Beam Loss Monitors

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

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

Examples of Beam Diagnostics with BLMs and Challenges associated to Measurements of Losses → many additional slides

Introduction

The important characteristic in "Beam Losses" is the number of particles lost per unit time $\Delta N/\Delta t$. The beam lifetime τ is defined with

$$N(t) = N_0 \; e^{-t/\tau}$$

where N_0 is the initial intensity. At the accelerator design stage, such questions as, "**What is the minimum/maximum possible beam lifetime**?" and, "**What (and where) is the tolerable beam loss rate for accelerator components**?" have to be answered. This lecture will discuss some of the typical beam loss mechanisms and how to measure them.

I like to divide beam losses into 2 classes:

I) Irregular (uncontrolled, fast) losses

II) Regular (controlled, slow) losses

Beam Dynamics and Beam Losses - Circular Machines ; V. Kain, 2014 Joint International Accelerator School : Beam Loss and Accelerator Protection

1a) Loss Classes I: Irregular 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.

1a) Loss Classes II: Regular Losses

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 due to various effects: Touschek effect, beam beam interactions, collisions, transversal and longitudinal diffusion, residual gas scattering, halo scraping, instabilities etc. These effects are suitable for machine diagnostic with a BLM system; the system should be **sensitive enough** to enable machine fine tuning and machine studies with the help of BLM signals:

- sometimes even at low beam intensity to avoid high losses and/or
- during machine commissioning and
- at various energies during acceleration

It is clearly advantageous to design a BLM System which is able to deal with both (irregular and regular) loss modes.

=> Very high dynamic range is required!!!

1a) Loss Classes III

Examples for regular (controlled, slow) losses.
Examples to make diagnostics with BLMs

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

Examples for Irregular (uncontrolled, fast) losses.
They might result in:

- Destruction of Vacuum-Components
- Superconducting machines: Quenching
- Activation of environment due to losses
- Commissioning: Obstacle
- Limited lifetime: Vacuum Problems (Coulomb Scattering)
- Limited lifetime: Microparticles
- Limited lifetime: UFOs

Examples are shown in the handouts

1b) Principles of loss detection

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**.

1b) Principles of loss detection

Signal Source or What should a Beam Loss Monitor monitor?

Ideal BLM system

While no ideal system exists, let us formulate the main features of such a hypothetical system:

1. Radiation detector with high dynamic range to be used for both regular (low) loss and irregular (high and fast) loss.
2. Sensitive only to radiation caused by beam loss. (Not: Synchrotron radiation, Dark current, …)
3. Allows one to find out the amount of beam lost (conversion from BLM signal to actual number of primary (lost) particles).
4. Resolves time structure of loss.
5. Resolves spatial distribution of beam loss.

The **signal source of beam loss monitors** is mainly …

Beam Loss Monitors (BLMs): Physics, Simulations and Applications in Accelerators, A. P. Zhukov, BIW10, Santa Fe, New Mexico USA

1b) Principles of loss detection

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

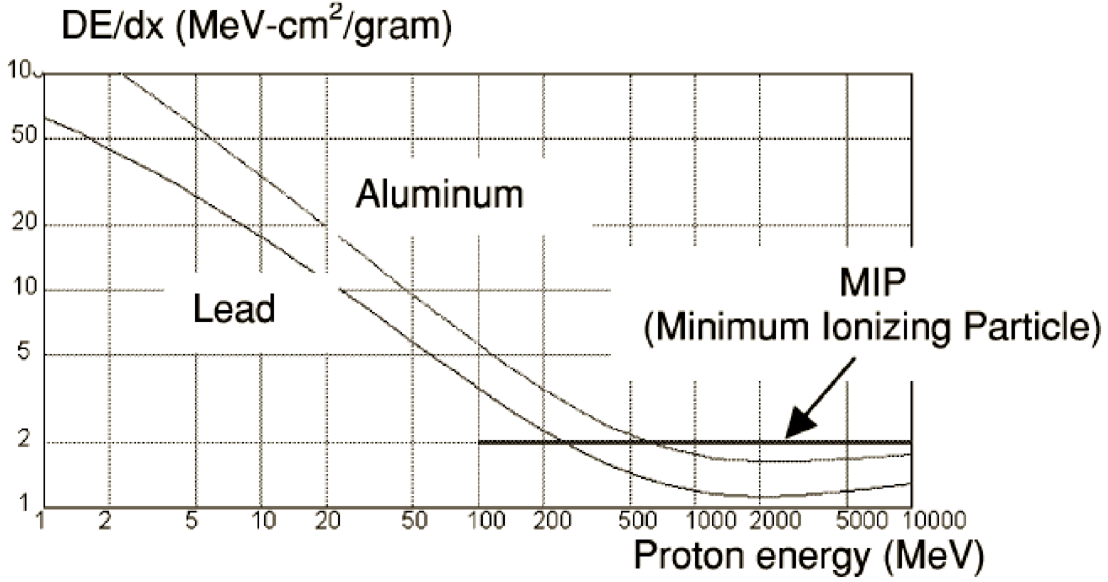


Figure 1. Plot of energy loss dE/dx vs. energy of incident proton.

$dE/dx_{Minimum}$ at:
≈ 2 MeV/(g/cm^2)
so called: minimum ionizing particle (MIP), valid for many materials.
This 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*.

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

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)

1c) Positioning of the BLM (I):

Each BLM at different locations needs its special efficiency-calibration in terms of signal/lost particle ($Sig_{BLM}(t)/N_{loss}(t)$, especially while the BLM detects secondaries and not the primary lost particle. This calibration can be calculated by:

1. Use of a **Monte Carlo Program** with the (more or less) exact geometry and materials between the beam loss and the BLM **to understand the measured Loss Efficiency** $\boldsymbol{\varepsilon_{BLM}} = N_{BLM}(t) / N_{loss}(t)$ with $N_{BLM}(t)$ = rate of (signal-generating) particles reaching the BLM.
2. Knowing the **Sensitivity** of the BLM (S_{BLM}) on (signal-generating) particles. (More in the 2nd part of this talk)

=> $\mathbf{Sig_{BLM}}(t) = S_{BLM} * N_{BLM}(t) \Leftrightarrow \mathbf{N_{loss}(t) = Sig_{BLM}(t) / (\varepsilon_{BLM} * S_{BLM})}$

Where to put the BLMs to measure beam losses with high efficiency $\boldsymbol{\varepsilon_{BLM}}$?
It should be clear, that ε_{BLM} depends on the **energy, the location of the BLM** in the accelerator and on **loss distributions/ loss mechanism around the ring**. Preferred locations for beam losses and therefore for BLMs might be Collimators, scraper, aperture limits, and high β-functions…, therefore also the (superconducting) quadrupoles => Monte Carlo Simulations required!

Positioning of the BLM (II):

The standard way of simulating radiation propagation in a medium is to employ Monte Carlo codes. Modern codes include vast physics models and capabilities to simulate realistic beam line geometries. Among most widely used codes are:

- MCNPX (LANL/ORNL)
- MARS (FNAL)
- GEANT4 (CERN/SLAC/ … and others)
- FLUKA (CERN/INFN/ …)
- SHIELD (INR), for hadrons only
- …

E.g. Geant4 contains different physics models, and the user can define which one to use. The electromagnetic interactions include:

Photon processes

- γ conversion into e+ e- pair
- Compton scattering
- Photoelectric effect
- Rayleigh scattering
- Gamma-nuclear interaction in hadronic sub-package

Charged processes

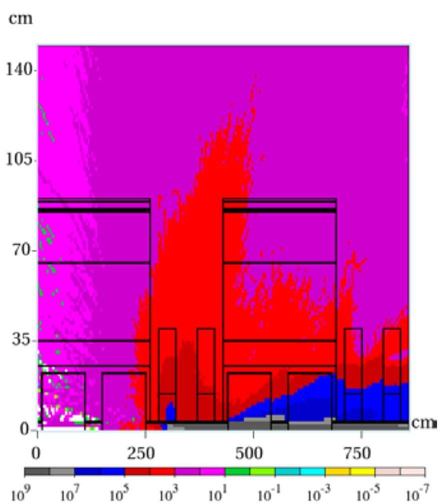
- Ionization
- Coulomb scattering
- Bremsstrahlung
- Nuclear interaction in hadronic sub-package
- Positron annihilation

} See Gero's first talk

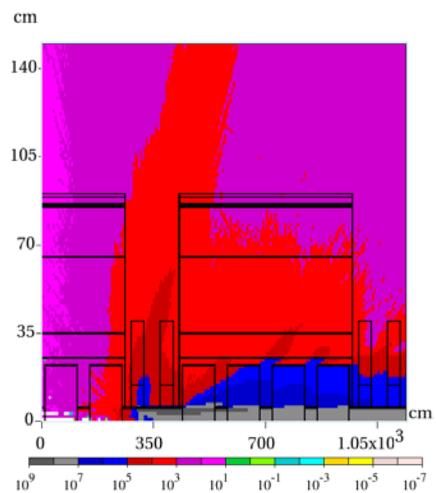
Monte Carlo calculations for calibration and positioning (III)

Energy dependence:
Low Energy Proton Beam = Shielded Shower

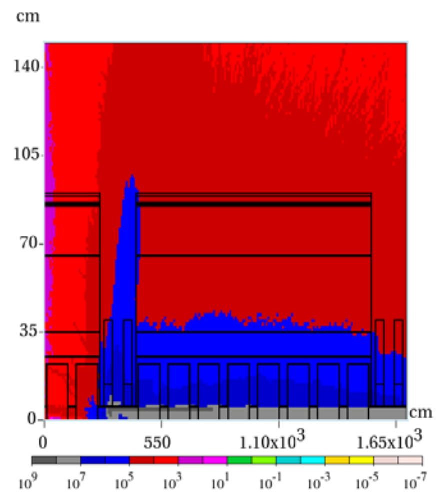
Important:
Loss Efficiency ε_{BLM} has to be calibrated by energy.



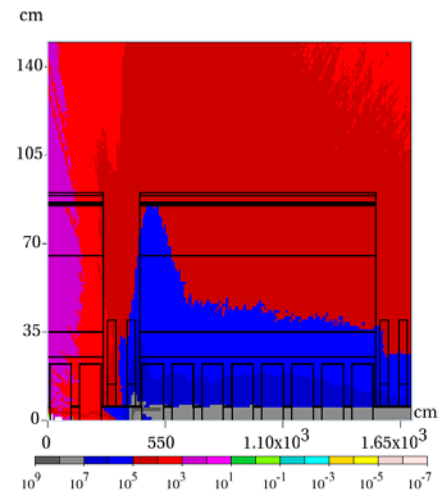
Loss in the middle of first quadrupole magnet, in xz plane, with 150 MeV energy.



Loss in the middle of first quadrupole magnet, in xz plane, with 200 MeV energy.



Loss in the middle of first quadrupole magnet, in xz plane, with 1 GeV energy.



Loss in the middle of first quadrupole magnet, in yz plane, with 2 GeV energy.

Loss location = middle of first quadrupole
Loss angle = 1.5 mrad
Loss intensity = 10^12 protons/sec

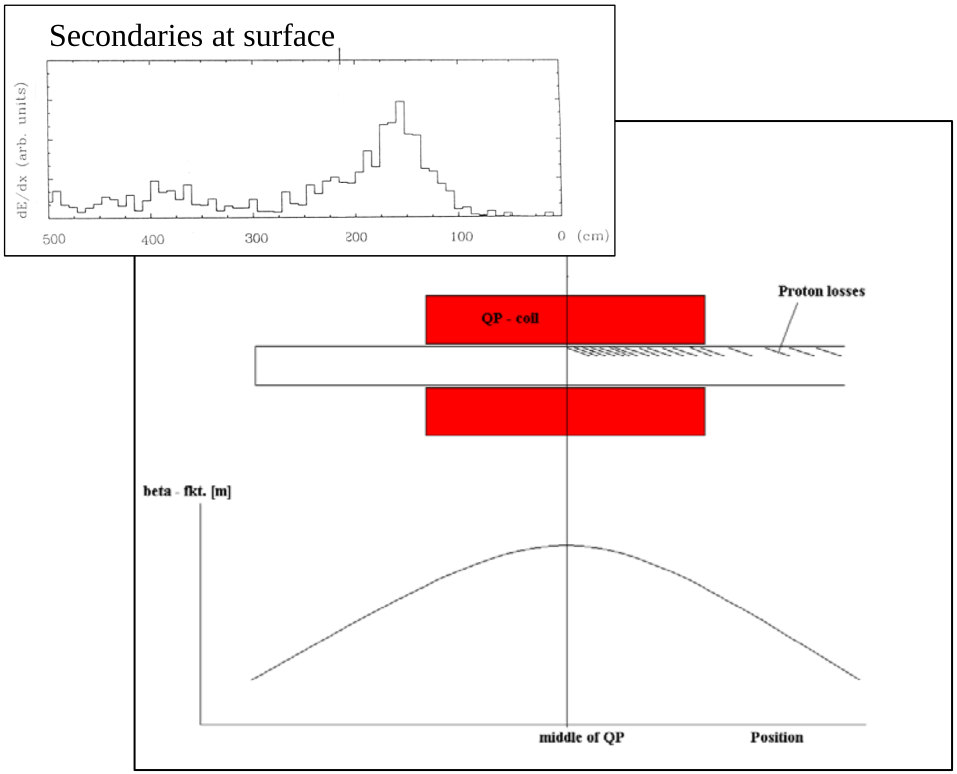
Technical Note ESS/AD/0032

Beam direction

Monte Carlo calculations for calibration and positioning (IV)

A local orbit distortion creates losses at high beta (in general at aperture limitations)

High Energy Proton Beam = Large Shower



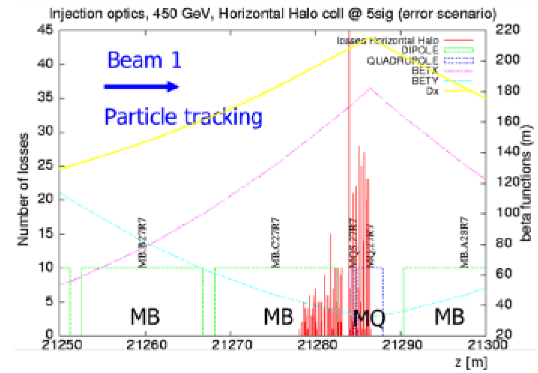


Fig. 2: Number of lost protons and beta function values with schematic of LHC regular cell as function of the location along the lattice. MB, bending magnet; MQ, quenching magnet.

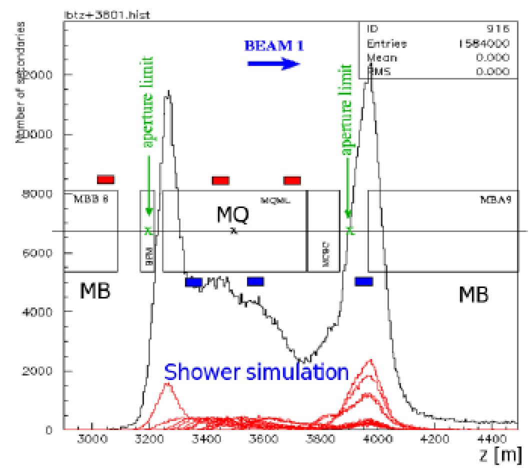


Fig. 3: Number of secondary particles as function of location along the lattice. MB, bending magnet; MQ, quenching magnet.

Beam Loss Monitors at LHC; B. Dehning, CERN Yellow Report CERN-2016-002, 2014 Joint International Accelerator School : Beam Loss and Accelerator Protection, Newport Beach, CA, USA

Beam direction

ositioning (V)

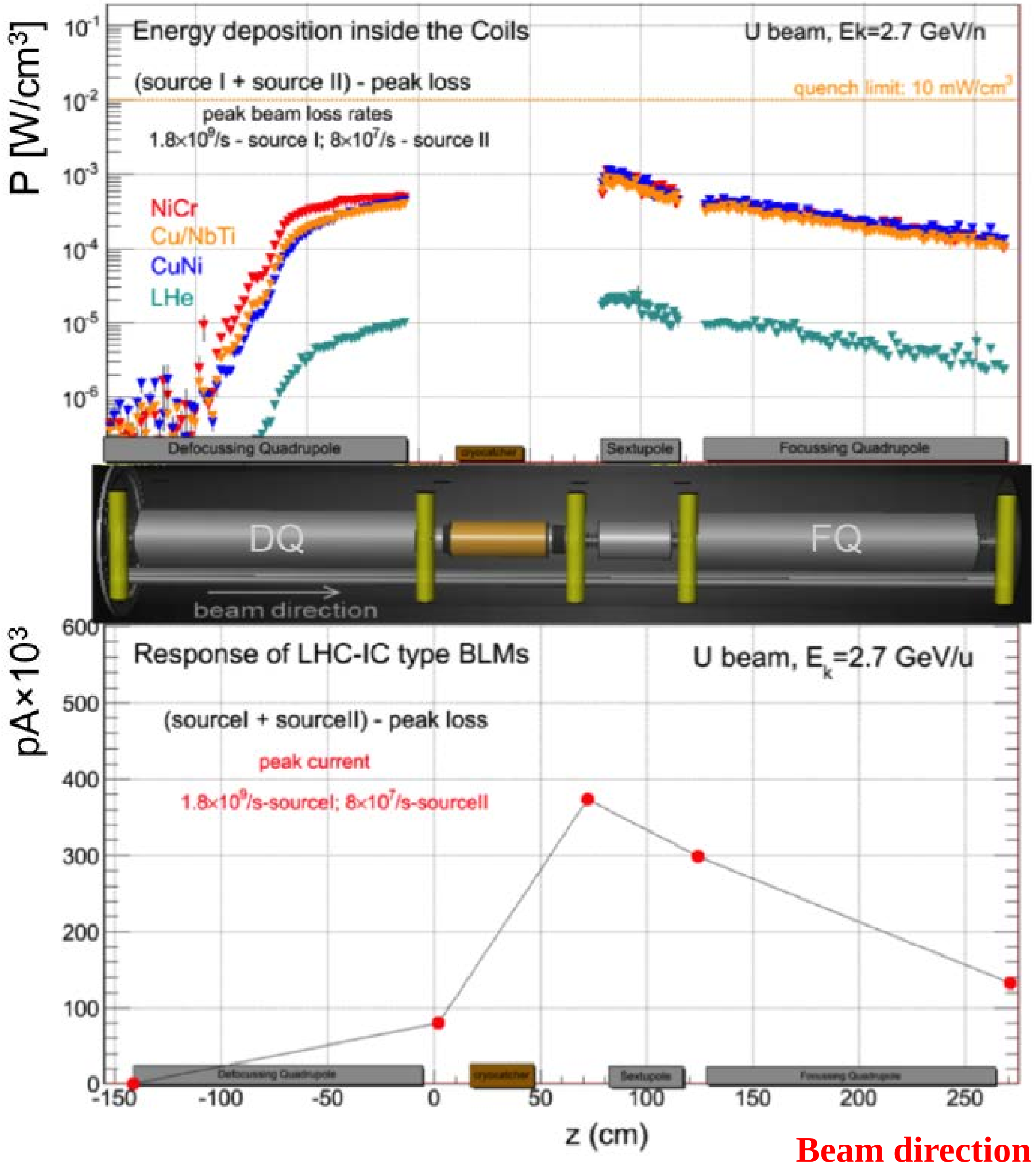


Figure 4: Correlation between the maximum power deposition in the SC coils and the BLM signals outside the cryostat due to ionization losses of the U^{28+} beams.

SIS100: FLUKA simulations were performed to calculate the response of the detectors to the expected losses as to the lowest level detectable (10 pA). Since the BLM system can be used not only for diagnostics, but could also play an essential role in the machine protection system, the FLUKA simulations were extended to estimate the BLM quench prevention thresholds for use in an interlock system preventing the superconducting magnets from quenches

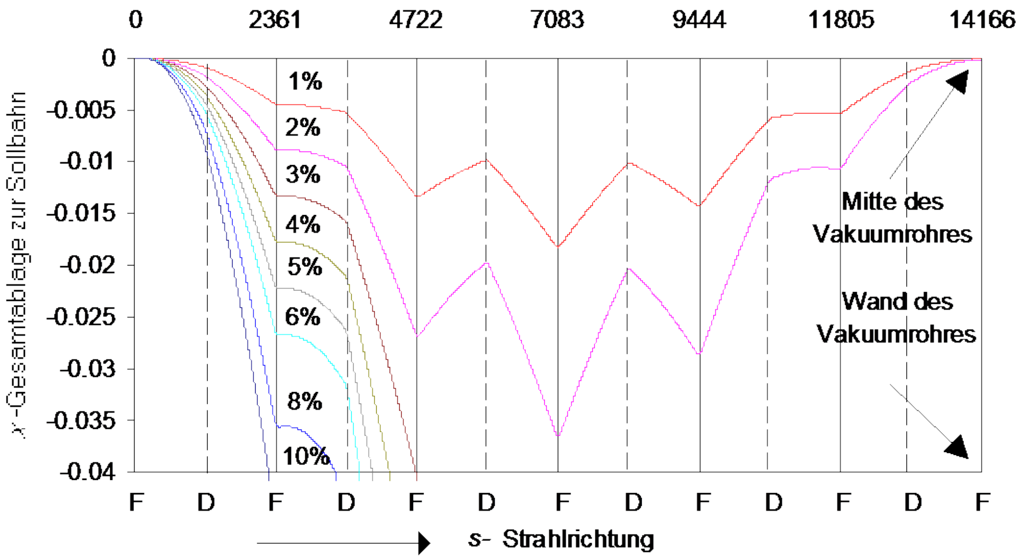
The Dual Use of Beam Loss Monitors at FAIR-SIS100: General Diagnostics and Quench Prevention of Superconducting Magnets; S. Damjanovic, et al., IPAC16, BEXCO, Busan Korea

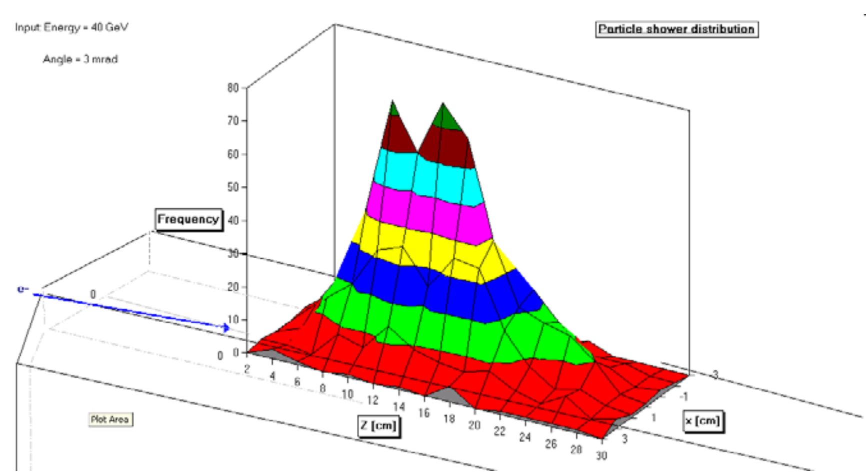
Monte Carlo calculations for calibration and positioning (VI)

Understanding the loss dynamics:

Losses due to: Touschek- or Coulomb scattering, Failures, Microparticles, Obstacle, …

Trajectory of electrons due to energy loss (Coulomb scattering)





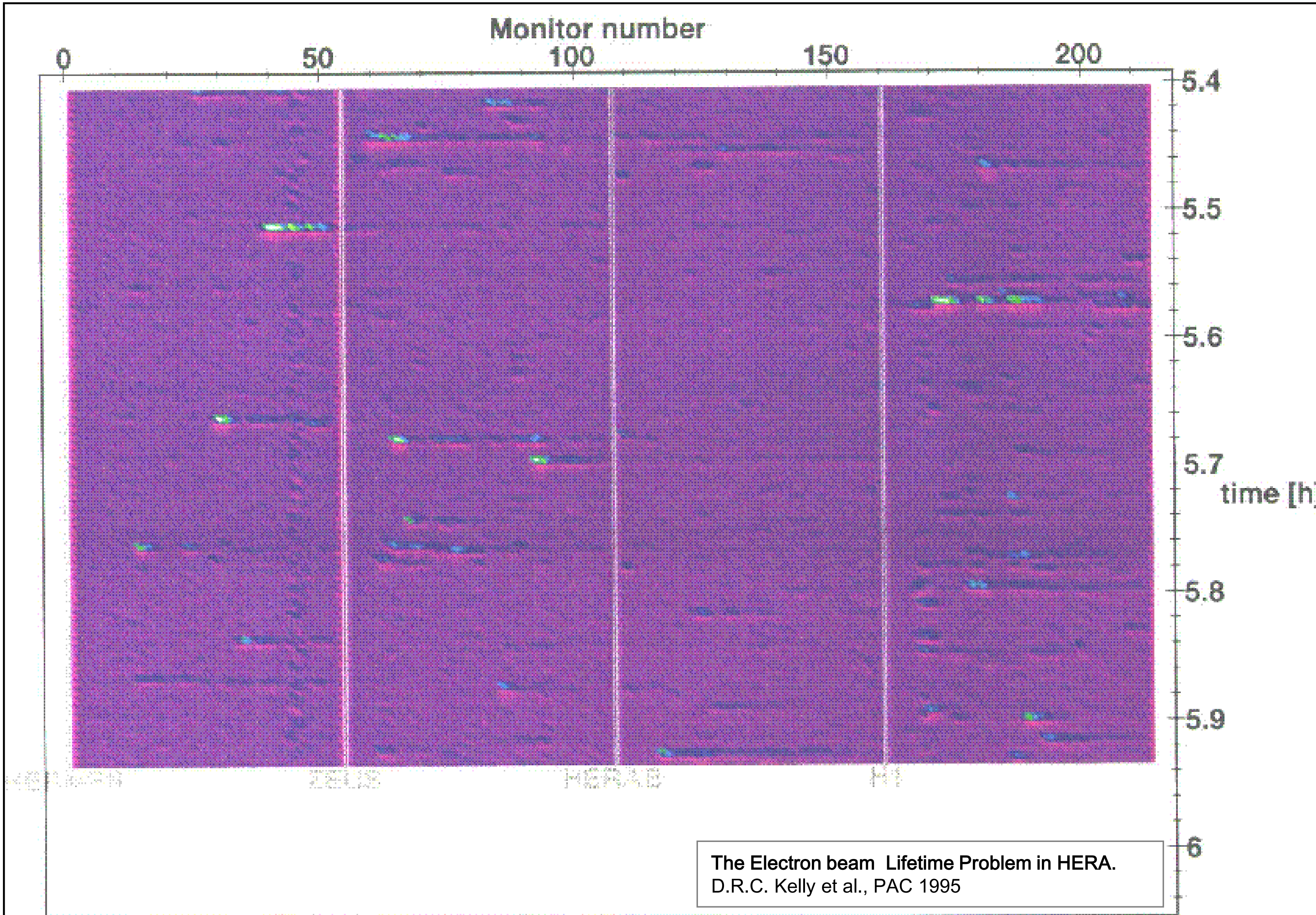
The loss of a high-energy particle in the wall of a beam pipe results in a shower of particles, which leak out of the pipe*. Use Monte Carlo simulations to find the optimum locations for the monitors, as well as to calibrate the monitors in terms of 'lost particles/signal'

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

The Loss Mechanism; inelastic scattering

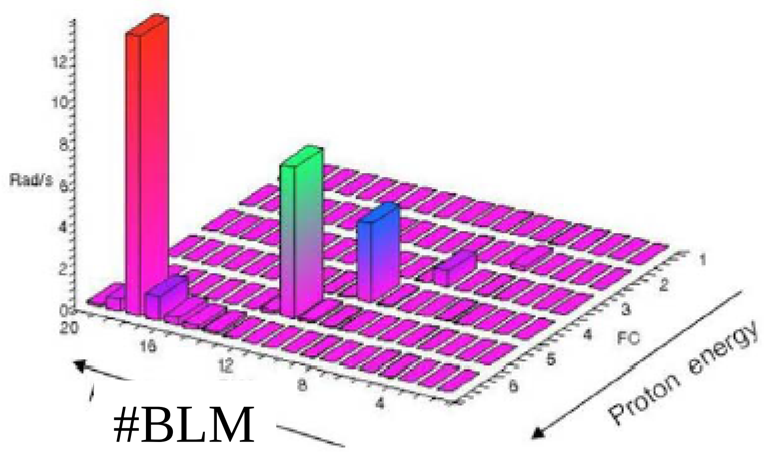
Electrons lose energy ΔE due to inelastic scattering (Bremsstrahlung) mainly on the nuclei of the residual gas molecules. The deviation of the electron orbit from the nominal orbit depends on the dispersion function in the accelerator and on ΔE. Therefore the electrons may be lost behind the following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

Electron Beam Loss Monitors for HERA, F. Ridoutt, et al, EPAC 1994 and
A New Theoretical Design of BLM System for HLS II, *Yukai Chenet al.*, IPAC 2013

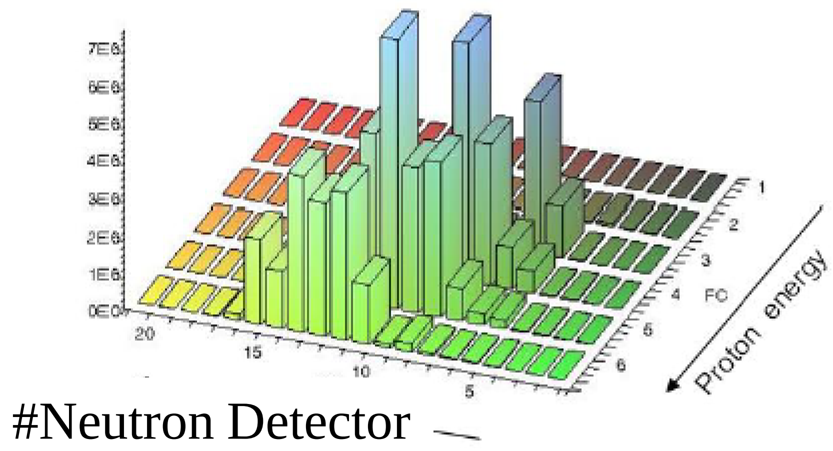


The Electron beam Lifetime Problem in HERA.
D.R.C. Kelly et al., PAC 1995

Monte Carlo calculations for calibration and positioning (VII)



Losses measured by ionization chambers



Losses measured by neutron detectors

This is explained by a neutron's ability to penetrate beam pipes (the main materials are copper and steel, which don't attenuate neutrons effectively), whereas ionization chambers detect mainly gammas, which are effectively attenuated by these materials. The ionization chambers respond to nearby loss and thus are able to resolve loss location, but they will be insensitive to loss occurring between two detectors. Conversely, the neutron detectors respond to any loss, close or remote, and are effectively covering a wider region, but are incapable of spatial resolution.

SNS: Beam Loss Simulation of SNS LINAC, A.P. Zhukov , PAC 07,Albuquerque, New Mexico, USA.
ESS: Technical Note ESS/AD/0032.
J=PARC: Signal Response of the Beam Loss Monitor as a Function of the Lost Beam Energy, K. Yamamoto, IBIC2015

Sensitivity

Where to put the BLMs to measure beam losses with high efficiency ε_{BLM}?

1. Use of a **Monte Carlo Program** with the (more or less) exact geometry and materials between the beam loss and the BLM **to define the Loss Efficiency** $\boldsymbol{\varepsilon_{BLM}}$ = $N_{BLM}(t)$ / with $N_{BLM}(t)$ = rate of (signal-generating) particles reaching the BLM. N_{loss} (t)

2. Number of lost Beam particles N_{loss} (t) by knowing the **Sensitivity** of the BLM (S_{BLM}) on (signal-generating) particles.

=> $\mathbf{Sig_{BLM}}(t) = S_{BLM} * N_{BLM}(t) \Leftrightarrow \mathbf{N_{loss}(t) = Sig_{BLM}(t) / (\varepsilon_{BLM} * S_{BLM})}$

2) BLM Types:

Mostly used devices:

Short ion chambers
Long ion chambers
Photomultipliers with scintillators (incl. Optical Fibres)
PIN Diodes (Semiconductors), Diamonds
Secondary Emission
Cherenkov light, Optical Fibres

Focus: Sensitivity (S_{BLM})

More exotic:

Neutron BLMs
…

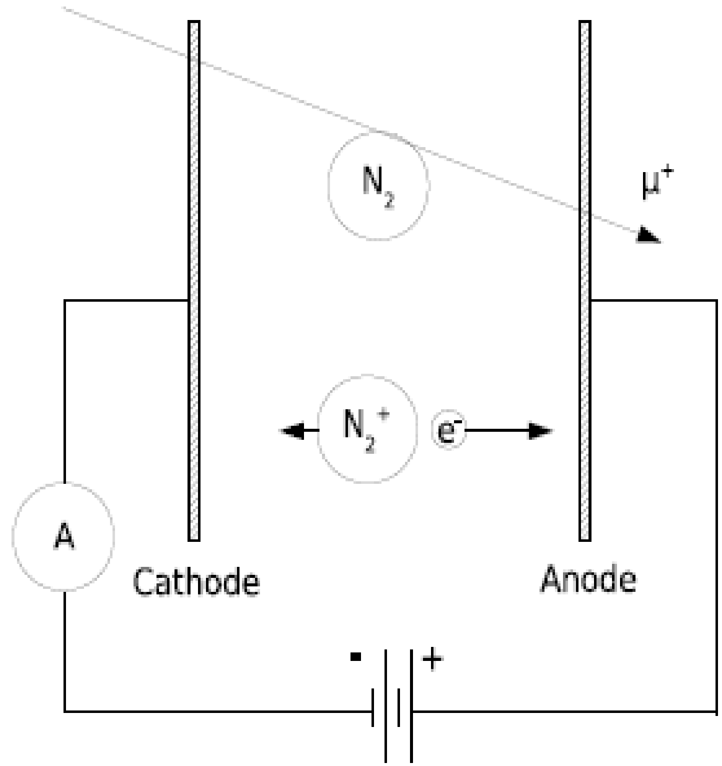
Dosimetrie is excluded here. Typically interest in long time scales (hours-days-years), BLMs in short time scales (few turns to 10 ms)
Differential beam current measurement is excluded here, no loss location measurement.

Short Ionization Chamber

Short ionization chambers are used in many accelerators.

Principe:

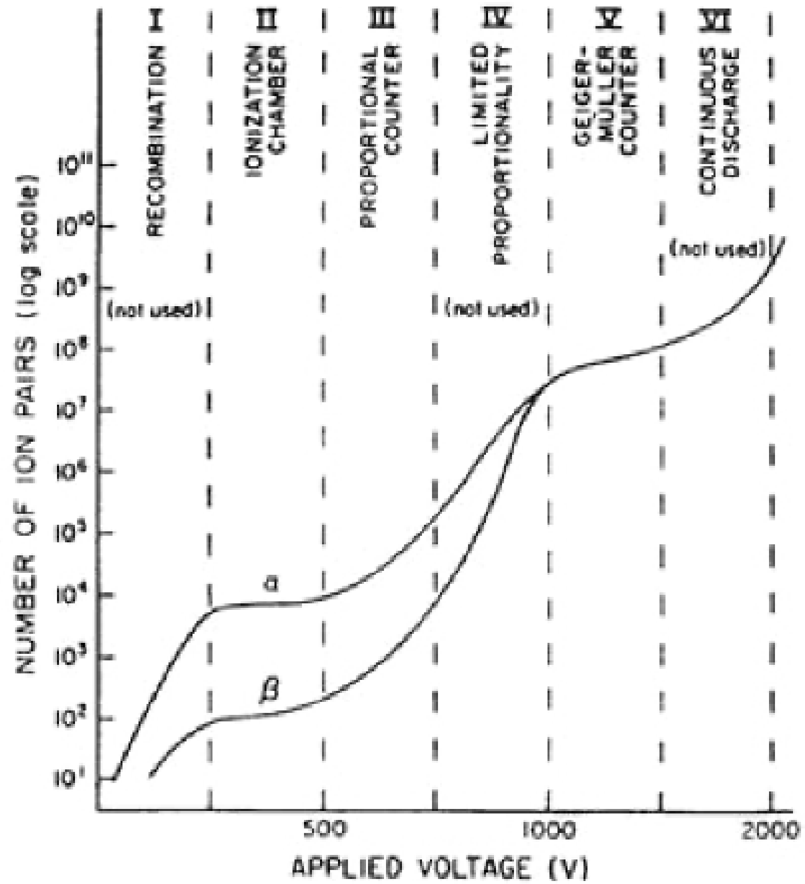
An ionization chamber in its simplest form consists of two parallel metallic electrodes (anode and cathode) separated by a distance D. High voltages, V, up to several kV, are applied to the anode. The gap, of width D, between the two electrodes is filled with gas (air, argon, xenon) or liquid of **density 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 field 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.

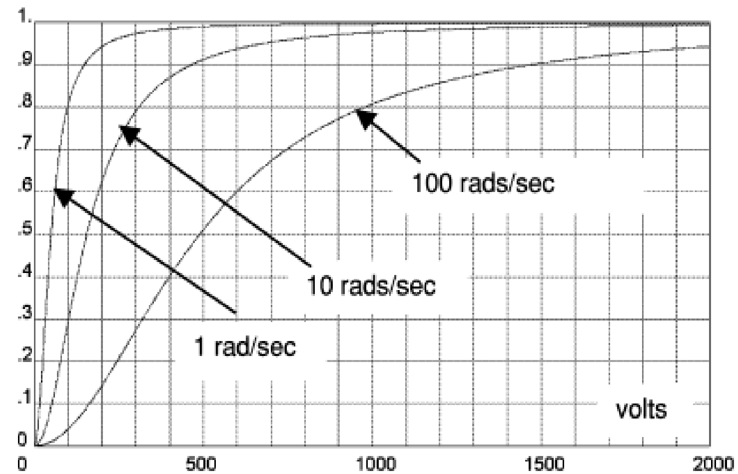
Saturation in high radiation:

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.

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

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

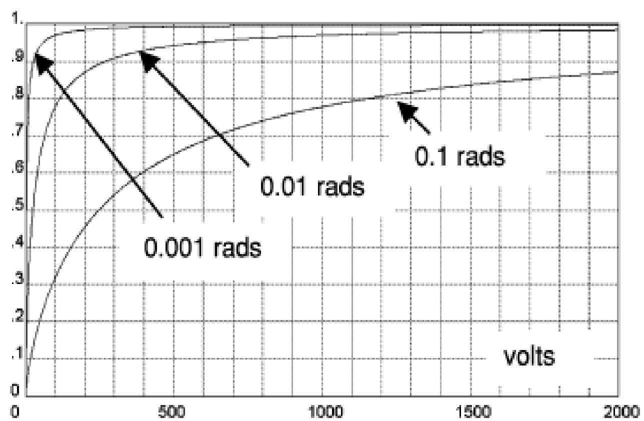


Figure 5. Predicted charge-collection efficiency for 3 pulsed doses vs. voltage.

Improving Ion Transit Time

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

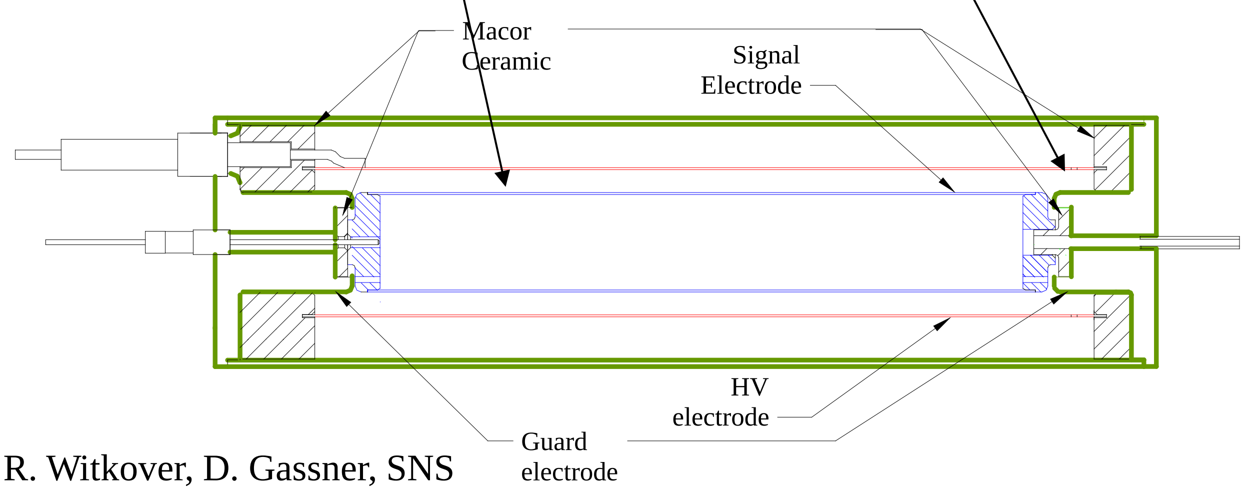
Where μ_0= Ion Mobility, V= Voltage, P/P_0 = Pressure (Atm)

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



Tevatron Ion Chamber (1983)

Short Ionization Chamber

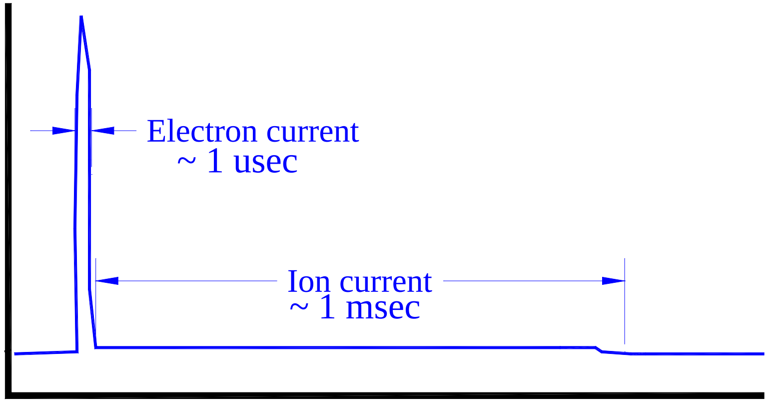
Fast reaction time=> high charge velocity v

$v = \mu \cdot V/D$
with μ = mobility [$cm^2/(V\ s)$];
V = Voltage, D = Gap [cm]

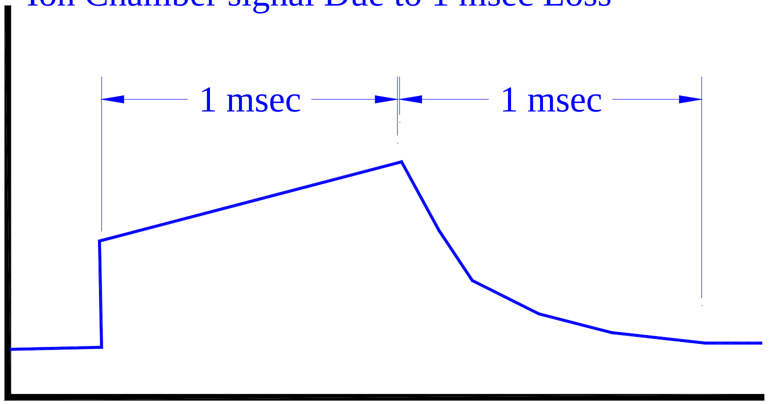
Ion mobility: $\mu_{ion} = 1.0 – 1.5\ cm^2\ atm/(V\ s)$ for typ. chamber gases at D = 1 cm, p = 1 atm, V = 1kV
=> response time of **t = 1 – 1.5 ms** which is often too slow for BLMs.

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:

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

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:
$\rho = 1.661 \cdot 10^{-3}$ g/cm^3 (20^{0}C, 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

$n_e \approx 100$/cm · D [e/ MIP]

Note: Cross section for nuclear interaction is about 5 $\cdot 10^{-6}$ 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.

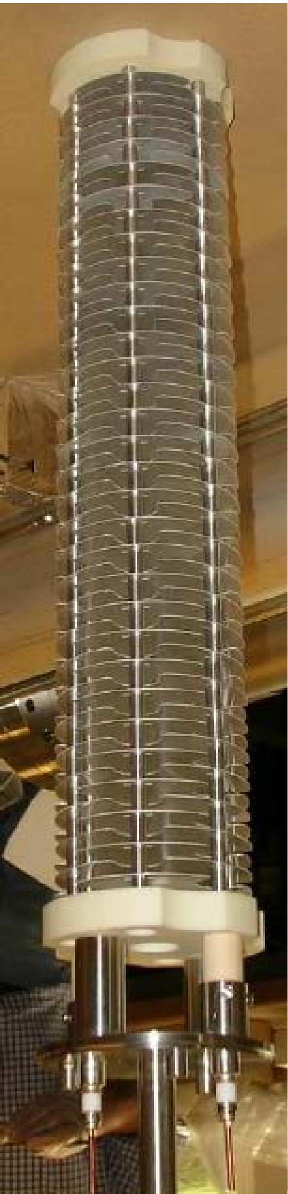
Sensitivity

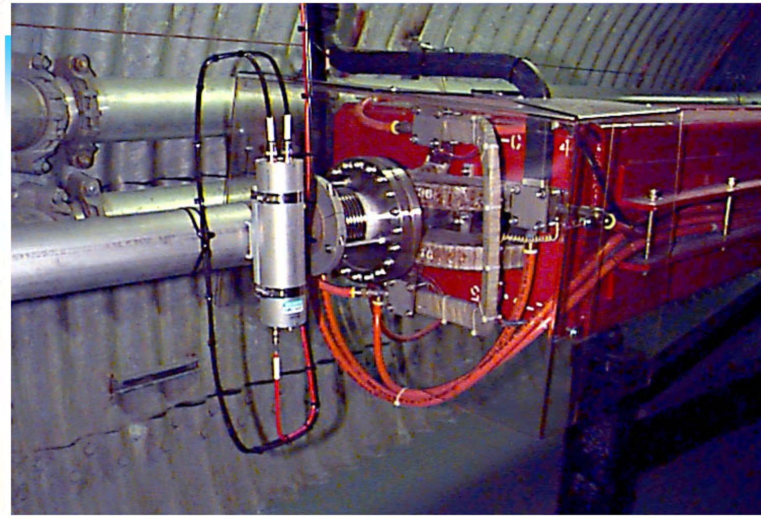
Sensitivity S_{Ion} [C/rad] of Ion-chamber depends on geometry!

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

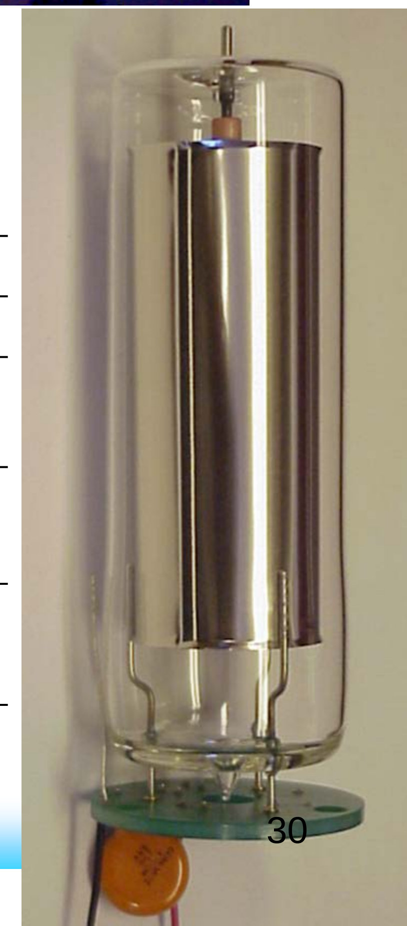
$$S_{Ion} = 100\frac{erg}{g} \cdot \frac{1eV}{1.6 \cdot 10^{-12} erg} \cdot \frac{1e^-}{26 eV} \cdot \frac{1.66 \cdot 10^{-3} g}{cm^3} \cdot 1000\, cm^3 \cdot \frac{1.6 \cdot 10^{-19} C}{e^-} = 638 \frac{nC}{rad}$$

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.

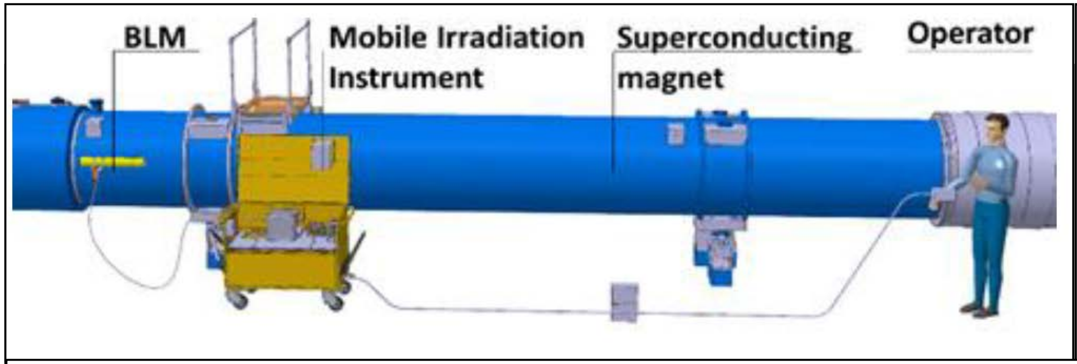
• Little **maintenance** required. Leakage in N2 filled chambers not critical

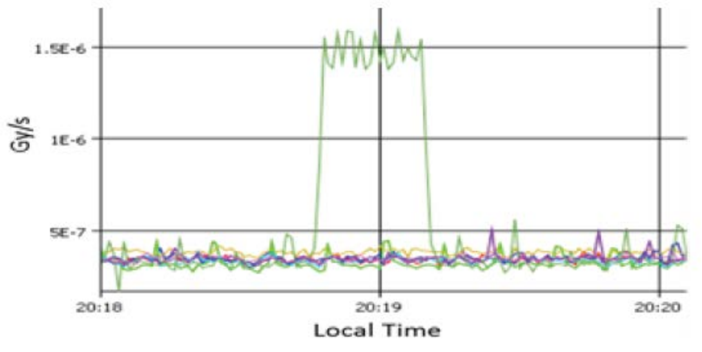
• Ion-chambers can be build from **radiation hard** materials (ceramic, glass metal), with no aging. Take care about the feedthroughs! No problems up to more than 10^8 rad

• Readout: **High dynamic range** need special signal processing (log. Amps, counting schemes, lot of ADC bits, … (LHC: dyn. Range ≈ 10^7

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

• **LHC:** It is necessary to periodically verify the connection to the corresponding channels of the electronic system and the **signal quality of all detectors by radioactive source**. -> remote by robot see later



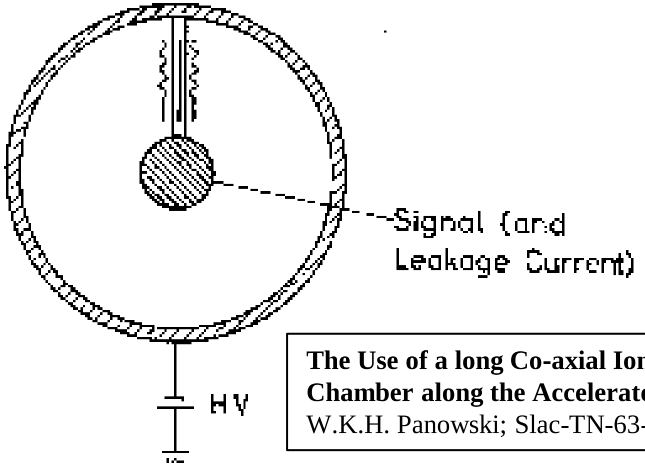


CONSTRUCTION OF A MOBILE IRRADIATION INSTRUMENT FOR THE VERIFICATION OF THE CERN LHC BEAM LOSS MONITORING SYSTEM
D. Gudkov, et al, IBIC17

"Panowskys" Long Ionization Chamber (PLIC)

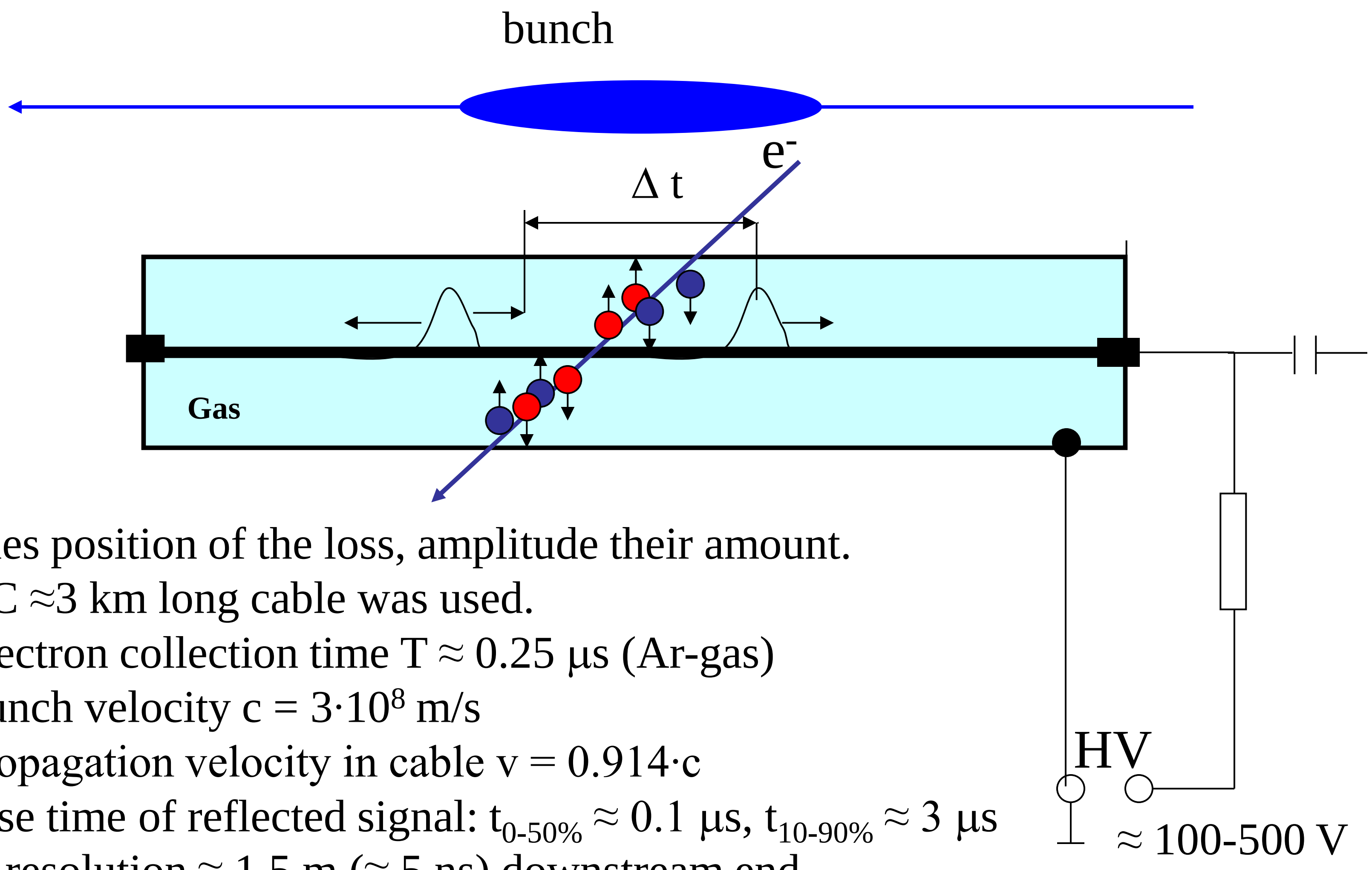
Heliax RF-cable

+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)



The Use of a long Co-axial Ion Chamber along the Accelerator;
W.K.H. Panowski; Slac-TN-63-57

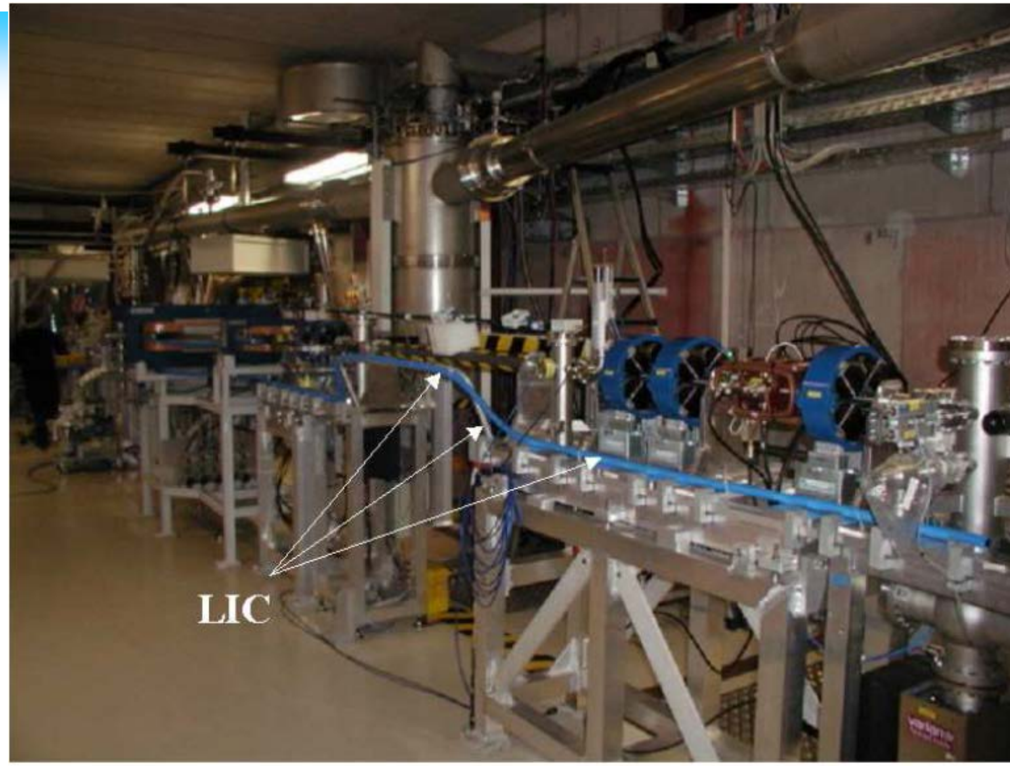
"Panowskys" Long Ionization Chamber (PLIC)



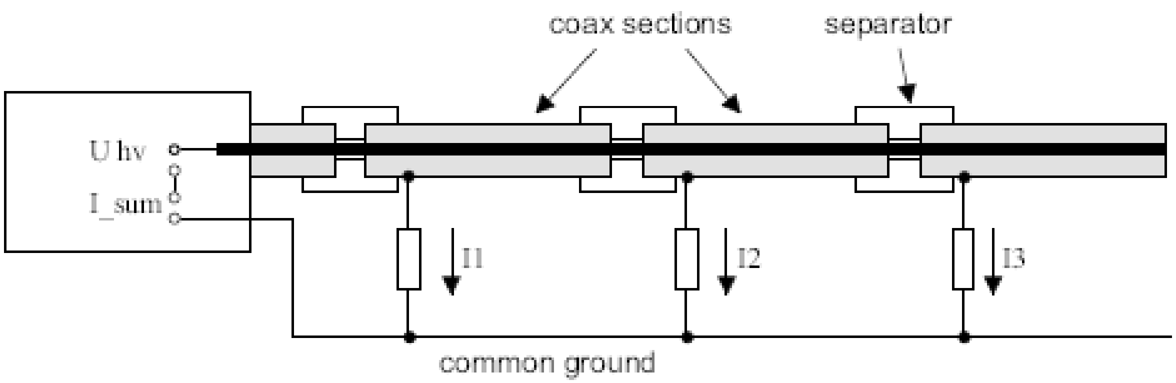
Δ t defines position of the loss, amplitude their amount.
At SLAC ≈3 km long cable was used.

- 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·c
- Rise time of reflected signal: $t_{0\text{-}50\%} \approx 0.1$ μs, $t_{10\text{-}90\%} \approx 3$ μs

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



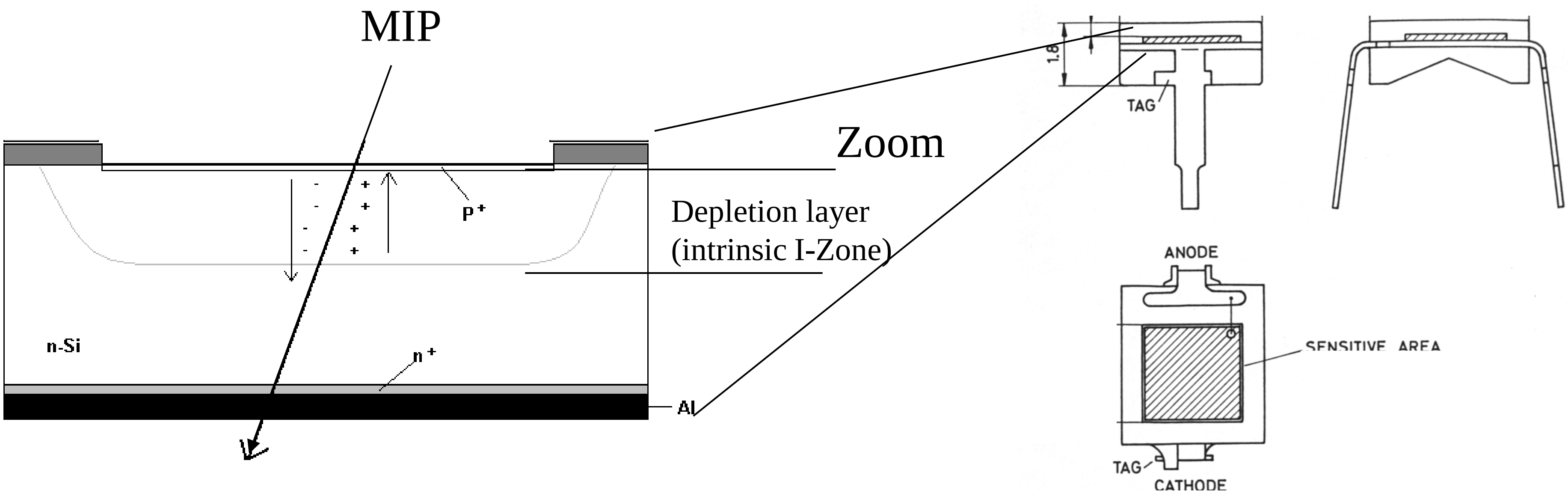
Installation of LIC at the ELBE beamline

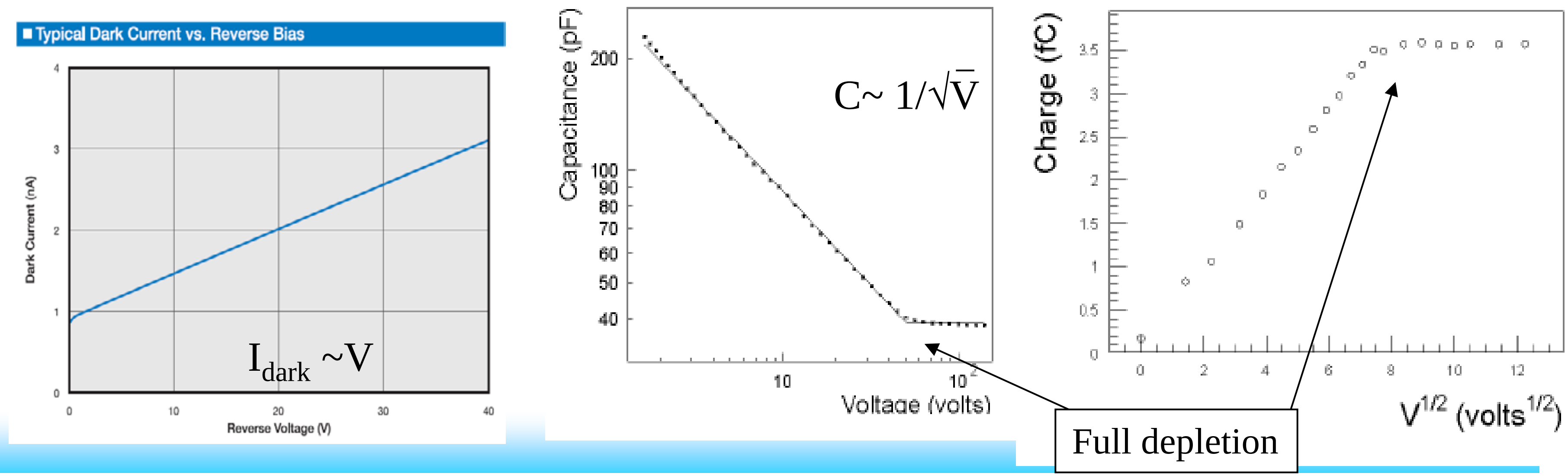


Principle of the sectioned beam loss monitor

Beam Loss Monitoring with Long Ionization Chambers at ELBE, A Beam Loss Monitor with Longitudinal Resolution, Michel, P. et al; Radiation Source ELBE Annual Report 2002, FZR-375 April 2003

Solid State Ion-Chamber – PIN Photodiode
(Semiconductor)





Solid State Ion-Chamber – PIN Photodiode
(Semiconductor)

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.)

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

$$\Rightarrow S_{PIN} = 10^4\,\frac{e}{MIP}\cdot 3.1\cdot10^7\,\frac{MIP}{cm^2\cdot rad}\cdot 1.6\cdot10^{-19}\,\frac{C}{e} = 50\,\frac{nC}{rad\cdot cm^2}$$

⇒S_{PIN} ≈ 50 nC/rad for 1cm^2 Diode

⇒ **Fast: ≈ 2 - 20 ns (Pulse Mode)**

Mobility μ_e = 1350 cm^2/(Vs)

μ_{hole} = 450 cm^2/(Vs)

⇒ Efficiency ε ≥ 80%

⇒ Works like an Ion Chamber (current mode)

Solid State Ion-Chamber – CVD Diamonds

Synthetic Diamond grown by chemical vapor deposition method

		Silicon	Diamond
Atomic number		5.43	3.57
Atomic mass		14	6
Mass density	[g cm^{-3}]	2.329 [49]	3.515 [49]
Melting point	[K]	1685 [49]	4100 [49]
RT Band gap	[eV]	1.124 [49]	5.48 [49]
LHe Band gap	[eV]	1.17 [50]	5.45 [50]
Breakdown field	[V/μm]	30	1000
Relative dielectric constant		11.9 [49]	5.7 [49]
Energy to create eh-pair	[eV]	3.6 [51]	13 [52]
Intrinsic resistivity	[Ω cm]	$2.3 \cdot 10^5$	$> 10^{15}$
Detector capacitance	[pF]	8...10	2
Thermal expansion coefficient	[10^{-6} K^{-1}]	2.59 [49]	0.9 [55]
Thermal conductivity	[W cm^{-1} K^{-1}]	1.4	21 [55]
Ionisation loss from MIP	[MeVcm^2/g]	1.67 [44]	1.76 [44]
Mean charge per MIP	[fC/100 μm]	1.4 [44]	0.62 [44]
Displacement energy	[eV]	25 [56]	43 [57]

Table 3.1: Comparison table between diamond and silicon detectors. The capacitance is given for the following detector dimensions: 0.3x5x5 mm^3 for Si and 0.5x5x5 mm^3 for diamond.

The investigated option is to locate the detectors as close as possible to the superconducting coil, where the signal ratio is optimal. Therefore the detectors have to be located inside the cold mass of the superconducting magnets in superfluid helium at 1.9 Kelvin.

The silicon diode's FWHM of the signal from a Minimum Ionising Particle (MIP) is of 2.5 ± 0.7 ns and that for the diamond detector the FWHM is of 3.6 ± 0.8 ns at liquid helium temperatures. With these detectors a fast detection system can hence be designed. Leakage current ≈1 pA – 1 nA (Diamond)

$S_{Diam} = 0.44 * S_{PIN}$

Both types are quite radiation hard.

Diamond Monitor Based Beam Loss Measurements in the LHC
C. Xu, B. Dehning, et al., IBIC2016, Barcelona, Spain

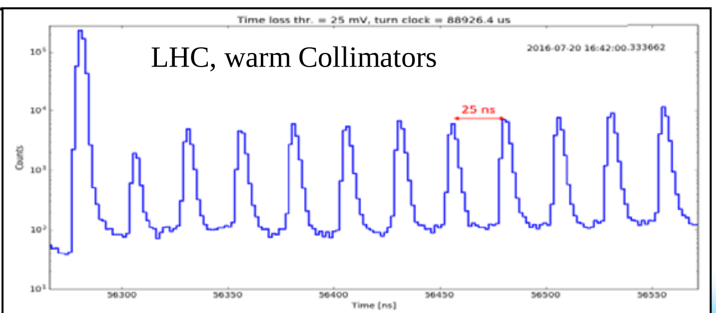
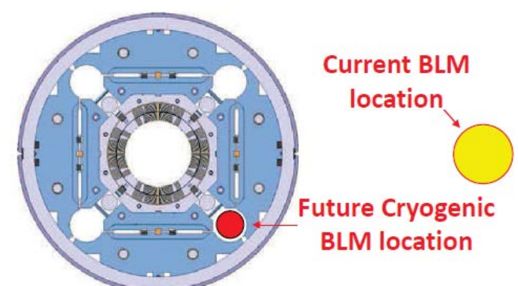


Figure 5: Zoom-in view of the 12-bunch train.



Cryogenic Beam Loss Monitoring for the LHC; C. Kurfuerst (TU Vienna), CERN-THESIS-2013-232

Operation of Silicon, Diamond and Liquid Helium Detectors in the Range of Room Temperature to 1.9 Kelvin and After an Irradiation Dose of Several Mega Gray; C. Kurfuerst, et al., IBIC2013, Oxford, UK

Use as counter:

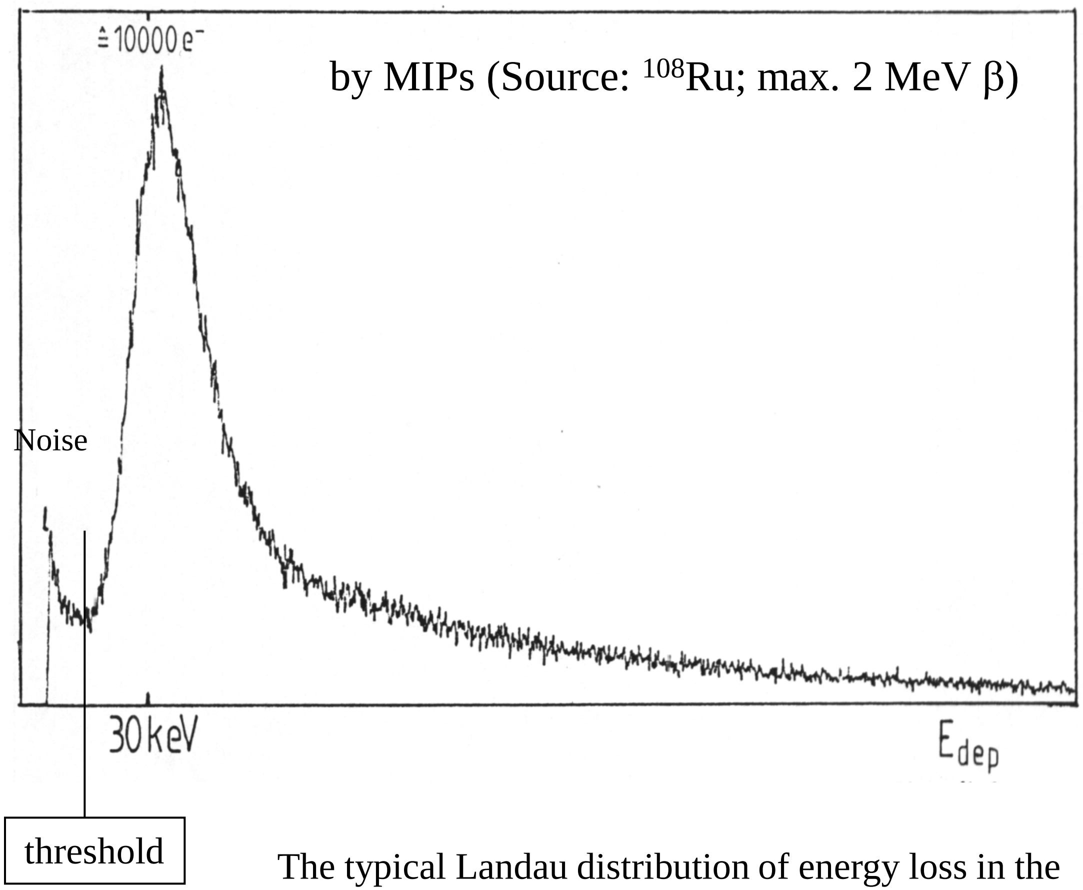
Enough signal to detect
1 MIP!

$\approx 10^4$ e/MIP (for 100μm dep.)

1 rad/s = $3.1\cdot10^7$ MIP/s/cm²

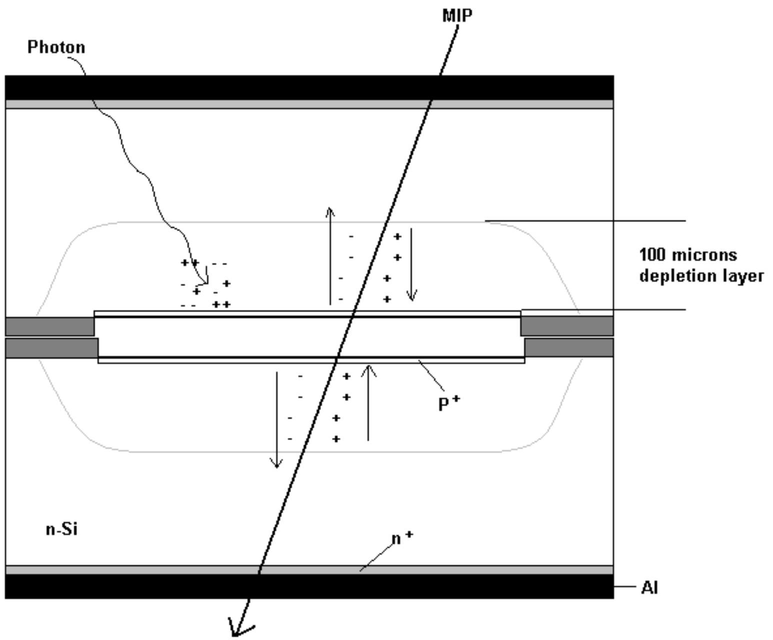
= $\varepsilon\cdot31$ MHz/cm²

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

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, $1cm^2$ Diodes)

+Very low noise:

+Dark count rate < 0.01 Hz

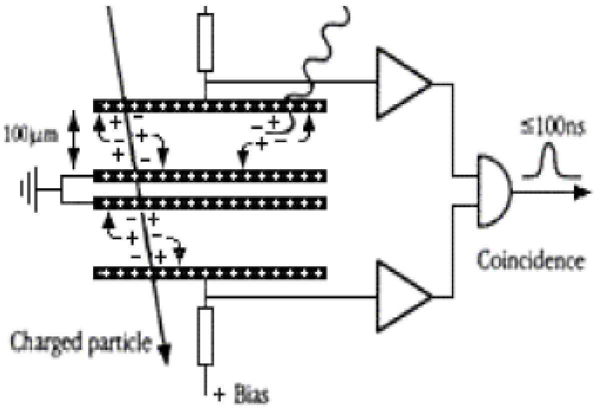
+max. count rate > 10.4 MHz

+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.)

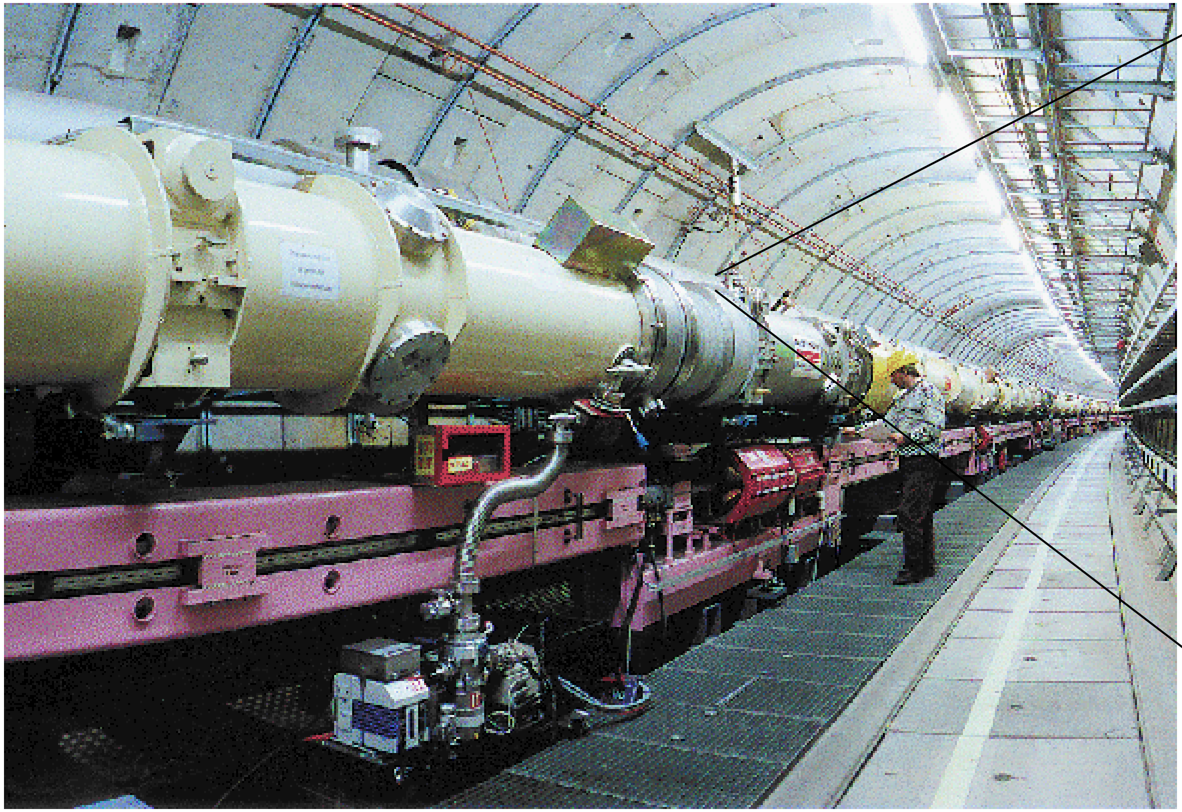


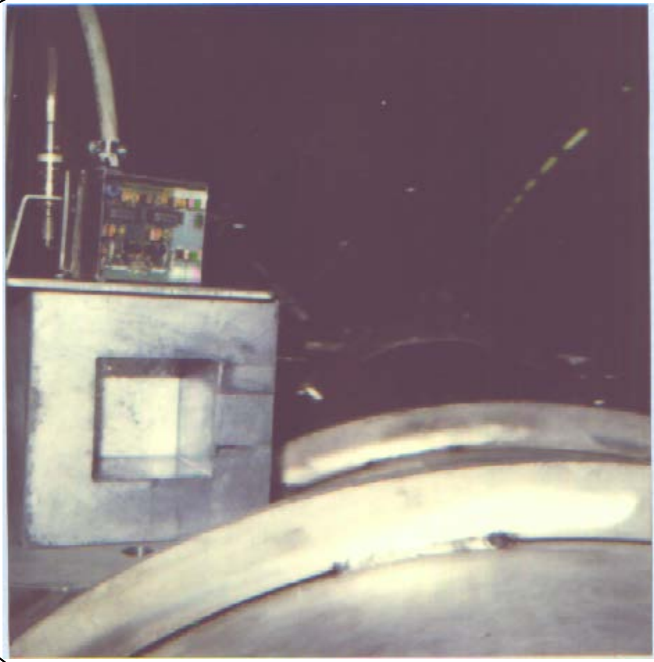
+ PIN Diodes + amplifiers were tested up to 10^8 rad without significant radiation damage; 13 years successful in HERA

- Complete saturation if count rate ≈ 1 count / bunch -> **Loss Efficiency ε_{BLM}**

THE PIN-DIODE BEAM LOSS MONITOR SYSTEM AT HERA, K. Wittenburg BIW2000

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.

Summing up

Devices using Ionization:

+ Simple, robust
+ Radiation hard
+ Cheap
+ Calibrated
+ Fast in Pulse Mode
(PIN + Diamond)
•(but due to small area=> insensitive)

Sensitivity:	
Ion Chambers:	**≈ 500 nC/rad (1ltr)**
PIN Diode:	**≈ 50 nC/rad for 1cm^2 Diode**
Diamond:	**≈ 0.44 * S_{PIN}**

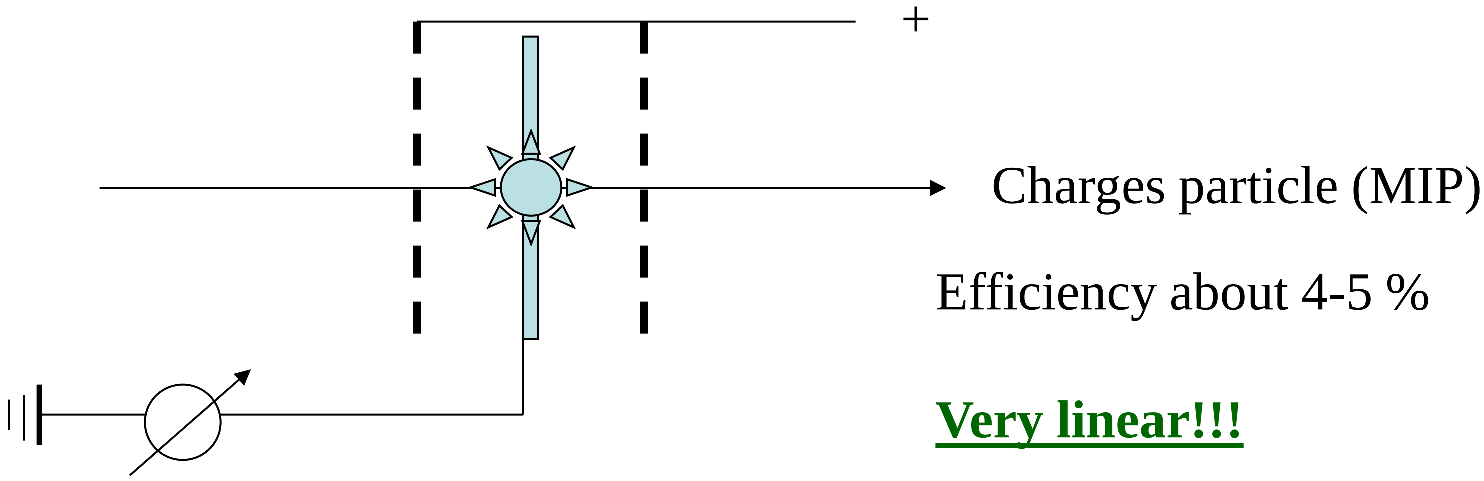
- Slow
    - (Ion Chambers ≈ μs,
    - (counting mode ≈ ms)
- **cannot measure bunch by bunch losses**

▪ Needs external amplification
▪ Moderate sensitivity

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

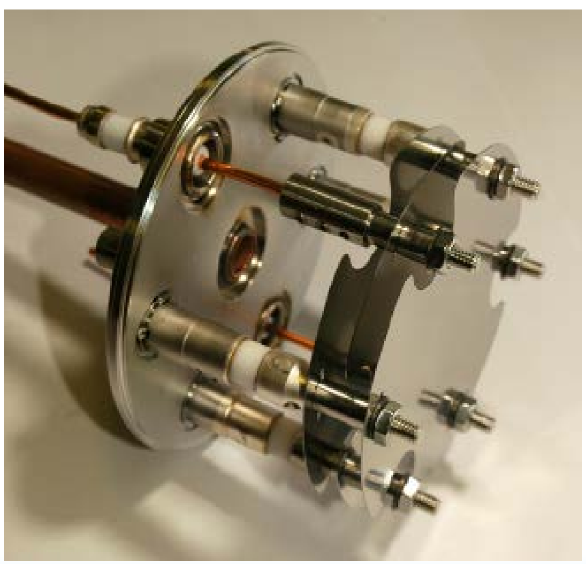


Efficiency about 4-5 %

Very linear!!!

Secondary Emission Monitors

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

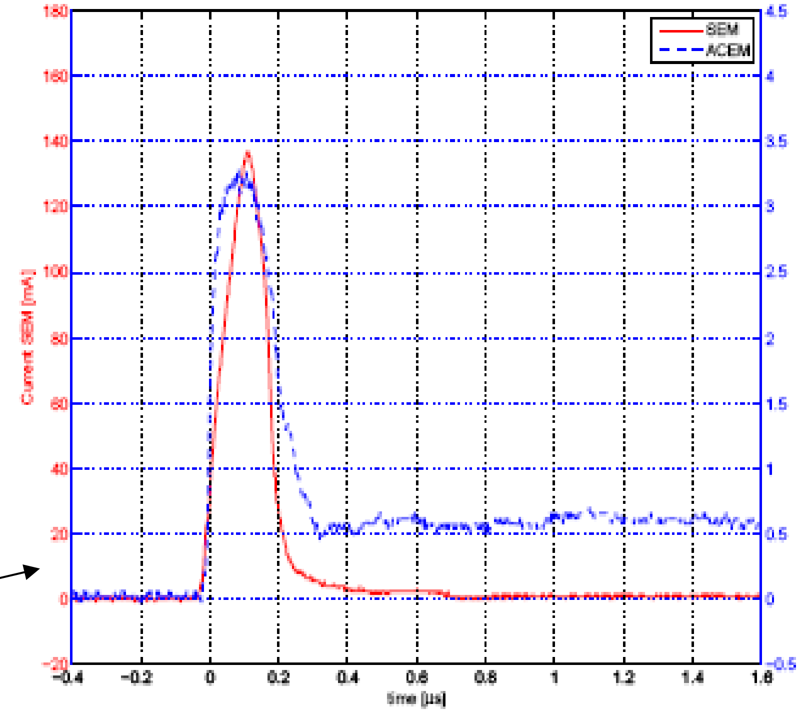


LHC

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 $2.16 \times 10^{12}\ p^+$ at 1.4 GeV).

Beam loss monitoring at the CLIC Test Facility 3; T. Lefevre,et al., EPAC'04, Lucerne, Switzerland

Secondary Emission Monitors

THORN EMI

NUCLEAR RADIATION DETECTOR TYPE: 9841

(Aluminium Cathode Electron Multiplier)

Description

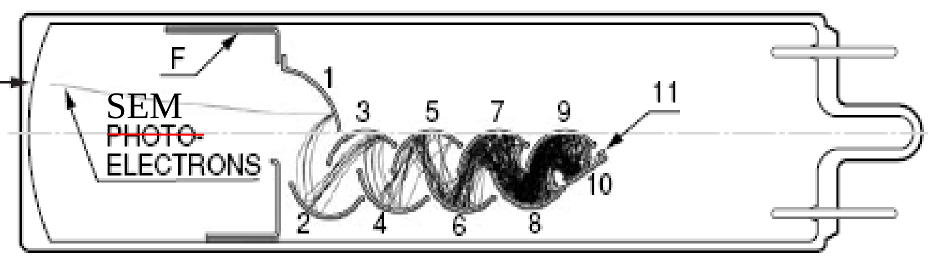
∅ 32 mm

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

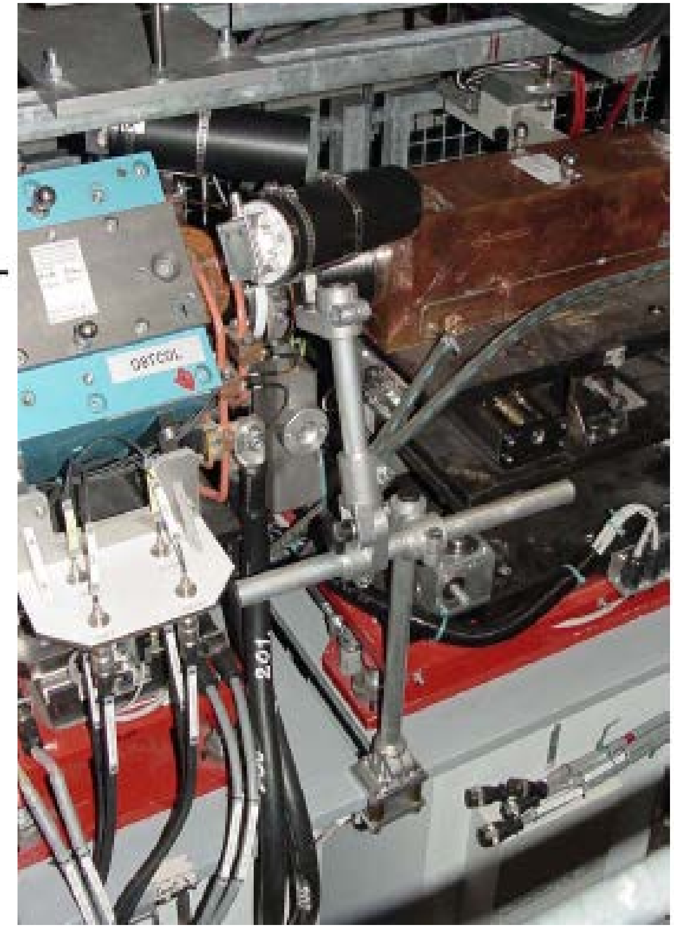
This tube is a development from the THORN EMI 9902 photomultiplier for direct measurement of ionising radiation, in the MeV to GeV region, associated with particle accelerators and nuclear reactors. It is intended as an alternative to the use of an ionisation chamber with improved linearity and response 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.

~~INCIDENT LIGHT~~

MIPs



1 to 10 = DYNODES
11 = ANODE
F = FOCUSING ELECTRODE



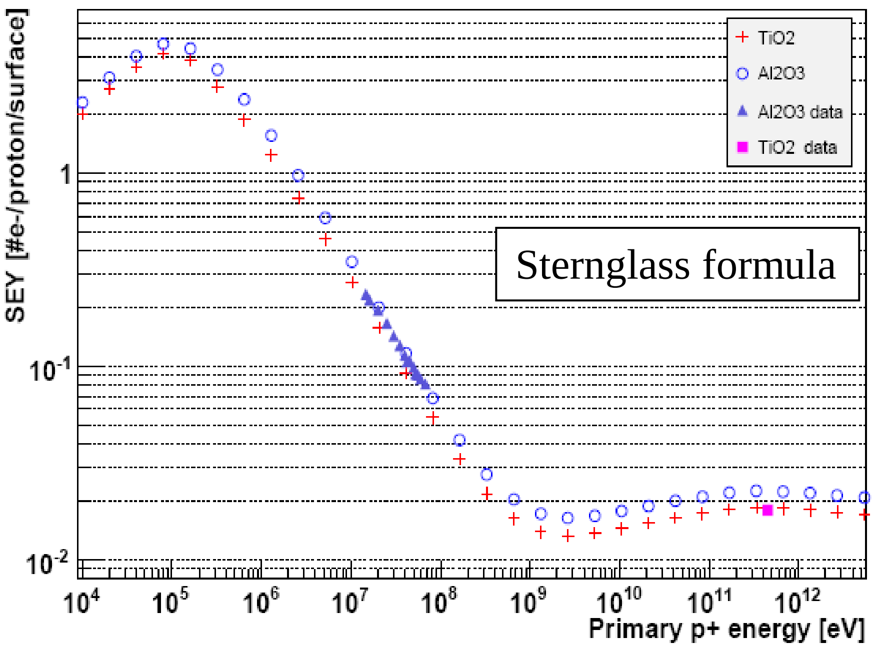
ACEMs at FLASH collimators

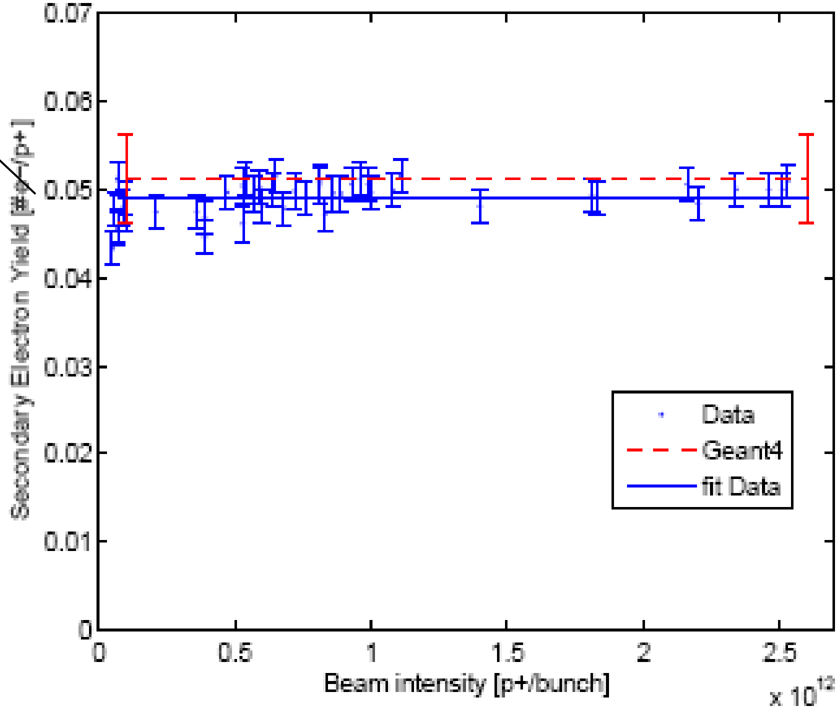
SEM Sensitivity (MIPs) :

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

Sensitive surface Ø = 3.2 cm = 8 cm^2

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





Summing up

Devices using SEM

+ 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})**

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

Scintillation counters

Using light

Remember:
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
+ It is easy to cut or form “Plastic Scintillators” to nearly any shape.

- Large inorganic crystals are expensive and small (NaJ, BGO, PbWO4, CsJ, …)
    - Mainly used for full absorption calorimeters in HEP-experiments

Scintillation counters

Examples of scintillator-PMT coupling with a light guide

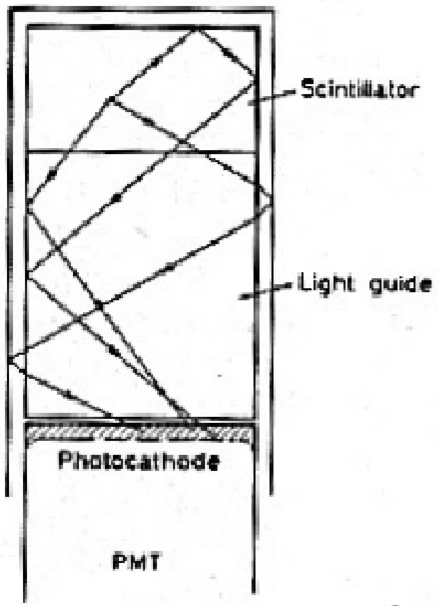
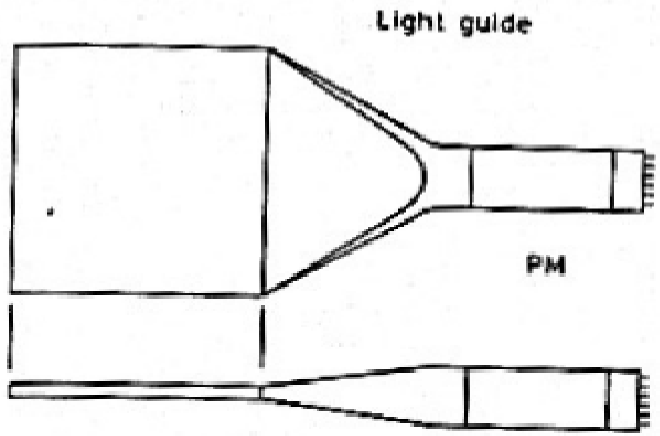
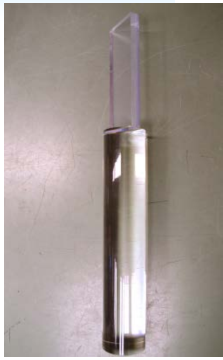


Fig. 9.5. Example of scintillator-PM coupling with a light guide



Scintillator with Plexiglass light guide



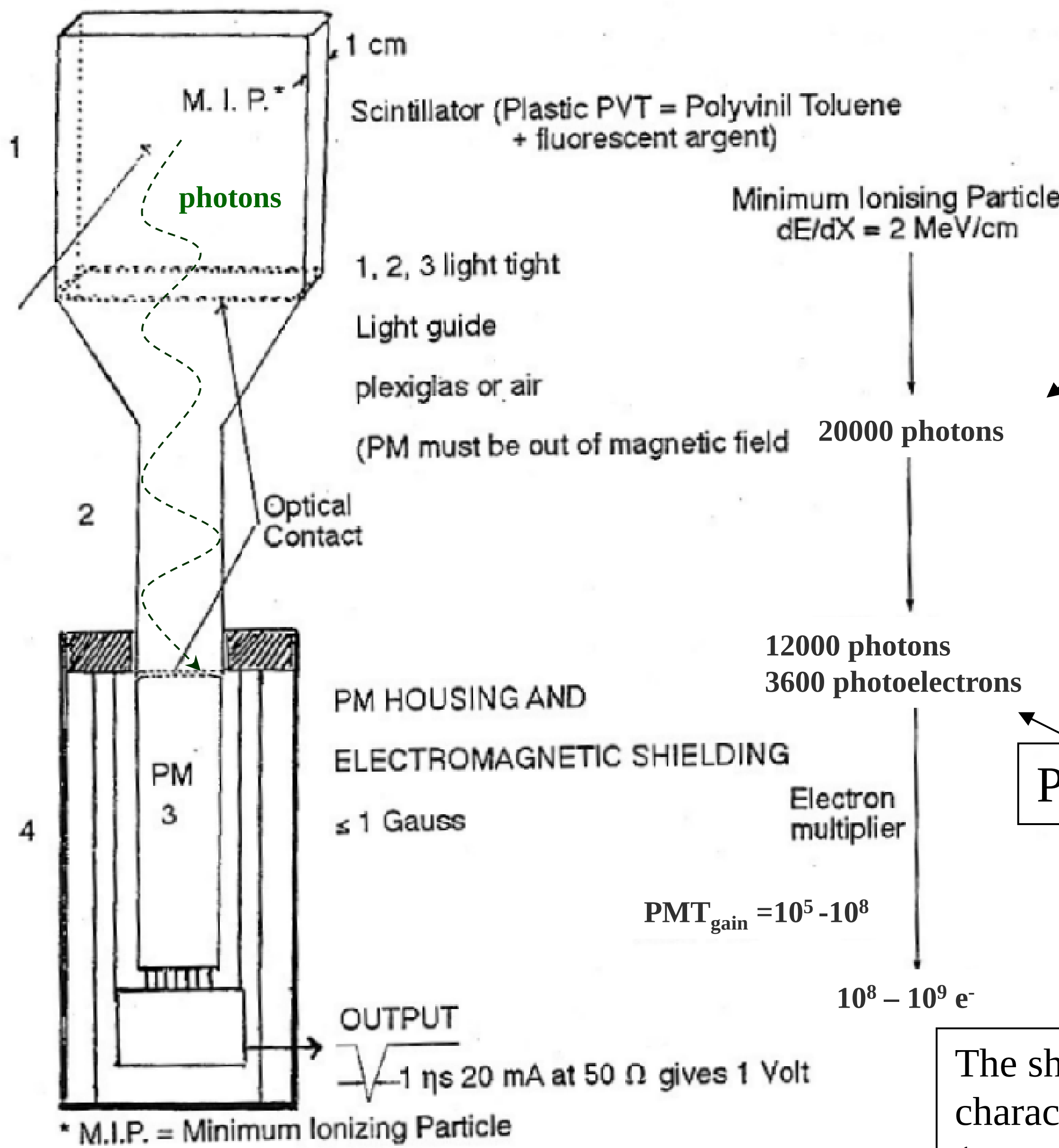
aluminum foil

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

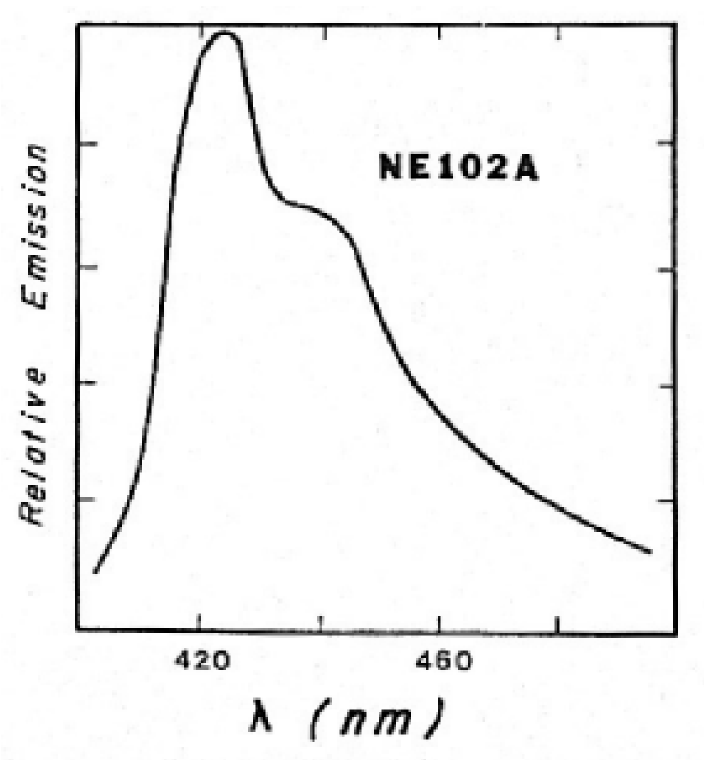
PMT: Photoelectrons are accelerated to first dynode. Tube has some 8 to15 dynodes with large (>>1) SEM coeff.

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.

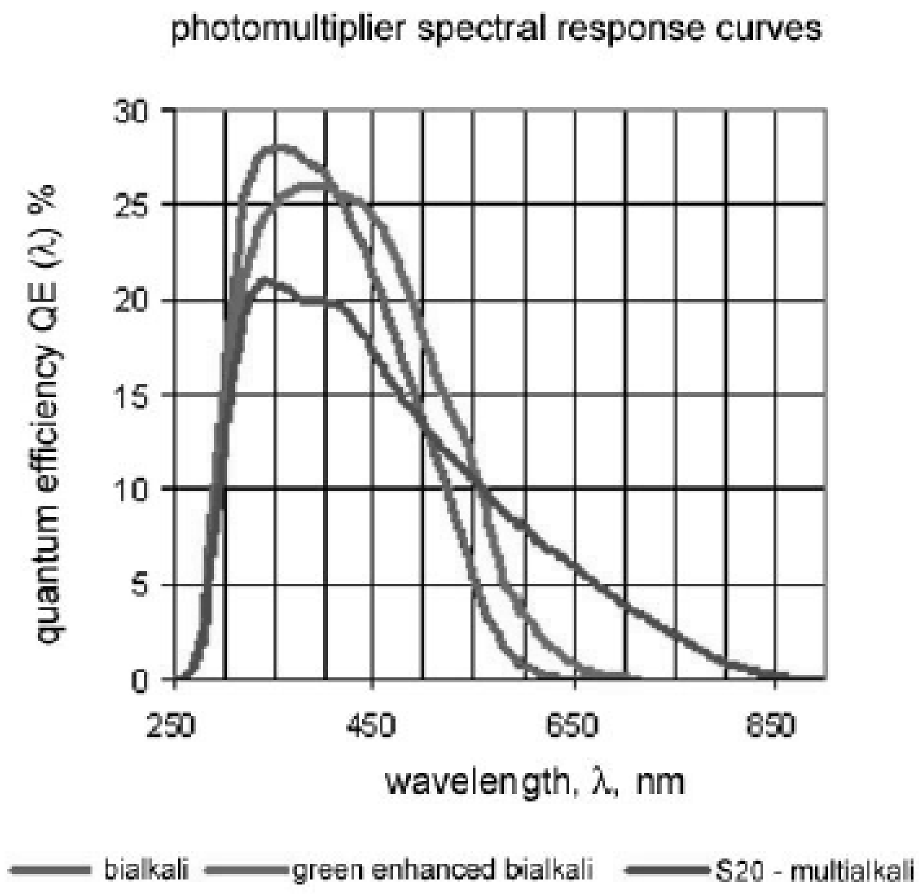
Ref. V Agoritsas, CERN PE-ED 001-92, rev. Nov. 1994

Scintillation counters

Emission spectrum of NE102A



Spectral response of a PMT photocathodes



Scintillation counters

Plastic (NE102)	Liquid (BC-501A)
25x16x2 cm^3	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,
ρ = 4.4 g/cm^3,
poor rad hardness)

Sensitivity:

1rad

$$\frac{100\,erg}{g\cdot rad}\cdot 830g\cdot\frac{1eV}{1.6\cdot 10^{-12}\,erg}\cdot R_s\approx 6\cdot 10^{14}\,\frac{photons}{rad} \Rightarrow$$

$$S_{Scint}=6\cdot 10^{14}\,\frac{photons}{rad}\cdot\varepsilon_{coll}\cdot\varepsilon_{cath}\left[\frac{elctrons}{photon}\right]\cdot\frac{1.6\cdot 10^{-19}\,C}{electron}\cdot PMT_{gain}=17\,\frac{\mu C}{rad}\cdot PMT_{gain}$$

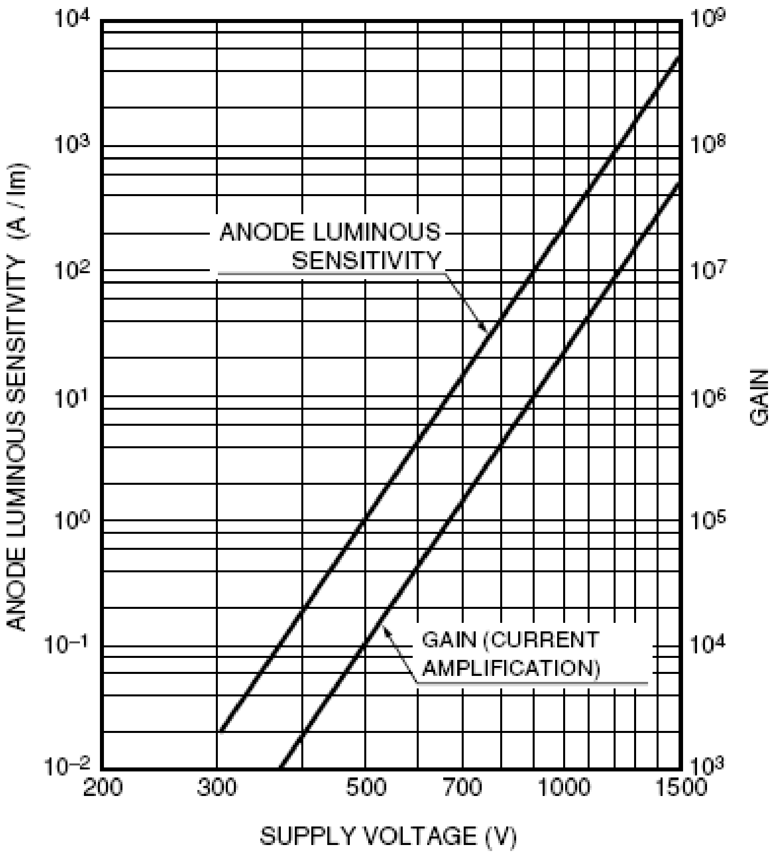


Figure 4-13: Gain vs. supply voltage

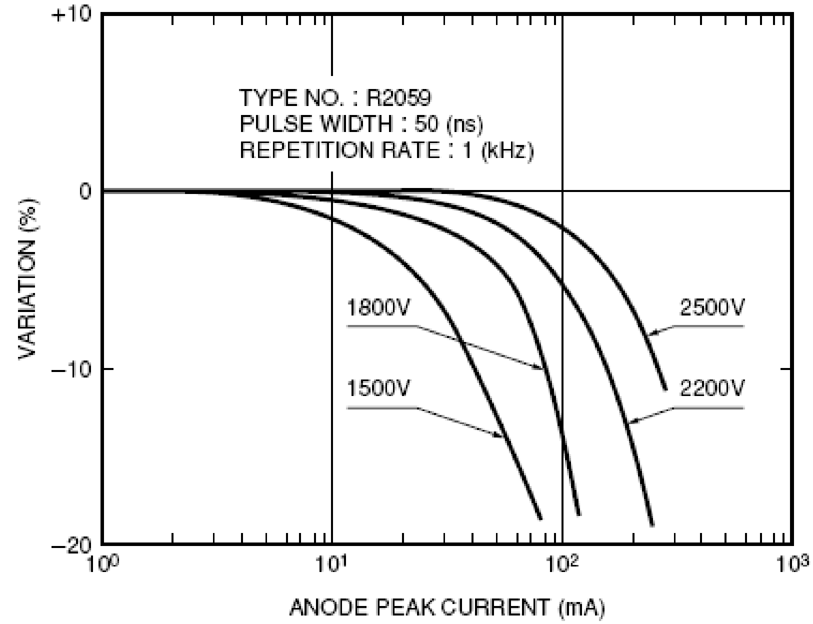


Figure 4-23: Voltage dependence of linearity

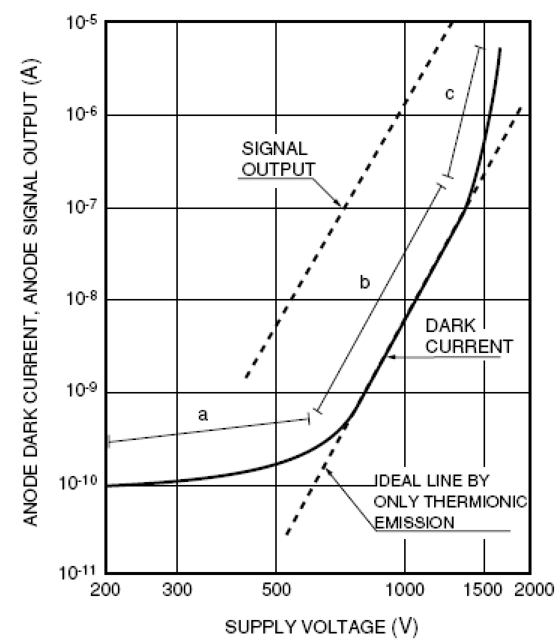


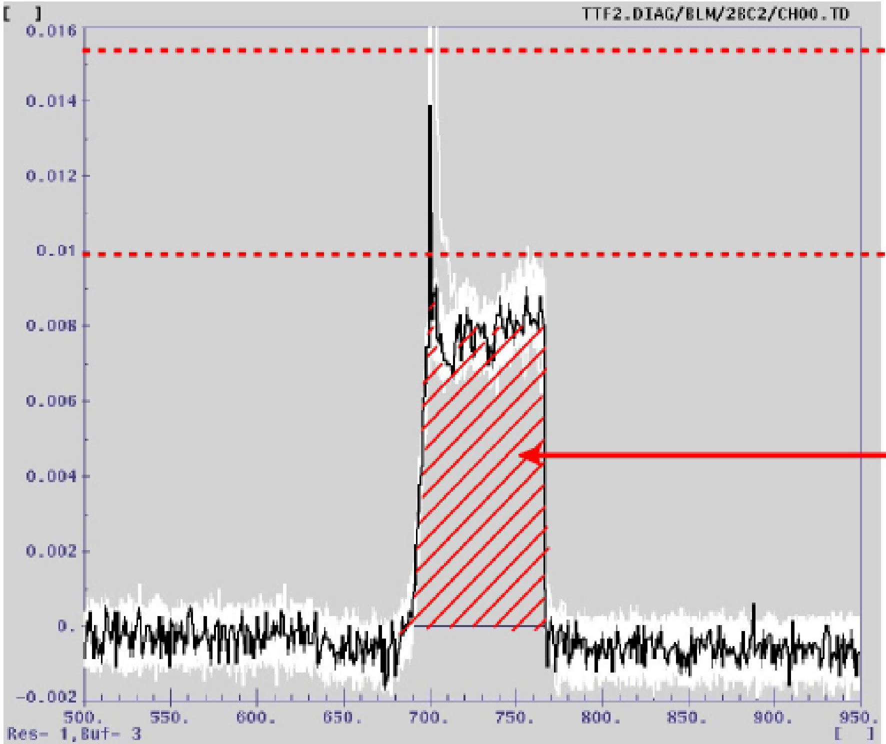
Figure 4-38: Typical dark current vs. supply voltage characteristic

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

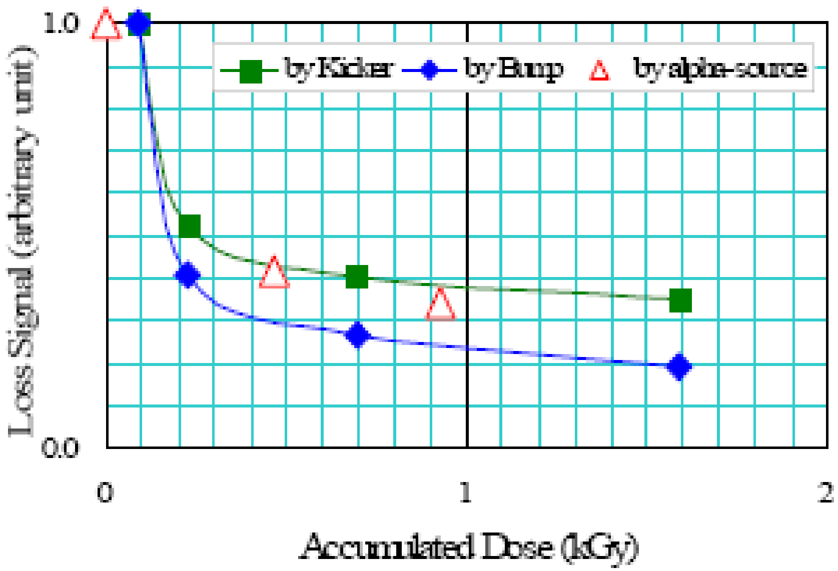
Scintillator assemblies and installations in FLASH and XFEL

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



XFEL Beam Loss Monitor System
A. Kaukher, et al., (BIW12)

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

S. Goulding, R.H. Pohl 1972

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.

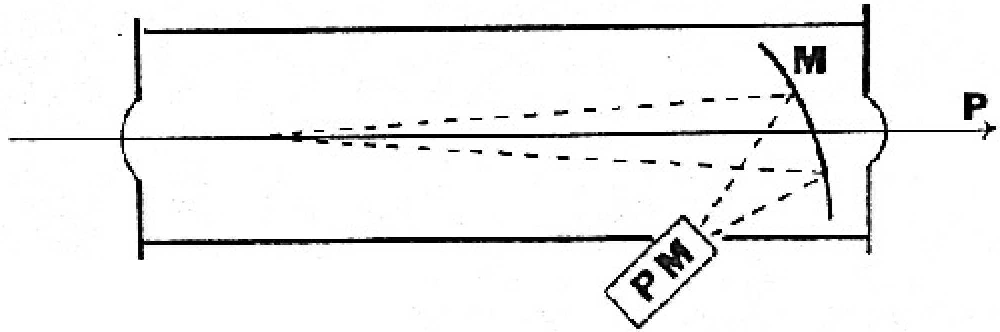
$$photon\ yield: \frac{dN}{dx} = 2 \cdot \pi \cdot \alpha \cdot \sin^2\Theta \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

$\cos\Theta = \frac{1}{\beta \cdot n}$ *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: => $\beta \approx 1$

Fused silica: => n= 1.55 => $\Theta = 49.8^0$ => 227 photons/cm

ε_{coll} =80% (only for directed light!!), ε_{cath} = 30%

A detector of 10x10x10 cm^3 (1 ltr.)

good radiation hardness

1 rad

$$\frac{3.1 \cdot 10^7 \, MIPs}{cm^2 \cdot rad} \cdot \frac{227}{MIP} \cdot 1000 cm^2 = 7 \cdot 10^{12} \, \frac{photons}{rad}$$

$$S_{Che} = 7 \cdot 10^{12} \, \frac{photons}{rad} \cdot \varepsilon_{coll} \cdot \varepsilon_{cath} \cdot \frac{1.6 \cdot 10^{-19} \, C}{e^-} \cdot PMT_{gain} = 270 \, \frac{nC}{rad} \cdot PMT_{gain}$$

- **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.

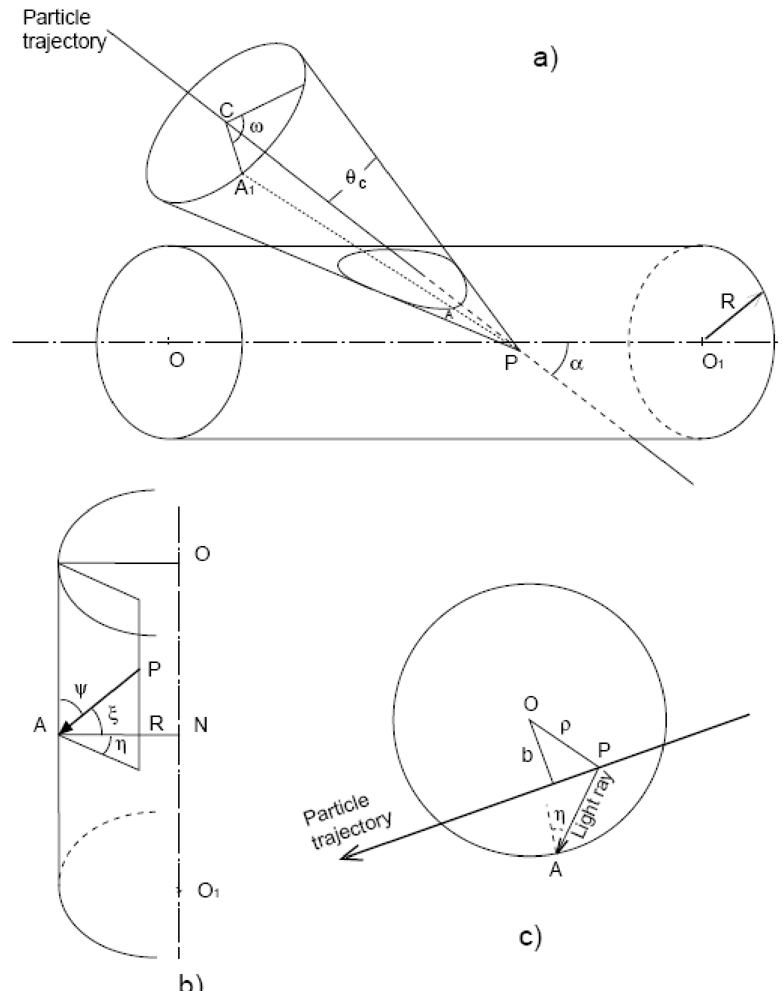
Cherenkov cone for β=1 particles is $\Theta \approx 47^0$.

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

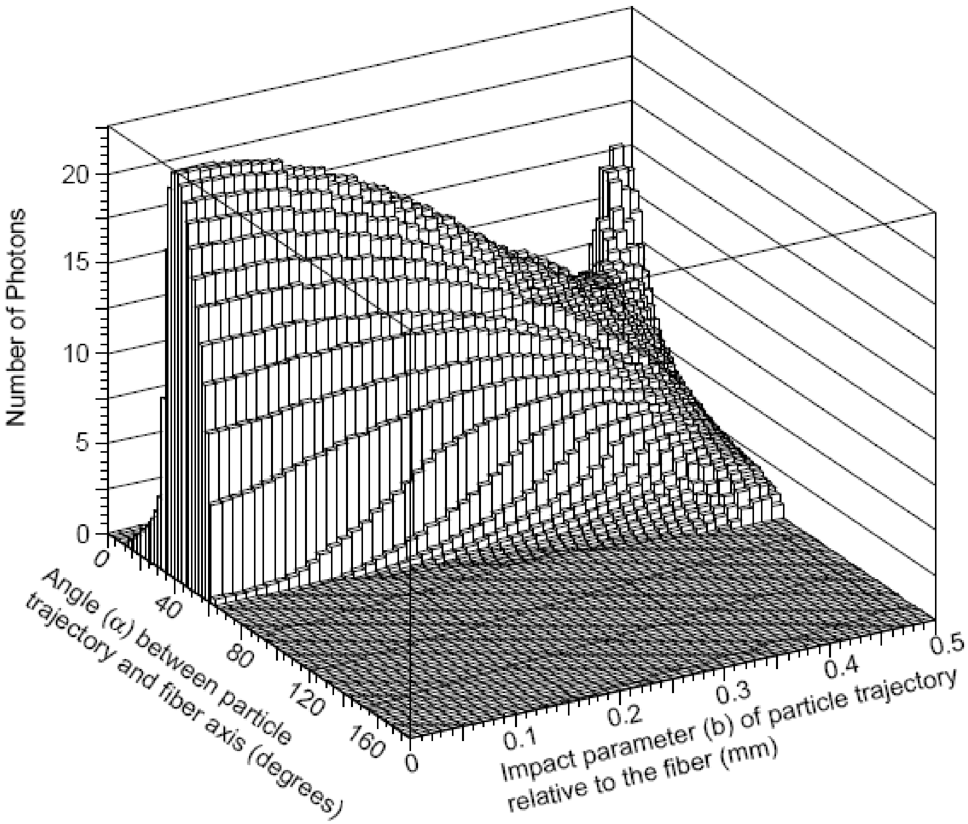


THE CHERENKOV EFFECT IN OPTICAL FIBERS.

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

Assume (simplified, assume same n)
R=100 μm = 0.01 cm
L = 100 cm
Vol = $R^2 * \pi * L = 0.03\ cm^3$
Compare with 1 ltr. ($1000 cm^3$):
S_{Che} = 270 nC/rad
$\Rightarrow S_{fibre} = S_{Che} * 3*10^{-5} * 0.37 =$

$\Rightarrow S_{fibre} = 3*10^{-3}$ nC/rad



Summing up

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)

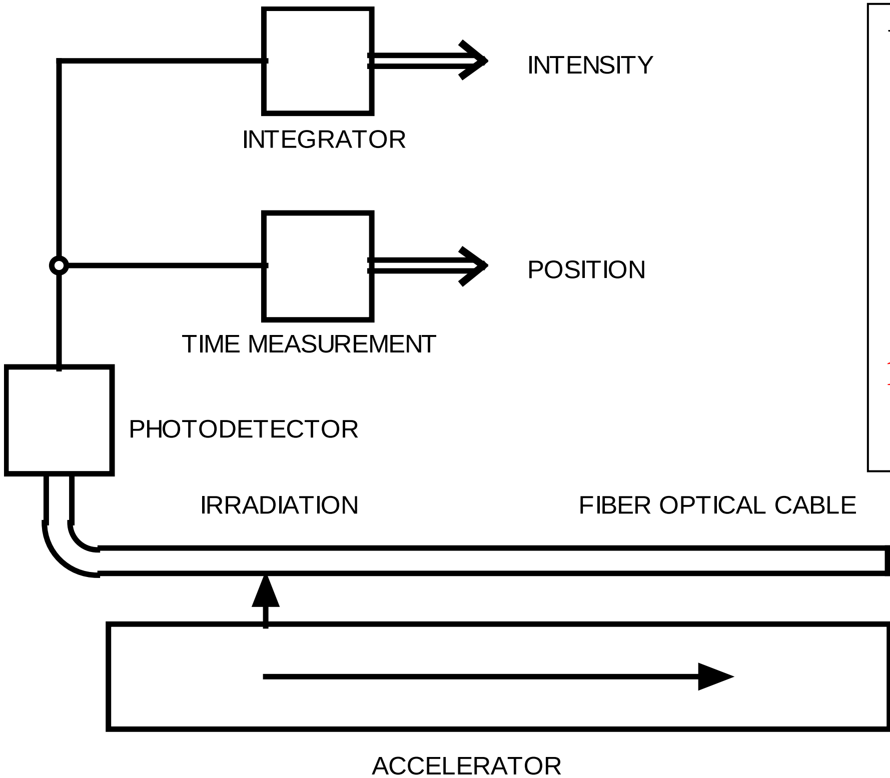
- Needs photon-to-charge converter (PMT, APD, PIN, …)

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.)**
	≈ $3 \cdot 10^{-3}$ nC/rad(· PMT_{gain}) for 1 m Cherenkov fiber

Optical fibers (Cherenkov light)

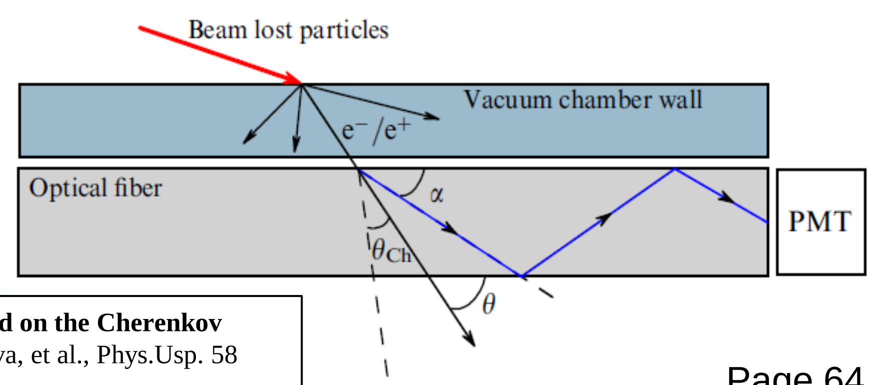
A Beam Loss Monitor (BLPM) based on Cerenkov light in optical fibers allows real time monitoring of loss location and loss intensity like in PLICs. The fast response of the Cerenkov signal is detected with photomultipliers at the end of the irradiated fibers.



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 ---



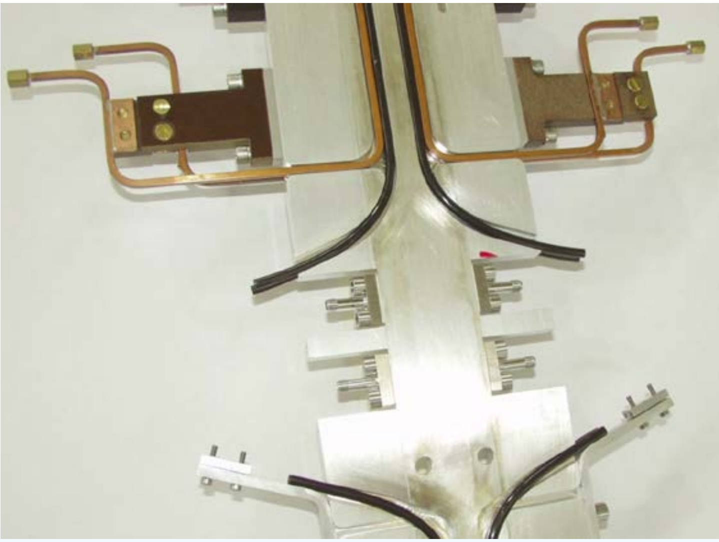
Local Beam Loss and Beam Profile Monitoring with Optical Fibers, F. Wulf, M. Koerfer DIPAC2009, Basel, Switzerland

Distributed beam loss monitor based on the Cherenkov effect in an optical fiber, Yu Maltseva, et al., Phys.Usp. 58 (2015) 5

Optical fibers (Cherenkov light)

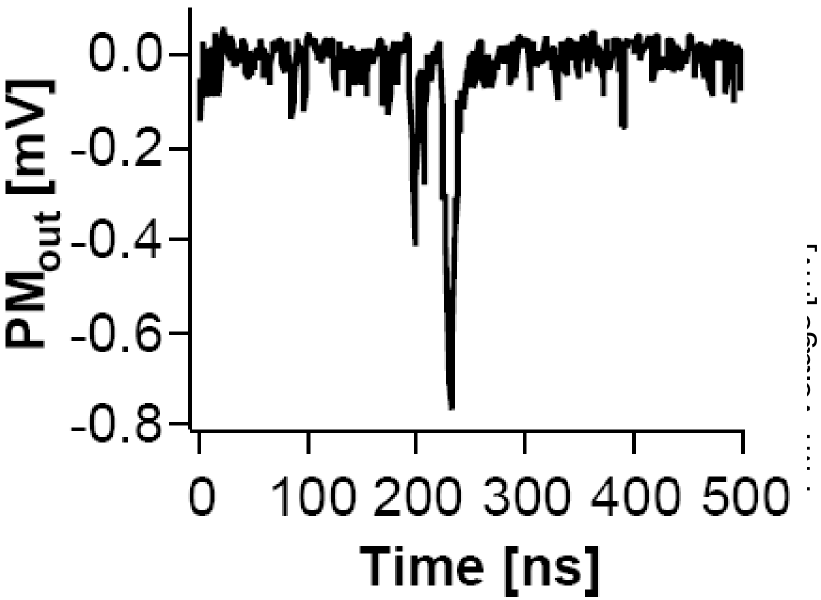
Fibers embedded in FLASH undulator vacuum chamber

Photos by U. Hahn, DESY

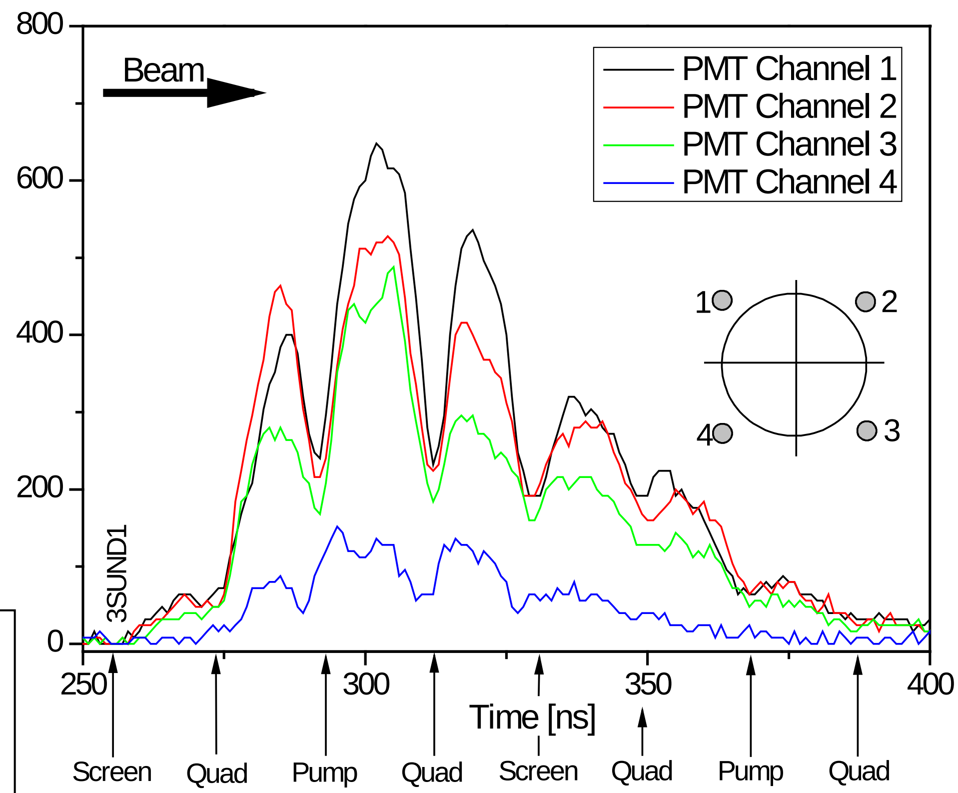


Optical fibers (Cherenkov light)

Along accelerator (TTF)



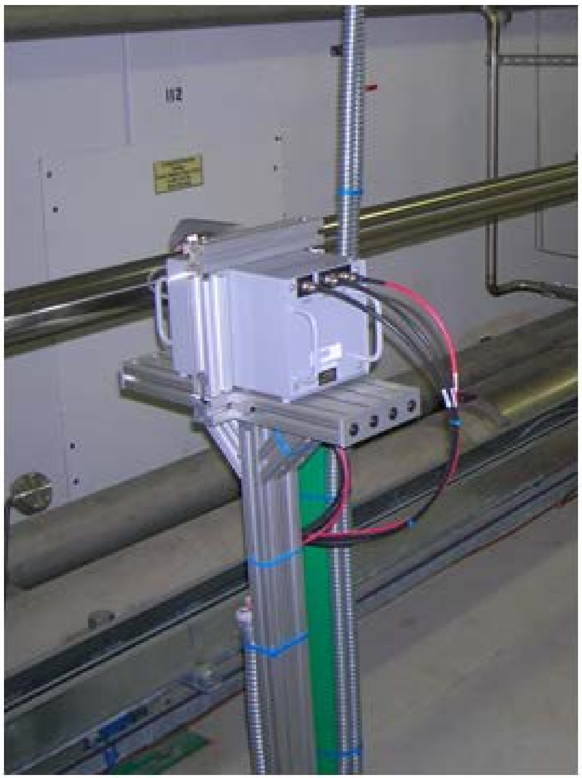
Longitudinal loss profile
and transversal loss position



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

BEAM LOSS POSITION MONITOR USING CERENKOV RADIATION IN OPTICAL FIBERS. M. Körfer et al., DIPAC 2005, Lyon, France

Neutron Detector



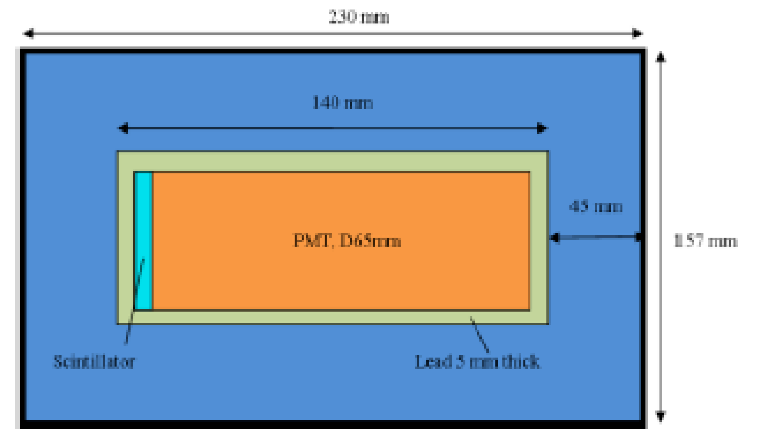
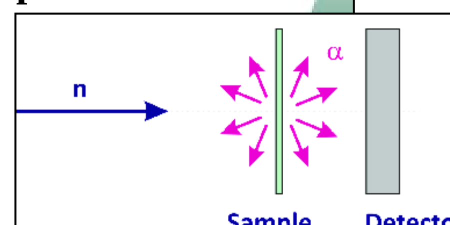


Figure 1: Neutron Detector is a 230x157x150mm box. PMT is inside x-ray shielding (lead) and is surrounded by polyethylene neutron moderator.

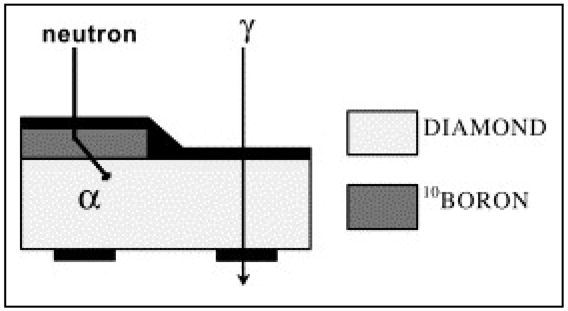
- 35 mm poly moderator
- Li (n,alpha)
- Scintillator detects the alphas
- PMT
- $10^4 - 10^8$n/cm^2/s
- 0.03eV - 3MeV



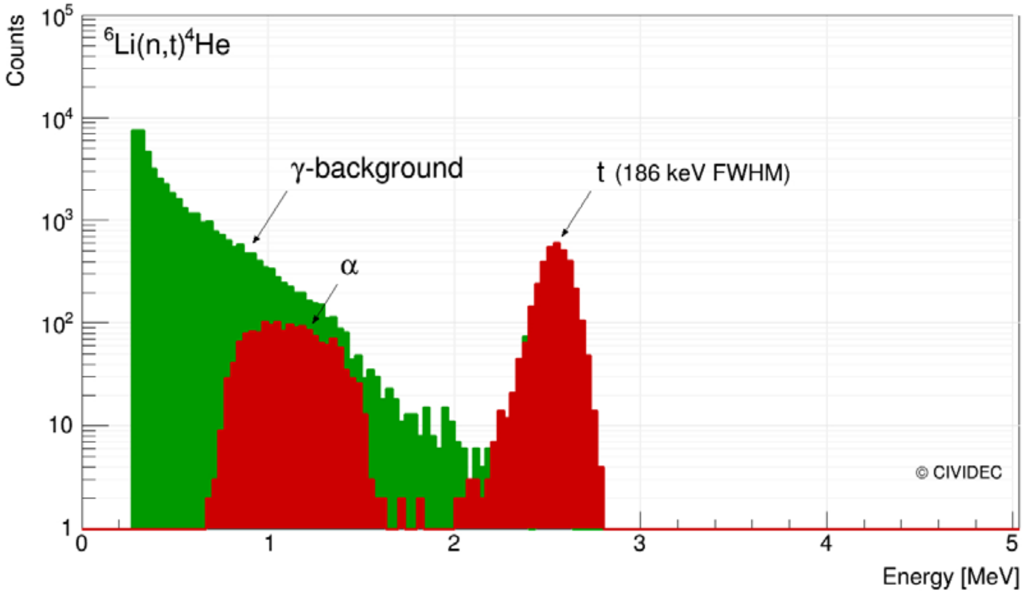
5 Managed by UT-Battelle for the Department of Energy

A. Zhukov SNS BLM System Overview Detectors, Measurements, Simulations WGF04 - HB2008 8/26/2008

Neutron BLMs



An insight into neutron detection from polycrystalline CVD diamond Films; C.Mer et al., Diamond and Related Materials 13 (2004)



The A7 Diamond Thermal-Neutron Monitor can be adapted for application where particle discrimination is of interest. With the **ROSY®** AX106 n-γ Discrimination Application, background photons are rejected in real time with an efficiency of 99%, for a puristic thermal-neutron measurement for count rates up to 3 MHz.

The Figure shows results from a measurement in the thermal neutron beam at the Institute of Atomic and Subatomic Physics of TU Wien, Vienna/Austria. Despite the high photon background from the reactor, the α particles from ^{6}Li(n,α)t could be extracted from the spectrum.

Detection efficiency: 0.5% for thermal neutrons
(A7 Diamond Thermal-Neutron Monitor Data sheet, **cividec.at**)

https://cividec.at/index.php?module=public.product&idProduct=6&scr=0

Do not forget: Electromagnetic particles (here photons) can generate neutrons!

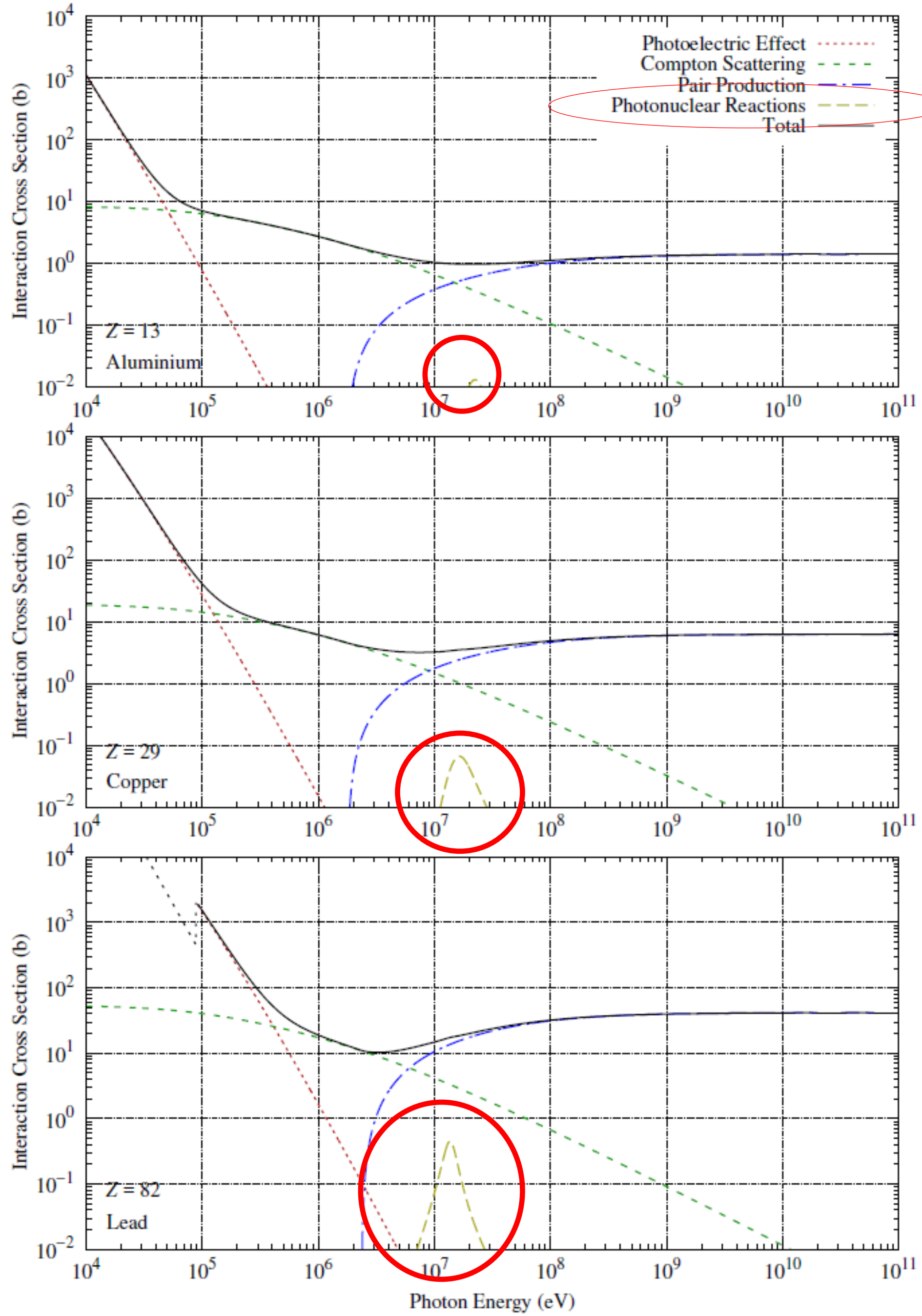


Fig. 5: Total cross-sections for photonic interactions in aluminium, copper, and lead

4. Conclusions I

For MIPs; without (tube-) amplification:

Detector	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	$\approx 17 \cdot 10^3$ (· **PMT_{gain}**) (1 ltr.)	
Inorganic Scint.	50 - 250	10^4 - 10^5	$\approx 100 \cdot 10^3$(· **PMT_{gain}**) (1 ltr.)	
Gas Ionization:	22 – 95	≈100 (Ar,1 atm., 20^0C)	≈ 500 (· **$Elec_{gain}$**) (1ltr)	
Semiconductor (Si):	3.6 13 (Diamond)	10^6 $3.6 \cdot 10^5$ (Diamond)	≈ 50 (· **$Elec_{gain}$**) (1 cm^2 PIN-Diode)	≈ 22 (· **$Elec_{gain}$**) (1 cm^2 Diamond)
Secondary emission:	2-5%/MIP (surface only)	0.02-0.05 e/MIP	$\approx 2 \cdot 10^{-3}$ (· **PMT_{gain}**) (8cm^2)	
Cherenkov light	10^5 - 10^6	≈10 (H_2O) -200 (fused silica)	≈ 270 (· **PMT_{gain}**) (1 ltr.)	$\approx 3 \cdot 10^{-3}$ (· **PMT_{gain}**) for 1 m Cherenkov fiber

>10^8 Difference in Sensitivity between different types

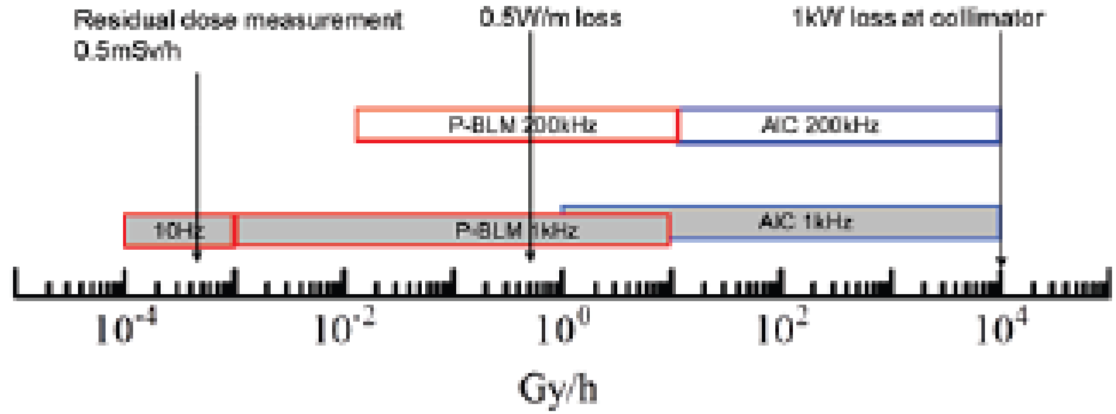
4. Conclusions II

Extending the useful dynamic range and speed of loss meas.:
Air Ion Chamber (AIC) +
Scintillator (SBLM) +
Proportional Counter (P-BLMs)+
Dose Measurement

SUMMARY

To measure the residual dose and intra-bunch beam loss phenomena, the BLM system is required to be upgrade. The essences of the upgrade plan are to extensively enhance the dynamic range and higher frequency band. The double monitor system, P-BLM and short-AIC, will improve the dynamic range up to 1E8. And, the introduction of the S-BLM makes it possible to study more complicated loss mechanism.

Improvement of the Dynamic Range by Short-AIC + P-BLM System



2017: The system dynamic range is now wider than 160 dB (10^8).

We are now designing another fast BLM system that shows bandwidth of more than 200 kHz

DEVELOPMENT OF WIDE DYNAMIC RANGE BEAM LOSS MONITOR SYSTEM FOR J-PARC MAIN RING; K. Satou et al., IPAC'17,

Upgrade Plan of BLM System of J-PARC MR
K. Satou, et al., IPAC12

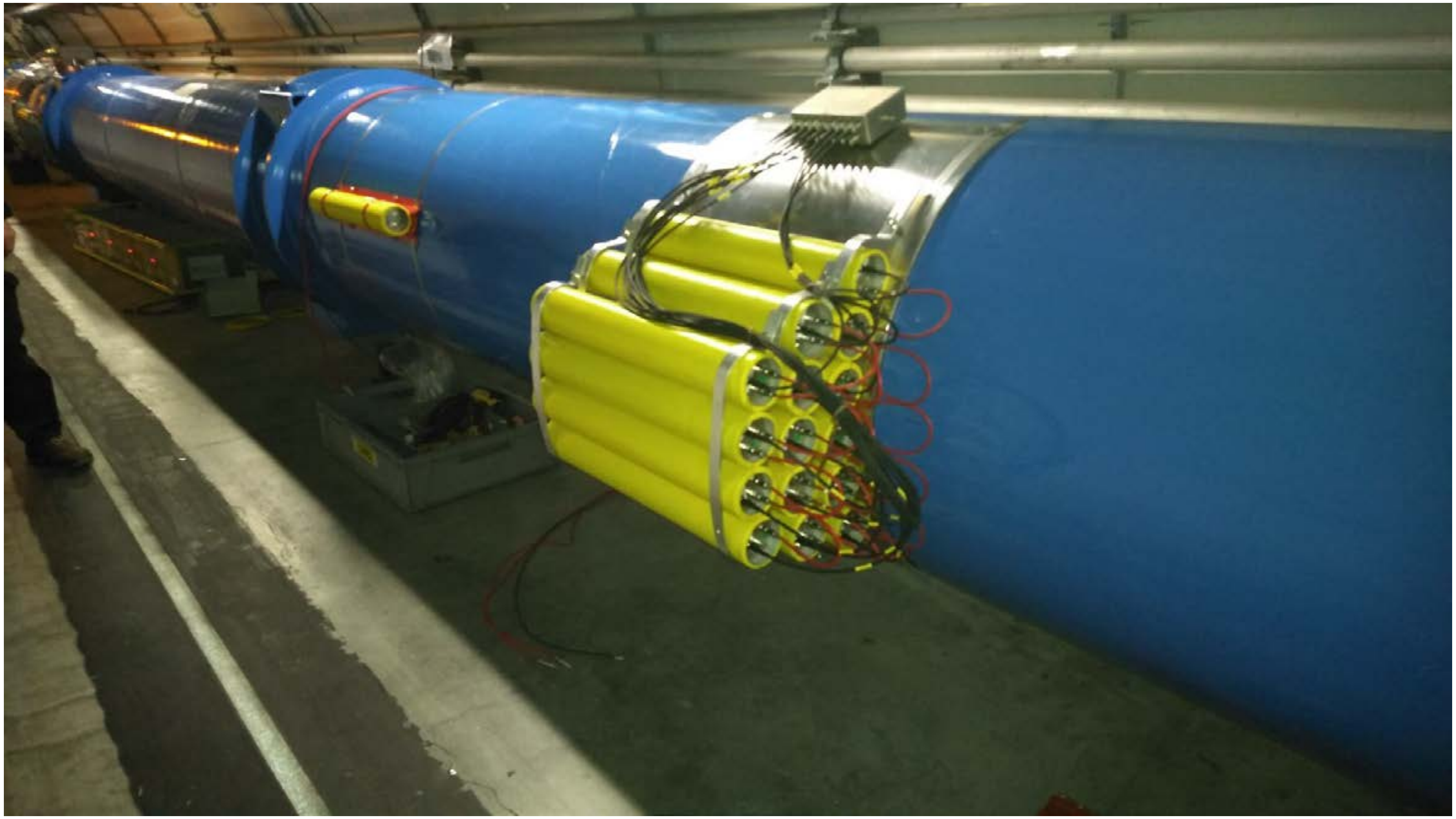
4. Conclusions III

One BLM System is not enough

for

your

accelerator!!!



Diagnostic Examples with BPMs

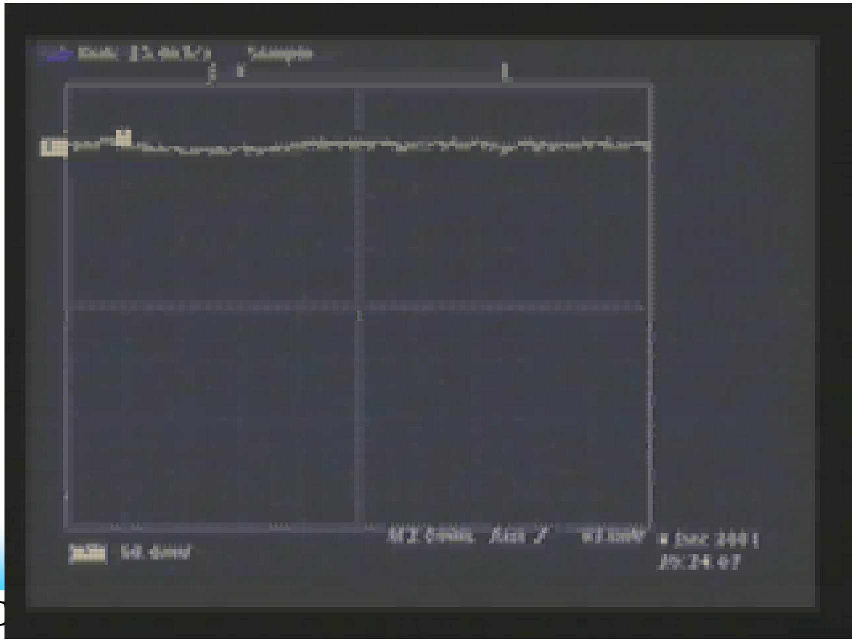
4. Conclusion IV

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.

BLM

Beam Loss

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



4. Conclusion V

MARWIN @ XFEL

ROBOT DESIGN

MARWIN: A MOBILE AUTONOMOUS ROBOT FOR MAINTENANCE AND INSPECTION, A. Dehne, ICALEPCS2017

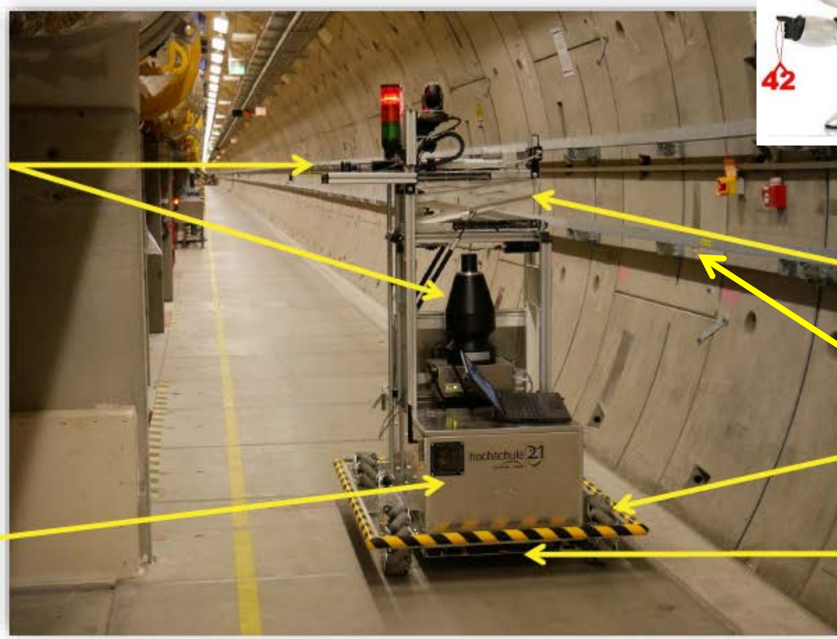
Linux + ROS

different sensors and actuators

additional 96.000 lines of code

redundant hardware inside

www.genialdual.de



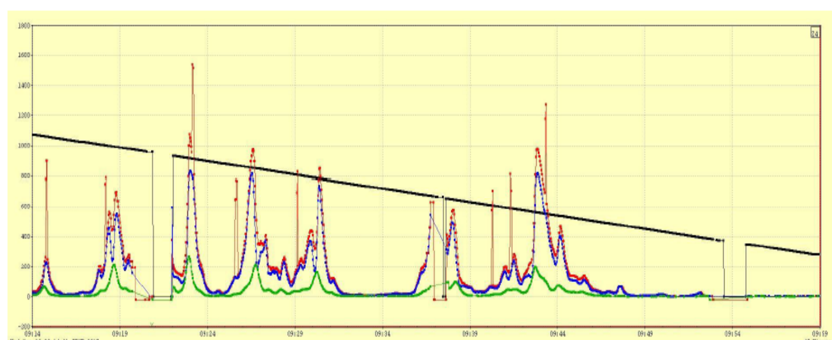
an expandable scissor lift

with QR-codes on XFEL wall, detected by a CCD camera

MECANUM wheels

LIDAR based localization

with 2D laser based SLAM algorithm



Radiation profile along XFEL accelerator
black: robot position [m]; red: dose rate [μSv/h]; blue: avg. gamma dose rate [μSv/h]; green: avg. neutron dose rate [μSv/h];
missing data: wireless data connection temporarily lost

Marwin Video

4. Conclusion V

MARWIN @ XFEL

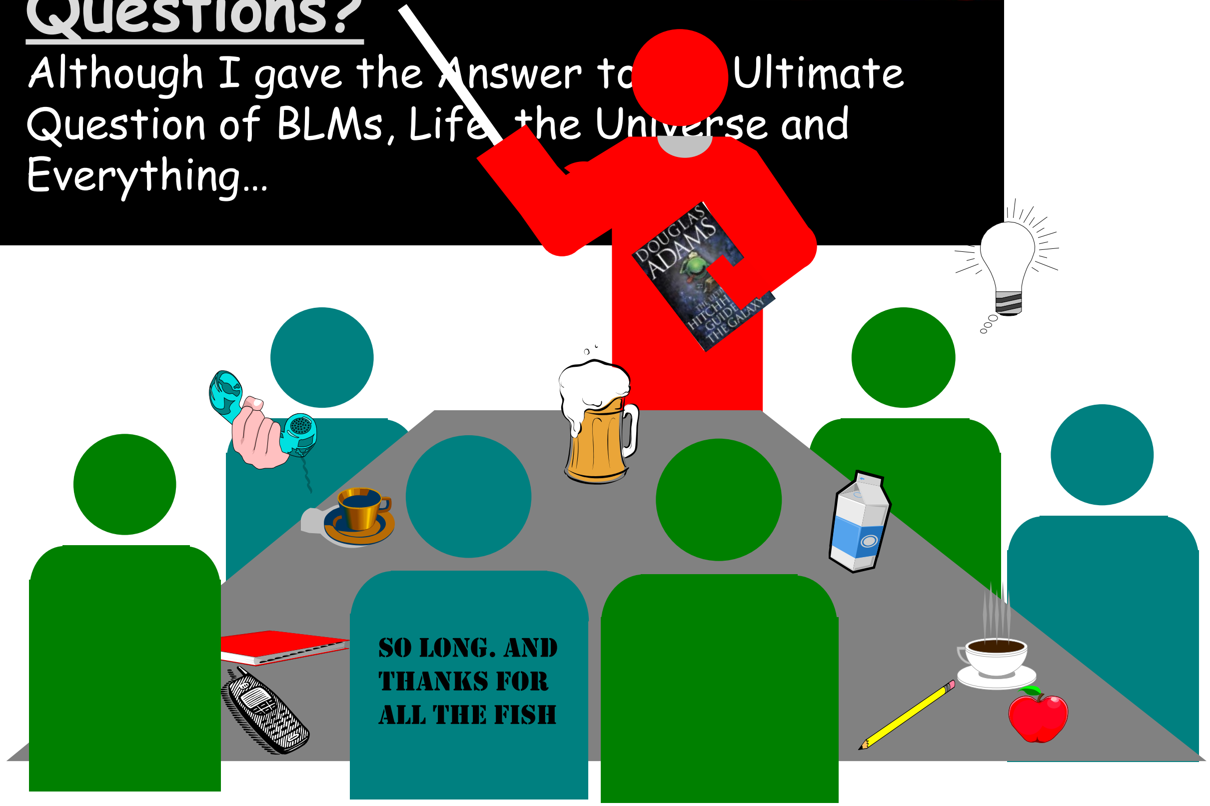
MARWIN: A MOBILE AUTONOMOUS ROBOT FOR MAINTENANCE AND INSPECTION, A. Dehne, ICALEPCS2017

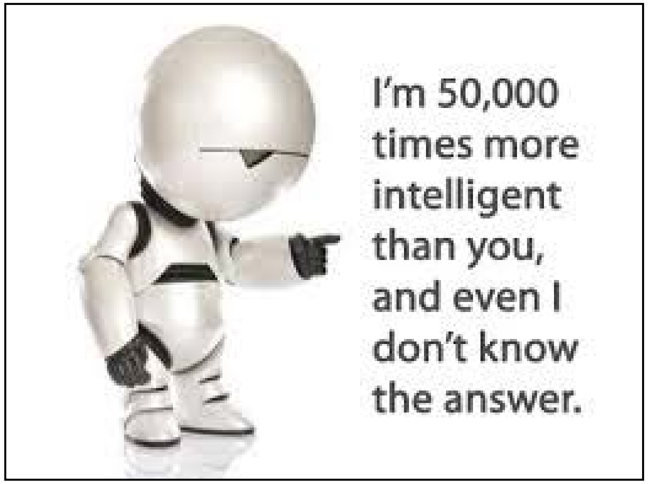
Interlock door at 1100m

The End

Questions?

Although I gave the Answer to the Ultimate Question of BLMs, Life, the Universe and Everything…




I'm 50,000
times more
intelligent
than you,
and even I
don't know
the answer.

Diagnostic Examples with BLMs

Beam Loss Monitoring and Control
Kay Wittenburg, 8th EPAC, *PARIS 2002*

3b. Examples: Regular Losses

- Injection studies
- Lifetime limitations (Touschek effect, etc.)
- Energy measurement
- Tail/Halo scans
- Loss Maps
- Tune scans
- Ground motion
- Diffusion

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 due to various effects: Touschek effect, beam beam interactions, collisions, transversal and longitudinal diffusion, residual gas scattering, halo scraping, instabilities etc. These effects are suitable for machine diagnostic with a BLM system; the system should be **sensitive enough** to enable machine fine tuning and machine studies with the help of BLM signals:

- sometimes even at low beam intensity to avoid high losses and/or
- during machine commissioning and
- at various energies during acceleration

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

ALS

- **Injection studies**
- Lifetime limitations (Touschek effect, etc.)
- Energy measurement
- Tail/Halo scans
- Loss Maps
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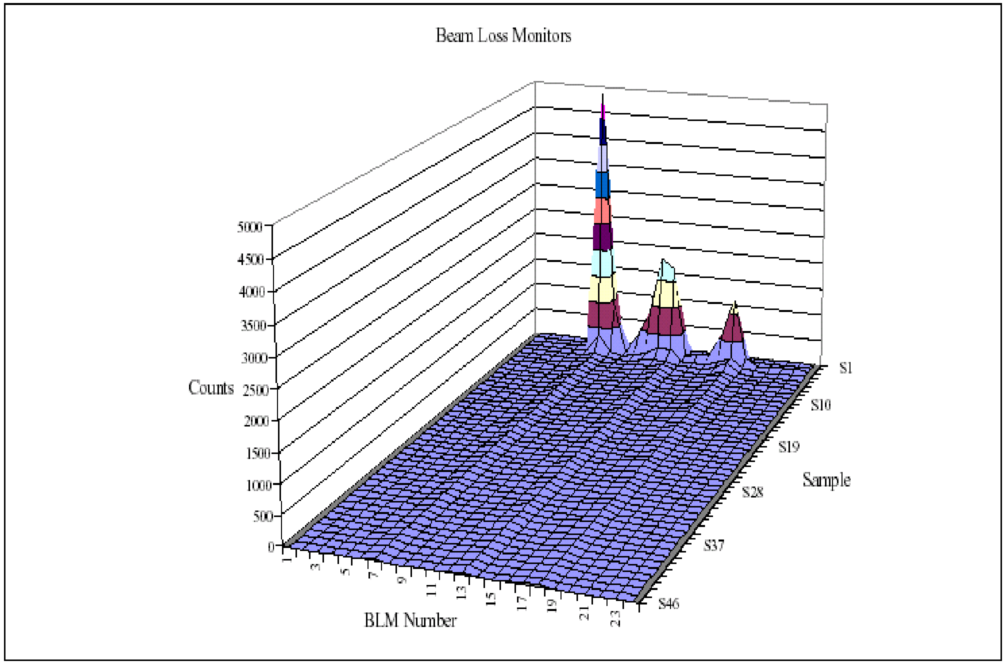
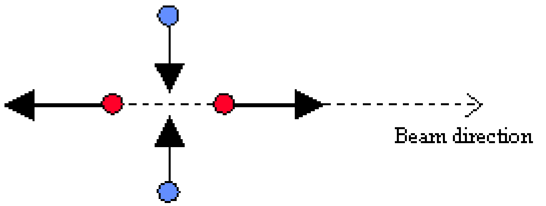
- Ground motion
- Diffusion

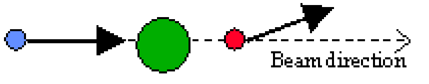
Several BPMs report high count rates at injection. After injection the loss rate is low which is commensurate with beam liftime of about 4 hours. From this graph one can identify the sites of highest beam loss.



Lifetime limitations



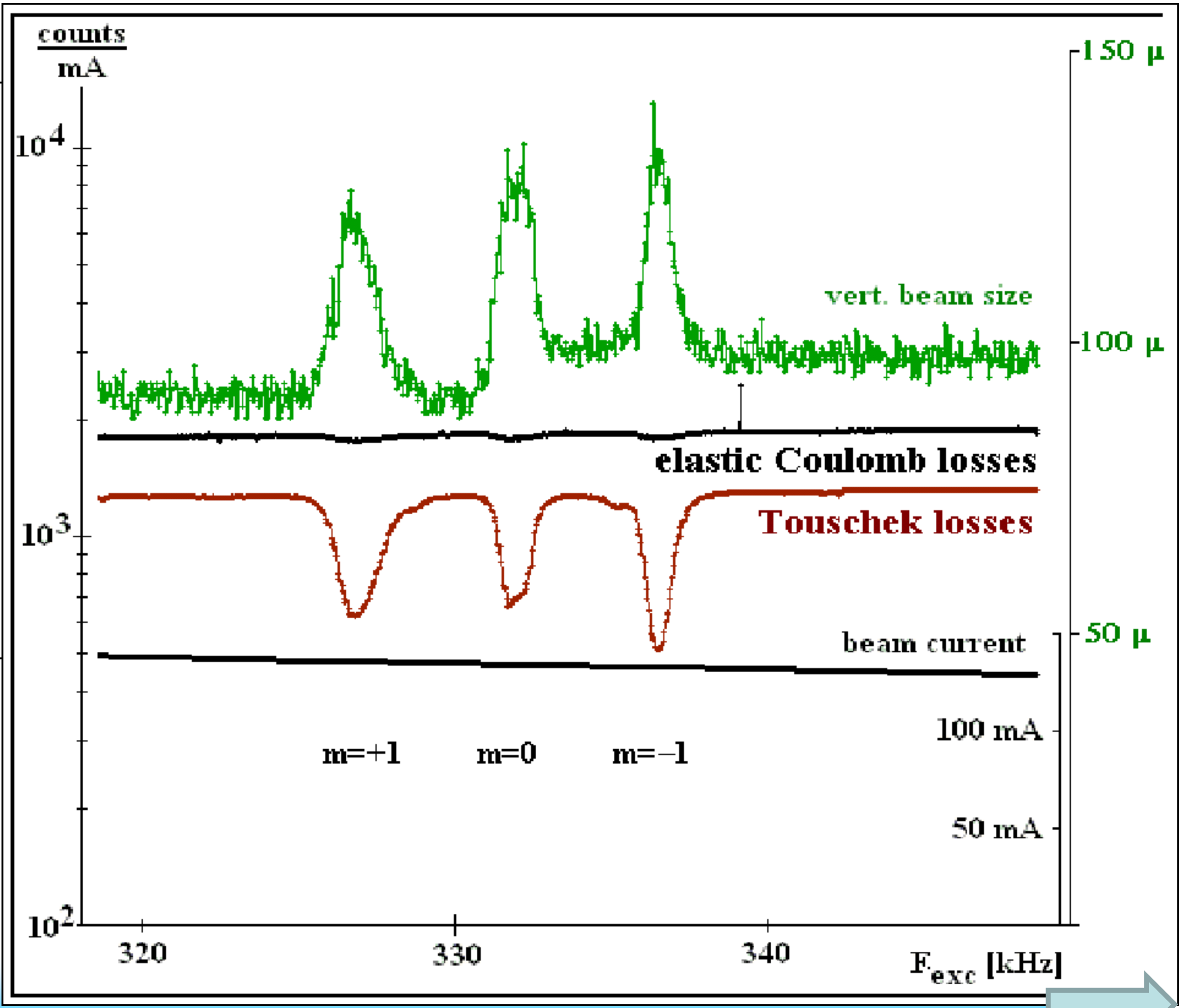
<u>Touschek effect</u>: Particles inside a bunch perform transverse oscillations around the closed orbit. If two particles scatter they can transform their transverse momenta into longitudinal momenta. If the new momenta are outside the momentum aperture the particles are lost. Good locations for the 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.

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

- Injection studies
- **Lifetime limitations** (Touschek effect, etc.)
- Energy measurement
- Tail/Halo scans
- Loss Maps
- Tune scans
- Ground motion
- Diffusion



P. Kuske, DIPAC2001, Accelerator Physics Experiments with Beam Loss Monitors at Bessy

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

- Injection studies
- Lifetime limitations (Touschek effect, etc.)
- **Energy measurement**
- Tail/Halo scans
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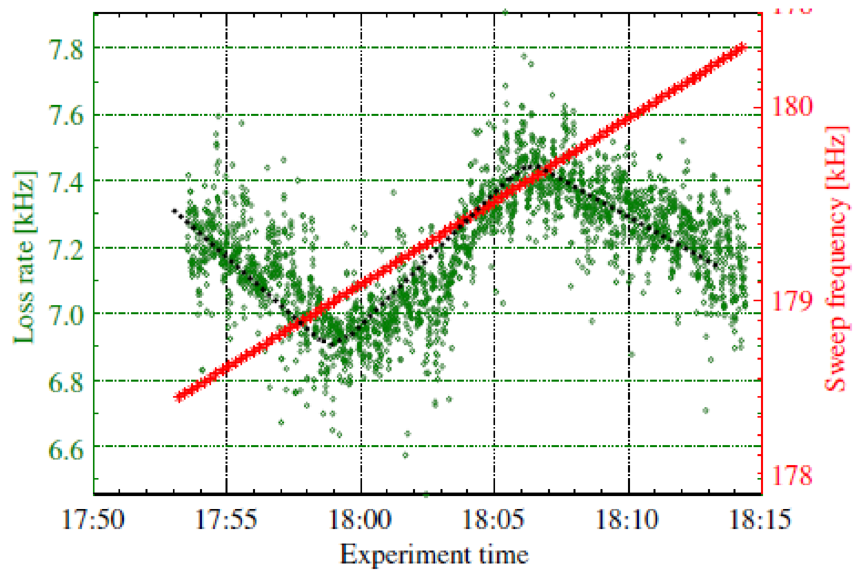
- Diffusion

This technique measures the **energy-dependent** precession frequency of the electron spin. An electron beam in a storage ring can become self-polarized due to the Sokolov-Ternov Effect. A storage ring has a number of depolarizing spin resonances. These energy dependent depolarization can be measured by a the frequency of a depolarizer and the change in the local beam loss rate since the **Touschek lifetime increases with the polarization of the electron beam**.



Measured beam energy at SOLEIL. The accuracy was $5.9*10^{-5}$ with beam energy as 2.73724 ±0.00016 GeV

Beam Energy Measurement by Resonant Depolarization Method at VEPP-4M, *Ivan Nikolaev, et al.*, CERN-BINP Workshop for Young Scientists in e+e- Colliders, Geneva, Switzerland, CERN-Proceedings-2017-001

Precise beam energy measurement using resonant spin depolarization in the SOLEIL storage ring. J. Zhang, et al., Nucl. Instrum. Methods A697 (2013) 1-6.

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

- Injection studies
- Lifetime limitations
  (Touschek effect, etc.)
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- **Tail/Halo scans**
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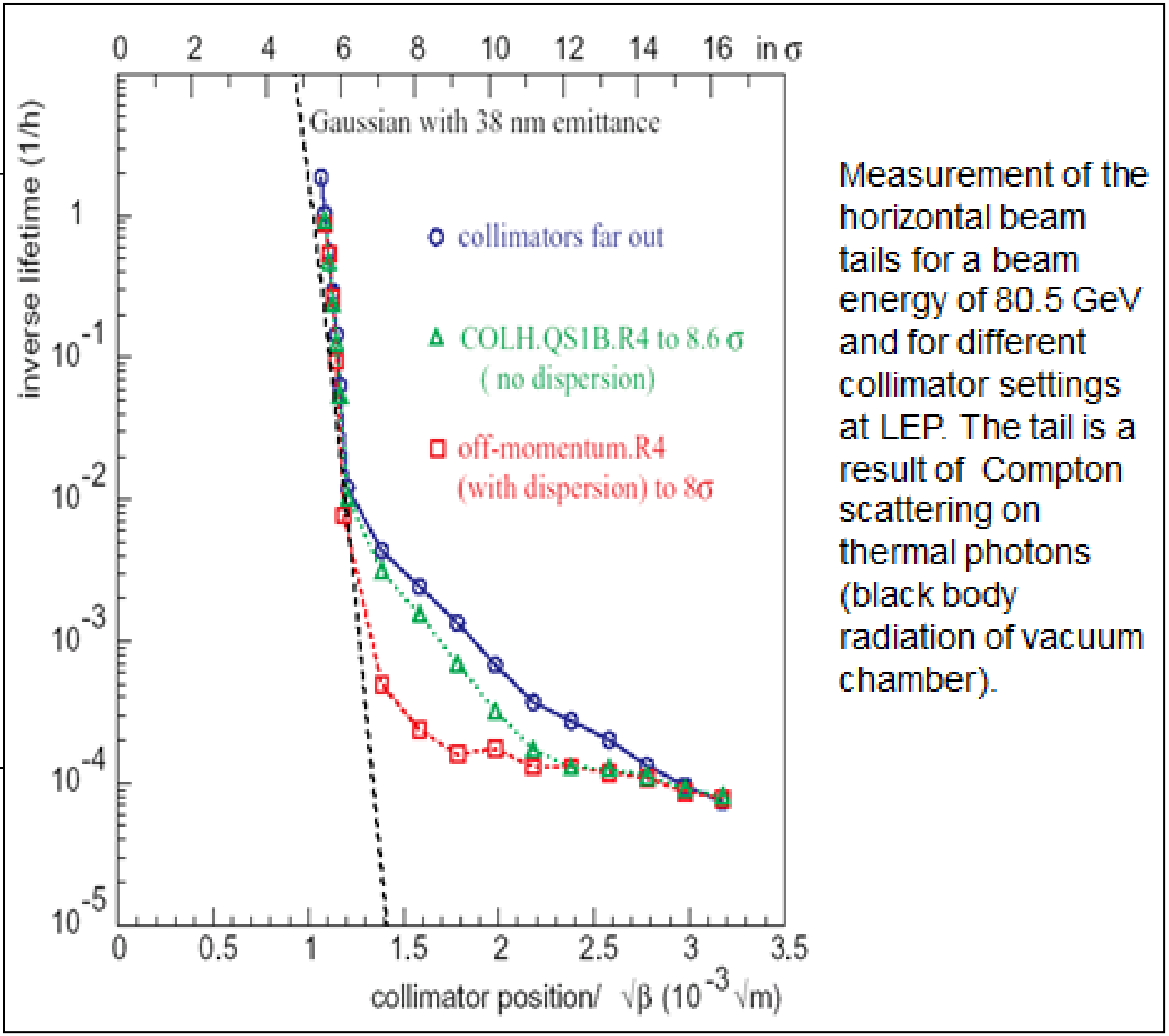
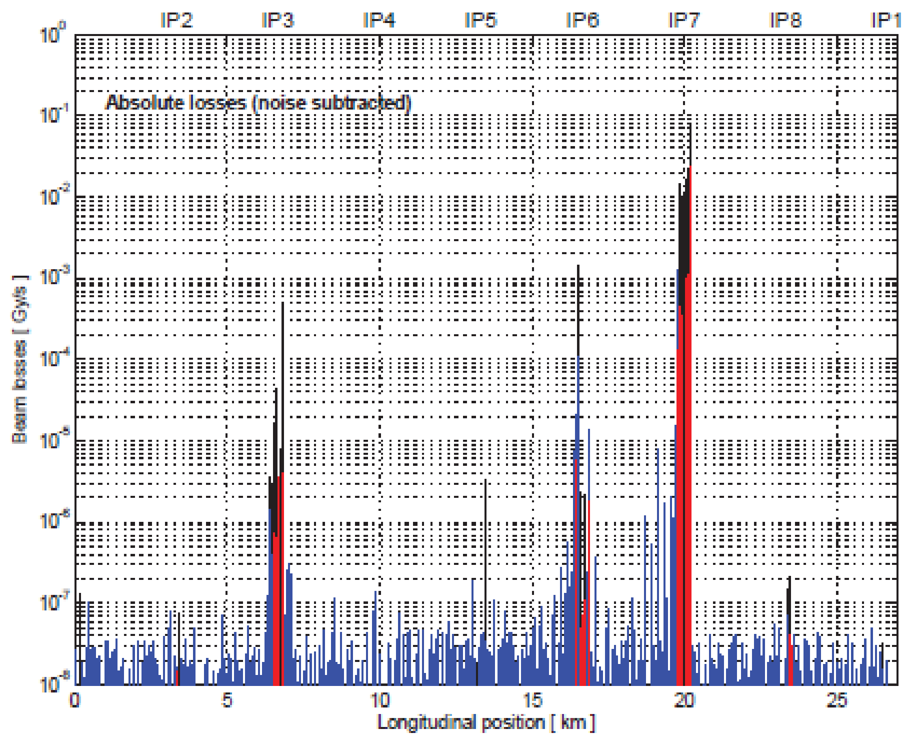


Measurement of the horizontal beam tails for a beam energy of 80.5 GeV and for different collimator settings at LEP. The tail is a result of Compton scattering on thermal photons (black body radiation of vacuum chamber).

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

- Injection studies
- Lifetime limitations (Touschek effect, etc.)
- Energy measurement
- Tail/Halo scans
- **Loss Maps**
- Tune scans
- Ground motion
- Diffusion

A controlled transverse blow-up of only a small number of bunches. This controlled blow-up is also desirable for measuring and verifying the mechanical aperture/collimators of the LHC. Here an increase of the transverse emittance of a low intensity bunch up to the mechanical aperture limit is performed.

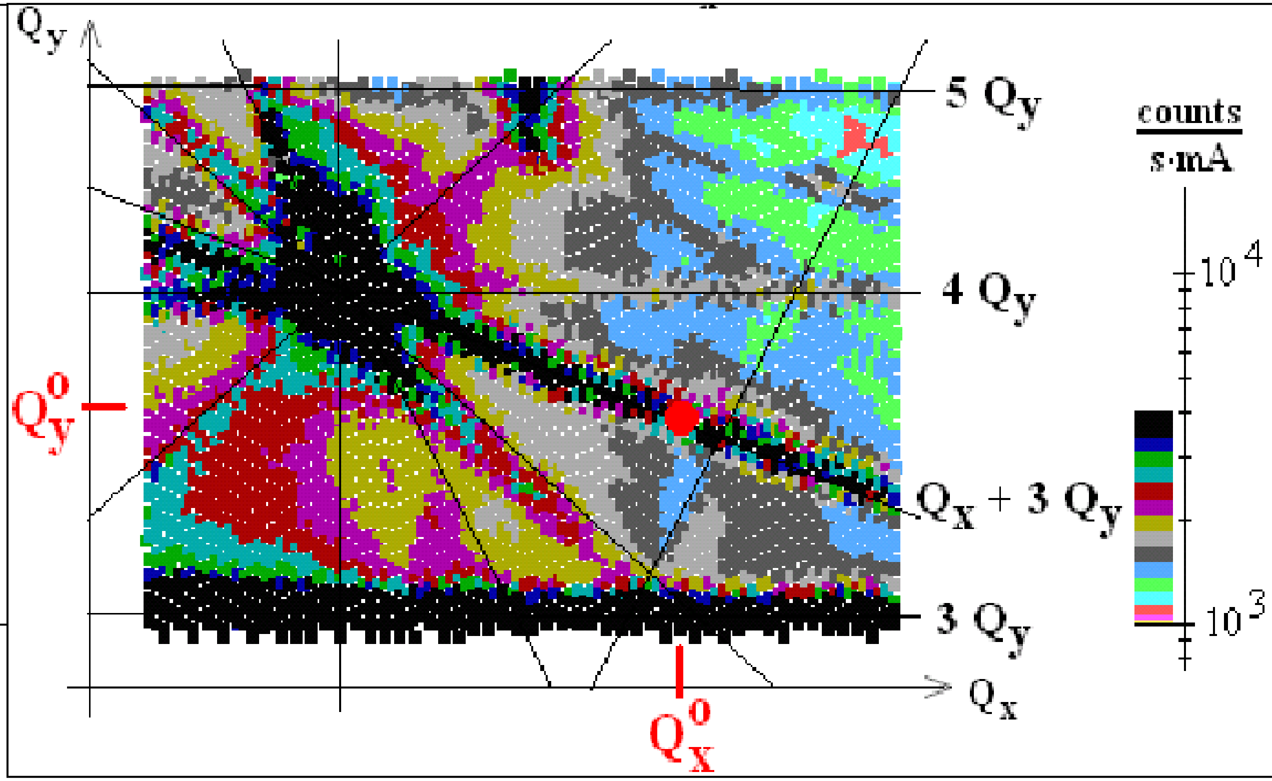


Loss maps obtained by crossing the third-order resonance with one nominal bunch in the LHC (blue: cold part of LHC, red and black: warm part).

Controlled Transverse Blow-Up of High Energy Proton Beams for Aperture Measurements and Loss Maps; W. Höfle et al., IPAC12, New Orleans, Lousiana, USA
Anomaly Detection for Beam Loss Maps in the Large Hadron Collider; G. Valentino et al., IPAC'17, Copenhagen, Denmark

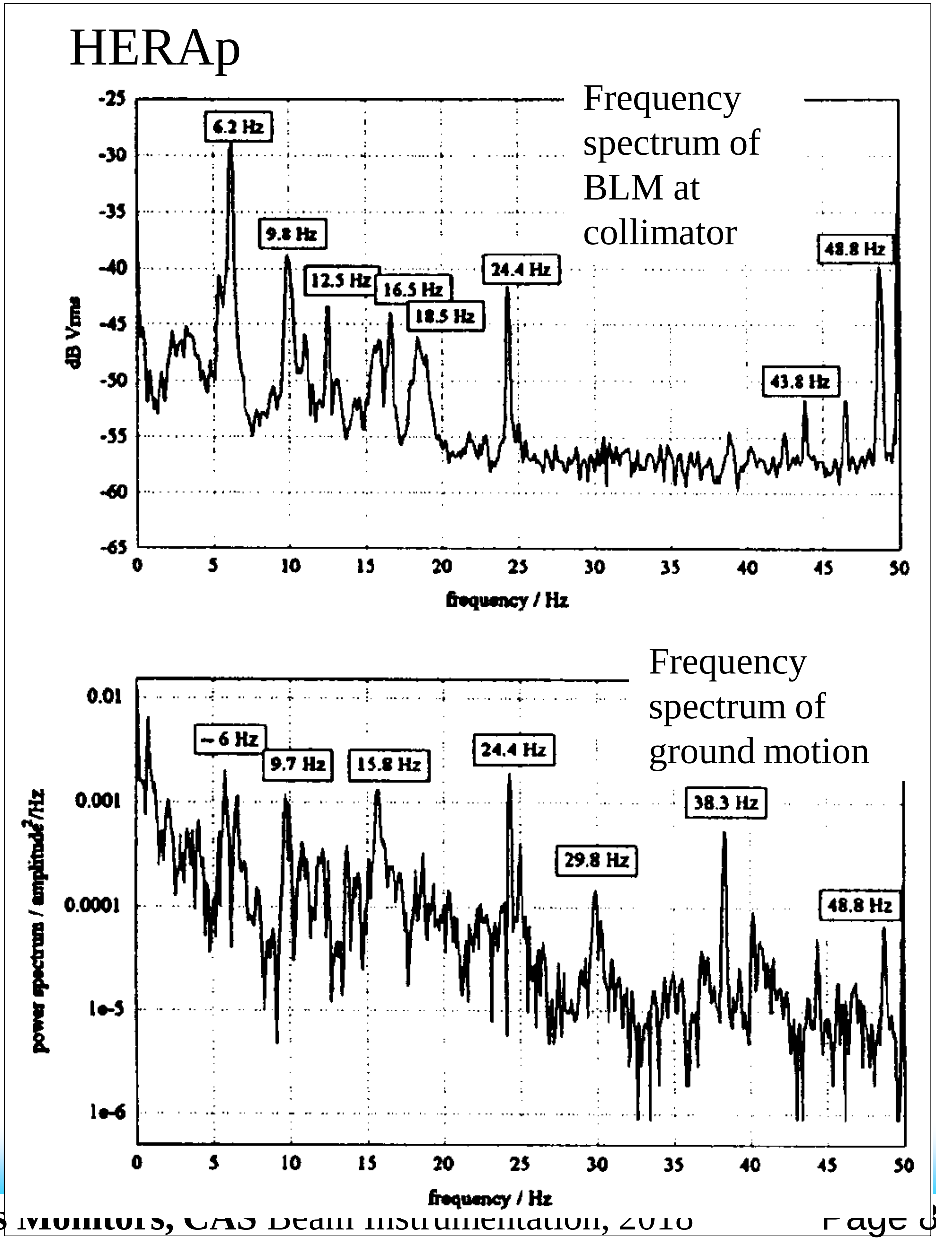
Some examples for regular (controlled, slow) Losses.
Examples to make diagnostics with BLMs

- Injection studies
- Lifetime limitations (Touschek effect, etc.)
- Energy measurement
- Tail/Halo scans
- Loss Maps
- **Tune scans**
- Ground motion
- Diffusion



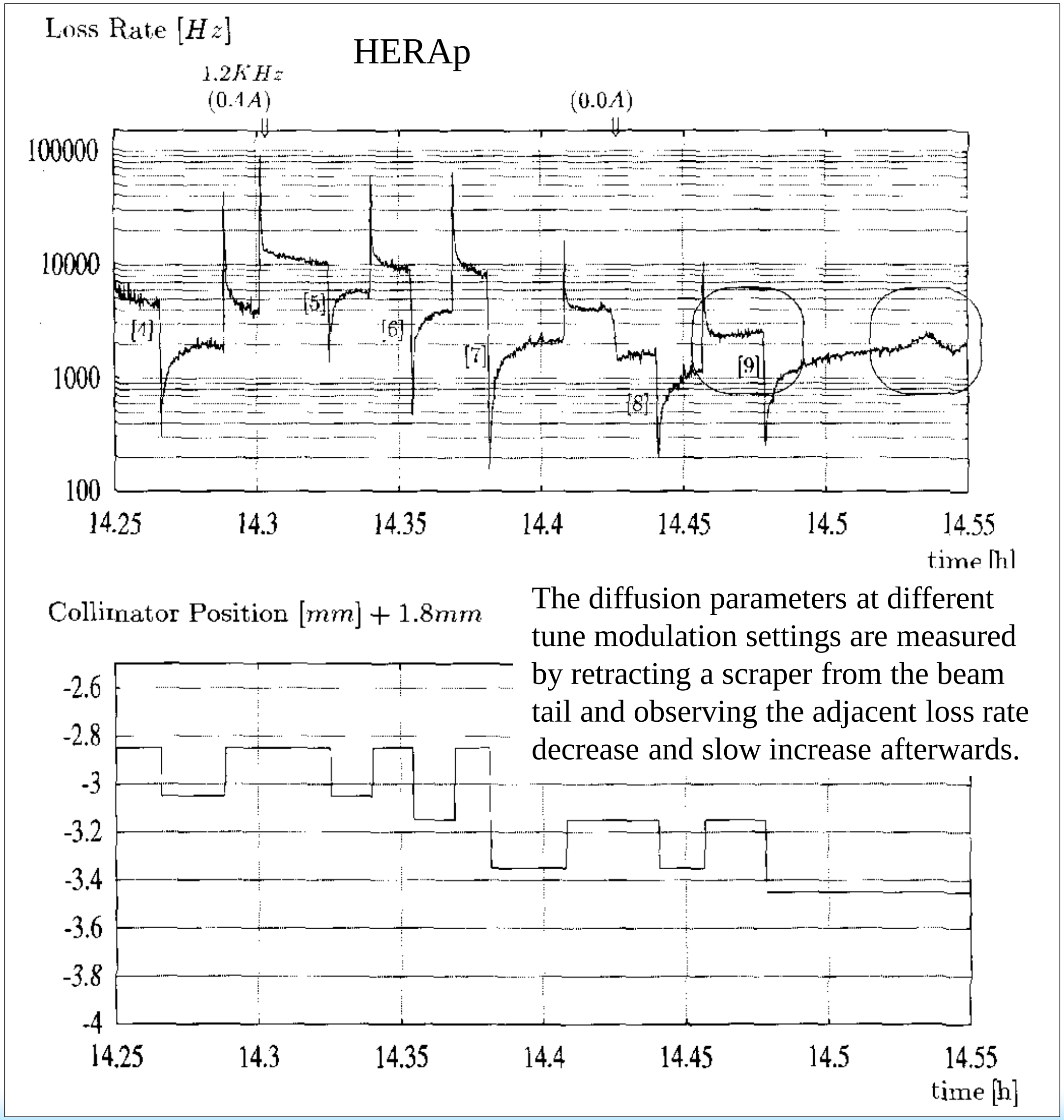
Some examples for regular (controlled, slow) Losses.
Examples to make diagnostics with BLMs

- Injection studies
- Lifetime limitations (Touschek effect, etc.)
- Energy measurement
- Tail/Halo scans
- Loss Maps
- Tune scans
- **Ground motion**
- Diffusion



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

- Injection studies
- Lifetime limitations (Touschek effect, etc.)
- Energy measurement
- Tail/Halo scans
- Loss Maps
- Tune scans
- Ground motion
- **Diffusion**



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.

Examples for Irregular Losses

Irregular (uncontrolled, fast) losses may result in:

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

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)

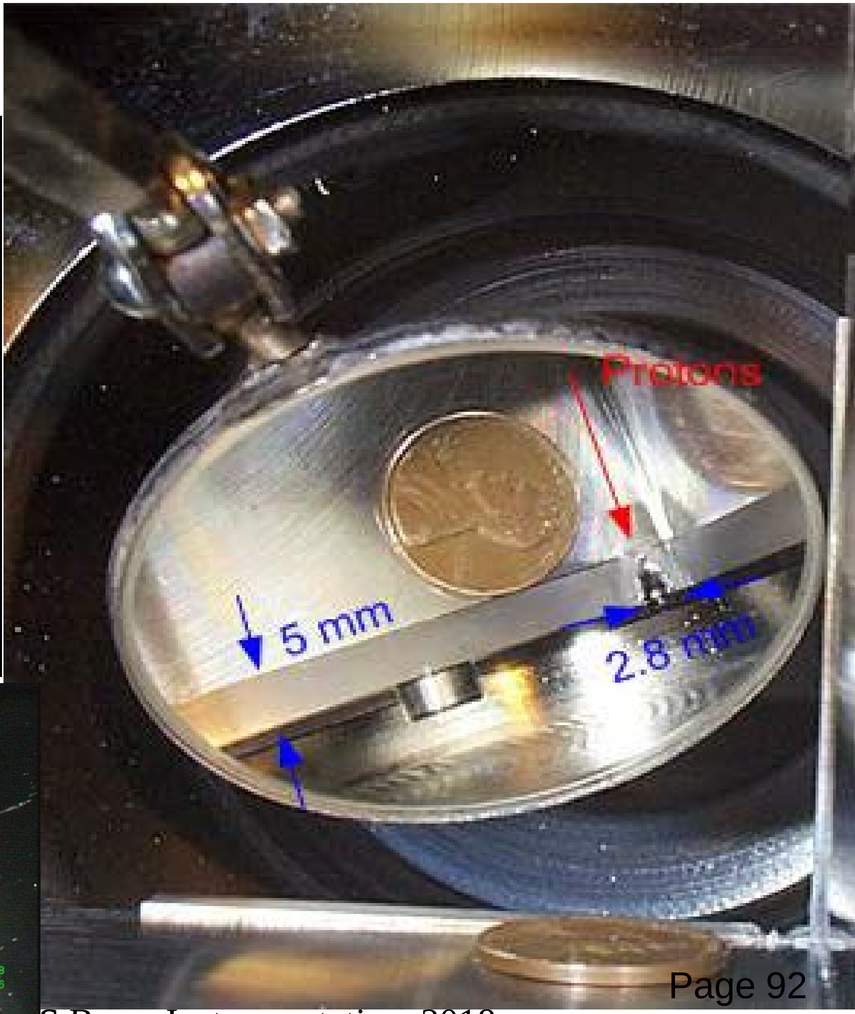
✓ to achieve long beam **lifetimes/efficient beam transport** to get high integrated luminosity for the related experiments.

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 (e.g. Kicker failures …) 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.



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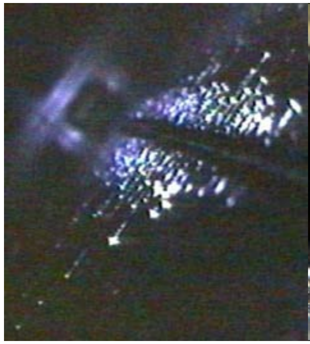

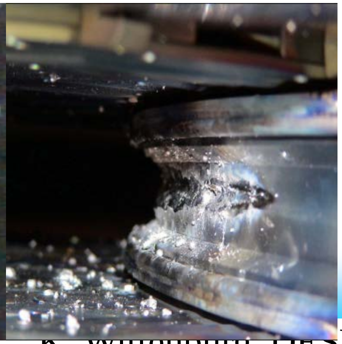

Irregular Losses

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.

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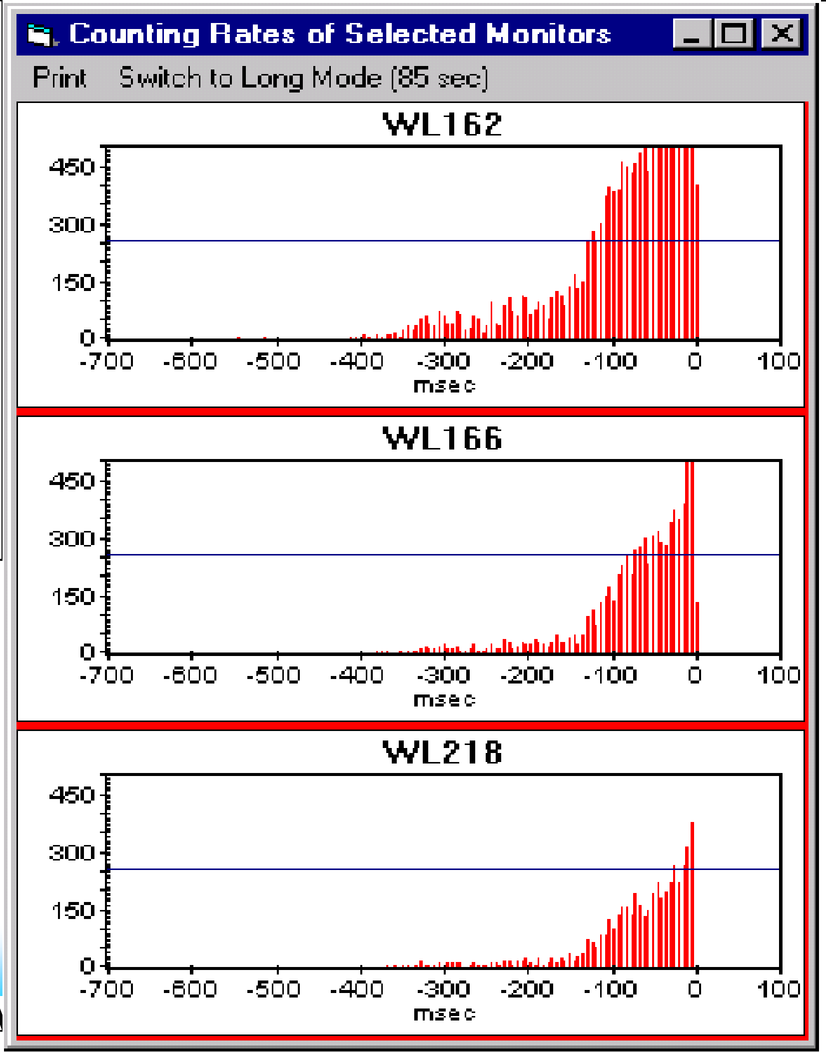

Irregular Losses

Activation is strongly correlated with beam losses. Very important issue for accelerators to shield components (e.g. hands-on maintenance, radiation damage) and the environment (e.g. ground water and air activation, personal safety)

Irregular (uncontrolled, fast) losses may result in:

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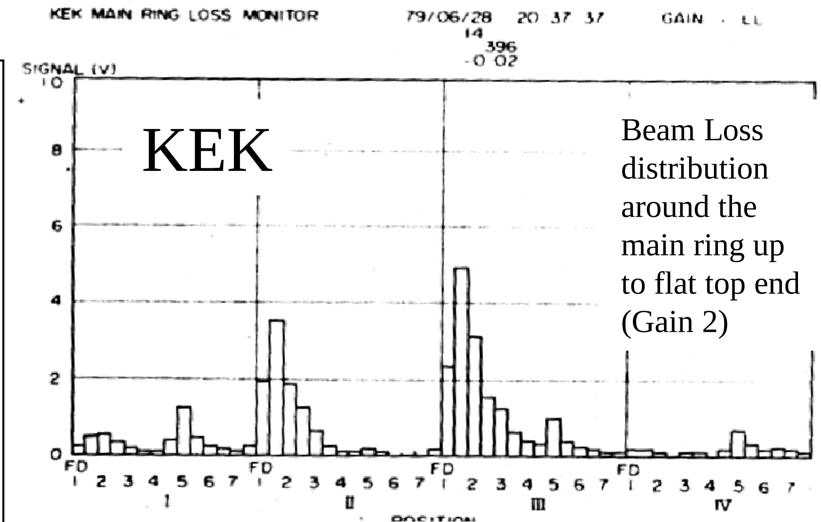

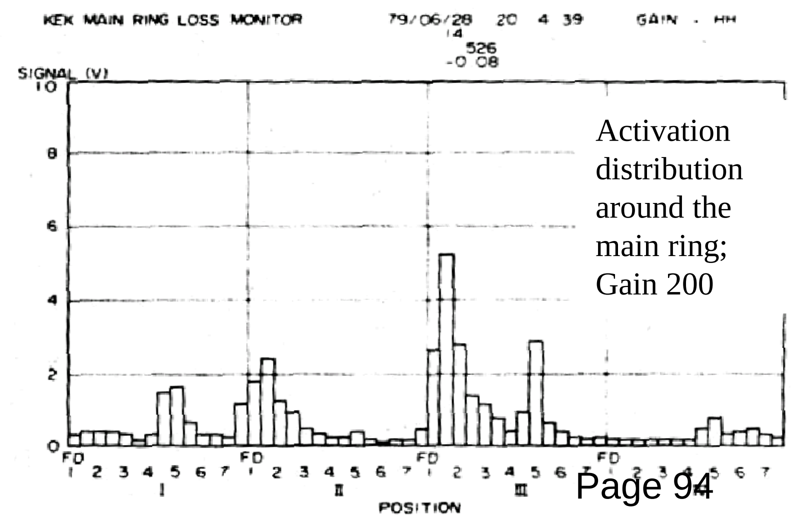

Beam Loss Monitoring System with free-air Ionisation Chambers, H. Nakagawa et al; NIM 174 (1980)

Measuring correlations between beam loss and residual radiation in the Fermilab Main Injector**.** Bruce C. Brown, et al., HB2010, Morschach, CH

Beam Loss and residual dose at 100 KW operation in the J-Parc Accelerator, K. Yamamoto et al., HB2010, Morschach, CH

Irregular Losses

An Obstacle in the beam will prevent beam transport or circulating: RHIC Commissioning: Loss pattern evolution as beam was steered locally around an apparent obstacle. When the losses there went away, beam began circulating. Reason found at 2 location: RF Fingers

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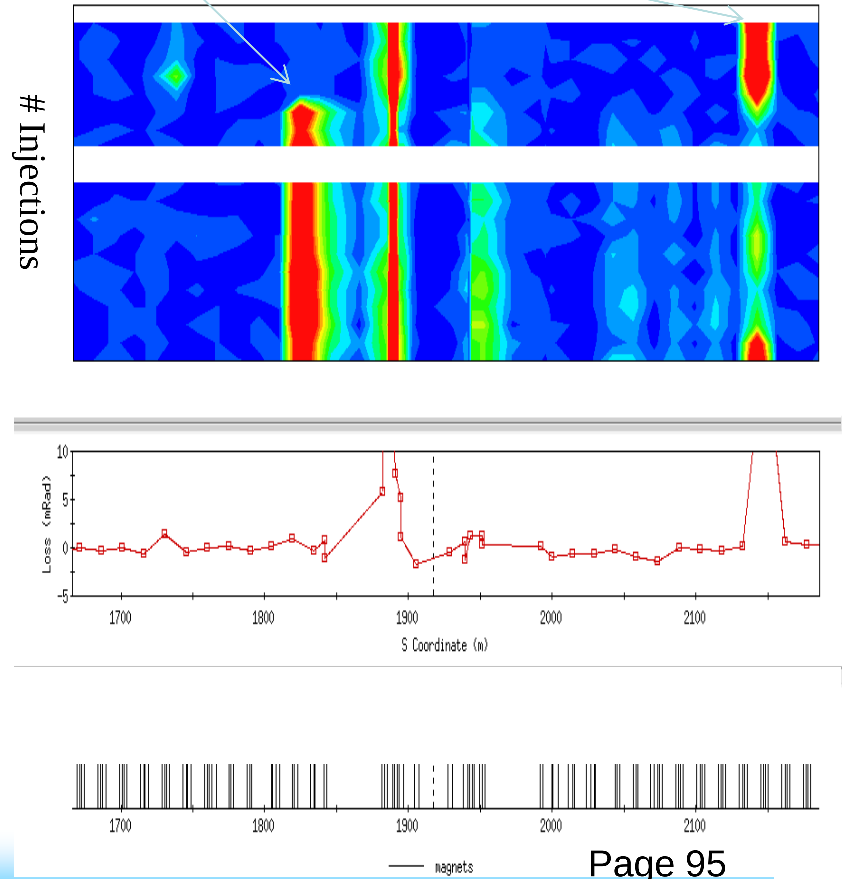
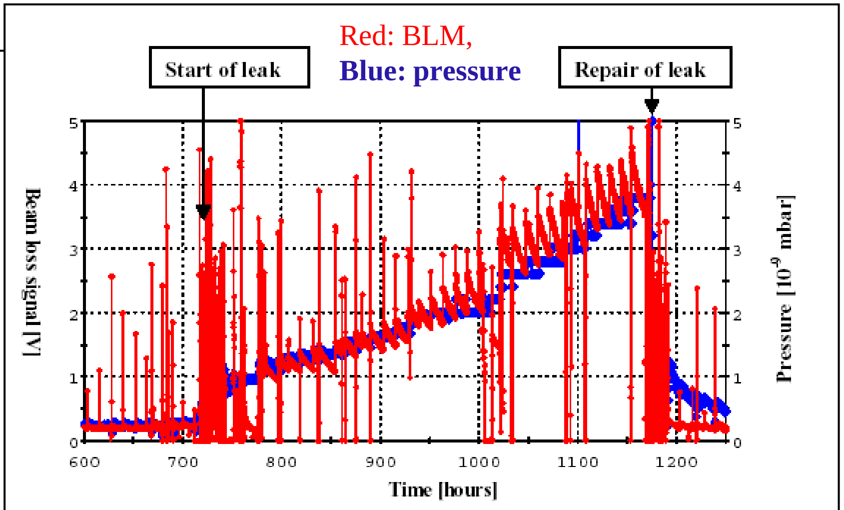


http://www.rhichome.bnl.gov/RHIC/YearZero/early_beam.html

Irregular Losses

There is a nice correlation of the beam loss detection and the vacuum pressure. Helps to detect leaks and improve residual activation.



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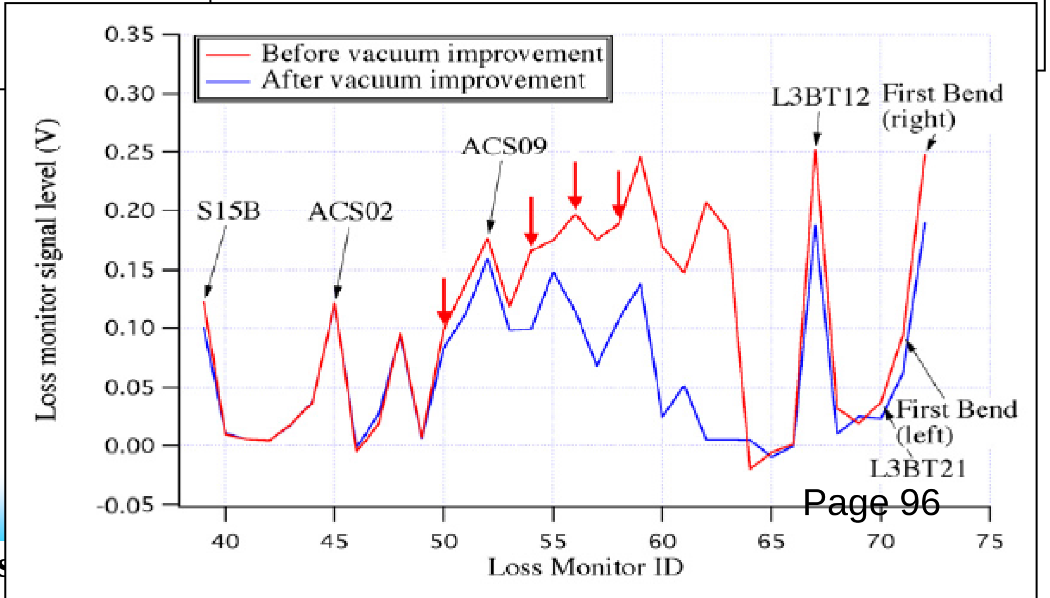


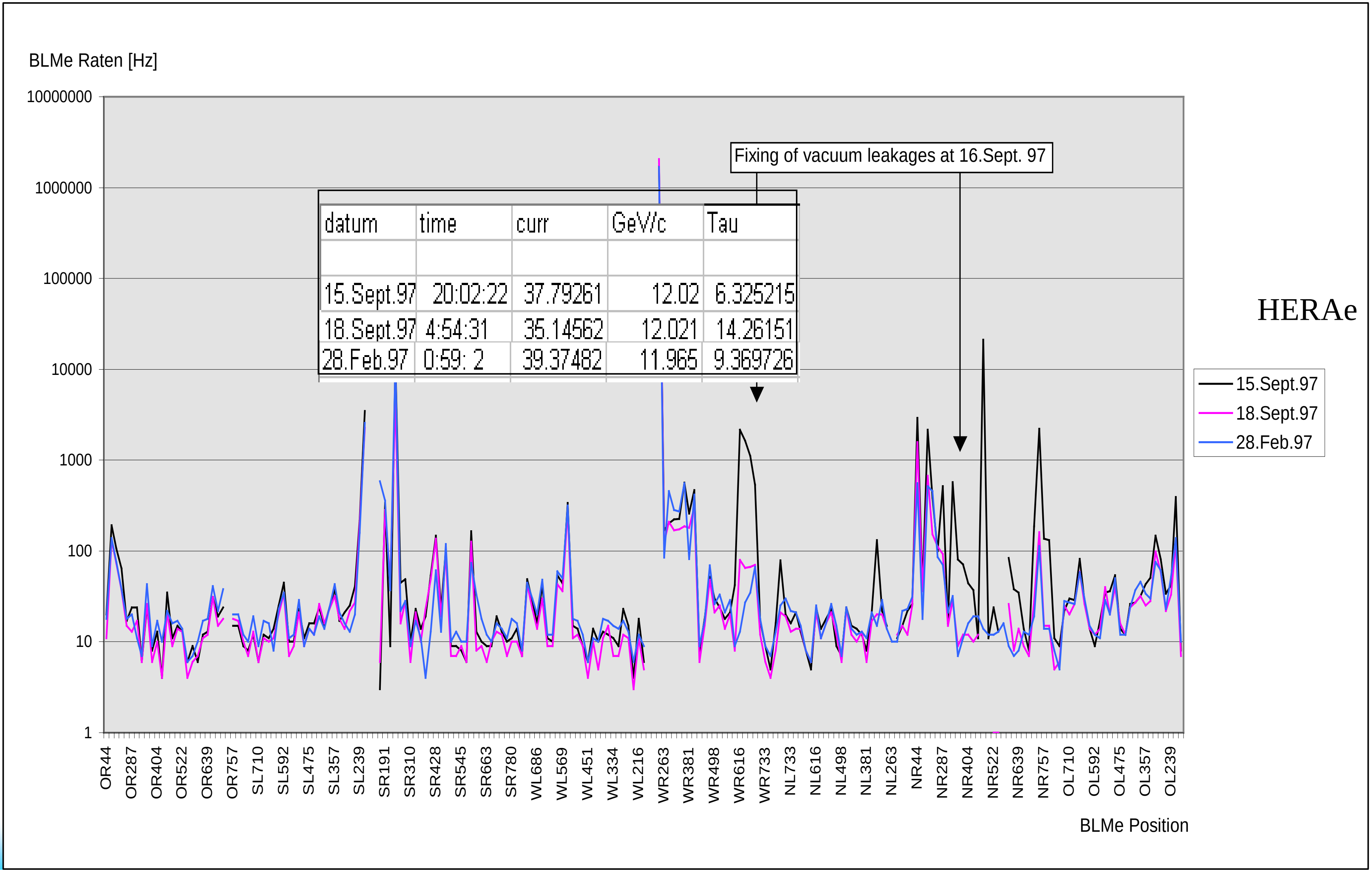
Residual Gas Pressure Dependence of Beam Loss, Akihiko Miura et al., LINAC10, Tsukuba, Japan

Dependence of Beam Loss on Vacuum Pressure Level in J-PARC Linac, Guohui Wei et al., IPAC´11, San Sebastian, Spain

Beam Loss Diagnostics Based on Pressure Measurements, E. Badura et al., DIPAC 2003 – Mainz, Germany

U. Weinrich, Mastering beam losses on small gap vacuum chambers in synchrotron light sources;ESRF Dortmund, Univ., Diss., 2000

Irregular Losses



datum	time	curr	GeV/c	Tau
15.Sept.97	20:02:22	37.79261	12.02	6.325215
18.Sept.97	4:54:31	35.14562	12.021	14.26151
28.Feb.97	0:59: 2	39.37482	11.965	9.369726

Irregular Losses

Lifetime reduction events correlate well with losses seen in the HERA electron loss monitors. In this example the brief disruption of lifetime is seen in the loss monitor SL191, and the irreversible disruption is seen in the monitor WR239

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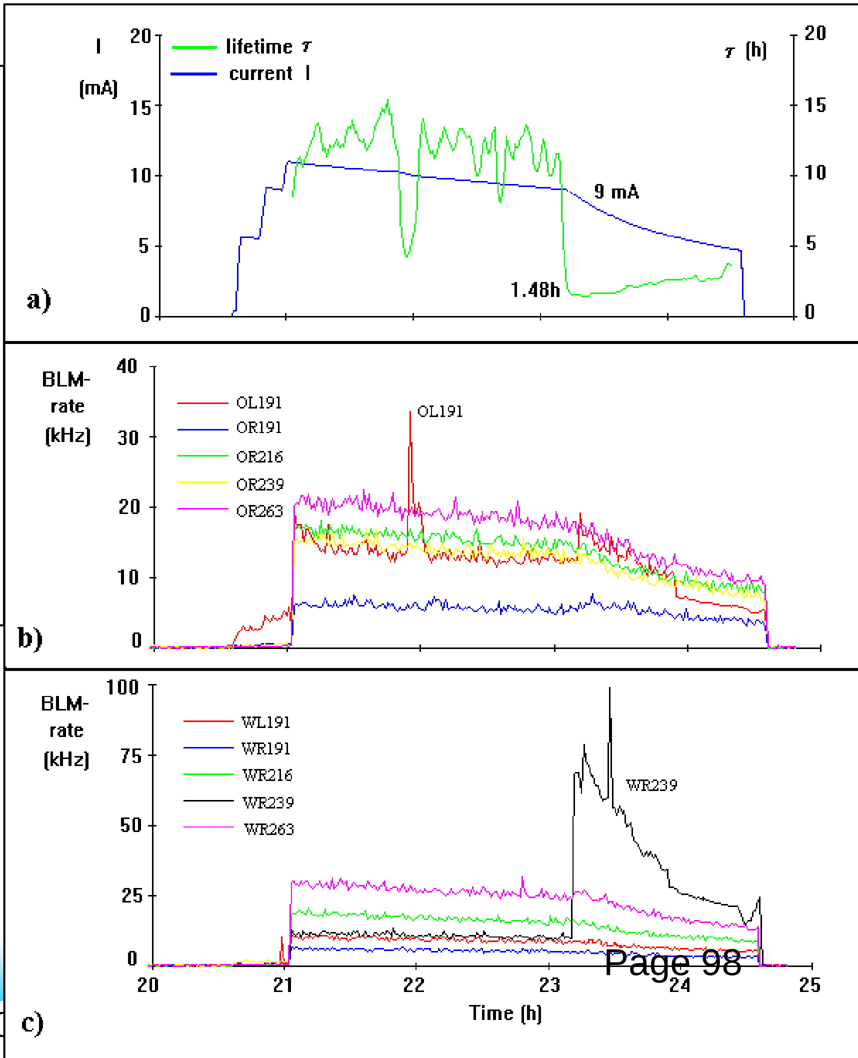
- UFOs



The Electron beam Lifetime Problem in HERA, D.R.C. Kelly et al., PAC 1995

Irregular Losses

UFO = Unidentified Falling Object. Many fills at LHC were terminated by exceeding BLM thresholds on short time scales. UFOs are presumably micrometer sized dust particles that lead to beam losses with a duration of about 10 turns when they interact with the beam. Many UFO events were far below the threshold.

Irregular (uncontrolled, fast) losses may result in:

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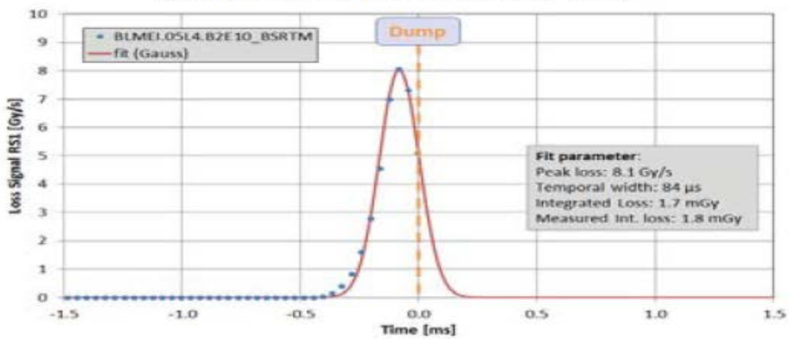
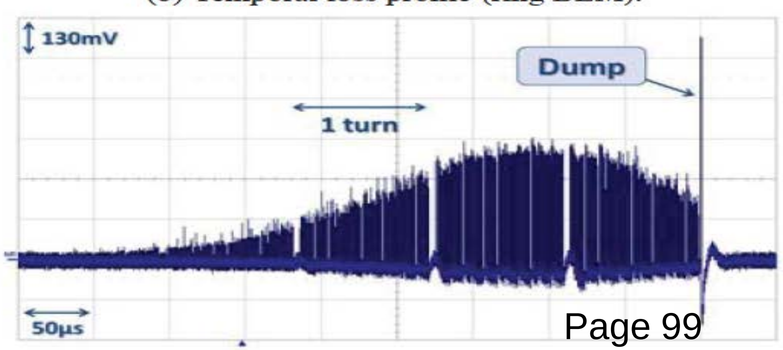
- Microparticles
- **UFOs**

(a) Spatial loss profile (ring BLMs).



(b) Temporal loss profile (ring BLM).



(c) Temporal loss profile (IR7 diamond BLM, 50 μs/div).

Just a small selection:

a. Very low energy machines

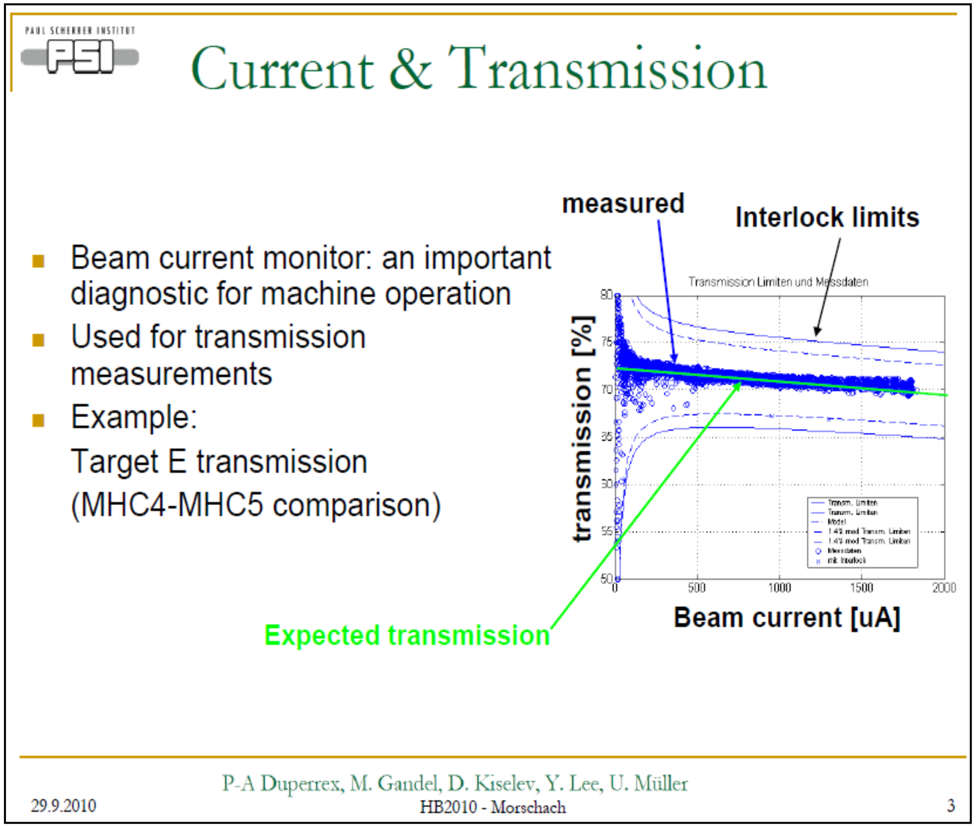
b. High background

4a) Challenges associated to measurements of losses at low energies

The problem: No or very few secondaries outside the vacuum chamber

Solutions:

- **Differential current measurement**
  - **Limited position resolution**
  - **LINAC/transport only**
- BLMs very close to beam pipe
  - Risk of wrong position
- BLMs sensitive to neutrons
  - Limited position resolution
- Very sensitive BLMs
- Use of BLMs at collimators



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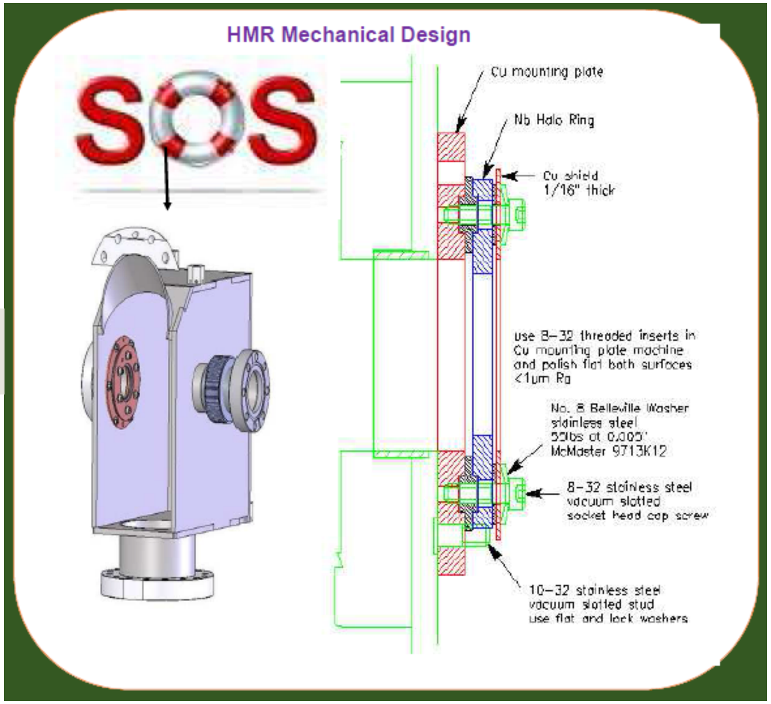
that complements ionization chambers. A specifically designed device, the halo monitor ring (HMR), is implemented upstream of each cryomodule to detect beam loss directly. Together



Beam Loss Monitor System for the Low-Energy Heavy-Ion FRIB Accelerator

Zhengzheng Liu, Tom Russo, Bob Webber, Yoshishige Yamazaki, Yan Zhang

IBIC 2013 poster

-> Also: Cryogenic BLMs (not at low energy)

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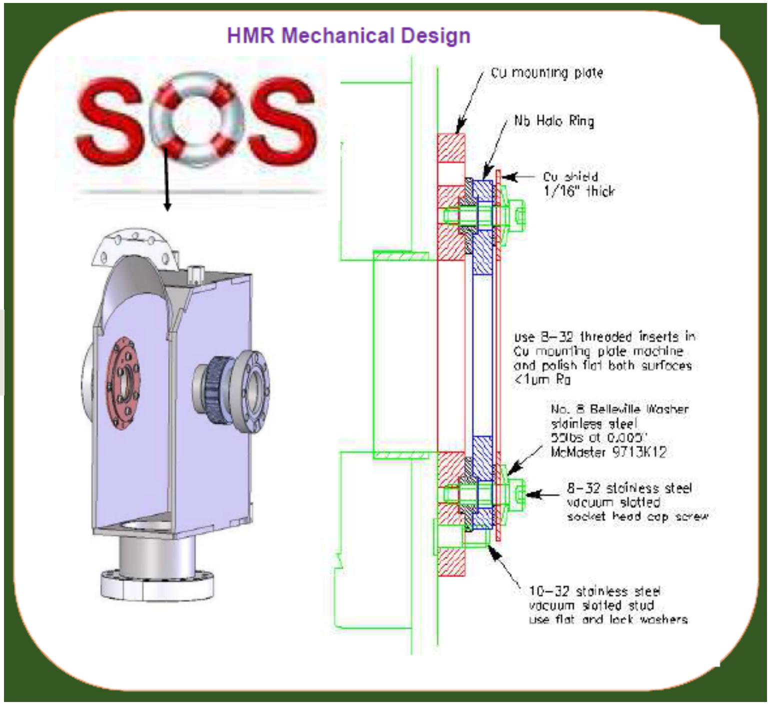

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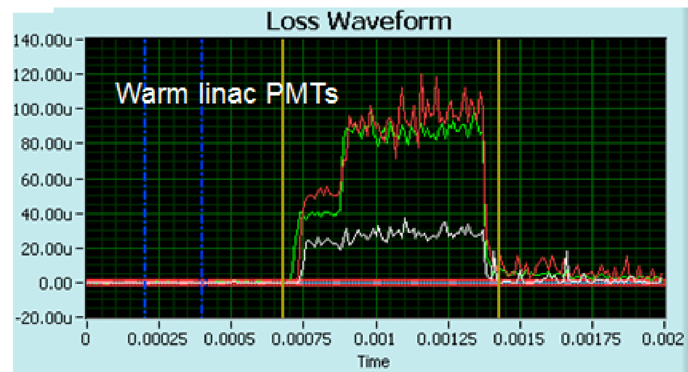
Challenges: Low energy part of linac

- low energy beam (<20MeV)
  - IC not sensitive enough
  - ND sensitive, but hard to calibrate (no sufficient experimental data for reliable simulation)
  - Still the biggest issue



9 Managed by UT-Battelle for the Department of Energy A. Zhukov SNS BLM System Overview Detectors, Measurements, Simulations WGF04 - HB2008 8/26/2008 OAK RIDGE National Laboratory

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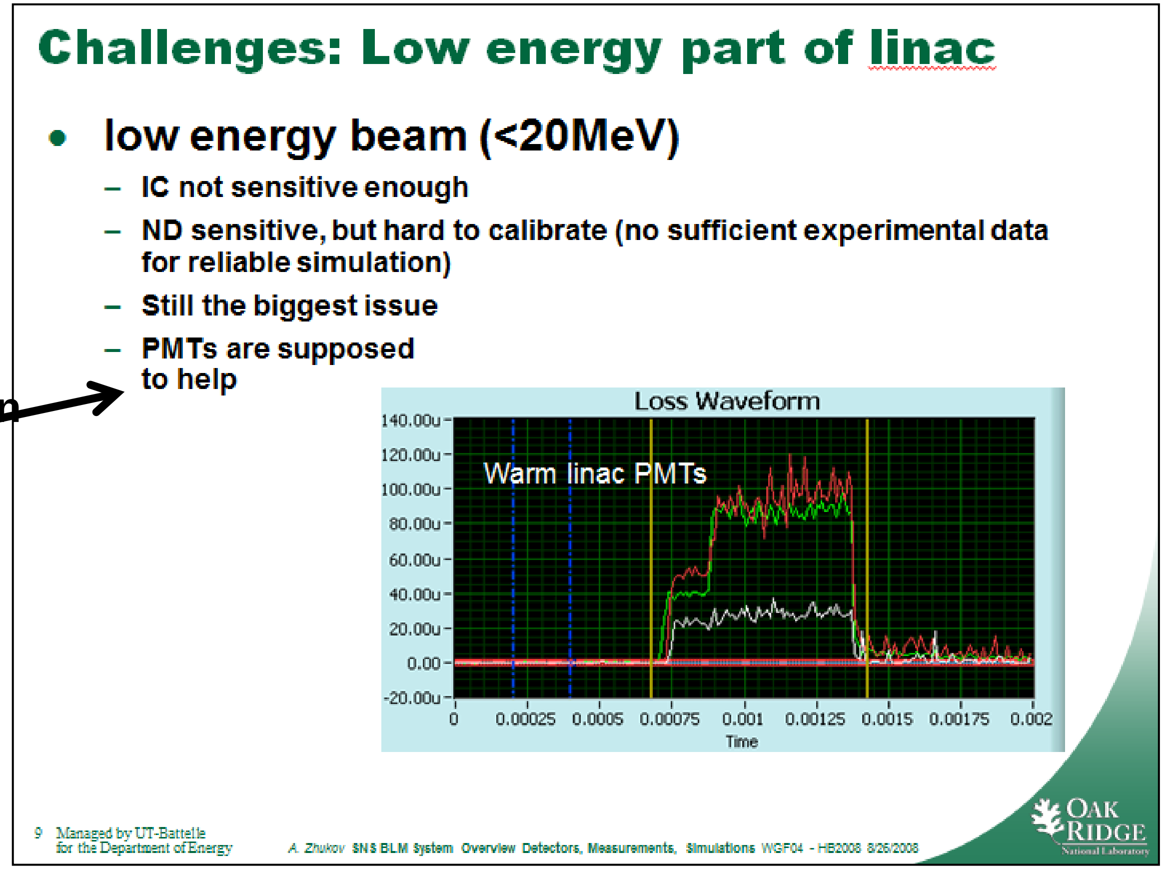

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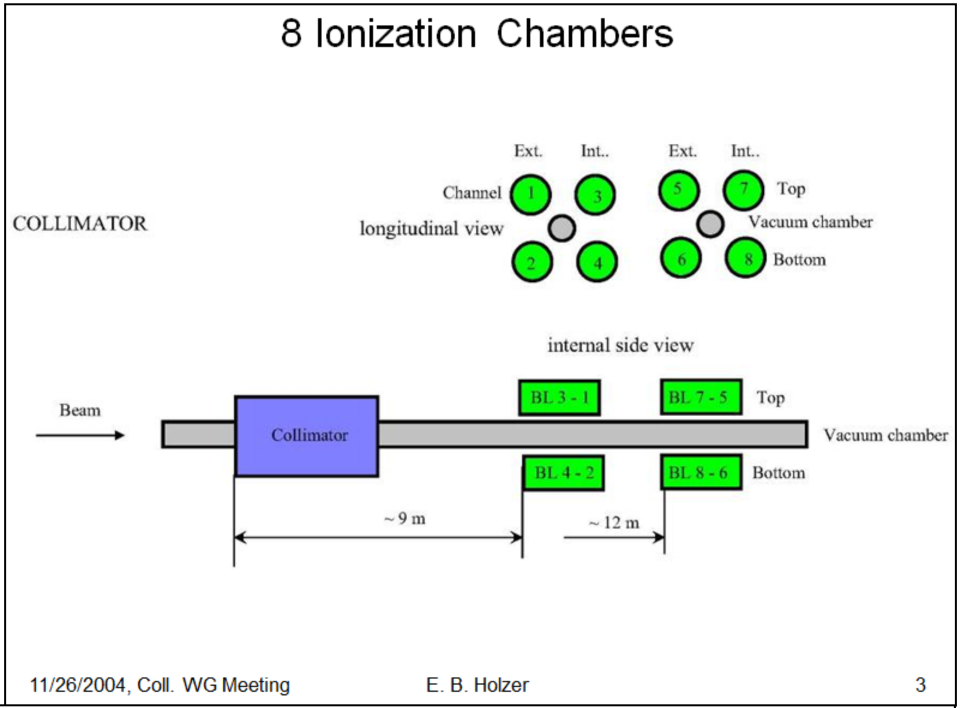
- **Use of BLMs at collimators**
  - **Known loss location**
  - Aperture limit
  - Highest loss rate (hopefully)
  - Machine + Collimator Protection



- "Tails" in distributions are from the beam.
- BLM signal is linear with proton intensity.
- Left-right asymmetry of the shower depends on the collimator gap size and gap position.
- Slight top-bottom asymmetry?
- BLM signal depends on the impact position on the jaw.
- Compares ~ OK with simulations (TT40).

4a) Challenges associated to measurements of losses at <u>low energies</u>

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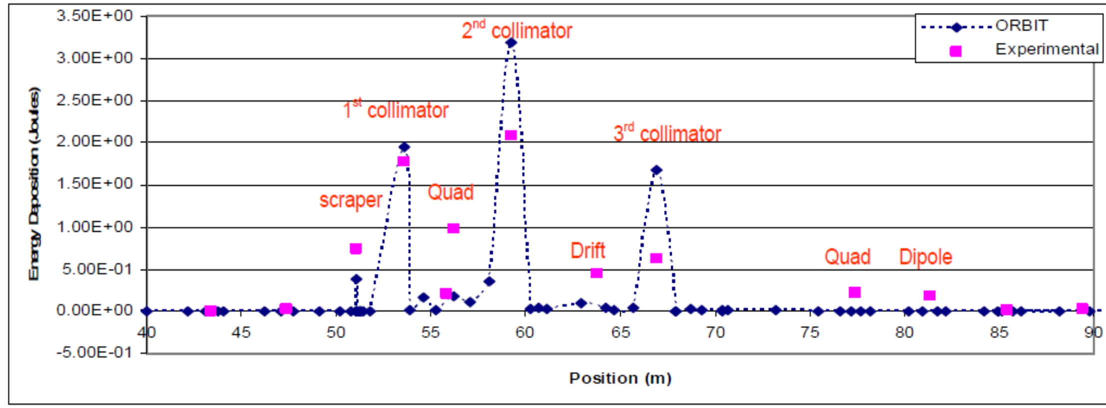
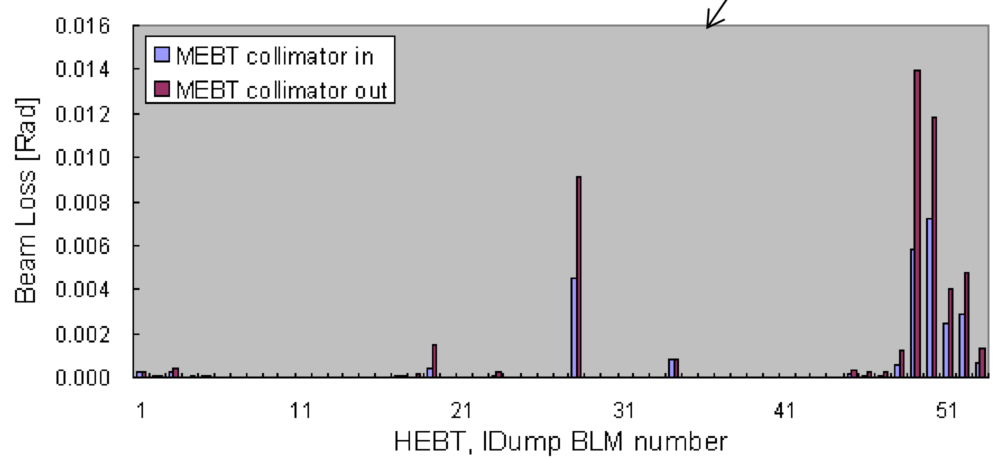
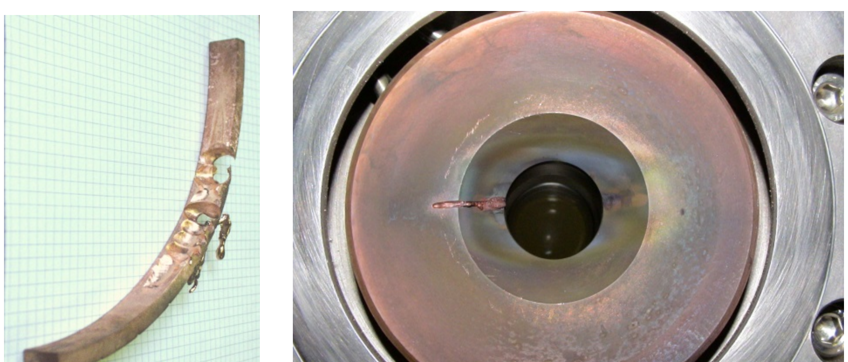


Figure 4. Benchmark of the beam loss pattern for a single minipulse of beam collimated in a two-stage system. The pink boxes are the measured BLM readings, converted to energy deposition, and the blue diamonds are the ORBIT simulation results.

SNS PAC07 LINAC10



Plot of measured beam loss along the HEBT and IDump (Injection Dump) with the MEBT collimator in and out. Data shows significant reduction in beam loss in the HEBT and IDump with the MEBT collimation.



0.9 and 72 MEV Proton collimator at PSI Cyclotron (Pic. From R. Dölling-PSI)

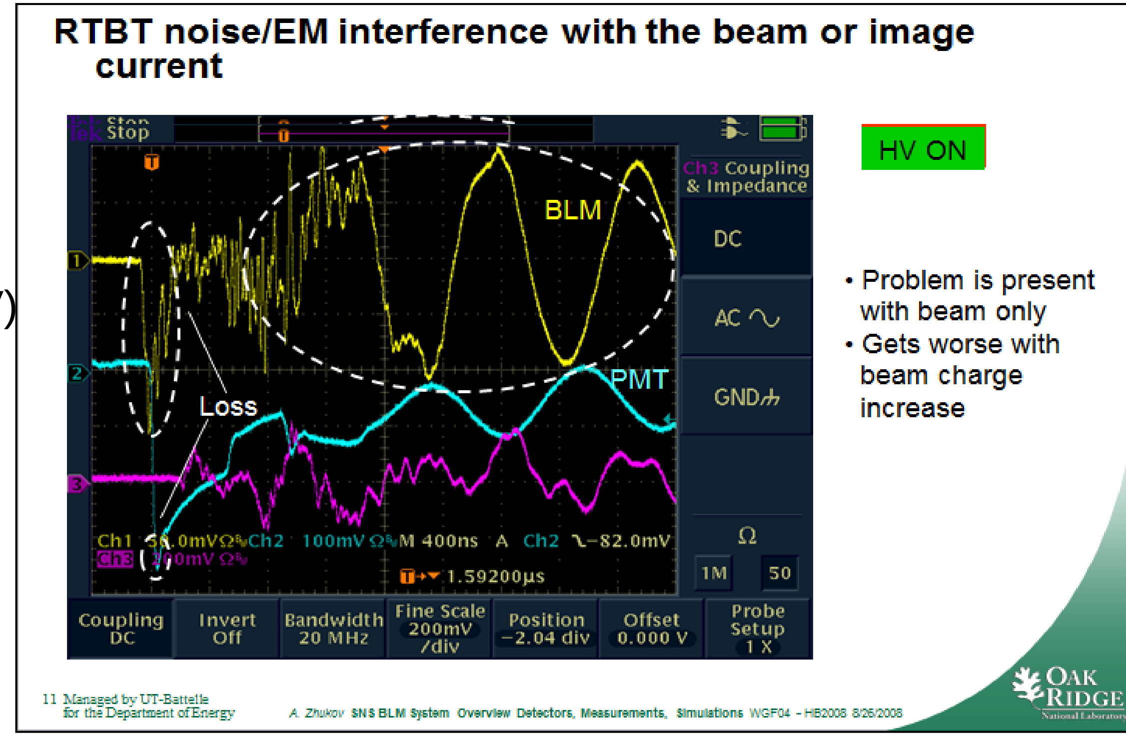
4b) Challenges associated to measurements of losses at high background

The problem: Limits the dynamic range

1. EM Noise

Reasons:

- Shielding
- Ground loops
- RF
- PS ripple (from magnets, from HV)
- Kickers, septum
- Magic
- Ghosts
- Sabotage
- …



Solutions:

Blame the others!

(not very useful, I know…)

4b) Challenges associated to measurements of losses at high background

The problem: Limits the dynamic range

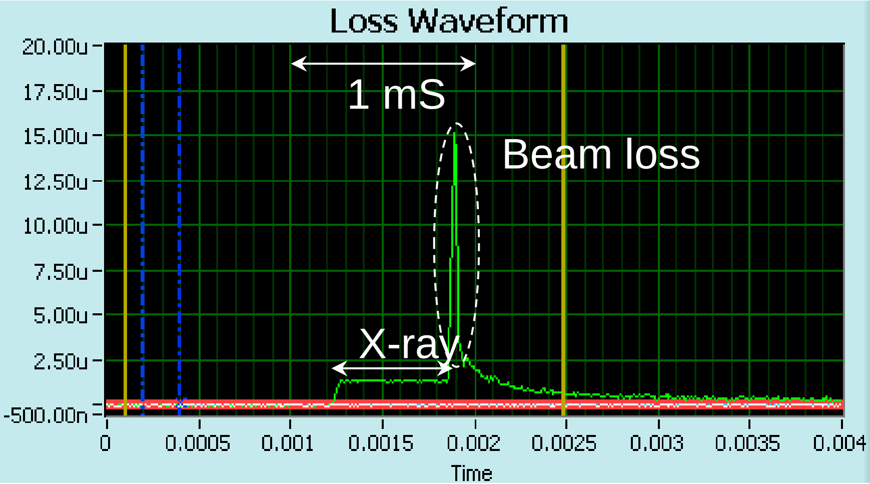
2. X-ray from cavities

Reasons:

- Released electrons from cavity
- Magic
- Ghosts
- Sabotage
- …

Solutions:

- **Subtraction by software**
- Use of a x-ray insensitive detector



SNS

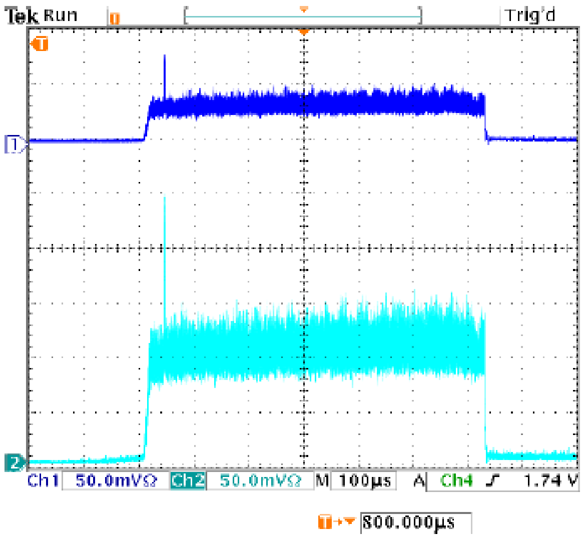


Figure 4: BLM signals from a single bunch and dark current at FLASH (April 2012): BLM with SQ1 synthetic fused silica (top, HV=700 V) and BLM with a scintillator (HV=550 V).

XFEL Beam Loss Monitor System
A. Kaukher, I. Krouptchenkov, D. Noelle (D. Nölle), H. Tiessen, K. Wittenburg
IPAC12

Optical Beam Loss Monitor for RF Cavity Characterisation
A.S. Alexandrova et al., IBIC2017, Grand Rapids, MI, USA

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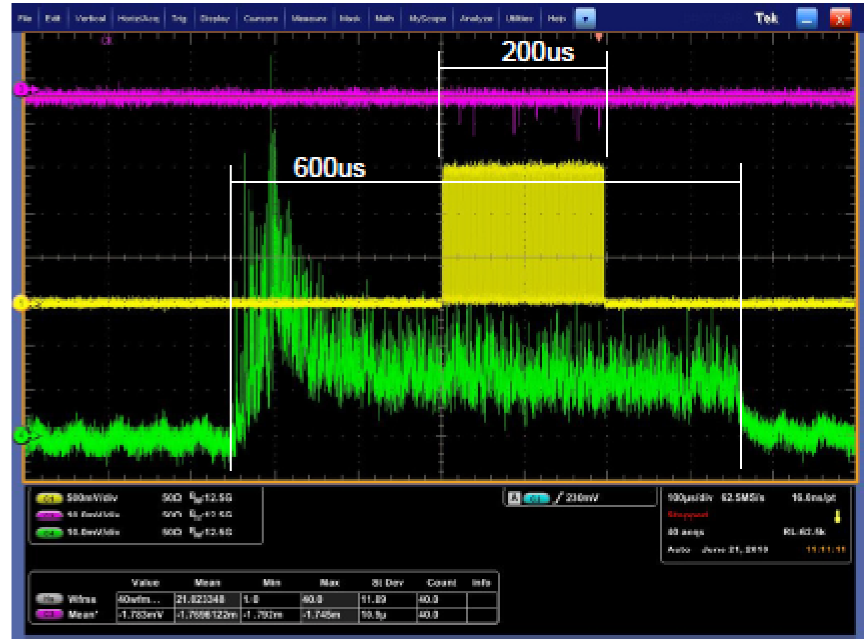


Figure 5: Signals from a gas proportional monitor (green) and plastic scintillation monitor (magenta) at SDTL13 section, during beam operation with chopped beam. The beam current signal with a current transformer is also shown (yellow).

Beam Loss Detected by Scintillation Monitor, Akihiko Miura, et al. IPAC´11

4b) Challenges associated to measurements of losses at high background

The problem: Limits the dynamic range

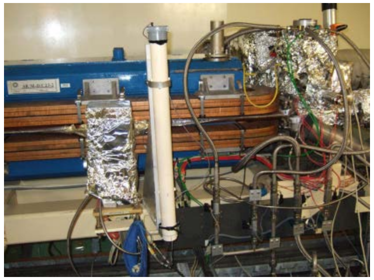
3. X-ray from Synchrotron radiation

Reasons:

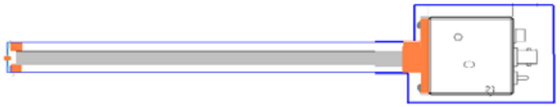
- SR is unavoidable

Solutions:

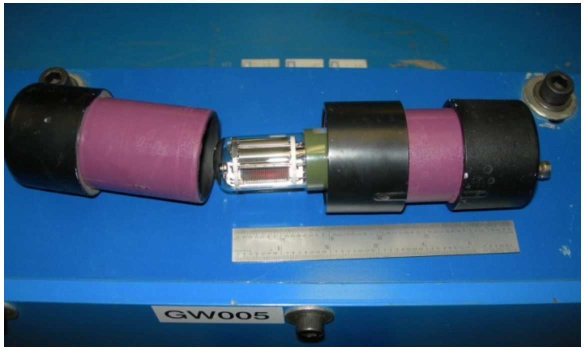
- Subtraction by software
- **Use of a x-ray insensitive detector: Cherenkov material: Quartz**
- Coincidence

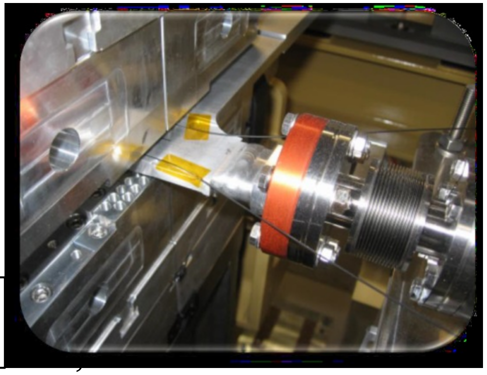
K. Scheid, ESRF, 7th DITANET Topical Workshop on Beam Loss Monitoring; 2011




S.L. Krameer NSLS II, 7th DITANET Topical Workshop on Beam Loss Monitoring; 2011



J. Perry, Jlab, PAC93



L. Fröhlich, FERMI, 7th DITANET Topical Workshop on Beam Loss Monitoring; 2011

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<u>Reasons:</u>

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Solutions:

- Subtraction by software
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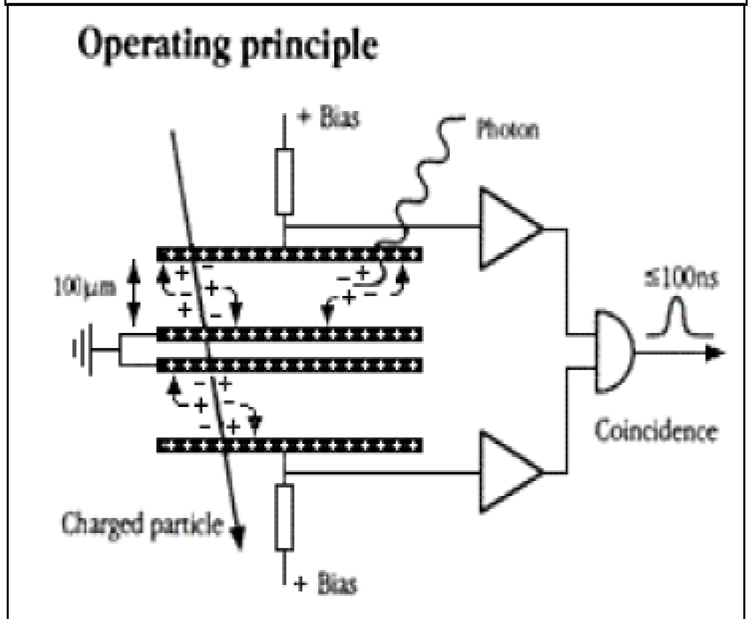
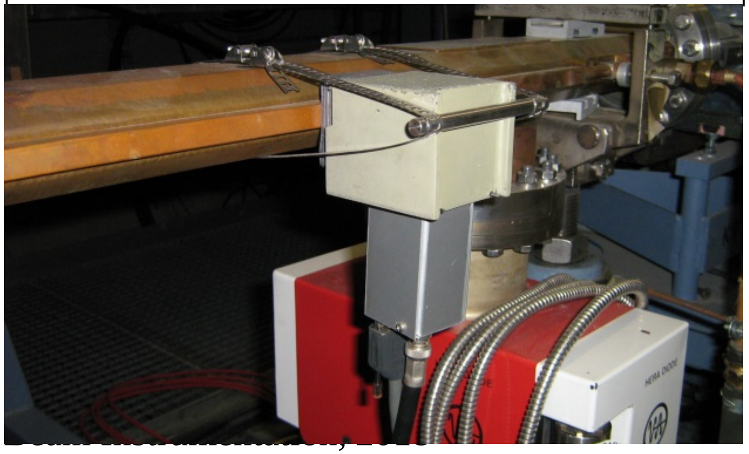
- **Coincidence: Counting**

Coincidence technique: SR-Photons stop in one **<u>or</u>** the other PIN diode and are not counted!





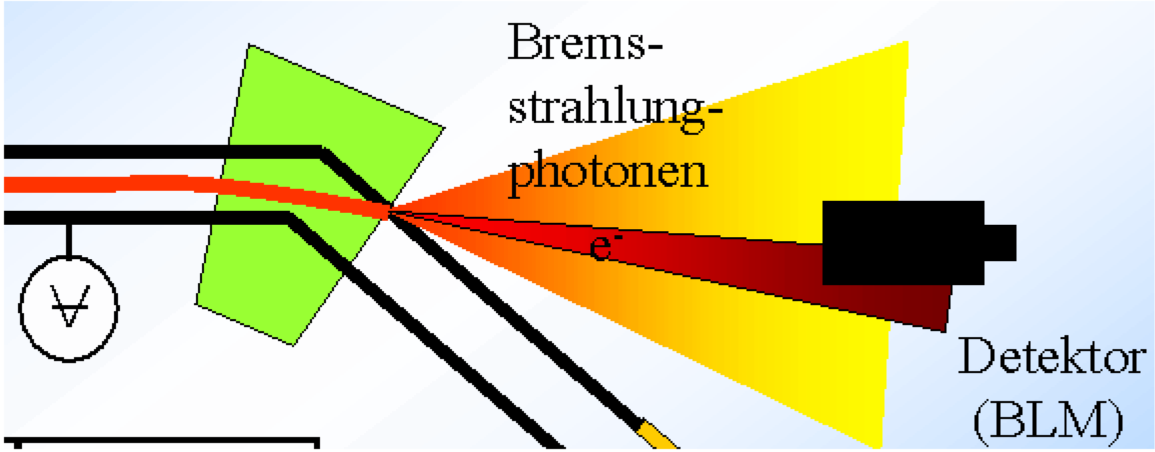
The Beam Loss Monitoring System at ELSA
Dennis Proft , IPAC12

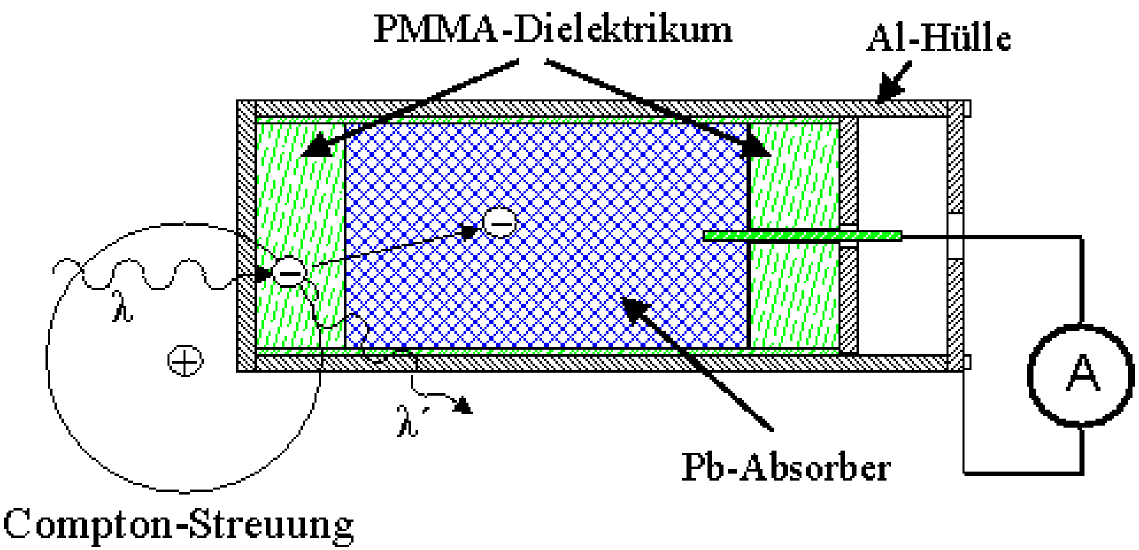
Installation and Test of a Beam Loss Monitor System for the S-DALINAC
Robert Stegmann, IPAC12

Beam Loss Monitors for the HERA Proton Ring
DESY HERA 90-11

Reserve slides

Only for photons !

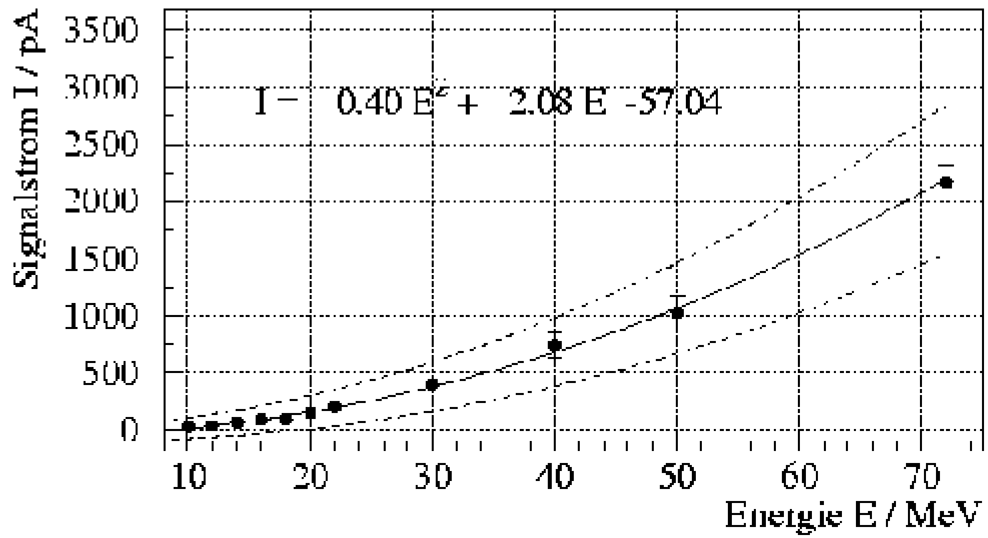




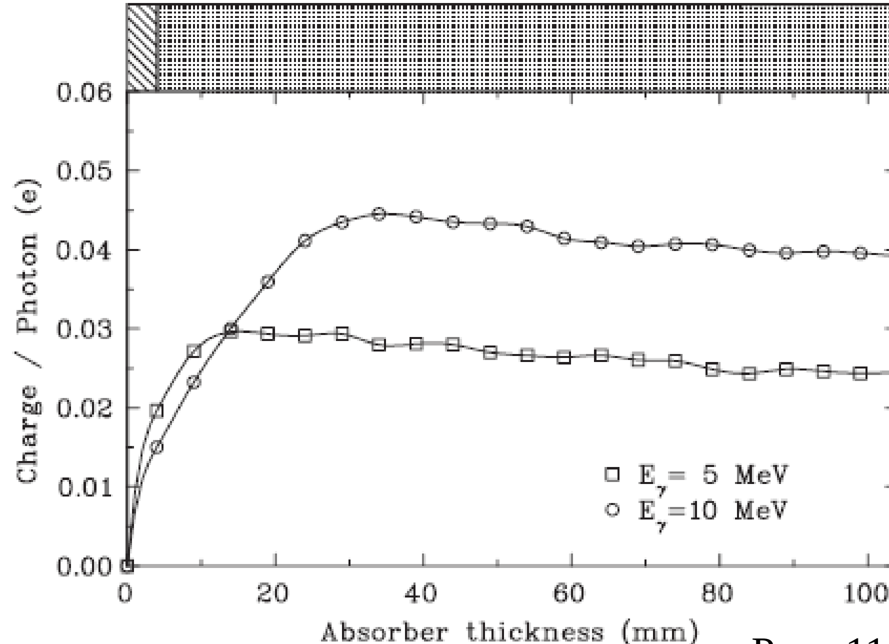
Compton Diode

“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.



Compton diodes as diagnostic tools in accelerator operation, H.-D. Gräf et al.; NIM A 512 (2003) 453–458



+Fast
+Simple, cheap
+Radiation hard

-Very moderate sensitivity
-Low energy photons only

bit	value
0	1.00E+00
1	2.00E+00
2	4.00E+00
3	8.00E+00
4	1.60E+01
5	3.20E+01
6	6.40E+01
7	1.28E+02
8	2.56E+02
9	5.12E+02
10	1.02E+03
11	2.05E+03
12	4.10E+03
13	8.19E+03
14	1.64E+04
15	3.28E+04
16	6.55E+04
17	1.31E+05
18	2.62E+05
19	5.24E+05
20	1.05E+06
21	2.10E+06
22	4.19E+06
23	8.39E+06
24	1.68E+07

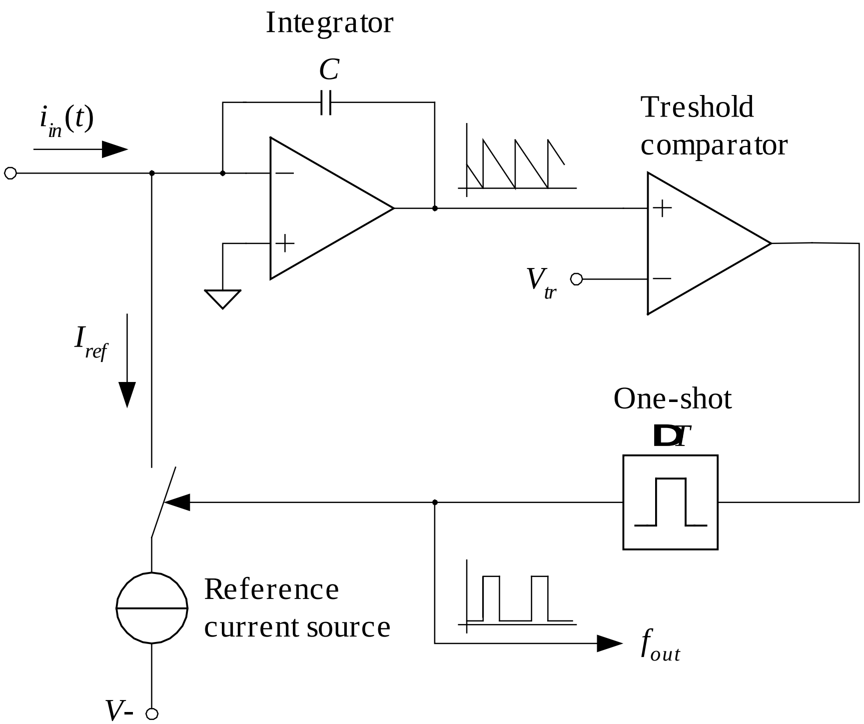
current to frequency converter:

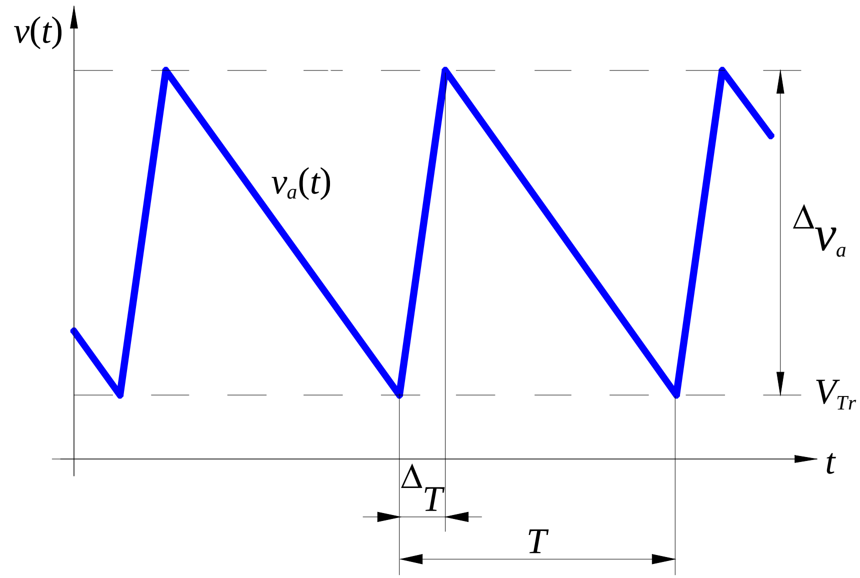
- first stage (input cable length up to 400 m):
  - dynamic: about 10^7
  - input current: 30 pA to 50 mA
  - output frequency: 0.05 to several MHz

Tevatron upgraded BLM System:

- **Dual Charge Integrator (Burr Brown ACF2101)**
  - Alternately integrating or being readout and reset
  - Provides continuous measurement
  - 50 kHz maximum sample rate
- **16-Bit SAR ADC**
- **DAC to give analog scope output**

Charge -balanced converter





$$f = \frac{\overline{i_{in}}}{I_{ref}\,\Delta T}$$

Comparison of Three Different Concepts of High Dynamic Range and Dependability Optimised Current Measurement Digitisers for Beam Loss Systems; W. Vigano, et al., IBIC2012, Tsukuba, Japan