-Bloch Formular:

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

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

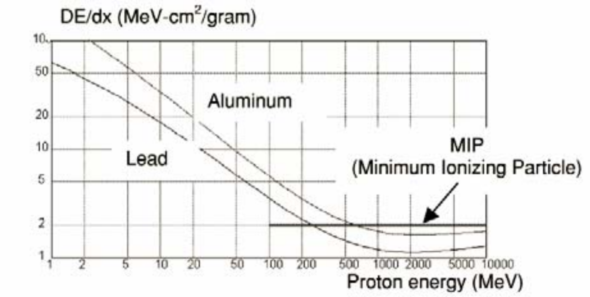


Figure 1. Plot of energy loss dE/dx vs. energy of incident proton.

$dE/dx_{Minimum}$ at:
≈1-2 MeV/(g/cm2)
so called: minimum ionizing particle (MIP), valid for many materials.
The energy can be used to create electron / ion pairs or photons in the BLM-detector material.

Useful:

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

$$1\,rad = \frac{100\,ergs}{gram}\cdot\frac{MeV}{1.6\cdot10^{-6}\,ergs}\cdot\frac{MIP\cdot gram}{2\,MeV\cdot cm^2} = 3.1\cdot10^7\ MIPs\ per\ cm^2$$

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

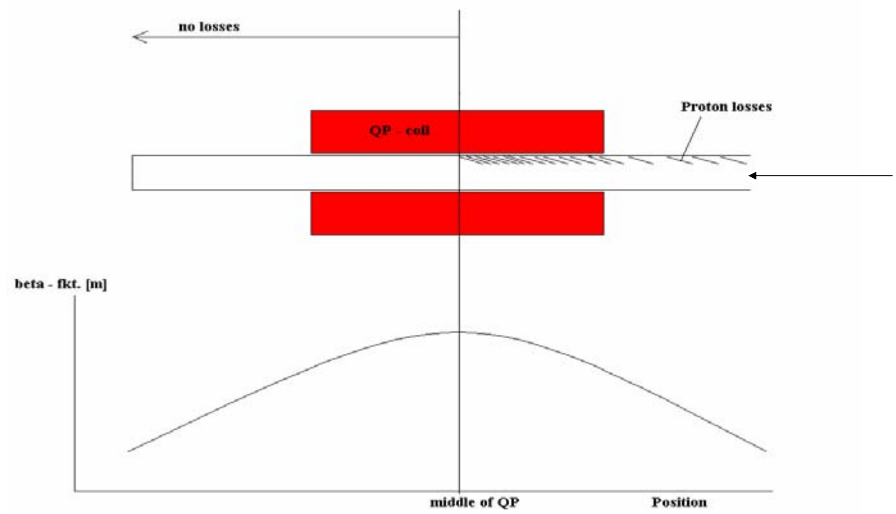
Positioning of the BLM (I):

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

Where to put the BLMs to measure beam losses?

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

Positioning of the BLM (II):



Monte Carlo calculations for calibration and positioning (III)

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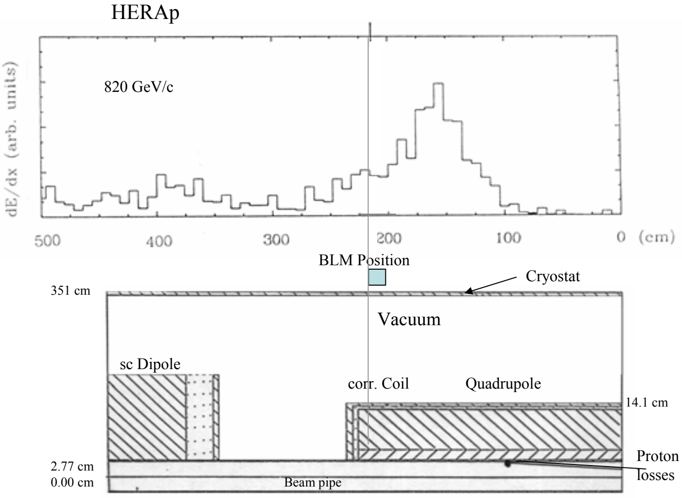
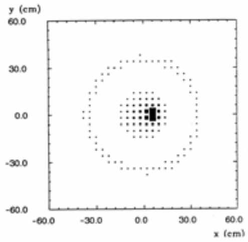
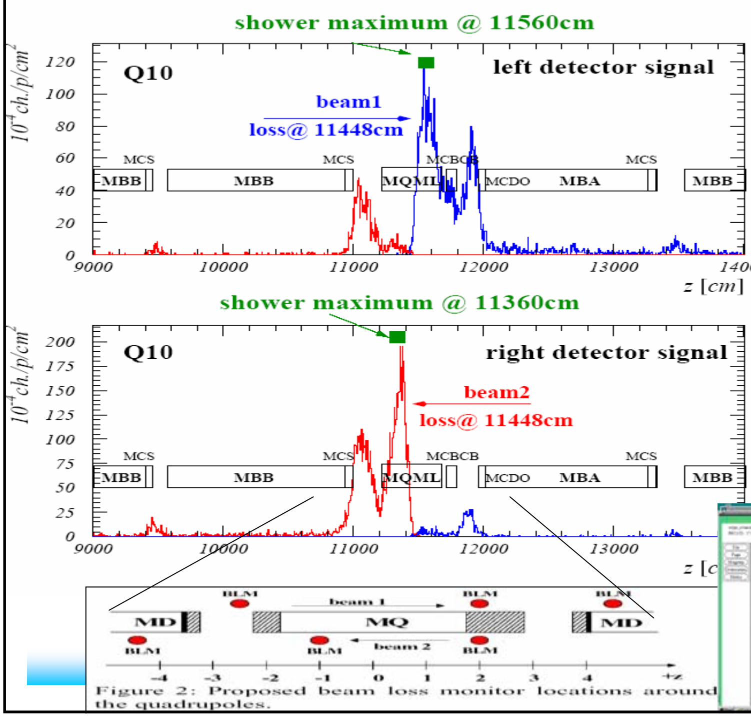


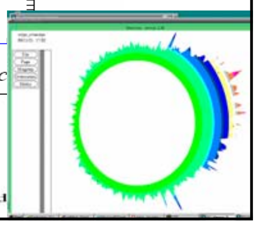
Longitudinal and radial energy/MIP distribution in the surface of the cryostat after proton losses in the middle of the sc-quadrupole



Symmetrical particle (MIP)and energy (dE/dx) distribution (radial) distributed over a few meters (longitudinal) => Efficiency is almost position independent



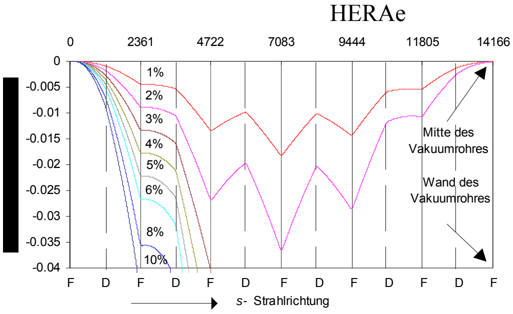
Simulation for superconducting LHC Magnets

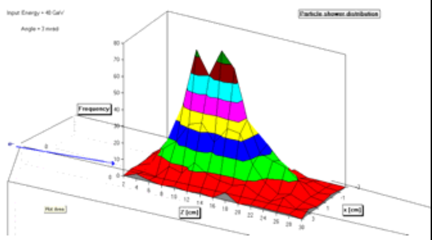


Monte Carlo calculations for calibration and positioning (V)

Understanding the loss dynamics:
Losses due to: Touschek- or Coulomb scattering, Failures, Microparticles, Obstacle, …

Trajectory of electrons due to energy loss (Coulomb scattering)





The Loss Mechanism; inelastic scattering

Electrons lose energy ΔE due to inelastic scattering (Bremsstrahlung) mainly on the nuclei of the residual gas molecules. The deviation of the electron orbit from the nominal orbit depends on the dispersion function in the accelerator and on ΔE. Therefore the electrons may be lost behind the following bending magnet on the inside wall of the vacuum chamber.

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*. Use Monte Carlo simulations to find the optimum locations for the monitors, as well as to calibrate the monitors in terms of 'lost particles/signal'

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

BLM Types:

Mostly used devices:
Short ion chambers,
Long ion chambers,
Photomultipliers with scintillators (incl. Optical Fibers),
PIN Diodes (Semiconductors),
Secondary Emission
Cherenkov light

Focus: Sensitivity

More exotic:
Compton Diodes,
Optical fibers,
…

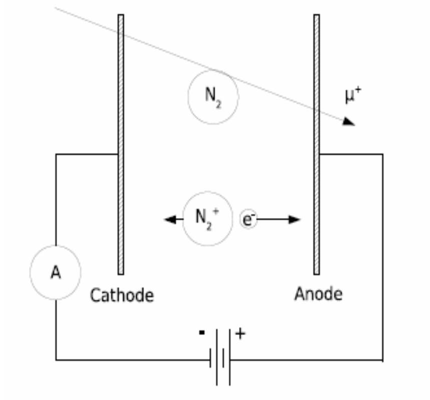
Dosimetrie is excluded here. Typically interest in long time scales (days-years), BLMs in short time scales (few turns to 10 ms)

Short Ionization Chamber

Short ionization chambers are used in many accelerators.

Principe:

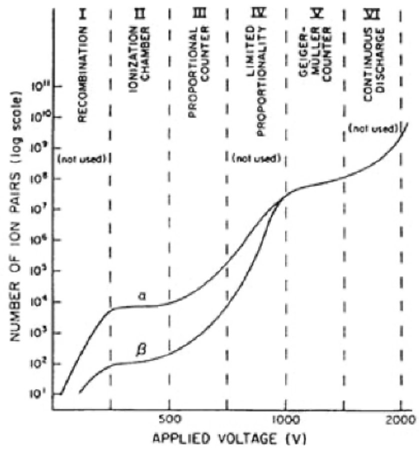
An ionization chamber in its simplest form consists of two parallel metallic electrodes (anode and cathode) separated by a distance D. High voltages, V, up to several kV, are applied to the anode. The gap, of width D, between the two electrodes is filled with gas (air, argon, xenon) or liquid of **density ρ and defines the sensitive volume of the chamber**. Ionizing particles traversing the sensitive volume ionize the gas or liquid and produce electron-ion pairs. The electric field E = V/D causes electrons and positive ions to drift in opposite direction toward the anode and cathode, respectively.



Short Ionization Chamber

The number of electrons reaching the anode depends on the applied voltage. If the voltage is very small, the electron produced by ionization recombines with its parent ion. If the electric fielc is larger than the Coulomb field in the vicinity of the parent ion, than electrons can escape this initial recombination. The number increases with voltage and the number of electrons collected at the anode increases with voltage up to saturation where all charges are collected. The region is called the **Ionization Region**.

At higher voltages, the electrons gain enough energy to produce ionization on their path => **Proportional Region**



•Avoid electronegative gases (O_2, H_2O, CO_2, SF_6,…), they capture electrons before reaching the electrode
•Nobel gases have negative electron affinities (Ar, He, Ne), better for the proportional region.

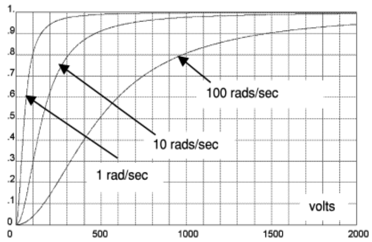
Short Ionization Chamber

Saturation in high radiation:

In addition to the initial recombination, electrons on their way to the anode may be captured by positive ions produced close to their trajectory (by other incoming particles) and do not contribute to the charge collection (important at high radiation levels).

•High voltage
•Small D
help

Charge collection fraction for 1,10, and 100 rads/sec dose rates vs. applied voltage, for the FNAL ionization chamber.



Predicted charge-collection efficiency for 3 dose rates vs. voltage.

Charge collection fraction for 0.001. 0.01 and 0.1 rads instantaneous pulsed dose for the FNAL ionization chamber.

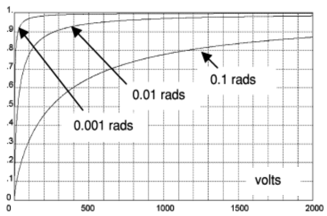


Figure 5. Predicted charge-collection efficiency for 3 pulsed doses vs. voltage.

Short Ionization Chamber

Improving Ion Transit Time

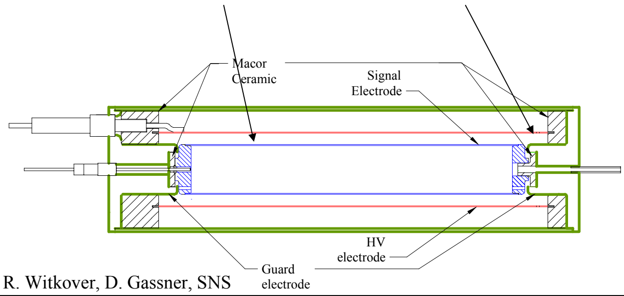
Ion speed $v_{ion} = \mu_0 E(P_0/P) = \mu_0 (V/d)(P_0/P)$

Where μ_0= Ion Mobility, V= Voltage, P/P_0 = Pressure (Atm)

Transit Time $t = d/ v_{ion} = D^2/[\mu_0 V (P_0/P)]$

For plane geometry D = Electrode gap
For cylindrical geometry $D^2= [(a^2 – b^2)/2] \ln (a/b)$

Where b = Inner radius and a = Outer radius

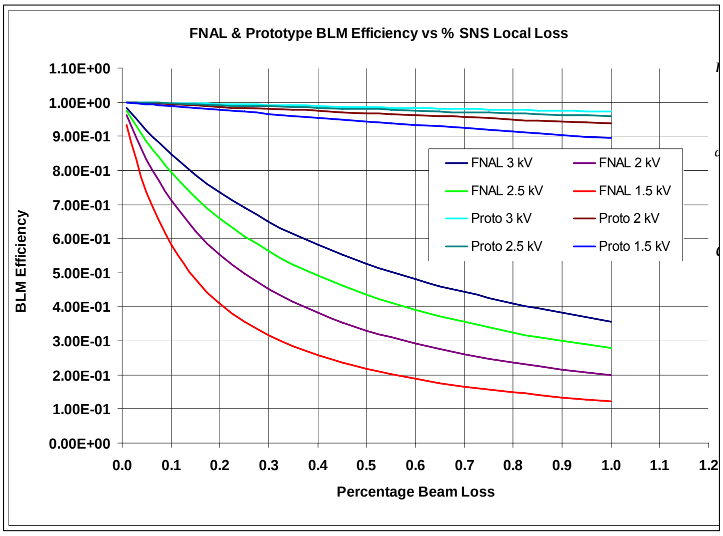


R. Witkover, D. Gassner, SNS

Tevatron Ion Chamber (1983)

Short Ionization Chamber

Saturation *Collection Efficiency for Continuous Loss*



The new design uses the same outer diameter of 1.5 inches but an inner diameter of 1 vs 1/4-inch and active length of 6.7 vs 4 inches to get the same sensitivity.

R. Witkover, D. Gassner, SNS

Short Ionization Chamber

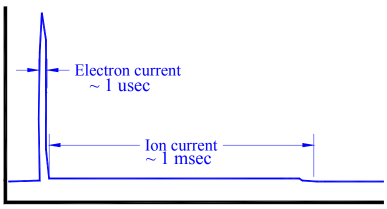
Fast reaction time=> high charge velocity v

$v = \mu \cdot V/D$
with μ = mobility [cm²/(V s)];
V = Voltage, D = Gap [cm]

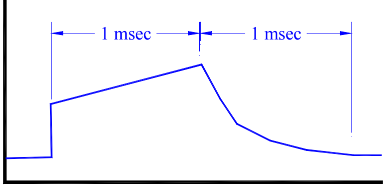
Ion mobility: μ_{ion} = 1.0 – 1.5 cm² atm/(V s) for typ. chamber gases at D = 1 cm, p = 1 atm, V = 1kV
=> response time of **t = 1 – 1.5 ms** which is often too slow for BLMs.

Electrons have a mobility of about **$10^3 \cdot \mu_{ion}$ => t = 1 – 1.5 µs**

Ion Chamber signal Due to Impulse Loss



Ion Chamber signal Due to 1 msec Loss



Calibration/Sensitivity

The number of electrons (n_e) produced in the gap by one minimum ionizing Particles (MIPs) is:

$$n_e = \frac{D \cdot \rho}{W} \cdot \frac{dE}{dx}(Medium) \leftarrow \text{Bethe-Bloch}$$

Note that the average energy needed to produce an electron-ion pair (W-factor) is larger than the ionization energy.
Is about constant for many gases and radiations.
Example: Argon:
ρ = 1.661 ·10^{-3} g/cm^3 (20^0C, 1 atm)
dE/dx = 1.52 MeV/(g/cm^2)

W [eV/e-]

Gas	first ionisation potential	fast electrons
Ar	15.7	26.4
He	24.5	41.3
H_2	15.6	36.5
N_2	15.5	34.8
Air		33.8
O_2	12.5	30.8
CH_4	14.5	27.3

n_e ≈ 100/cm · D [e/ MIP]

Note: Cross section for nuclear interaction is about 5 ·10^{-6} times the ionization cross section (10^{-16} cm^2). Cross section for excitation is about 10^{-17} cm^2.
Rutherford (nuclear) scattering does not produce significant energy transfer, but angular spread.

Short Ionization Chamber

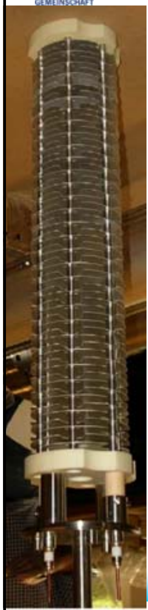
Sensitivity

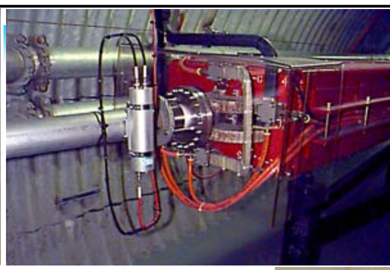
Sensitivity S_{Ion} [C/rad] of Ion-chamber depends on geometry!

Example: 1 ltr. Argon filled chamber, 100% charge sampling efficiency:
ρ = 1.661 ·10^{-3} g/cm^3 (20^0C, 1 atm)

$$S_{Ion} = 100\frac{erg}{g} \cdot \frac{1\,eV}{1.6\cdot 10^{-12}\,erg} \cdot \frac{1e^-}{26\,eV} \cdot \frac{1.66\cdot 10^{-3}\,g}{cm^3} \cdot 1000\,cm^3 \cdot \frac{1.6\cdot 10^{-19}\,C}{e^-} = 638\frac{nC}{rad}$$

1 rad, eV---> erg, W, ρ, 1 ltr., e^- charge





LHC	TEVATRON/RHIC/SNS
T = 0.3 µs (t$_{fall}$ 200µs)	T = 10 **=> 3** µs (t$_{fall}$ 560 => 72 µs)
1.5 ltr N_2 at 1.1 bar	0.11 ltr Ar at 1 bar
V = 800 – 1800 V	500 - 3500 V
Dynamic range >10^8 (>10^{-12} – <10^{-3} A)	Dynamic range >10^6 300 pA – 500 µA
Leak current <1 pA	Leak current 10 pA **=> <100 fA**
S: 156 pA/(rad/h) (Cs^{137}) (560 nC/rad)	19.6 pA/(rad/h) (Cs^{137}) (70 nC/rad)
Collection effeciency: ?	Collection effeciency: 77% -> 92 %

Courtesy B. Dehning, M Stockner; CERN

Short Ionization Chamber

More

• A beneficial characteristic of ion chambers is that their **calibration** is determined by geometry, and that the calibration is relatively independent of the applied voltage.

• Little **maintenance** required. Leakage in N2 filled chambers not critical

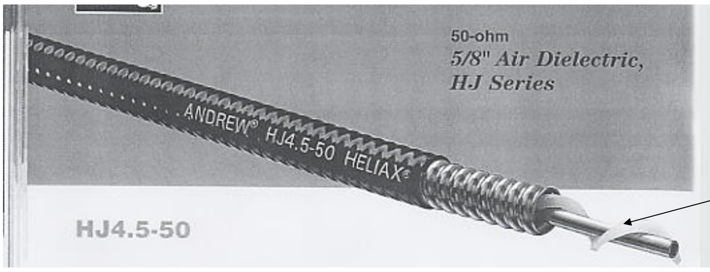
• Ion-chambers can be build from **radiation hard** materials (ceramic, glass metal), with no aging. Take care about the feedthroughs! No problems up to more than 10^8 rad

• Readout: **High dynamic range** need special signal processing (log. Amps, counting schemes, lot of ADC bits, …

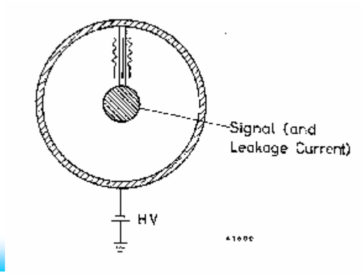
• Typ. large numbers are needed (>4000 in LHC)=> have to be **cheap**

"Panowskys" Long Ionization Chamber (PLIC)

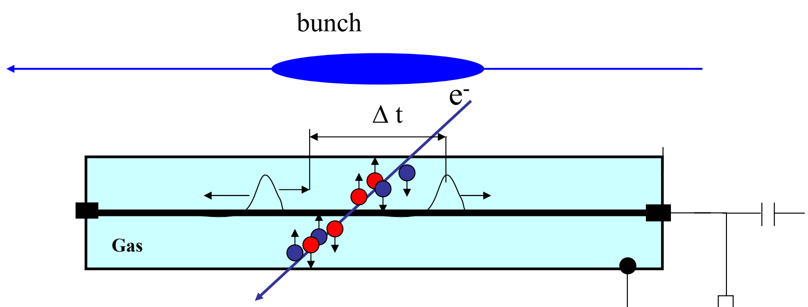
Heliax RF-cable



+Cheap
+Simple
+Uniform sensitivity
• Isolation not very radiation hard
(but >20 years operation in SLAC)
• leakage current ≈ 0.1 pA/m
• Sensitivity S ≈ 200 nC/rad/m => 0.5 µrad/s
• (still okay, even with 3 km cable => 0.3 nA)



"Panowskys" Long Ionization Chamber (PLIC)

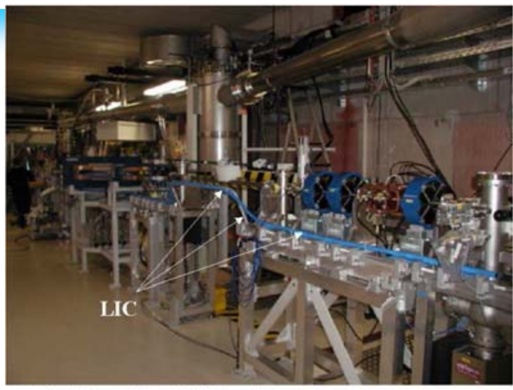


Δ t defines position of the loss, amplitude their amount.
At SLAC ≈3 km long cable was used.

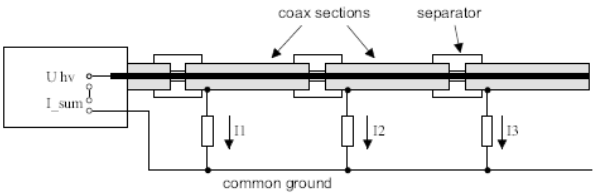
- Electron collection time T ≈ 0.25 µs (Ar-gas)
- Bunch velocity $c = 3 \cdot 10^8$ m/s
- Propagation velocity in cable $v = 0.914 \cdot c$
- Rise time of reflected signal: $t_{0\text{-}50\%} \approx 0.1$ µs, $t_{10\text{-}90\%} \approx 3$ µs

HV
≈ 100-500 V

Position resolution ≈ 1.5 m (≈ 5 ns) downstream end
≈ 15 m (≈ 50 ns) upstream end (6 km travel)

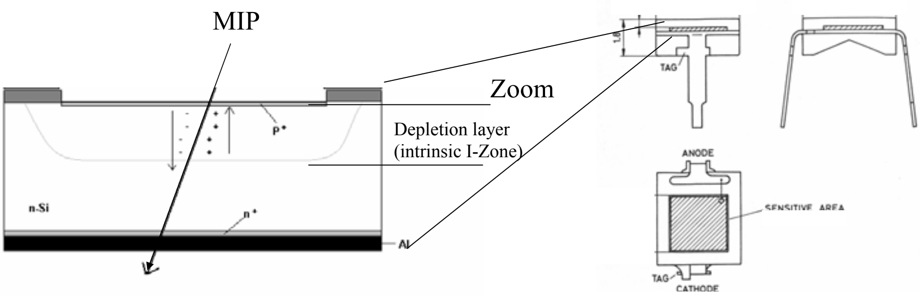


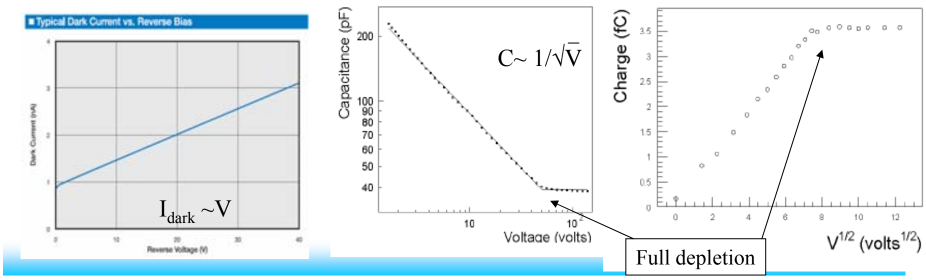
Installation of LIC at the ELBE beamline



Principle of the sectioned beam loss monitor

Solid State Ion-Chamber – PIN Photodiode





Solid State Ion-Chamber – PIN Photodiode

At about 20 V bias:

- Depletion layer ≈100 (– 300) μm
- 2 nA dark current
- dE/dx_{Si} (MIP) = 3.7 MeV/cm
- 3.7 eV for e^--hole pair

⇒ ≈ 10^4 e/MIP (for 100μm dep.)

$$1\,rad = \frac{100\,ergs}{gram}\cdot\frac{MeV}{1.6\cdot10^{-6}\,ergs}\cdot\frac{MIP\cdot gram}{2\,MeV\cdot cm^2} = 3.1\cdot10^7\ MIPs\ per\ cm^2$$

$$\Rightarrow S_{PIN} = 10^4\frac{e}{MIP}\cdot3.1\cdot10^7\frac{MIP}{cm^2\cdot rad}\cdot1.6\cdot10^{-19}\frac{C}{e} = 50\frac{nC}{rad\cdot cm^2}$$

⇒S_{PIN} ≈ 50 nC/rad for 1cm² Diode

⇒ **Fast: ≈ 2 - 20 ns**

Mobility μ_e = 1350 cm²/(Vs)

μ_{hole} = 450 cm²/(Vs)

⇒ Efficiency ε ≥ 80%

⇒ Works like an Ion Chamber (current mode)

Use as counter:

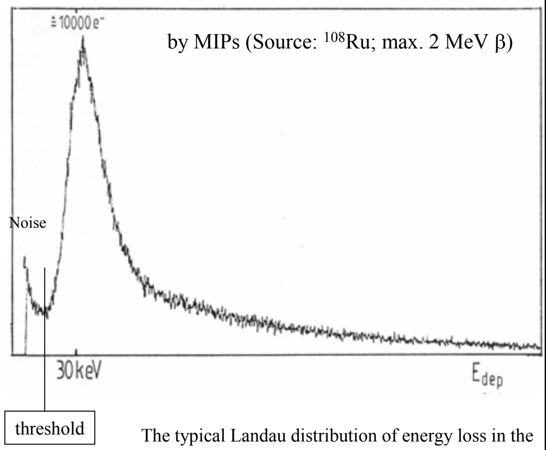
Enough signal to detect 1 MIP!

≈ 10^4 e/MIP (for 100μm dep.)

1 rad/s = $3.1\cdot10^7$ MIP/s/cm²

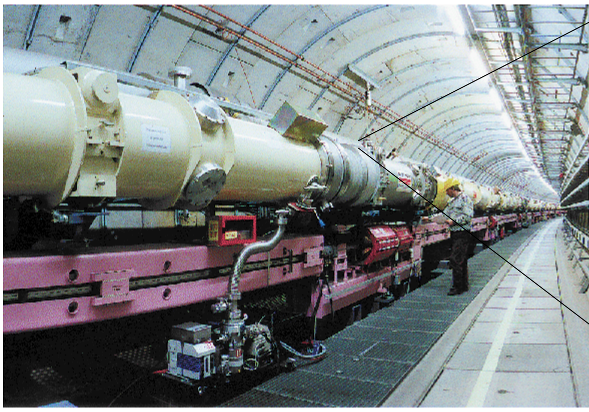
= ε·31 MHz/cm²

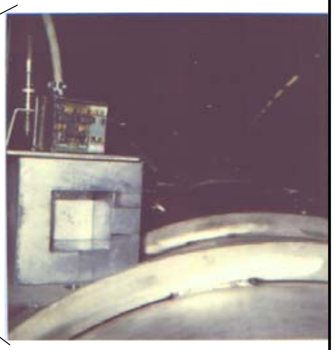
Spectrum of the deposit energy in the PIN Diode



The typical Landau distribution of energy loss in the 100 micron depletion layer of the PIN Diode

PIN Photodiodes to satisfy the special conditions in HERA

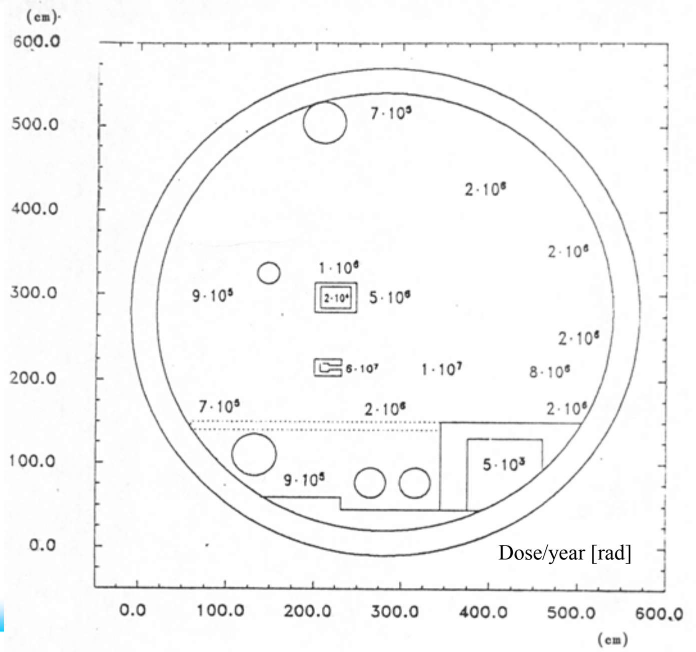




DESY BLM with lead hat (removed) on top of a sc quadrupole

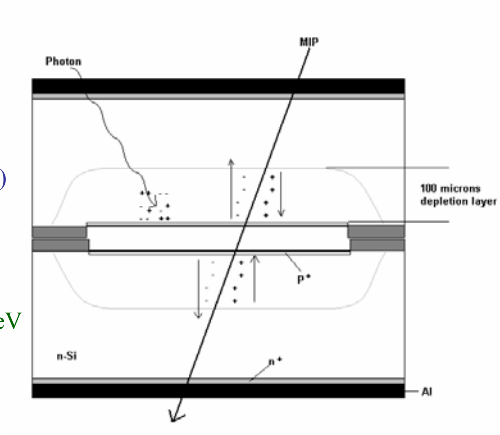
The view into the 6.3 km long HERA tunnel shows on top the superconducting magnets of the proton storage ring and at the bottom the electron storage ring.

PIN Photodiodes to satisfy the special conditions in HERA



PIN Photodiodes to satisfy the special conditions in HERA

Coincidence technique: SR-Photons stop in one **or** the other diode and are not counted!



Efficiency to MIPs (measured): $\varepsilon_{coinc} = 30\%$

- 1 count ≈ 0.1 µrad (MIPS, 1cm² Diodes)

+Very low noise:

- +Dark count rate < 0.01 Hz
- +max. count rate > 10.4 MHz

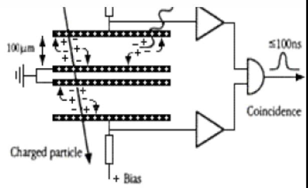
+Very high dynamic range: $>10^9$

+Insensitive to synchrotron radiation E_{crit} = keV

- +Efficiency to γ: $\varepsilon_\gamma = 3.5 \cdot 10^{-5}$
- +Coincidence + lead: <0.1 Hz at γ dose of 150 rad/h (e- ring at max.)

+ PIN Diodes + amplifiers were tested up to 10^8 rad without significant radiation damage; 13 years successful in HERA

- complete saturation if count rate ≈ 1 count / bunch



More see handouts

1. Conclusion

Devices using Ionization:

+ Simple, robust
+ Radiation hard
+ Cheap
+ Calibrated

Sensitivity:	
Ion Chambers:	**≈ 500 nC/rad (1ltr)**
PIN Diode:	**≈ 50 nC/rad for 1cm² Diode**

- Slow
  - (current mode ≈ µs, except PIN-Diode (but due to small area=> insensitive)
  - (counting mode ≈ ms)
- **cannot measure bunch by bunch losses** (except PIN Diodes in current mode)

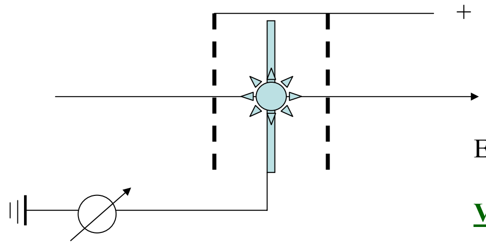
- Needs external amplification
- Moderate sensitivity (need to integrate the signal)

=> **Need of bunch by bunch loss determination (≤ 1 µs) (e.g. Linacs)**

Secondary Emission Monitors

Useful at very high radiation areas, very radiation hard

=> Secondary Emission Monitors
(with or without amplification)
Electron emission from surface due to crossing charged particles



Charges particle (MIP)

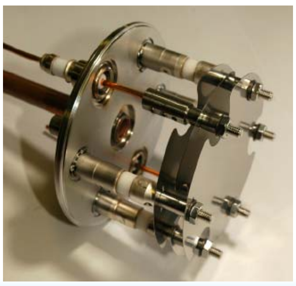
Efficiency about 4-5 %

Very linear!!!

Secondary Emission Monitors

CLIC

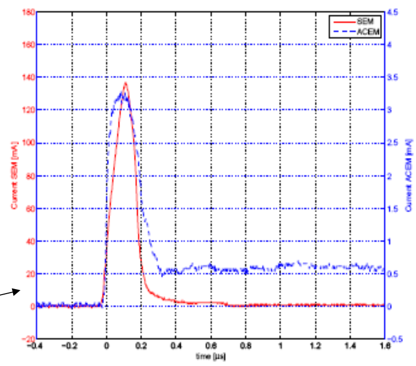
Gas sealed (ion chamber, slow) or in high vacuum (SEM, fast)



LHC

Integrated NEC foil

$<10^{-4}$ mbar
< 1% ionization to avoid nonlinearities



200 ns/div

Figure 4: Time response to single bunch compared to reference ACEM detector (160 ns bunch of 2.16×10^{12} p^+ at 1.4 GeV).

Secondary Emission Monitors

THORN EMI

NUCLEAR RADIATION DETECTOR TYPE: 9841

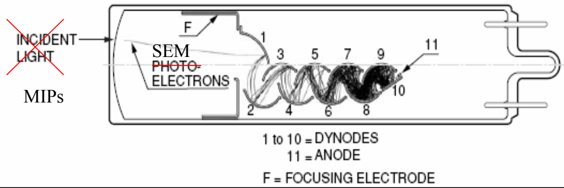
(Aluminium Cathode Electron Multiplier)

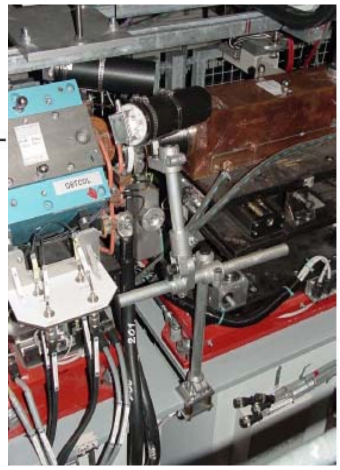
Description

Ø 32 mm

Cathode; Aluminium.
Window; Borosilicate.
Dynodes; 10 linear focused type with CsSb secondary emitting surfaces.
Base; B14B.

This tube is a development from the THORN EMI 9902 photomultiplier for direct measurement of ionising radiation, in the MeV to GeV region, associated with particle accelerators and nuclear reactors. It is intended as an alternative to the use of an ionisation chamber with improved linearity and response time over a wide dynamic range. The tube also has a high resistance to radiation and its high gain capability removes the need for additional high gain amplifier stages.





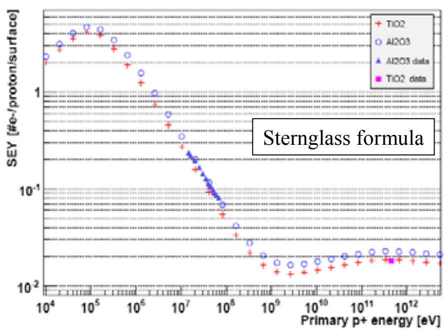
ACEMs at FLASH collimators

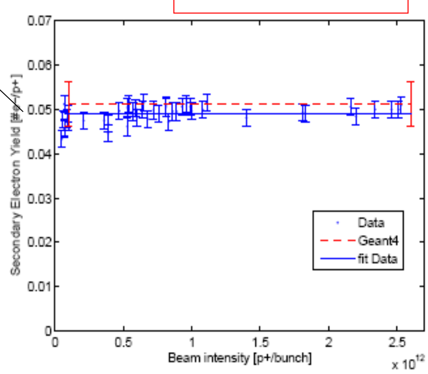
SEM Sensitivity (MIPs) :

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

sensitive surface Ø = 3.2 cm = 8cm^2

=> S_{SEM} = 2.5·10^8 MIPs/rad · 0.05 e$^-$/MIP · 1.6 ·10^{-19} C/ e$^-$ = 2 pC/rad (· **PMT$_{gain}$**)





2. Conclusion

Devices using SEM/Compton Diode:

+ Simple, robust, cheap
+ Radiation hard
+ very linear
+ Calibrated (watch the PMT gain!!!)
+ Very fast
• Needs external amplification
− Very moderate sensitivity (need to integrate the signal)

Sensitivity (MIPs):

Ion Chambers:	≈	500 nC/rad (1ltr)
PIN Diode:	≈	50 nC/rad for 1cm^2 Diode
SEM:	**≈**	**2 pC/rad (· PMT_{gain})**
Compton diode	=	4 nC/rad (photons only!)

⇒ See handouts

=> **Need of *sensitive* bunch by bunch loss determination (≤ 1 ms) (e.g. Linacs)**

Scintillation counters

Using light

Remember 1):
The amount of losses is proportional to the number shower particles
=> Fully absorption is not necessary.
=> Thin layer of scintillator is sufficient

+ Large area plastic scintillators and liquid scintillators are available
- Large inorganic crystals are expensive and small (NaJ, BGO, PbWO4, CsJ, …)
  • Mainly used for full absorption calorimeters in HEP-experiments

Scintillation counters

Organic scintillators are aromatic hydrocarbon compounds produced from benzenic cycles. In organic scintillators, the mechanism of light emission is a molecular effect. It proceeds through **excitation of molecular levels in a primary fluorescent material which emits bands of ultraviolet (UV) light during de-excitation**. This UV light is absorbed in most organic materials with an absorption length of a few mm, **the scintillator is not transparent for its own scintillation light**. The extraction of a light signal becomes possible only by introducing a **second fluorescent material** in which the UV light is converted into visible light ("wavelength shifter"). This second substance is chosen in such a way that its absorption spectrum is matched to the emission spectrum of the primary fluor, and its emission should be **adapted to the spectral dependence of the quantum efficiency of the photocathode "PM"**. These two active components of a scintillator are either dissolved in **suitable organic liquids or mixed with the monomer of a material capable of polymerization ("Plastic").** It is possible to obtain emission spectrum with a maximum wavelength in the range 350-500 nm. For example, anthracene has a maximum wavelength of about 450 nm. Organic scintillators can also be of liquid type. It is relatively easy to add material to increase their efficiency for a specific application. For instance, the efficiency of liquid scintillator for neutron detection can be increased by adding boron which has a large cross section for neutrons.

<u>And it is easy to cut or form "Plastic Scintillators" to nearly any shape.</u>

Review of Radiation Detectors; Claude Leroy; 4th International Summer School and Workshop on Nuclear Physics Methods and Accelerators in Biology and Medicine, Prague, Published in AIP Conf.Proc.958:92-100,2007.

Scintillation counters

Examples of scintillator-PMT coupling with a light guide

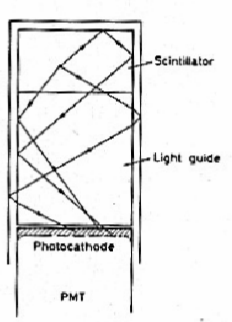
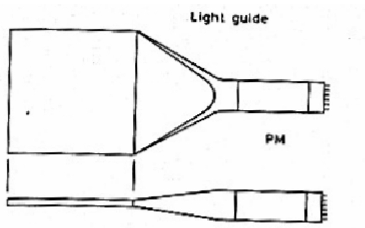
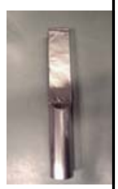


Fig. 9.5. Example of scintillator-PM coupling with a light guide



Scintillator with Plexiglass light guide

aluminum foil

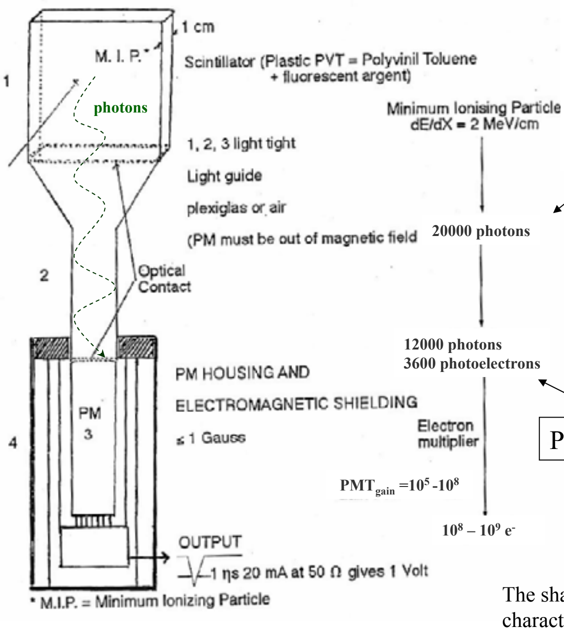


black plastic foil adhesive tape and test pulse LED

Note that the flux density of photons into the light guide is "incompressible" !

<u>=> The cross section of the scintillator should not be larger than the cross section of the light guide</u>

B. Michalek (DESY)



The light L produced by a particle of energy in a scintillator is **for small dE/dx (e.g. for MIPs)**:
$dL/dx = R_s\, dE/dx$, where R_s is the ratio of the average number of emitted photons to the energy of the incident radiation absorbed by the scintillator

NE102A: $1/R_s \approx 100$ eV/photon

The scintillation light is transported from the scintillator layers to the photosensitive device via light guides with about ε_{coll} **= 60%** efficiency (internal multiple reflections).

Photocathode efficiency: $\varepsilon_{cath} \approx 30\%$

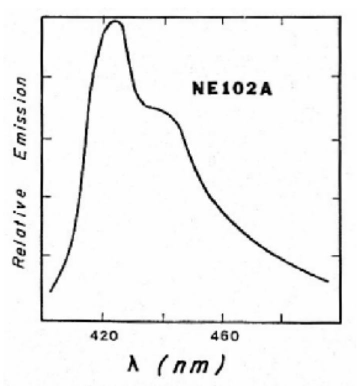
PMT: Photoelectrons are accelerated to first dynode. Tube has some 8-15 dynodes with large (>>1) SEM coeff.

The shape of the scintillation pulse is characterized by a fast rise time of the order of 1 ns and a decay time of a few ns.

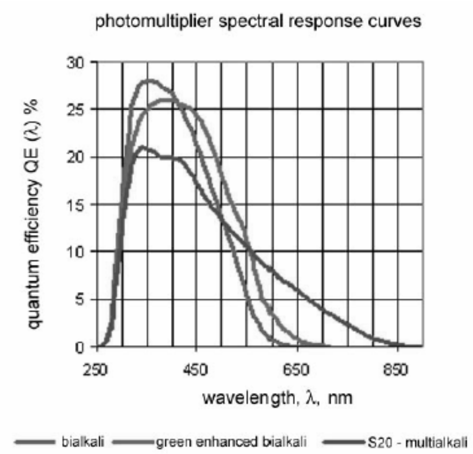
Ref. V Agoritsas, CERN PE-ED 001-92, rev. Nov. 1994

Scintillation counters

Emission spectrum of NE102A



Spectral response of a PMT photocathodes



Scintillation counters

	Plastic (NE102) $25x16x2\ cm^3$	Liquid (BC-501A) $950\ cm^3$ (≈ 1ltr)
Rad sensitivity (1/e)	≈ 1 Mrad	≈ 10 Mrad
Density ρ:	$1.032\ g/cm^3$	$0.874\ g/cm^3$
Light output R_s:	0.01 photon/eV	0.013 photon/eV

(CsJ(Tl):
Rs = 0.06 photon/eV,
$\rho = 4.4\ g/cm^3$,
poor rad hardness)

Sensitivity:

1rad

$$\frac{100\,erg}{g\cdot rad}\cdot 830g\cdot\frac{1eV}{1.6\cdot10^{-12}erg}\cdot R_s \approx 6\cdot10^{14}\frac{photons}{rad} \Rightarrow$$

$$S_{Scint}=6\cdot10^{14}\frac{photons}{rad}\cdot\varepsilon_{coll}\cdot\varepsilon_{cath}\left[\frac{elctrons}{photon}\right]\cdot\frac{1.6\cdot10^{-19}C}{electron}\cdot PMT_{gain}=17\frac{\mu C}{rad}\cdot PMT_{gain}$$

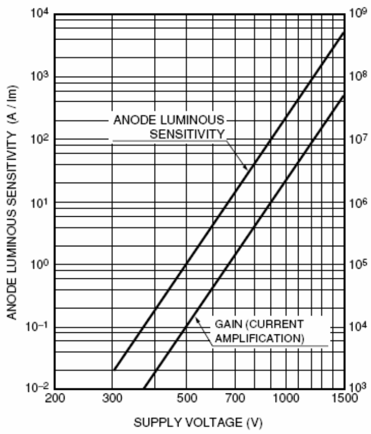


Figure 4-13: Gain vs. supply voltage

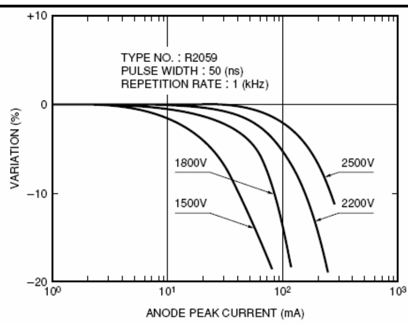


Figure 4-23: Voltage dependence of linearity

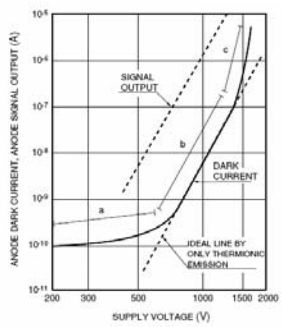


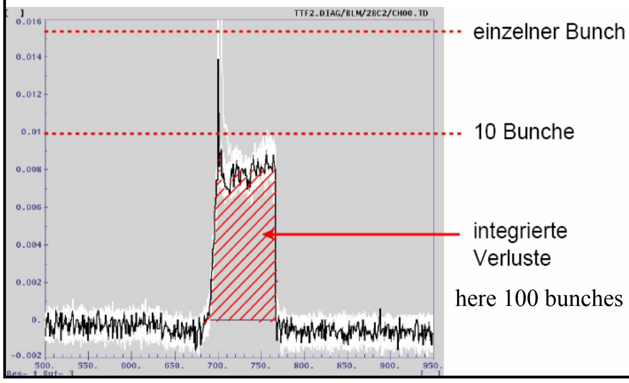
Figure 4-38: Typical dark current vs. supply voltage characteristic

PMT-Gain depends on HV => Need stable PS
Without gain variation=> Dynamic range 10^3

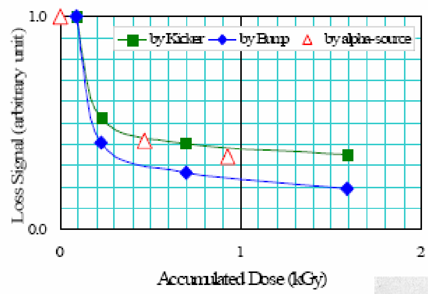
http://sales.hamamatsu.com/assets/pdf/catsandguides/PMT_handbook_v3aE.pdf

Scintillator assemblies and installations in FLASH

LED for testing the functionality of the BLM
Otherwise => No BLM signal =
okay for MPS



Change of light transmission due to radiation



Sample name	By γ-ray [kGy]	By proton beam loss [kGy]
Plastic Scintillator	1100	230

The radiation Dose which makes 1/e reduction of the original transparency

S. Goulding, R.H. Pohl 1972

=> Radiation Hard Scintillator:
e.g. Liquid Scintillators

Reviewing relevant papers is an essential part of any survey. In this case, we feel rather like the schoolboy asked to discuss the color of water. He recalled reading of "the blue Mediterranean", "the green lagoons of the south-seas" "the gray Baltic Sea", and "the blood-red ocean reflecting the setting sun". Naturally, he concluded that the color of water depends on both the time and place of observation! The literature on radiation damage in detectors could well lead to an equally valid conclusion.

Some other light based BLM Types: Cherenkov light

Cherenkov effect: Occurs when the velocity of a charged particle traversing a dielectric medium is faster than the speed of light in that medium. Photons are emitted at an angle defined by the velocity of the particle β and the refraction index n of the medium. The light can be focused on PMT to build an BLM.

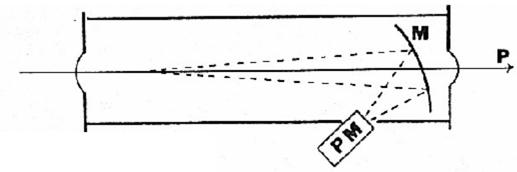
$$photon\ yield: \frac{dN}{dx} = 2\cdot\pi\cdot\alpha\cdot\sin^2\Theta\cdot\left(\frac{1}{\lambda_1}-\frac{1}{\lambda_2}\right)$$

$\cos\Theta = \frac{1}{\beta\cdot n}$ *with* $\beta > 1/n$; $\alpha = 1/137.036$ *and* $\lambda_{1,2} =$ wavelength interval

Photocathode sensitive at 350-500 nm=> $\frac{dN}{dx} = 390\cdot\sin^2\Theta\ \frac{photons}{cm}$

Cherenkov light

$$\frac{dN}{dx} = 390\cdot\sin^2\Theta\ \frac{photons}{cm}$$



Assuming
MIPs: => β≈1
Fused silica: => n= 1.55 => Θ = 49.8⁰ => 227 photons/cm
ε_{coll} **=80% (only for directed light!!)**, ε_{cath} = 30%
A detector of 10x10x10 cm³ (1 ltr.)

good radiation hardness

1 rad: $\frac{3.1\cdot10^7\,MIPs}{cm^2\cdot rad}\cdot\frac{227}{MIP}\cdot1000cm^2 = 7\cdot10^{12}\frac{photons}{rad}$

$$S_{Che} = 7\cdot10^{12}\frac{photons}{rad}\cdot\varepsilon_{coll}\cdot\varepsilon_{cath}\cdot\frac{1.6\cdot10^{-19}C}{e^-}\cdot PMT_{gain} = 270\frac{nC}{rad}\cdot PMT_{gain}$$

3. Conclusion

Devices using Scintillation/Cherenkov light:

+ Very high sensitivity (Scintillation)
+ Radiation hard (Cherenkov)
+ Very fast
+ Huge variation of shapes possible (Scintillator)
− Expensive (PMT + HV)
− Calibration: PMT gain has to be stable (drifts)
− Moderate radiation hardness (Scintillator)

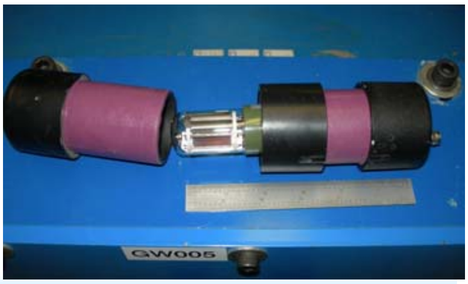
- Needs photon-to-charge converter (PMT, APD, PIN, …)

Sensitivity S (MIPs):	
Ion Chambers:	≈ 500 nC/rad (1ltr)
PIN Diode:	≈ 50 nC/rad for 1cm^2 Diode
SEM:	≈ 2 pC/rad (· **PMT$_{gain}$**) (8cm^2)
Compton diode	≈ 4 nC/rad (photons only!)
Org. Scintillator	**≈ 17 µC/rad (· PMT$_{gain}$) (1 ltr.)**
Cherenkov	**≈ 270 nC/rad (· PMT$_{gain}$) (1 ltr.)**

Čerenkov light in PMT glass

- **JLAB FEL:** detect Čerenkov light in PMT glass
- cheap 931B PMT, mainly blue sensitive
- quite radiation tolerant, darkening of glass compensated by HV (~10% HV change needed this far)
- cheap housing (1.5" plastic water pipes)

- controls strong beam losses
- not sensitive enough for „normal losses“



Kevin Jordan, JLAB

THE CHERENKOV EFFECT IN OPTICAL FIBERS.

There are two major issues to address when considering the Cherenkov effect in single quartz optical fibers.

1) the light yield caused by the passage of a single charged particle in a fiber.

2) the probability of survival of the emitted photons.

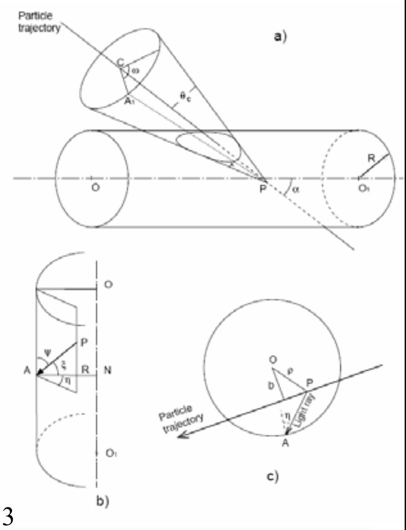
Cherenkov cone for β=1 particles is $\Theta \approx 47^0$.

The condition for capture and transport down the fiber is given by:

$$\xi \geq ar\sin\left(\frac{n_{clad}}{n_{core}}\right)$$

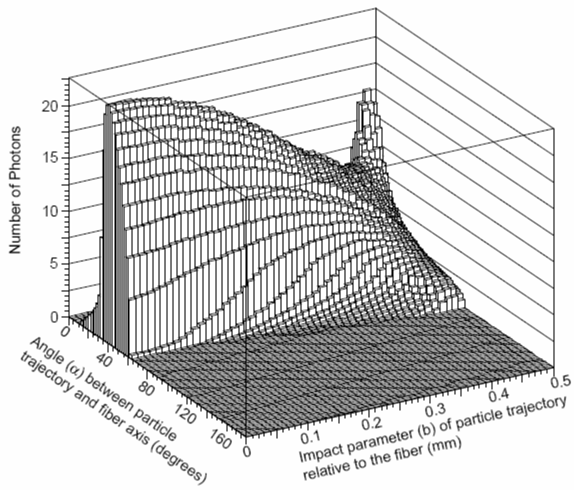
and ξ depends on (shower) particle trajectory.

$$\sqrt{n_{core}^2 - n_{clad}^2} = NA$$ Numerical Aperture ≈ 0.3



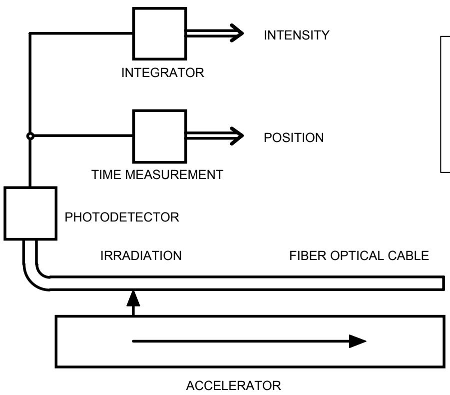
THE CHERENKOV EFFECT IN OPTICAL FIBERS.

The distribution of photons trapped inside a fiber as a function of the impacting particle's angle α and impact parameter b. NA =0.37



Optical fibers (Cherenkov light)

A Beam Loss Monitor (BLPM) based on Cerenkov light in optical fibers allows real time monitoring of loss location and loss intensity like in PLICs. The fast response of the Cerenkov signal is detected with photomultipliers at the end of the irradiated fibers.



Using high purity quartz fibers (suprasil):
- Only Cherenkov emission,
- n=1.457,
- withstand 30 $\cdot 10^9$ rad,

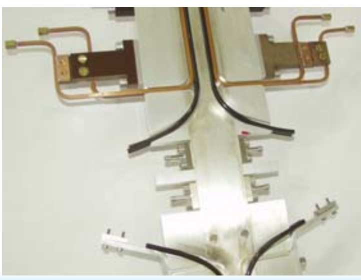
•Scintillating fibers are very sensitive to radiation (1/e at $\approx 10^8$ rad)---

• Give about factor 1000 more light ---

Optical fibers (Cherenkov light)

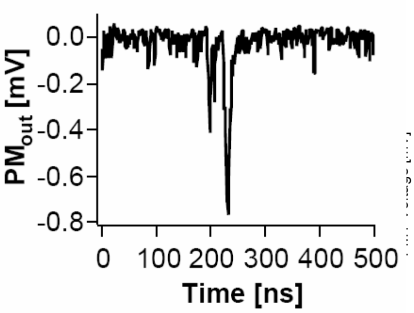
Fibers embedded in FLASH undulator vacuum chamber

U. Hahn

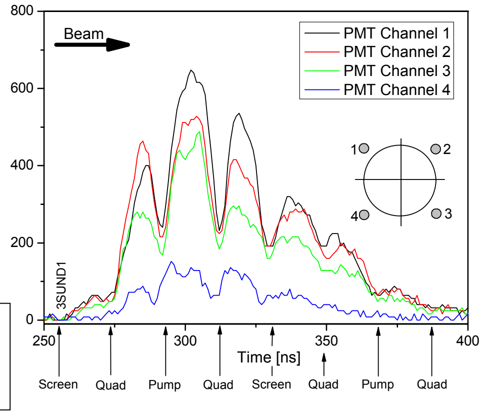


Optical fibers (Cherenkov light)

Along accelerator (TTF)



Longitudinal loss profile
and transversal loss position



Light travelling speed ≈0.66·c
Position resolution ≈ 1 ns ⇒ 20 cm
Some km long fibers possible

4. Conclusion

For MIPs; without (tube-) amplification:

Detector Material	energy to create one electron [eV/e]	number of [e / (cm MIP)] (**depends on dE/dx, resp. density**)	Sensitivity S (for MIPs) [nC/rad]
Plastic Scintillator:	250 – 2500	10^3 - 10^4	≈17·10^3 (· $\mathbf{PMT_{gain}}$) (1 ltr.)
Inorganic Scint.	50 - 250	10^4 - 10^5	≈ 100·10^3(· $\mathbf{PMT_{gain}}$) (1 ltr.)
Gas Ionization:	22 – 95	≈100 (Ar,1 atm., 20°C)	≈ 500 (· $\mathbf{Elec_{gain}}$) (1ltr)
Semiconductor (Si):	3.6	10^6	≈ 50 (· $\mathbf{Elec_{gain}}$) (1 cm² PIN-Diode)
Secondary emission:	2-5%/MIP (surface only)	0.02-0.05 e/MIP	≈ 2·10^{-3} (· $\mathbf{PMT_{gain}}$) (8cm²)
Cherenkov light	10^5 - 10^6	≈10 (H_2O) -200 (fused silica)	≈ 270 (· $\mathbf{PMT_{gain}}$) (1 ltr.)

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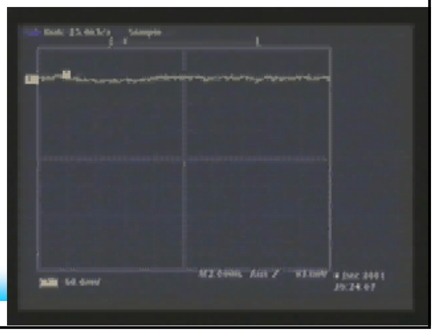
Last Conclusion

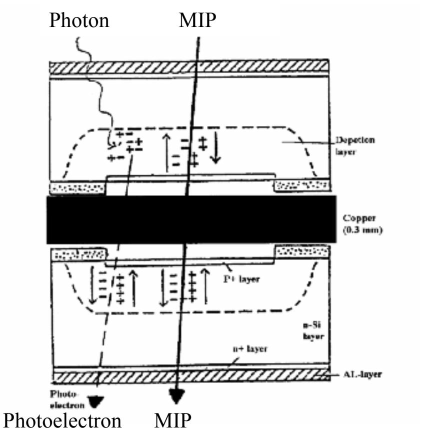
BLM-systems are multi-faceted beam instrumentation tools, which opens a wide field of applications. A precondition is a proper understanding of the physics of the beam loss to place the monitors at their adequate positions.

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



Reserve slides

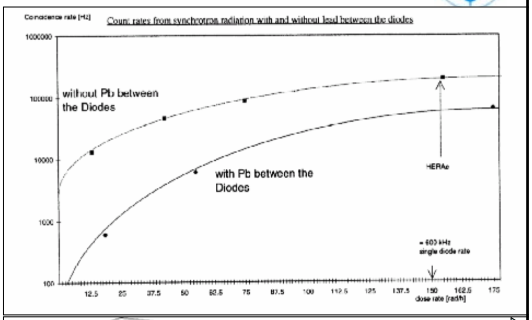
PIN Photodiodes to satisfy the special conditions in electron machines

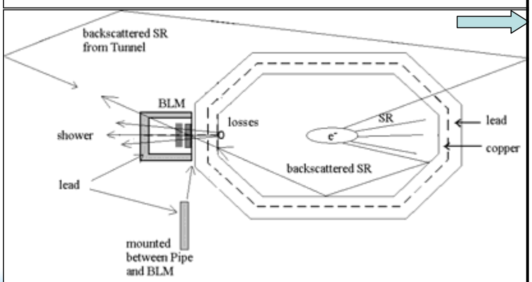


95% of 660 keV e^- will stop in about 300 µm Cu-layer

Range of electrons in matter

Useable in SR-light sources

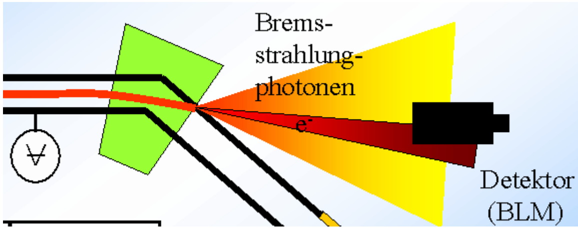


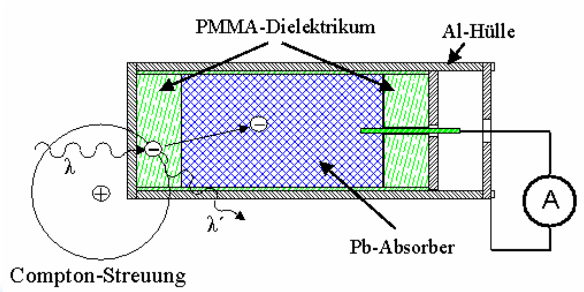


The backscattered SR in pipe is the dominating background source

Compton Diode

Only for photons !





Compton Diode

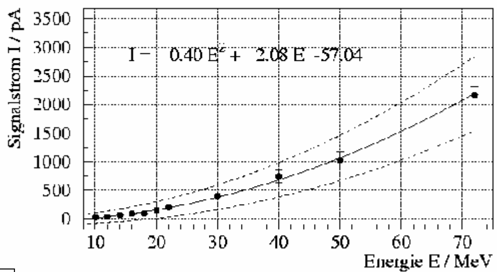
"For a Plexiglas insulator and a gamma energy of 10 MeV; the model predicts a Compton current of 415 nA /(Gy/s)"

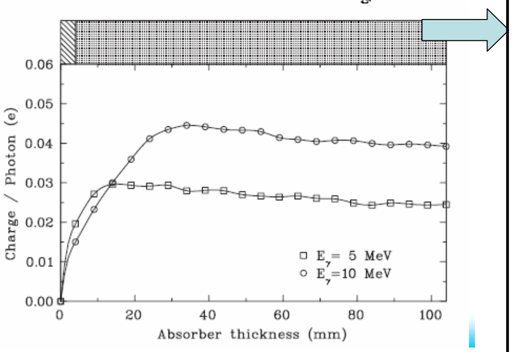
= 4.5 nC/rad.

Nuclear Instruments and Methods in Physics Research A 512 (2003) 453–458
Compton diodes as diagnostic tools in accelerator operation
H.-D. Gräf et al.

+Fast
+Simple, cheap
+Radiation hard

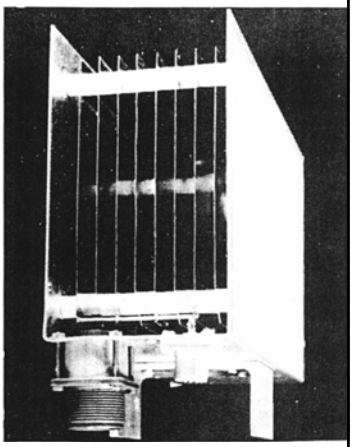
-Very moderate sensitivity
-Low energy photons only





Short Ionization Chamber

Short ionization chambers are used in many accelerators. 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 TEVATRON relies on **216 Argon filled glass sealed coaxial ionization chambers** to protect the superconducting magnets from beam loss induced quenches. The volume of each chamber is 110 cm^3. 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. Modified versions at RHIC and SNS.
LHC needs a dynamic range of 10^8! => Shorter path of ionization products to avoid recombining. 1.5 ltr N_2



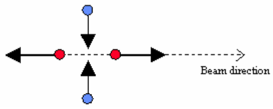
Air Ionisation Chamber at the PS (1968). The cover is removed

Short Ionization Chamber

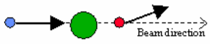
LHC Ion-Chamber (2006)

Tevatron Ion Chamber (1983)

Lifetime limitations



<u>Touschek effect</u>: Particles inside a bunch perform transverse oscillations around the closed orbit. If two particles scatter they can transform their transverse momenta into longitudinal momenta. If the new momenta are outside the momentum aperture the particles are lost. Good locations for the detection of Touschek scattered particles are in high dispersion sections following sections where a high particle density is reached. Since the two colliding particles loose and gain an equal amount of momentum, they will hit the in- and <u>outside</u> walls of the vacuum chamber. In principle the selectivity of the detection to Touschek events can be improved by counting losses at these locations in coincidence.



<u>Coulomb scattering:</u> Particles scatter elastically or inelastically with residual gas atoms or photons or emit a high energy photon (SR). This leads to betatron or synchrotron oscillations and increases the population of the tails of the beam. If the amplitudes are outside the aperture the particles are lost. Losses from elastic scattering occur at aperture limits (small gap insertions, septum magnet, mechanical scrapers and other obstructions). If, in an inelastic Coulomb collision, the energy carried away by the emitted photon is too large, the particle gets lost after the following bending magnet on the <u>inside</u> wall of the vacuum chamber.