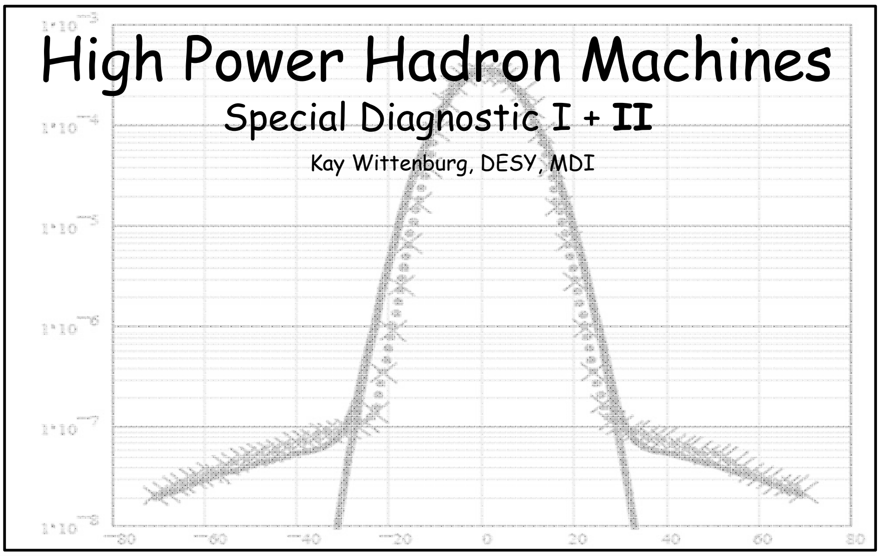
Deutsches Elektronen Synchrotron DESY

CAS2011 – Bilbao-

High Power Hadron Machines

Special Diagnostic I + **II**

Kay Wittenburg, DESY, MDI



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Outline

1) Needs for High Power Machine Diagnostic:
   - What is the goal of the instrumentation and diagnostic

2) Instruments: & Diagnostic methods:

Instruments:
- Beam Current/Shape
- Beam Position
- Beam Profile

Diagnostic methods:
- Emittance
- Energy
- Mismatch

Saturday

Instruments:
- **Beam Loss**

Diagnostic methods:
- **Machine Protection Systems**
- **Transversal and Longitudinal Halo**
- **E-clouds**

Today

Concentrate in the instrument, not on the readout (electronics)

Beam Loss Monitors

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.

Beam Loss Monitors (BLM)

Beside the task of machine protection the BLM-System has more major goals:

- It should limit the losses to a level which ensures hands-on-maintenance of accelerator components during shutdown and it should limit the radiation outside the accelerator shielding.
  - The hands-on limit has been found approximately between 0.1 to 1 W/m.
  - 1 W/m corresponds to 1 GeV·nA/m, therefore the limit of losses shrinks with beam energy.
- Ground water activation and radiation damage to components may put additional constrains to tolerable beam losses.
- Detecting the physical locations of a beam loss within a certain resolution in space. Often the resolution is limited by the spacing of the individual BLMs.
- Determination of the fraction of the lost particles relative to the beam, within a certain time interval.
- 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.

This includes the comparison of the detected loss with computer models (Monte Carlo and beam tracking programs) and the analysis of the behaviour

=> Very high dynamic range is required!!!

Beam Loss Monitors (BLM)

Regular (controlled, slow) losses (in a few minutes)
and
Irregular (uncontrolled, fast) losses:

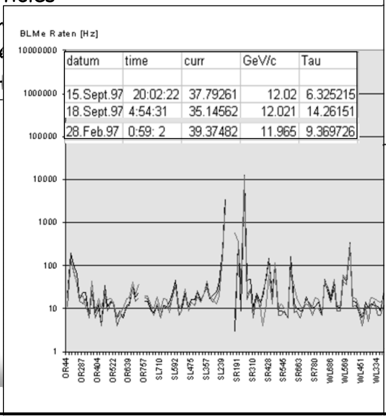
- May occur with a fast transient, therefore the reaction time of the BLM System has to be matched to the transient time.
  - In LINACS even a bunch by bunch loss measurement is required
  - In (superconducting) storage rings about 0.1 – 10 milliseconds are sufficient.
- Dangerous conditions (thresholds!) are defined by the acceptable energy deposition of the lost particles and its adjacent shower in sensitive materials of the accelerator environment
  - incl. Quench protection and protection of the detector components.
  - Monte Carlo simulations are most helpful to calculate the thresholds for each specific BLM location as well as to calibrate the response of the BLM in terms of lost particles.

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

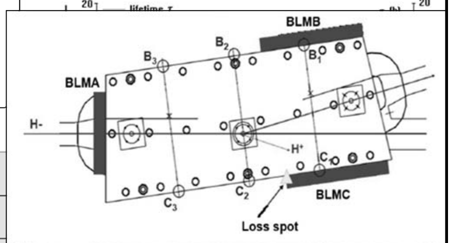
Irregular Losses

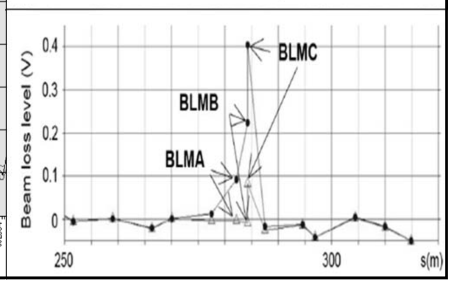
Examples for irregular (uncontrolled, fast) losses :

- Superconducting machines: Quench protection
- Activation of environment due to losses
- Commissioning: Obstacle
- Vacuum Problems
- Microparticles
- High curr
  Linac): De
- Reduce H



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





Loss Classes (II)

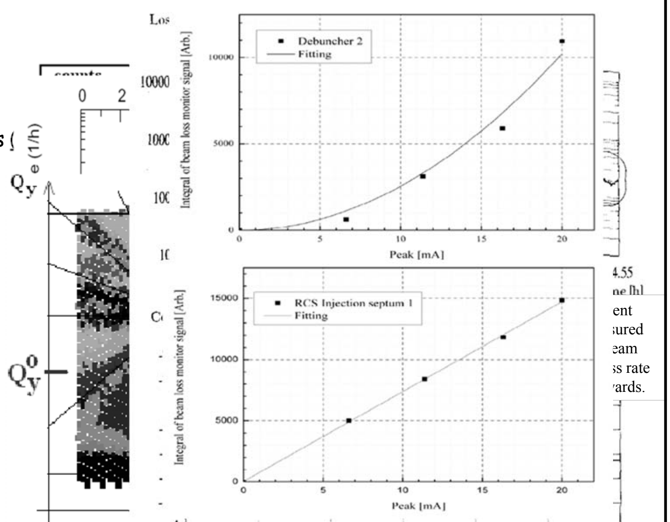
Regular (controlled, slow) loss:
Those losses are **typically not avoidable** and are often localized on the collimator system or on other (hopefully known) aperture limits. They might occur continuously during operational running and correspond to the lifetime/transport efficiency of the beam in the 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, space charge, 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. => High dynamic range!

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

- Injection studies
- Lifetime limitations (
- H^- stripping source
- Tail scans
- Tune scans
- Ground motion
- Diffusion
- Setting up the collimator system



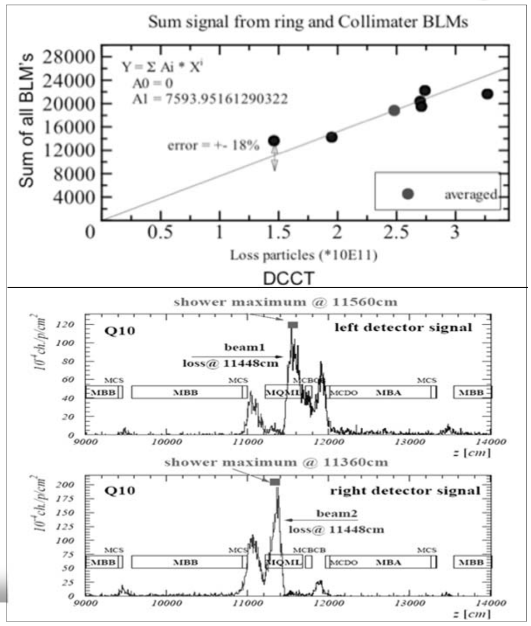
J-Parc H^- LINAC (**very preliminary (HB2010)**)
Upper: intra-beam stripping as source of the beam loss(quadratic).
Lower: stripping by residual gas (linear)

Calibration and Positioning of the BLM:

Beam Loss Monitoring Using Proportional Counters at J-PARC, T. Toyama, et al; HB2008

Calibration of BLM-signal in terms of lost particles:

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.



Calibration and Positioning of the BLM:

BLMs should be localized in areas with higher probability of beam losses, e.g. collimators, high dispersion regions, high β-amplitudes.

- **Different types of BLMs** are used sometimes at the same location to extend the dynamic range of the system: sensitive BLMs to measure small losses and more insensitive ones to cover the high loss rates.
- **Covering different time scales**: Scintillator based BLMs for ns response times and ionization chambers for ms response times
- At **beam energy below the pion-threshold** (< 150 MeV) the (additional) use of neutron sensitive BLMs is useful since the charged particles hardly escape the vacuum chamber.

Considerations in selecting a Beam Loss Monitor

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**

Especially for high intensity beams a common aspect is the required large dynamic range, but also theirs radiation resistance, saturation characteristics and others.

*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**.*

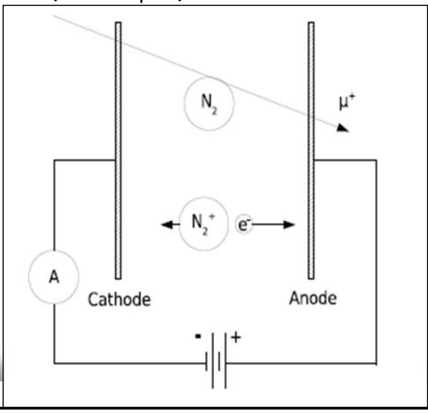
BLM Types:

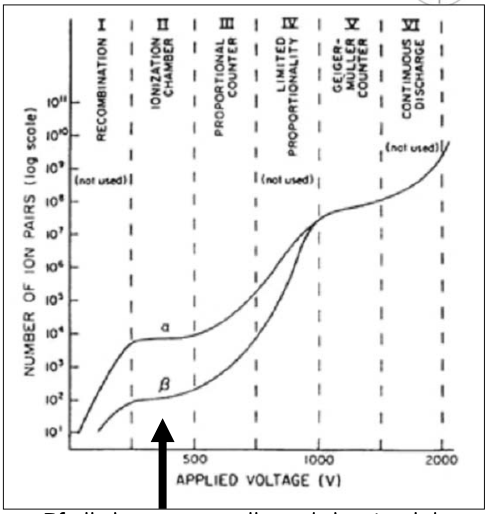
Discussed devices (most common):
Ionization chambers,
Photomultipliers with scintillators (incl. Optical Fibers and Cherenkov light),
PIN Diodes (Semiconductors),
Secondary Emission

A more detailed discussion of various types of BLMs can be found in:
Beam Loss Monitors; CAS, Dourdan, France, 2008, CERN-2009-005

Ionization Chamber

An ionization chamber in its simplest form consists of two parallel metallic electrodes. High voltages, are applied to the anode. The gap is filled with gas (air, argon, xenon) or liquid. Ionizing particles traversing the sensitive volume ionize the gas or liquid and produce electron-ion pairs (≈36 eV/pair).





If all charges are collected the signal does not depend on the applied voltage (Ionization Region).

Ionization Chamber

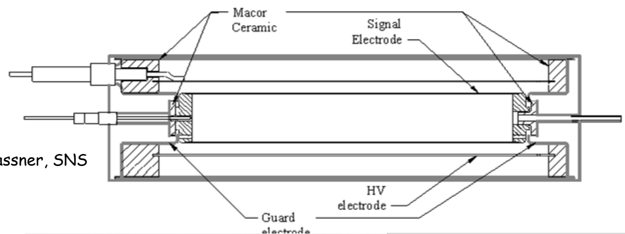
Saturation in high radiation:

The flatness of the plateau of the Ionization Region depends on the collection efficiency of the electrons or ions on the electrodes. Especially at high radiation levels , 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**

are preferred to achieve

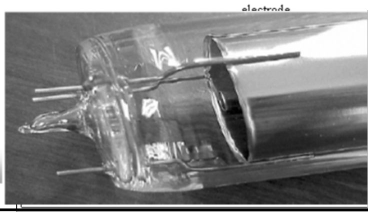
- **high dynamic range**
- **faster response time**



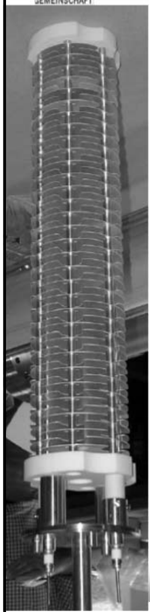
R. Witkover, D. Gassner, SNS

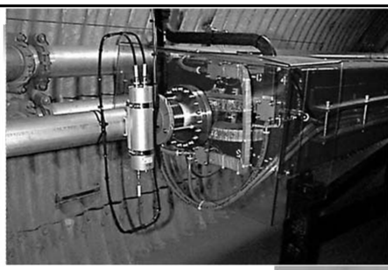
The new design uses the same outer diameter of 1.5 inches but an **inner diameter of 1 vs 1/4-inch** and active length of 6.7 vs 4 inches to get the same sensitivity.

R. Witkover, D. Gassner, SNS



Tevatron Ion Chamber (1983)





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

Ionization Chamber

• The **dynamic range** of an ionization chamber is defined by its upper and lower current signal.

- The upper limit is given by the nonlinearity due to the recombination rate at high dose; typ a few hundred mA.
- The lower limit is given by the dark current between the two electrodes. A very careful design of the chamber is necessary to very low dark currents in the order of few pA. => **dynamic range of up to 10^8.**

• **Signal processing**: variable gain amplifiers (KEK), logarithmic amplifiers (NUMI), high ADC resolution (Tevatron) and current to frequency conversion (LHC) are in use.

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

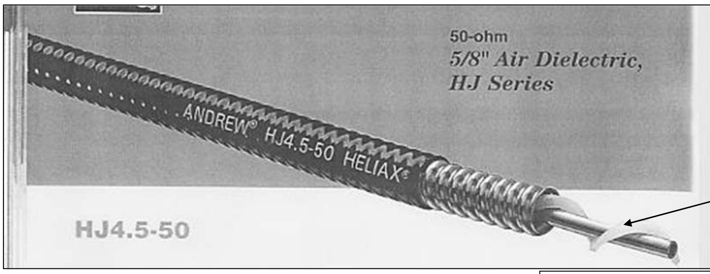
• Little **maintenance** required. Leakage in N2 filled chambers not critical.

• 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.

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

"Panowskys" Long Ionization Chamber (PLIC)

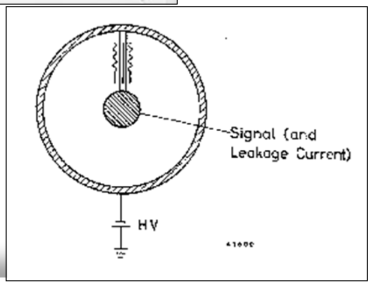
Heliax RF-cable



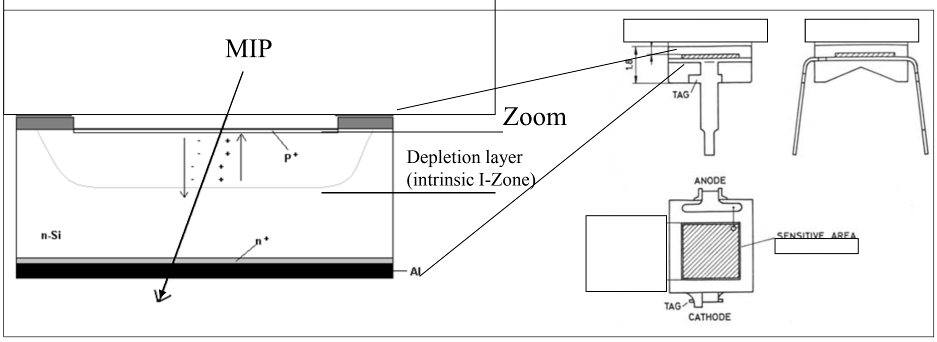
Used in:
ELBE
ISIS
AGS booster
…

Isolator

+Cheap
+Simple
+Uniform sensitivity
• Isolation not very radiation hard
(but >20 years operation in SLAC)
• leakage current ≈ 0.1 pA/m => dynamic range ≈ 10^4
• Sensitivity S ≈ 200 nC/rad/m => 0.5 µrad/s
• (still okay, even with 3 km cable => 0.3 nA)



Solid State Ion-Chamber – PIN Photodiode



PIN Diode with its intrinsic depletion layer is a "solid state ionization chamber".
At about 20 V bias:
• Depletion layer ≈100 - 300 µm
• 2 nA dark current
⇒S ≈ 3.6 eV/pair ≈ 50 nC/rad for $1cm^2$ Diode
⇒ **<u>Fast: ≈ 2 - 20 ns</u>**
Efficiency ε ≥ 80%
⇒ **Due to <u>high dark current lower dynamic range in "current mode"</u>.**

PIN Photodiode in counting mode

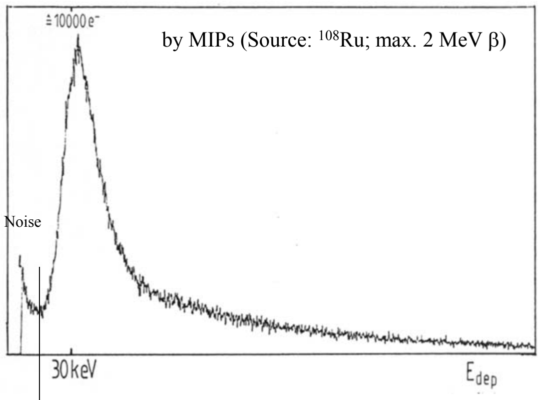
Use as counter:

Enough signal to detect 1 crossing MIP!

≈ 10^4 e/MIP (for 100μm dep.)
1 rad/s = $3.1\cdot10^7$ MIP/s/cm^2
= $\varepsilon\cdot31$ MHz/cm^2

with ε = 80% efficiency

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 Photodiode in counting mode

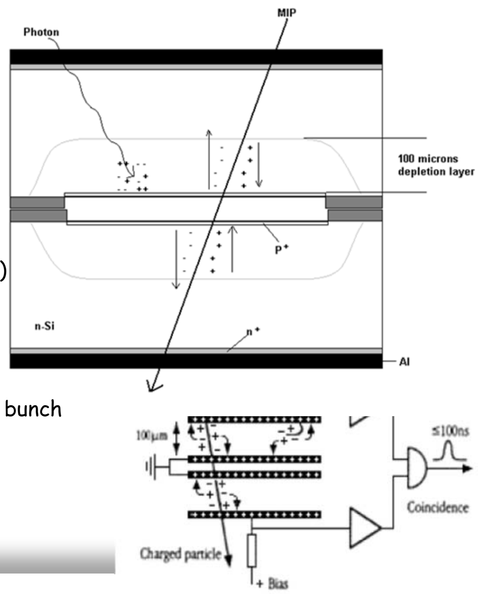
Coincidence technique:
Uncorrelated noise (dark current and SR-Photons) are not counted!

Efficiency to MIPs (measured): ε_{coinc}= 30%
- 1 count ≈ 0.1 μrad (MIPS, 1cm^2 Diodes)

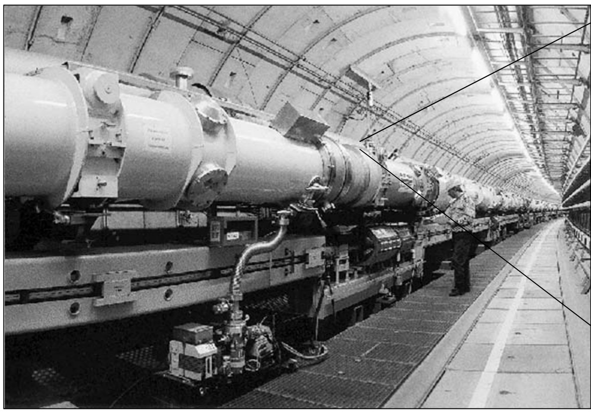
+ Very low noise:
  - Dark count rate < 0.01 Hz
  - max. count rate > 10.4 MHz

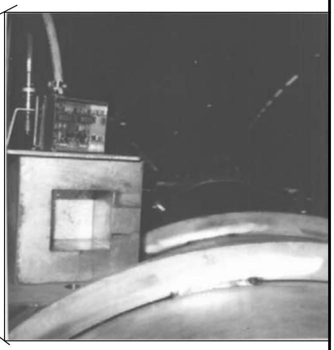
+ **Very high dynamic range: >10^9**
+ Insensitive to x-rays (from SR or RF cavities)
+ PIN Diodes + amplifiers were tested up to 10^8 rad without significant radiation damage; 13 years successful in HERA
+ insensitive to magnetic field

- complete saturation if count rate ≈ 1 count / bunch



PIN Photodiode in counting mode





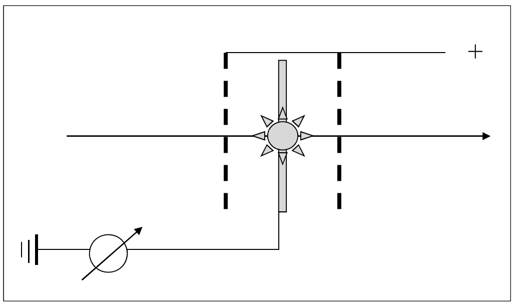
DESY BLM with lead hat (removed) on top of a sc quadrupole

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.

Secondary Emission Monitors

Useful at very high radiation areas, very radiation hard

=> Secondary Emission Monitors
Electron emission from surface due to crossing charged particles

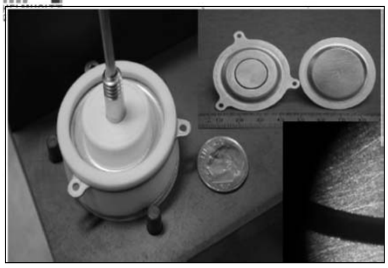


Charges particle (MIP)

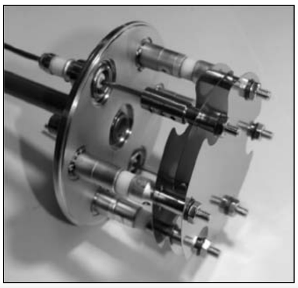
Efficiency about 4-5 %
=> 2 pC/rad (· **PMTgain**)

<u>Very linear</u>
<u>Very fast</u>
<u>Insensitive</u>

CLIC Secondary Emission Monitors



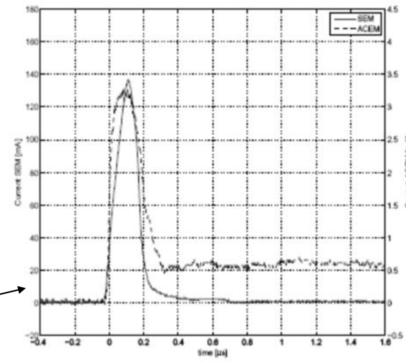
Gas sealed (ion chamber, slow) or in high vacuum (SEM, fast)



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 2.16×10^{12} p^+ at 1.4 GeV).

Secondary Emission Monitors

With internal amplification

THORN EMI

NUCLEAR RADIATION DETECTOR TYPE: 9841

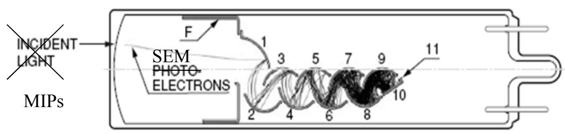
(Aluminium Cathode Electron Multiplier)

Description

Ø 32 mm

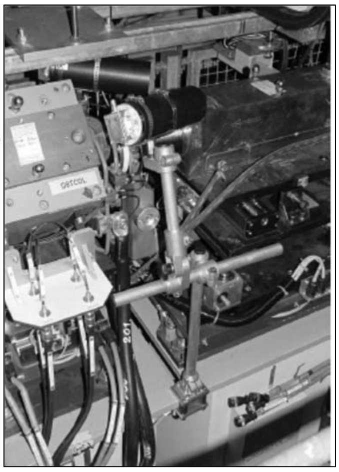
Cathode; Aluminium.
Window; Borosilicate.
Dynodes; 10 linear focused type with CsSb secondary emitting surfaces.
Base; B14B.

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.



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

EMI Aluminum Cathode Electron Multipliers: CERN TESTS. *V. Agoritsas and C. Johnson; (1971)*



ACEMs at FLASH collimators

Scintillation counters

Using light

SEM based BLMs are very fast but still have a moderate sensitivity. An equivalent speed (few ns) but much higher sensitivity can be achieved with scintillation counters, a combination of a scintillating material and a photomultiplier tube (PMT).

+ Large area plastic scintillators and liquid scintillators are available
  - **easy to cut** or form "Plastic Scintillators" to nearly any shape.
  - **Large size** to enhance the solid angle of beam loss detection if the resulting radiation is not uniformly distributed. This is often true if the BLM is located very close to the beam pipe where the radiation is peaked into a solid angle and at low beam energies.
  - Typically a **thin layer** of scintillator (0.3-3 cm) is sufficient to ensure sensitive loss detection, even at very limited space conditions

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

Scintillation counters

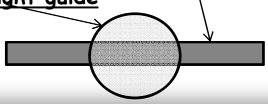
Note that the light transmission though the scintillator (and the light guide) changes due to **radiation damage**.

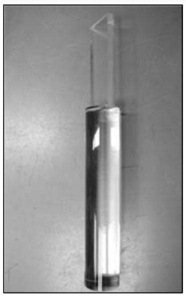
➢ This depends strongly on the scintillator and light guide material, but for organic scintillators a typical value can be assumed: The **transmission decreases to 1/e** of its original value happens after about **0.01-1 MGy (1-100 Mrad)** collected dose.

➢ Liquid scintillators are somewhat radiation harder and have about the same sensitivity

The **flux density** of photons into the light guide is **"incompressible"** !

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





Scintillator with Plexiglass light guide

aluminum foil

black plastic foil adhesive tape and test pulse LED

B. Michalek (DESY)

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

Sensitivity ≈ 17 μC/rad * PMT_{gain}

(CsJ(Tl):
Rs = 0.06 photon/eV,
ρ = 4.4 g/cm3,
poor rad hardness)

PMT-Gain depends on HV => Need stable PS
Without gain variation=> Dynamic range ≈ 10^3
A dynamic rage of 10^8 was measured at LEDA with gain adjustments.

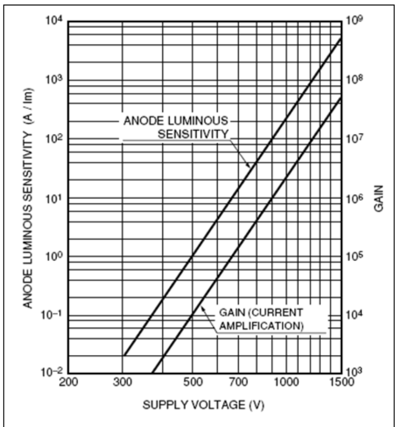


Figure 4-13: Gain vs. supply voltage

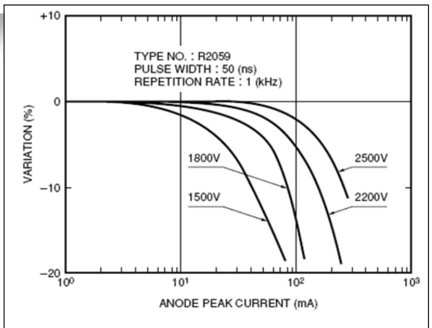


Figure 4-23: Voltage dependence of linearity

Hamamatsu.PMT_handbook

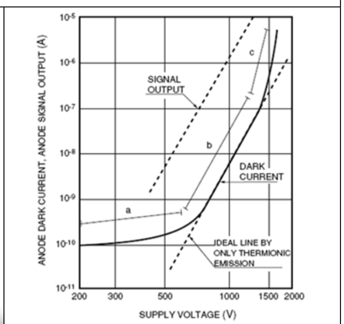
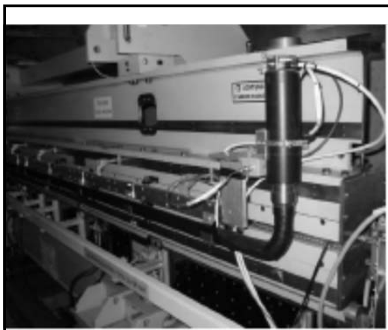


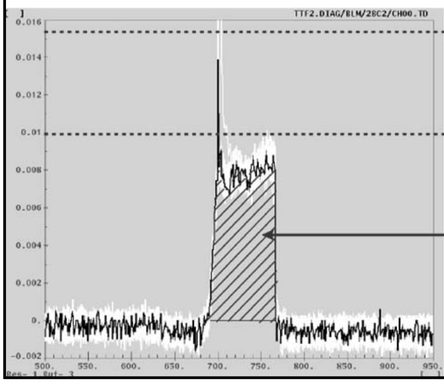
Figure 4-38: Typical dark current vs. supply voltage characteristic

EXPERIENCE WITH PHOTOMULTIPLIER BASE BEAM LOSS MONITORS AT THE LOW ENERGY DEMONSTRATION ACCELERATOR (LEDA) W. C. Sellyey et al, PAC2001

Scintillator assemblies and installations in FLASH



LED for testing the functionality of the BLM
Otherwise => No BLM signal = ⌿ okay for MPS ⌿
(Other methods: Dark current, Modulation of HV (IC), radioactive source, …)

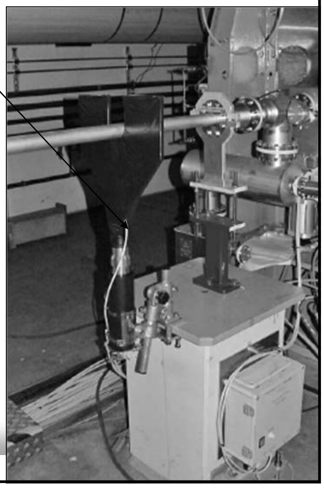


3 different thresholds:

Single bunch

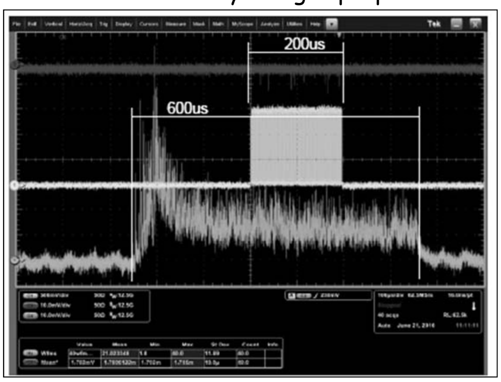
10 bunches

Integral (here 100 bunches)

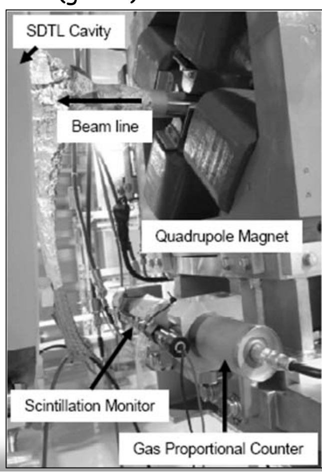


Scintillation counters and prop. chamber at J-Parc

Plastic scintillation monitors with <u>less X-ray sensitivity</u> installed to measure the beam loss (magenta). Because the gas proportional counter received the high background of X-ray emitted from RF cavities, the essential beam loss cannot be detected by the gas proportional counter (green).



The beam current signal is also shown (yellow).

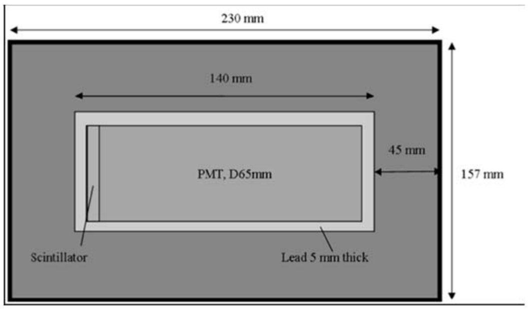


Status of Beam Loss Evaluation at J-PARC Linac; Akihiko Miura, etal., LINAC10,

Scintillation counters

So far all detectors are sensitive to "local" losses that occur within proximity of detector.

- Neutron detectors (ND) are good at detecting losses occurring meters away from the detector itself. This makes NDs hard to interpret but more reliable for MPS purposes.
- Especially at beam energy below the pion-threshold (< 150 MeV) the (additional) use of NDs is useful since the charged particles hardly escape the vacuum chamber
- Solely relying on "normal" BLMs can lead to hiding of losses instead of eliminating them because the tuning process may move the loss to a place where it is not seen by the normal BLM.



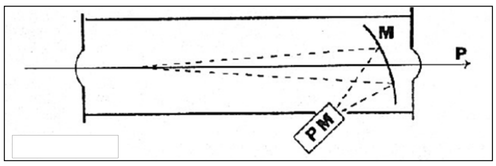
Neutron Detector is a 230x157x150mm box. PMT is inside x-ray shielding (lead) and is surrounded by polyethylene neutron moderator. (Scintillator Li-doped $^{6}Li(n,\alpha)$

SNS BLM System Evolution: Detectors, Electronics, and Software; A.P. Zhukov, et al, PAC2009

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 b and the refraction index n of the medium. The light can be focused on PMT to build an BLM.

Sensitivity: (1 ltr) $$S_{Che} \approx 270 \frac{nC}{rad} \cdot PMT_{gain}$$



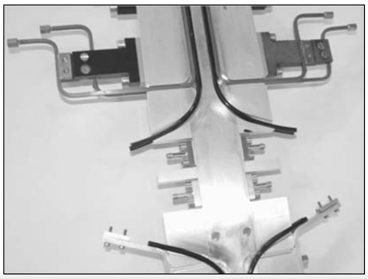
JLAB FEL: detect Čerenkov light in PMT glass

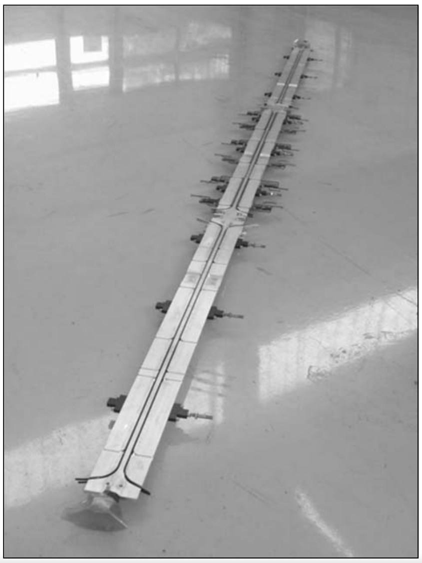
+ cheap 931B PMT, mainly blue sensitive
+ quite radiation tolerant, darkening of glass compensated by HV (~10% HV change needed this far)
+ cheap housing (1.5" plastic water pipes)
• controls strong beam losses
- not sensitive enough for „normal losses"

Optical fibers (Cherenkov light)

Optical Fibers (Cerenkov) embedded in FLASH undulator vacuum chamber

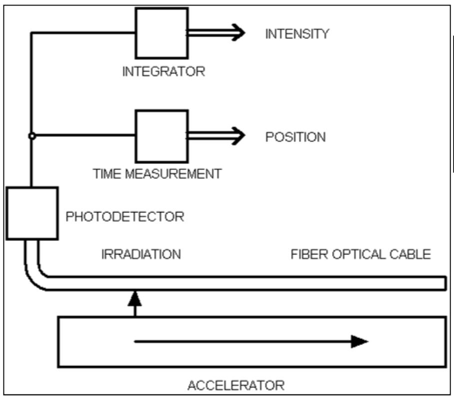
U. Hahn - DESY





Optical fibers (Cherenkov light)

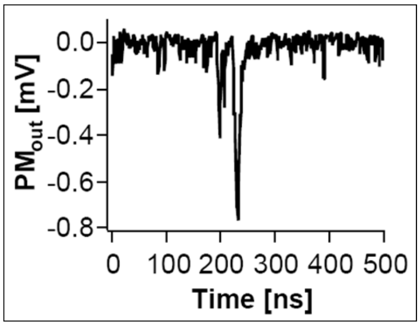
A Beam Loss Monitor (BLPM) based on Cerenkov light in optical fibers allows real time monitoring of loss location and loss intensity like in PLICs. The fast response of the Cerenkov signal is detected with photomultipliers at the end of the irradiated fibers.



Using high purity quartz fibers (suprasil):
- Only Cherenkov emission, no scintil.
- 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 ---

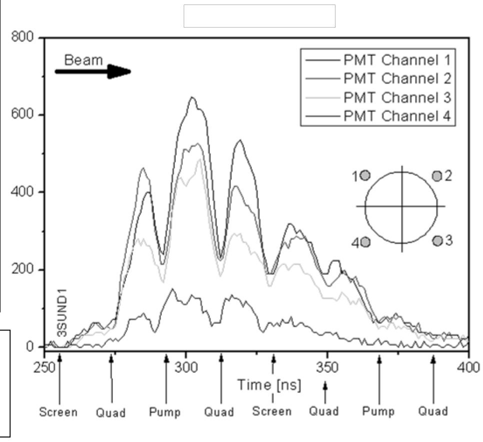
Optical fibers (Cherenkov light)

Along accelerator (TTF)



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

Longitudinal loss profile
and transversal loss position



Scintillation counters

Change of light transmission due to radiation

S. Goulding, R.H. Pohl 1972

1.0

=>

e.g

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.

BLM Summary

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

BLM Summary

Ionization chambers	
LEDA	160 ccm N_2 Ion chamber
ISIS	Long Ar ionisation tubes (3-4m)
SNS Ring	113 ccm Ar Ion chambers
SNS Linac	113 ccm Ar Ion chambers
PSI	Air Ionization chambers
PEFP	
J-PARC,RCS, MR, LINAC	Ar+CO_2 proportional ccounters (80 cm) and coaxial cable ion chambers air filled (4-5 m)
PSR	ion chambers filled with 160 cm^3 of N_2 gas
LANSCE	180 ccm N2 ion chamber
CSNS	110 cm3 Ar ion chamber
AGS	Ar filled long coaxial ion chambers
NuMI	Ar filled Ion glass tubes
SPS, CNGS	Air filled ion chambers (1 ltr)
APT	like LEDA
MI, Booster, Tevatron	Ar filled Ion glass tubes, 190 ccm
CERN LHC	N_2 filled ion chambers 1.5 ltr.
Rhic	Ar filled Ion glass tubes

BLM Summary

Scintillator	
LEDA	CsI Scintillator PMT-Based
ISIS	Plastic Scintillator (BC408)
J-PARC RCS, MR, LINAC	GSO Scintillator
SNS Ring	Scintillator-PMTs
SNS Linac	PMTs with a neutron converter
PSR	Liquid scintillator with PMT (old)
CSNS	Scintillator-PMTs
SEM chambers	
LHC	SEM chambers
PIN Diodes	
HERA	PIN Diodes in counting mode
Tevatron	PIN Diodes in counting mode
Rhic	PIN Diodes in counting mode

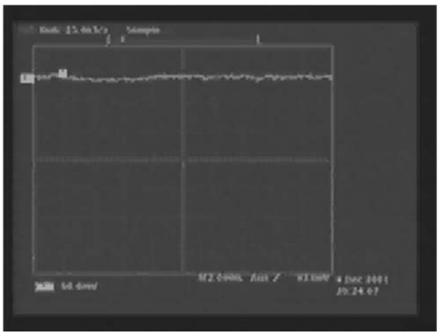
Last Conclusion

BLM

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.

Beam Loss

Play



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

Some special diagnostics
(related to high intense hadron beams)

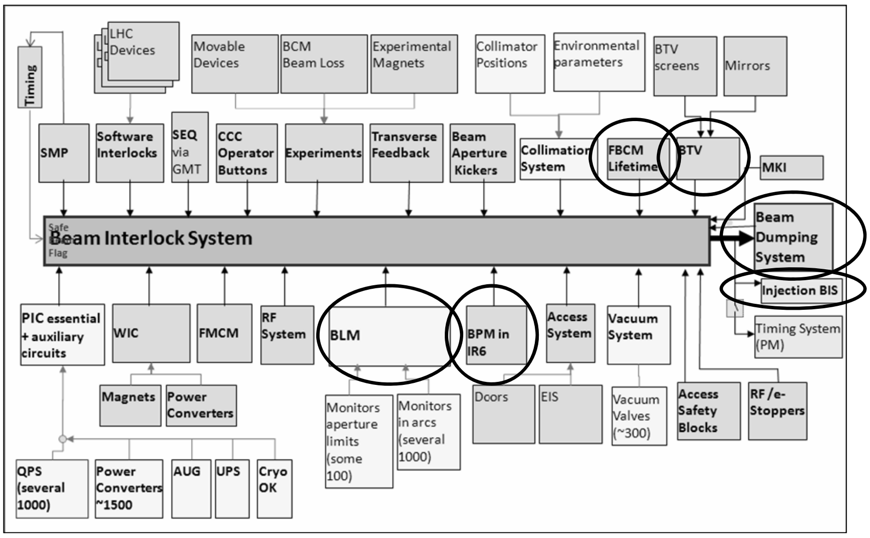
Machine Protection System
- Little shop of horrors

Halo and Bunch Purity
- What is Halo
- Transversal halo measurements
- Longitudinal halo measurements (bunch purity)

Electron cloud diagnostic:
- BPMs
- Pressure rise
- Retarding Field Analyzer (RFA)
- Tracks
- Microwaves

More about standard techniques (Tune, Chromaticity, …) in:
Lectures given at the CAS course on:
"Beam Diagnostics"
Le Normont Hotel, Dourdan, France
28 May - 6 June 2008

Machine Protection System –MPS-



LHC MPS (from: **Commissioning and Operation of the LHC Machine Protection System**
M. Zerlauth, R. Schmidt, J. Wenninger; HB2010

-MPS-

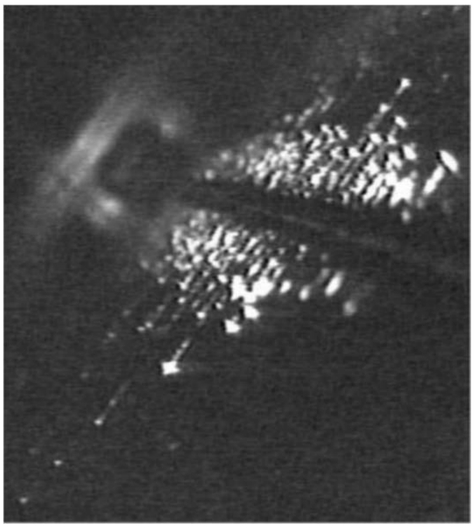
Little shop of horrors

TEVATRON:
The initial reason of the large quench was found to be caused by a CDF Roman Pot **reinserting itself** back into the beam after it had been issued retract commands.

Faulty MPS condition:
BLM's (Beam Loss Monitors) are ***masked off*** during a store to prevent accidental aborts from the losses.

This was the philosophy adopted many years ago when collider operation began (and beam current was low).

⇒ **Interlock everything which can go into the beam (Valves, Screens, Pots, Wire Scanners (short disable can be useful!)**
⇒ **Do not switch of BLMs!**



Nikolai Mokhov, HB2006

-MPS-

Little shop of horrors

Complete loss of the particle beam leading to severe damage to PSI cyclotron.

Faulty MPS condition:
Lack of redundancy in MPS, defect of high-level interlock module

⇒ **MPS should be highly reliable with redundancy but not overshooting.**

Control and Protection Aspects of the Megawatt Proton Accelerator at PSI
A.C. Mezger, HB2010

-MPS-

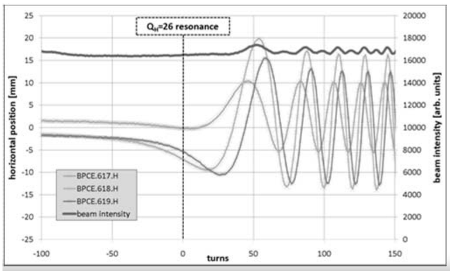
Little shop of horrors

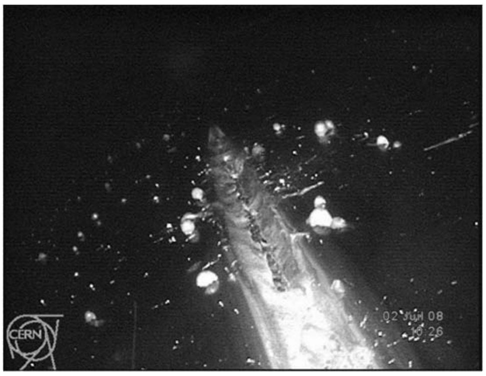
SPS: Hitting a tune resonance during ramp down after timing (extraction) failure. $t_{loss} \approx 70\ \mu s$

Faulty MPS condition:

⇒ **Fast BPM interlock on turn by turn base needed.**

⇒ **Take care of internal delay of the MPS, sometimes some ten ms!**





Beam impact of high intensity CNGS beam ($\approx 3 \cdot 10^{13}$ protons @ 400 GeV = 2 MJ)

Tune Resonance Phenomena in the SPS and Related Machine Protection; T. Baer et al, HB2010

-MPS-

Little shop of horrors

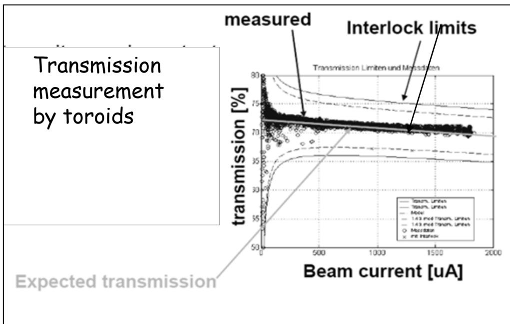
Faulty MPS condition:

No injection inhibit!

⇒ Beam drills a hole while permanently injecting (searching for transmission?)

⇒ **Check of transmission by comparing toroids (and BLMs)**

⇒ **Disable <u>full</u> injection in case of alarms.**



Courtesy P. Michel, ELBE

Current and Transmission Measurement Challenges for High Intensity Beams, P.-A. Duperrex, et al, HB2010

–MPS-

Little shop of horrors

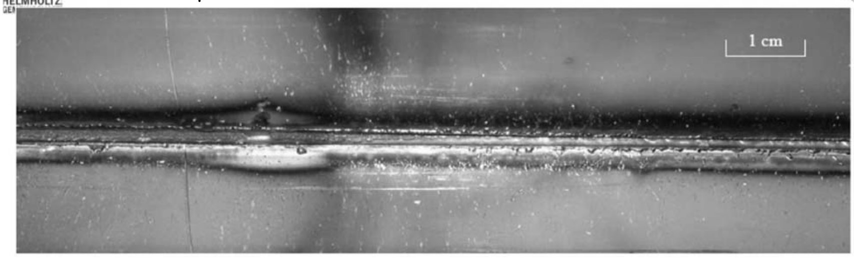
Faulty MPS condition:

- The scintillator-based loss limiting system failed to trip due to **saturation** at the low rep rate (6Hz instead of >60 Hz) that was being used
- The HWTM failed because the relevant current monitors were in fringe fields of magnets and were also **saturated**

- **Beware of saturation (or "off")! It's often read as "0".**

Macek: LANSCE experience with accidental beam loss, HB04

Transfer line damage during high intensity proton beam extraction from the SPS



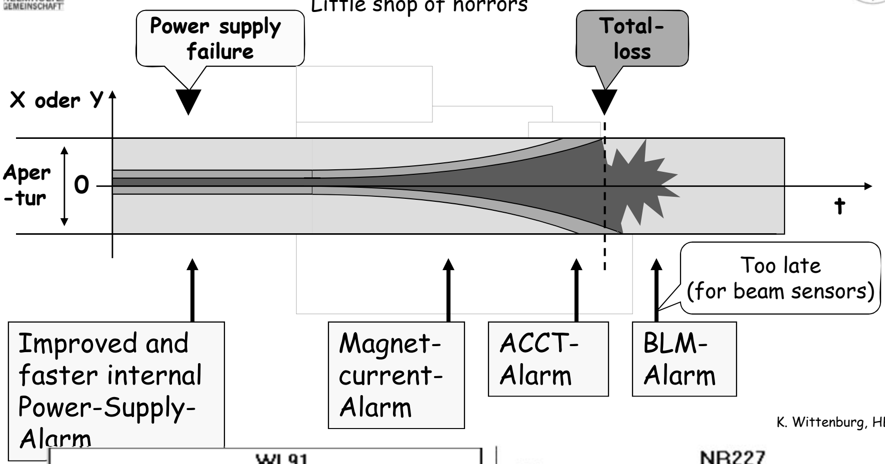
Faulty MPS condition:

1. **Lack of preparation** for high intensity beam commissioning of extraction. No high intensity commissioning procedures established → crucial steps were overlooked or ignored.
2. **Inadequate acceptance tests** of machine protection system (interlock and surveillance systems working together with equipment) without and with beam.
3. Insufficient understanding of risks (problems with the fast current decay monitoring of septum and **EMC pick-up**, which should have detected and solved without extracting).
4. **Incorrect interlock logic** – detected fault should always inhibit the beam first, before cutting the equipment (was requested but not implemented).
5. … Some **organization issues**
6. … " "
7. **Known problems** which occurred (noise-induced trips, measuring bumped beam) **were not solved** before continuing to increase beam intensity – and were still present with full intensity.

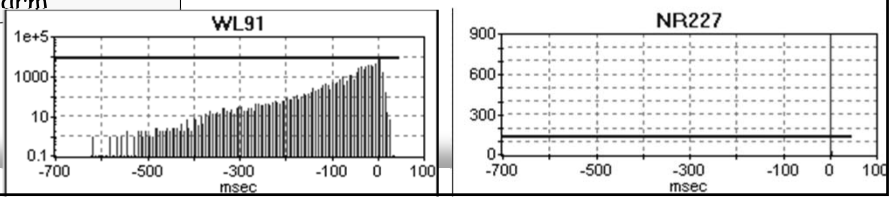
B.Goddard HB2006

Alarm timing/speed

Little shop of horrors



K. Wittenburg, HB2006



Halo and Bunch Purity Monitoring

= Very High Dynamic Beam Profile Measurements; Transversal and Longitudinal

What is Halo?

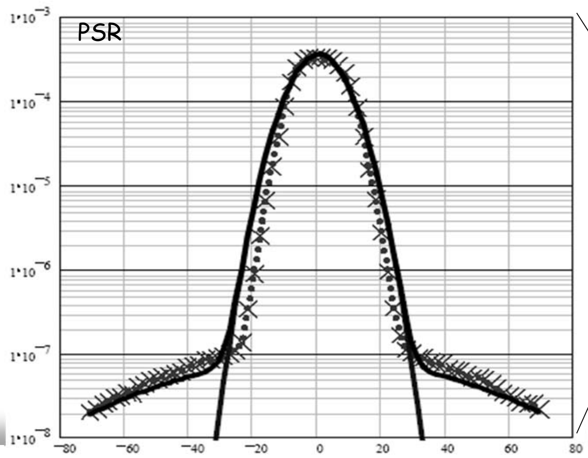
…it became clear that even at this workshop (HALO 03) **a general definition of "Beam Halo" could not be given,** because of the **very different requirements** in different machines, and because of the **differing perspectives** of instrumentation specialists and accelerator physicists.

<u>From the diagnostics point of view, one thing is certainly clear – by definition halo is low density and therefore difficult to measure…</u>

A quantification of the halo requires a more or less simultaneous <u>measurement of the core and the halo of the beam</u>. Therefore halo measurements require very high dynamic range instruments and methods as well as very sensitive devices to measure the few particles in the halo.

What is Halo?

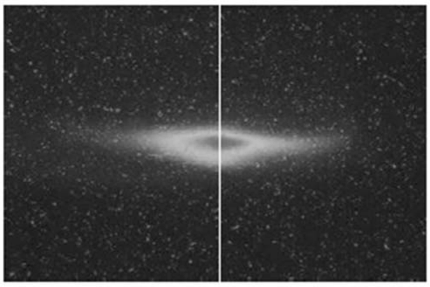
<u>From the diagnostics point of view, one thing is certainly clear – by definition halo is low density and therefore difficult to measure…</u>

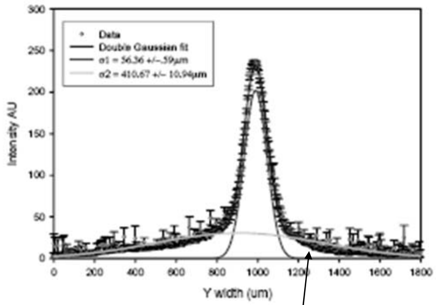


Halo measurements require **high dynamic range instruments** and methods

Dynamic range > 10^5

What is Halo?



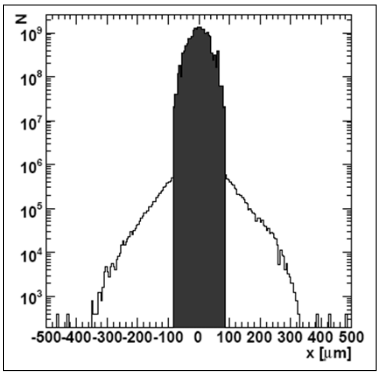


- **Profile measurements are often questioned at the level of a few percent**, the difficulty is easily seen in making halo measurements already at the level of 10^{-4} and beyond.

That's not halo, that's a tail!
Dynamic range $<10^3$

What is Halo?

- **Sources of halo are:**
  - space charge
  - mismatch (long. and transv.)
  - beam beam forces
  - instabilities and resonances
  - RF noise
  - Scattering (inside beam, residual gas, macroparticles, photons, obstacles (stripping foil, screens), …)
  - nonlinear forces
  - misalignments
  - electron cloudes
  - etc.



HALO ESTIMATES AND SIMULATIONS FOR LINEAR COLLIDERS H. Burkhardt, CLIC-note 714

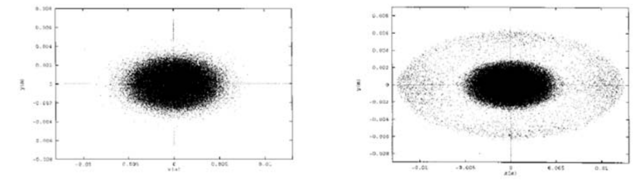


FIGURE 4. This figure shows a typical representation of the extent to which mismatches can cause halo growth. The figure on the right shows the transverse profile of a beam well-matched to a transverse periodic lattice. The figure on the right shows that a 50% mismatch can cause halo growth.

Techniques for Intense-Proton-Beam Profile Measurements; J. D. Gilpatrick, BIW98

Halo Measurements

- The focus of the **accelerator physicists** is on designing and operating their machines to minimize this halo.
- The focus of the **collimation experts** is on cleanly and efficiently disposing of this halo as it appears, a consequence of the clean and efficient disposal being that useful diagnostic information is often lost, buried in the collimators.
- The focus of the **instrumentation specialists** is twofold;
  - ✓ to provide information useful to the accelerator physicists in their machine tuning efforts to avoid halo formation, and
  - ✓ to provide direct measurement of halo.

This lesson

Definition of halo diagnostics: Classification into three categories.

1. Devices that directly measure halo and halo evolution, and the prime example is the wire scanner.
2. Devices that contribute to the diagnosis of machine conditions that cause halo formation, and an example would be a tune measurement system.
3. Devices that measure the effects of halo development, and an example would be the loss monitor system.

Transversal Halo Measurements

Transversal Halo Measurements with:

- **Wire Scanners and Scrapers (slow)**
- **Optical Methods (fast but for e^- only (SR, OTR))**

The light generation in scintillation and phosphor screens suffers form nonlinearities and might therefore be not applicable for huge dynamic range measurements.

For
- IPM (**I**onization Beam **P**rofile **M**onitor)
- LPM (**L**uminescence Beam **P**rofile **M**onitor)
- Laser

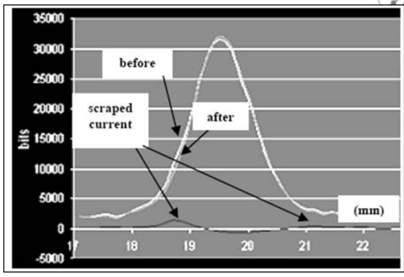
some comments at the beginning.

Their dynamic range end at about 10^3!

IPM: Dynamic range did not exceed 10^3???

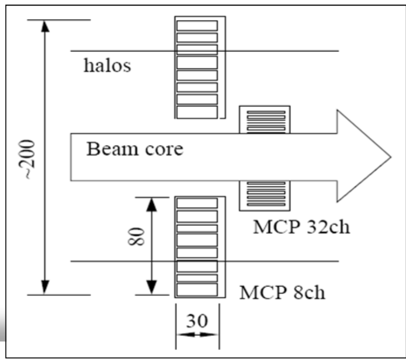
- CERN: Results of scraping vertically 1% of the distribution of a beam of $2.6 \cdot 10^{12}$ protons as seen by the IPM.

Scraping for LHC and collimation tests in the CERN SPS;
M. Facchini, et al, CERN-AB-2005-070



- J-Parc RCS: Idea to use additional MCP arrangement with lower resolution but high gain for halo observations.

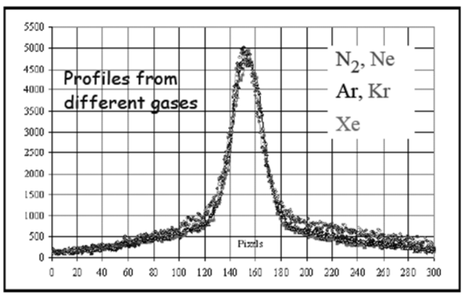
S.Lee et al. ; DESIGN STUDY OF A NONDESTRUCTIVE BEAM PROFILE AND HALOS MONITOR BASED ON RESIDUAL GAS IONIZATION FOR THE J-PARC RCS; The 14th Symposium on Accelerator Science and Technology, Tsukuba, Japan, November 2003



Luminescence Profile Monitor

I.P.H.I: We have to carry on additional experiments in order to understand more accurately the observed beam profiles… Huge background from several secondary processes. Try to discriminate background from real profile by Doppler shift of Balmer series.

Example: Ion source 100 keV, 100 mA protons
P. Ausset et al. (Orsay/Saclay)

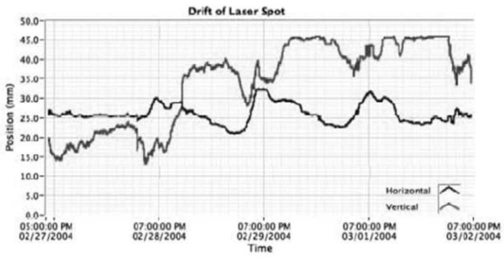


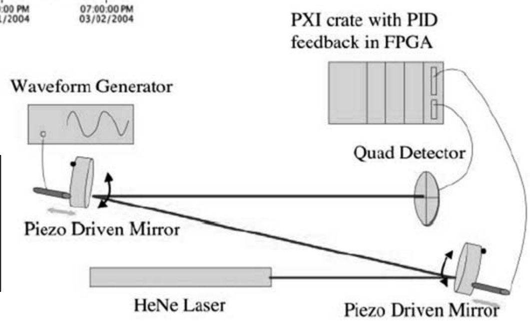
Optical Transverse Beam Profile Measurements for High Power Proton Beams
P. Ausset, etal. EPAC02

=> Instrumental effects make it useless for Halo determination.

Laser Profile Monitor

- Halo Issue: Mechanical drift and vibration (SNS)
  - Compensation scheme foreseen, main frequencies up to 10 Hz





SNS:
Profiles down to 3σ,
dynamic range $\geq 10^3$

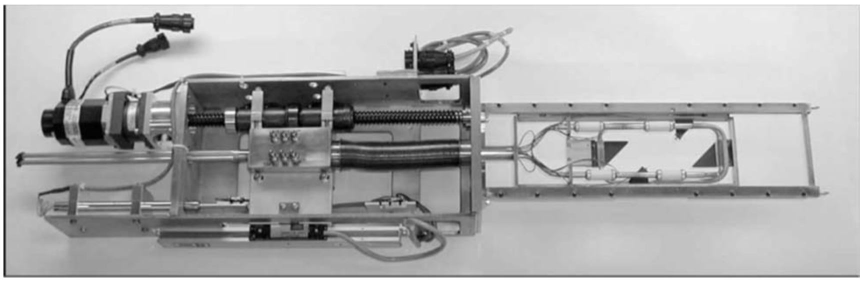
SNS Laser Profile Monitor Progress, EPAC04

Wire Scanners and Scrapers

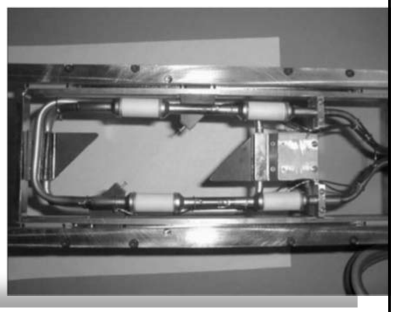
- Used around the world,
- Problems are well known:
  - Emittance blow up, wire heating.
- Readout by Scintillators and/or SEM
- Huge dynamic range by:
  - Log-amplifier (PSR)
  - Wire + Scrapers (LEDA)
  - scanning + counting (J-Lab, DESY, AGS)
  - Scraping with collimators (LEP)
  - Other methods
- **Real Halo Measurements**

Wide Dynamic-Range Beam-Profile Instrumentation for a Beam-Halo Measurement: Description and Operation; J. D. Gilpatrick, HALO03

Wire Scanners at LEDA
(Proton LINAC, SEM readout)



WS can move a <u>33-µm carbon mono filament and two halo scraper consisting of two graphite scraping devices</u> (one for each side of the distribution). The high-heat flux testing performed on the prototype scrapers revealed that the design can withstand the thermally induced fatigue loading. The peak heat flux that these scrapers have experienced in actual service is approximately 600 kW/cm^2



Wide Dynamic-Range Beam-Profile Instrumentation for a Beam-Halo Measurement: Description and Operation; J. D. Gilpatrick, HALO03

Wire Scanners at LEDA

To plot the complete beam distribution for each axis, the **wire scanner and two scraper data sets must be joined**. To accomplish this joining, several <u>analysis tasks</u> are performed on the wire and scraper data including:

1. Scraper data are spatially differentiated and averaged,
2. Wire and scraper data are acquired with sufficient spatial overlap (where the wire scanner signal rises above the noise),
3. Differentiated scraper data are normalized to the wire beam core data,
4. Normalize data to axis (simple if on same fork)
5. Normalize data to beam current and beam position (true for all kind of halo measurements)!!!!

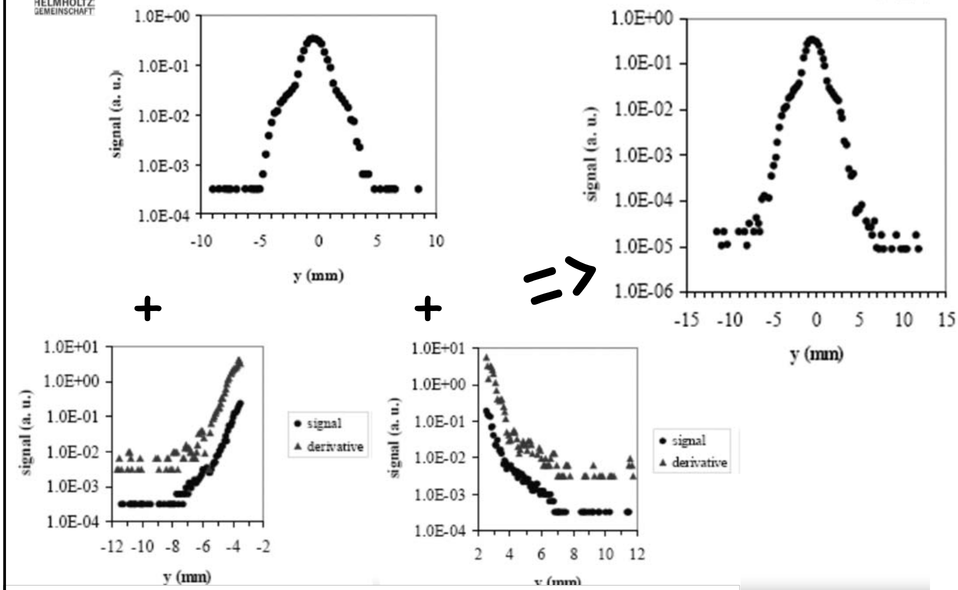
Before scan: define safe scraper insertion limits (avoid too much heat load) by wire scan data. In SEM mode avoid thermal electron emission!

Procedure explained in:

ANALYSIS OF DATA FROM THE LEDA WIRE SCANNER/HALO SCRAPER*
J. H. Kamperschroer,† General Atomics, Los Alamos,
J. F. O'Hara, Honeywell, L. A. Day, J. D. Gilpatrick, and D. M. Kerstiens, Los Alamos National Laboratory
PAC2001

Wire Scanners at LEDA

Y-axis wire scan   Combined distribution in y.

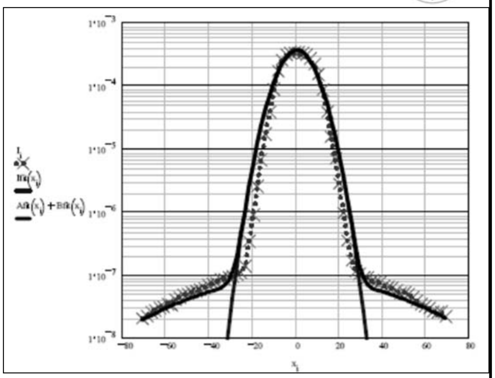


-Y and + Y scrape signal and derivative. The derivative has been multiplied by ten.

Wire Scanners at PSR

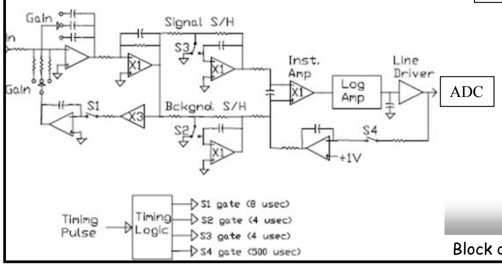
Linear amplification and 10^5 dynamic range
=> 16-bit D/A converter

As an alternative solution is to use a logarithmic amplifier. The log amplifier allows the use of standard 12-bit A/D converters.



A normal function shown in solid blue has been fit to the data (red x's). A sum of two normal functions is shown in solid black. The x-axis is scaled as scanner position in mm's and the y-axis is log-amp input current in Amps.

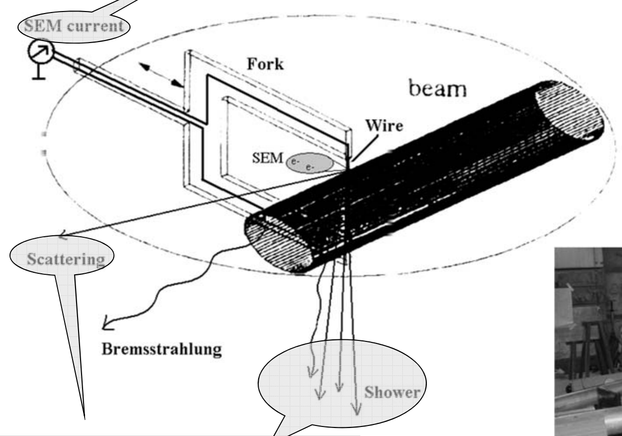
Halo Measurements of the Extracted Beam at the Los Alamos Proton Storage Ring; A. Browman, et al., PAC03



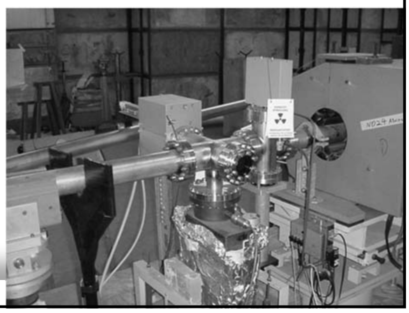
Block diagram of amplifier

Wire Scanners

SEM (LEDA, PSR)

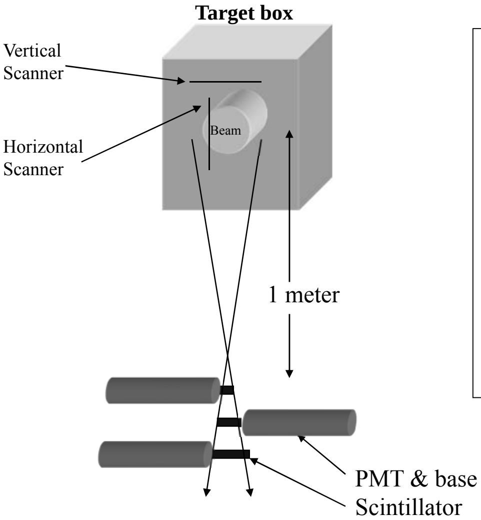


Counting mode, bunch by bunch



Wire Scanners

Telescope Operation at the extracted beams (AGS)



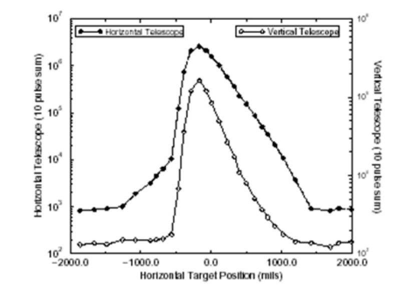
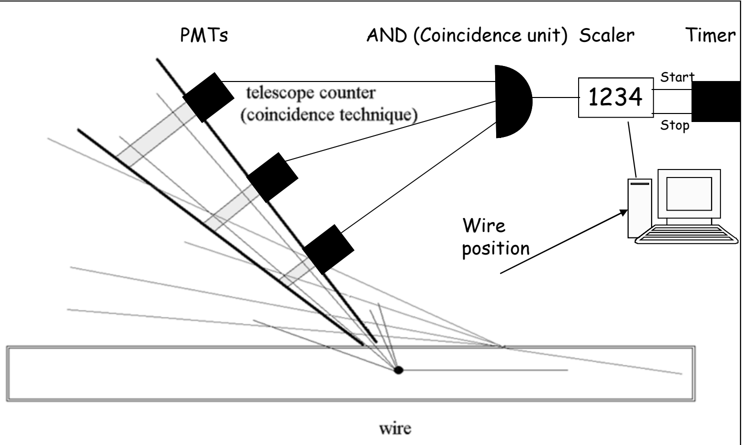


Figure 2: Horz. and Verti. Telescope triples for Horz. Scan

Solid angle remains the same through scan. Narrow acceptance, reduces noise. Telescope acceptance about 10^{-4} steradian.

Scintillator Telescope in the AGS Extracted B e a m l i n e
D. Gassner, K. A. Brown, and I. H. Chiang, HALO03

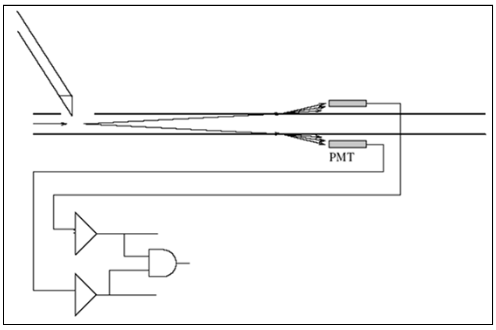
Wire Scanners



Normalize counts to time interval!
Reduced background from dark counts and beam losses!

Wire Scanners at Jefferson Lab

Huge dynamic range (10^8) by coincident counting:



Large Dynamic Range Beam Profile Measurements
Freyberger, DIPAC05

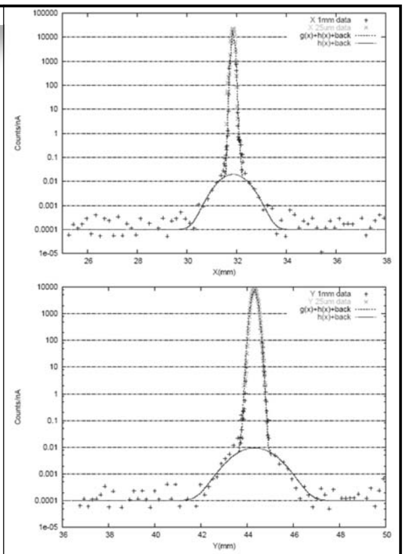
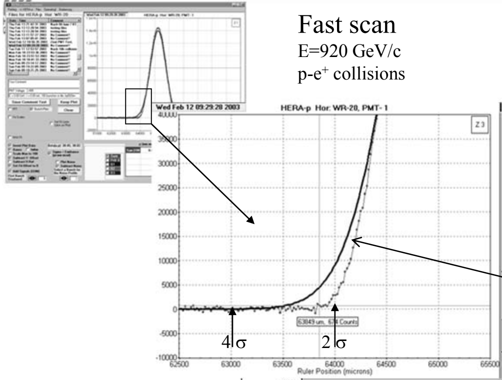


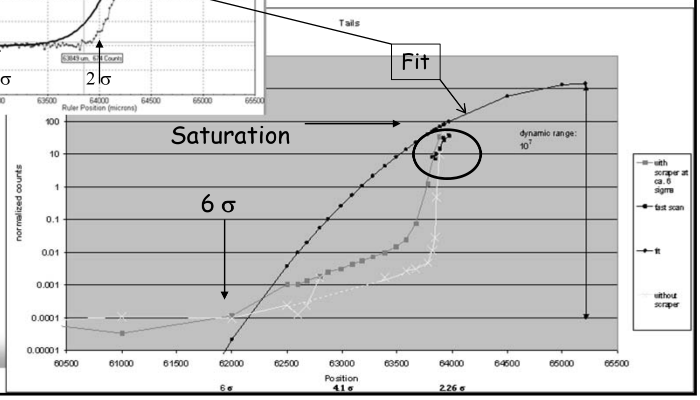
Figure 4: Beam Profile combining the 25μm and 1mm Fe wire data. The top(bottom) plot shows the X(Y) data and results of the fit to the data. The red points represent the 1mm wire data, the green points the 25μm wire data, the blue curve is the overall fit to the data and the red curve is the halo portion of the fit. The ordinate is plotted with a log-scale and the count rate is normalized to the beam current.

Wire Scanners at HERA

Fast scan
E=920 GeV/c
p-e+ collisions



Huge dynamic range by scanning + counting, no scraping, single scintillator! (HERA):
Very clean beam conditions (no losses)
No halo,
even smaller than gaussian.

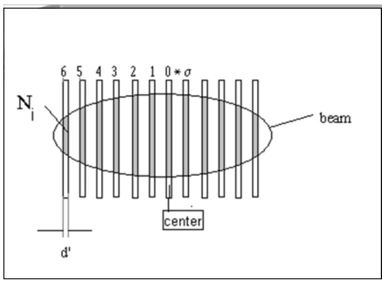


= Overlapping data

Beam Tail Measurements using
Wire Scanners at DESY
S. Arutunian, et al, HALO03

Wire Scanners at HERA

Saturation effects



$$N_i = n_{bunch} \cdot \int_{i\cdot\sigma-\frac{d'}{2}}^{i\cdot\sigma+\frac{d'}{2}} \frac{1}{\sigma_h \cdot \sqrt{2\cdot\pi}} \cdot \exp\left(\frac{-x^2}{2\cdot\sigma_h^2}\right) dx$$

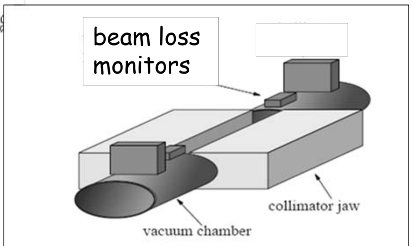
Rate: [Counts/bunch] [Counts/s]

Position	N_i =	Eff_i =	S_i =	
Center	$1.484\cdot10^8$	14.837	$1.543\cdot10^8$	Saturation
1 σ	$8.999\cdot10^7$	8.999	$9.359\cdot10^7$	
2 σ	$2.008\cdot10^7$	2.008	$2.088\cdot10^7$	
…	$1.648\cdot10^6$	0.165	$1.714\cdot10^6$	
Useful range	$4.978\cdot10^4$	$4.978\cdot10^{-3}$	$5.177\cdot10^4$	
	553.033	$5.53\cdot10^{-5}$	575.154	
6 σ	2.26	$2.26\cdot10^{-7}$	2.351	
	$3.399\cdot10^{-3}$	$3.399\cdot10^{-10}$	$3.534\cdot10^{-3}$	Lower limit
	$1.88\cdot10^{-6}$	$1.88\cdot10^{-13}$	$1.955\cdot10^{-6}$	
	$3.825\cdot10^{-10}$	0	$3.978\cdot10^{-10}$	
	$2.864\cdot10^{-14}$	0	$2.978\cdot10^{-14}$	

N = **protons intersecting wire area**
σ = beam width (0.527 mm)
d' = wire diameter (7 mm)
N_{bunch} = 2.8 * 10^{10} protons
Bunch Rate R_B = 10.4 MHz
limits the max count rate

Signal efficiency of ε=10^{-7}
Eff = N · ε, Signal Rate S = Eff · R_B

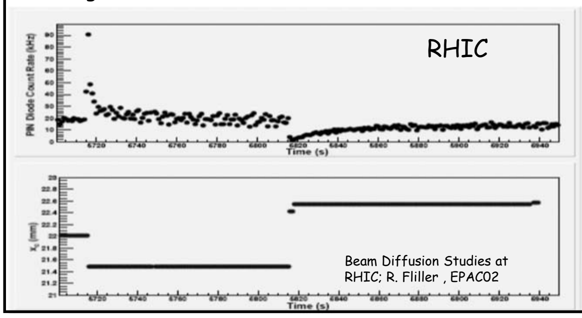
Scraping by collimators



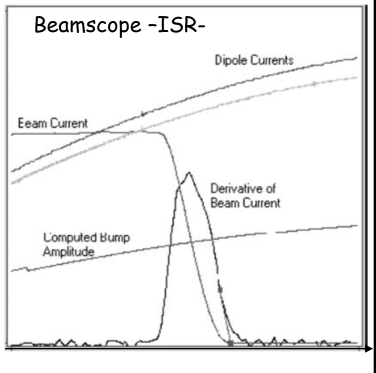
TRANSVERSE BEAM TAILS DUE TO INELASTIC SCATTERING; H. Burkhardt et al. CERN-SL-99-068 (OP)

Measurements were performed by moving one jaw of a collimator closer to the beam in steps. Beam current and beam size measurements were recorded for each collimator setting. The derivate gives the profile/halo.

Beware of diffusion processes from core to halo. Scanning should be faster than diffusion rate.



Beam Diffusion Studies at RHIC; R. Fliller , EPAC02



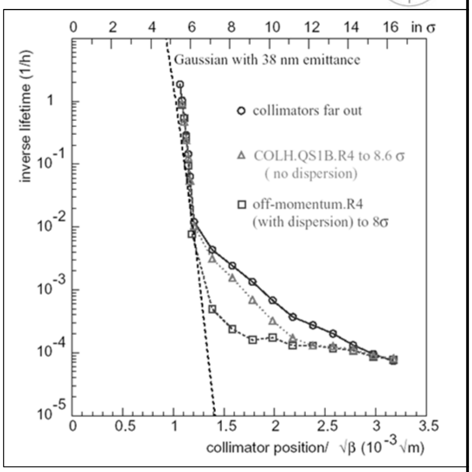
BEAMSCOPE - A NOVEL DEVICE FOR MEASURING EMITTANCES AND BETATRON AMPLITUDE DISTRIBUTIONS. (TALK). By H. Schonauer (CERN). 1979. Published in IEEE NS 26

Scraping by collimators + BLM

A complete scan of the whole beam might be impossible since the jaws might not withstand the full beam intensity.

- Therefore a calibration of the halo contents (relative to the beam core) is often not possible or contains large errors.
- But relative changes of the halo can be detected at a very low level and far outside the beam core, e.g. ground motion frequencies and diffusion parameters

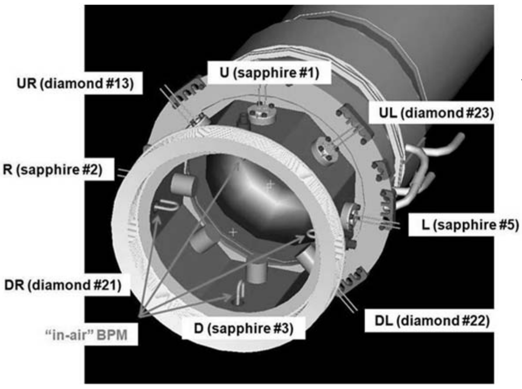
In a synchrotron one jaw will scrape both sides of the beam distribution.
=> meas. symmetric halo
Such a tail scan yields information about particles which oscillate with an amplitude larger than the position of the collimator



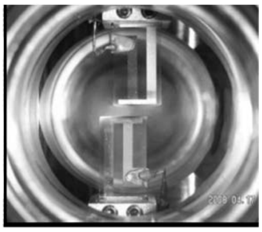
Measurement (left) of the horizontal beam tails for a beam energy of 80.5 GeV and for different collimator settings at LEP.

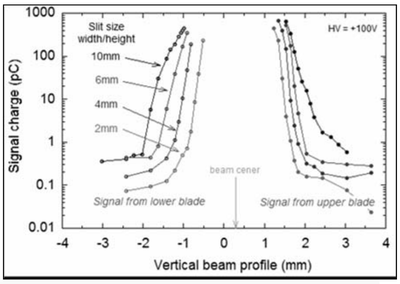
Other sensitive, high dynamic halo monitors

Diamonds and Sappires
Very fast (ns) and very rad. hard



<-- FLASH
Spring-8 -->





Test at SPS: "The detector has proven its sensitivity for single particles as well as its robustness for high-intensity beam losses that saturated the electronics. …The dynamic range of the detector material is over many orders of magnitude …"

Erich Griesmayer; Diamond Detectors as Beam Monitors; BIW10

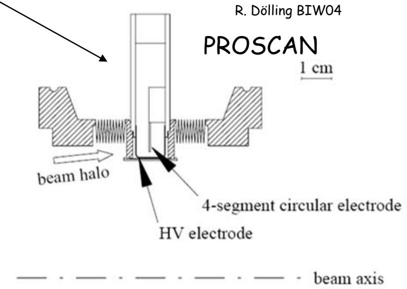
Y. Asano, DIPAC2009; A. Ignatenko, TESLA-FEL 2010-05

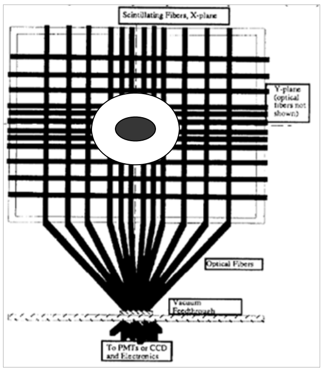
Other sensitive, high dynamic halo monitors

Ion chamber, SEM

Profile, Current, and Halo Monitors of the PROSCAN Beam Lines
R. Dölling BIW04

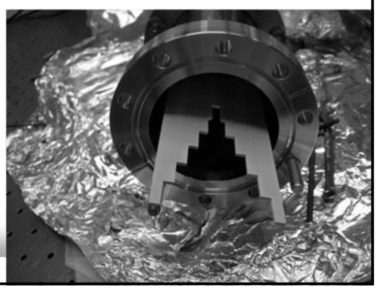
- Direct measurement by inserting monitor or by an intercepting monitor





But a normalization to the beam core has still to be done (like in scraping measurement.

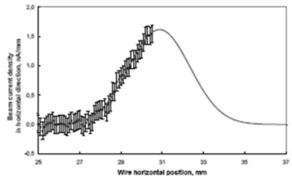
A Scintillating Fiber Beam Halo Detector for Heavy Ion Beam Diagnostics; McMahan, PAC 1993



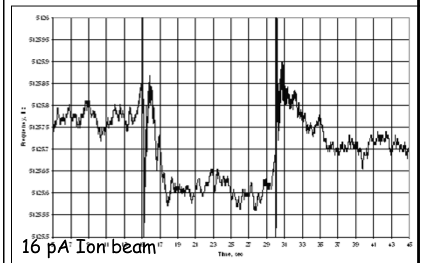
JLab FEL

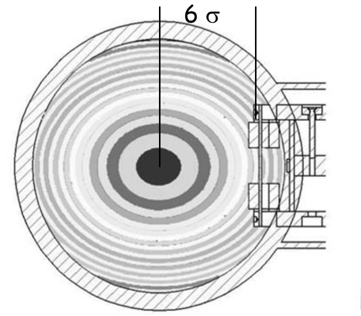
Vibrating wire scanner

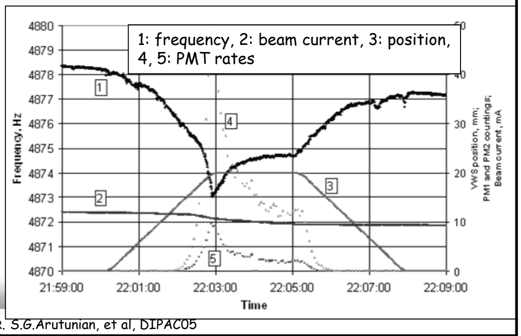
VWS mounted on the vacuum below with 1 μm step motor feed



Scan of the electron beam at the Injector of Yerevan Synchrotron with an average current of about 10 nA (after collimation) and an electron energy of 50 MeV







PETRA PROTON BEAM PROFILING BY VIBRATING WIRESCANNER. S.G.Arutunian, et al, DIPAC05

Summary transversal halo

Machine	Type	Signal	Dynamic range	Status
LEDA (LANL) (6.7MeV p)	Scanner+ Scraper	SEM	10^5-10^6	Working in control-system
AGS slow extraction line (2GeV p)	Scanning Target	Counting mode + SEM	10^4-10^5 10^2-10^3	De-commissioned
PSR extraction line (LANL) (800MeV p)	Wire Scanner with thin wire	SEM Log amp	10^6	In regular operation
SNS LINAC (2.5MeV to 1GeV H^-)	Laserwire scanner	Photo-neutralization, electron detection	10^3-10^4	In operation
DESY HERA (40 – 920GeV p)	Wire Scanner with thin wire	Counting mode	10^7-10^8	In operation, Readout prototype
Yerevan (20 MeV e^-) DESY PETRA (40GeV p)	Wire Scanner with thin wire	Vibrating wire; natural frequency	10^6-10^7	Preliminary tests; More tests planed
KEK PS (12GeV p)	Wire Scanner with thin wire	Scintillators	~10^3	In operation
RHIC (polarized p, ions)	IPM	Current	10^2-10^3	In operation

TABLE 1. Presented instruments for beam profile measurements, their dynamic range and operational status

29th ICFA Advanced Beam Dynamics Workshop on Beam Halo Dynamics, Diagnostics, and Collimation,held May 19-23, 2003, at Long Island, New York.
Halo Diagnostics Summary by P. Cameron and K. Wittenburg

- Longitudinal Halo
  - Bunch Purity => **important for time resolving SR experiments**
  - **"Beam in Gap"**
  - **Coasting Beam**

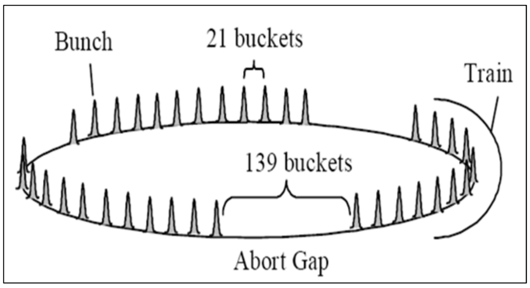
  } by Temporal Loss Distribution / Synchrotron Radiation

Beam in Gap

Beam in Gap (hadrons) due to:
- Injection errors (timing)
- debunching
- diffusion
- RF noise/glitches
- …

If beam (AC or DC) in gap, extraction kicker ramp will spray beam.
➔ Will result in:
- Quenches (SC-magnets)
- activation
- spikes in experiments
- equipment damage
- …

Therefore a <u>continuous determination of the amount of beam in the gap</u> is necessary to either clean the gap or dump the whole beam before major problems arise.

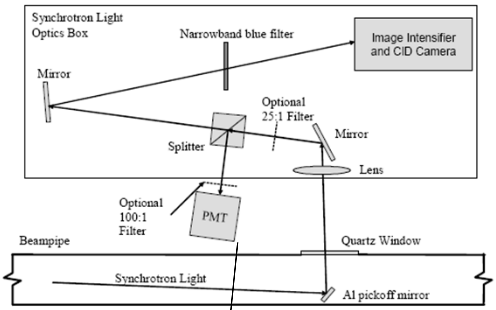


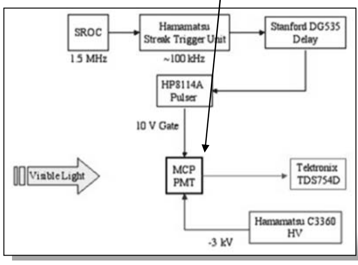
Measurement of the intensity of the beam in the abort gap at the Tevatron utilizing synchrotron light. R. Thurman-Keup, FERMILAB-CONF-05-139

Development of an abort gap monitor for the Large Hadron Collider. J.F. Beche, LBL-55208 (04/07,rec.Nov.)

Beam in Gap

Proton Synchrotron Light (Tevatron, LHC)

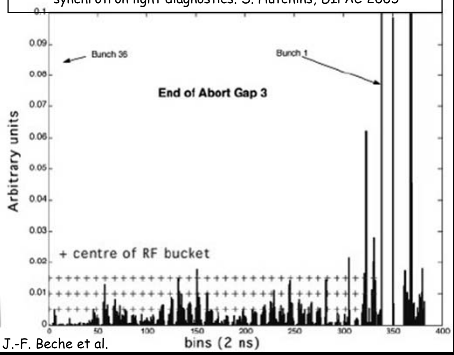




Successful test at ALS for LHC with gated MCP/PMT (AC beam),

Tests at TEVATRON with MCP-PMT with time correlated single photon counting Mode (TCSPC)

Studies with Single-Photon Avalanche Detectors (time correlated) for LHC are ongoing Single photon detector tests for the LHC synchrotron light diagnostics. S. Hutchins, DIPAC 2005



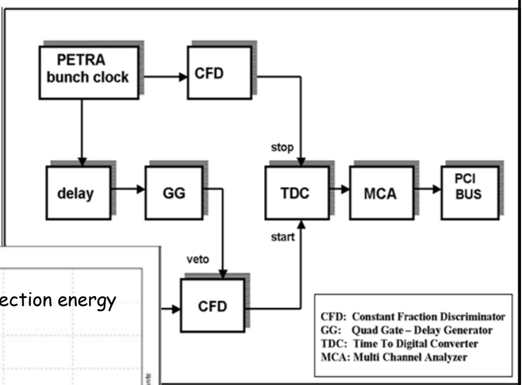
LARP Note 1, Design of an Abort Gap Monitor for the Large Hadron Collider; J.-F. Beche et al.

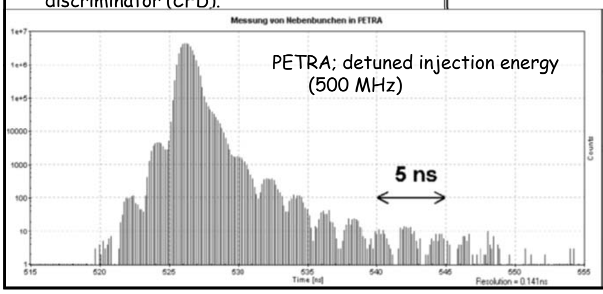
TCSPC

The **arrival time of single photons** emitted by the bunches passing through a particular dipole or wiggler in the storage ring **is measured**. The photon arrival time is measured relative to a clock pulse which is **synchronized to the bunch revolution** frequency via the storage ring RF system.

The amplified signal is analyzed using a time-to-digital-converter (**TDC**) and a multichannel-analyzer (**MCA**).
=> 10^7 dynamic range

To reduce the influence of the so-called "walk" and to reduce the background due to electronic noise the amplified detector signal is filtered by a constant-fraction-discriminator (CFD).





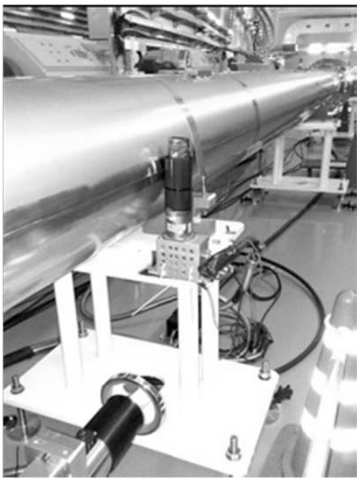
PETRA; detuned injection energy (500 MHz)

PARASITIC BUNCH MEASUREMENT IN e+/e- STORAGE RINGS; H. Franz et al, DIPAC 2003

Beam in Gap

Note that in principle any other fast process, e.g. Beam Induced Gas Scintillation, Secondary Electron Emission or beam loss monitor signals (e.g. at halo scrapers or at wire scanners) can serve as a signal source, which are not limited to very high beam energy. A fast and gate-able detector which is synchronized by the revolution frequency is most useful to avoid saturation due to the signal of the main bunches.

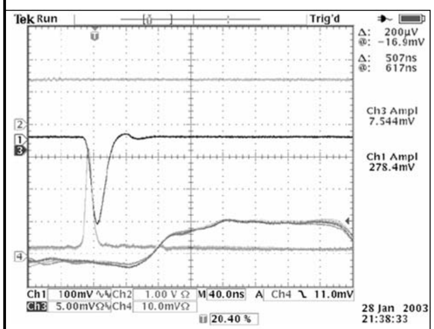
Measurement at J-PARC with fast Kickers + Scintillator-BLM:
"We first found that (supposed to be) empty bucket contains 10^{-5} level of the main pulse. …
Any existing beam monitor could not detect this level of the beam. Surprisingly, it is accelerated both in the RCS and the MR without any monitor signal as a invisible beam."



Measurements of Proton Beam Extinction at J-PARC
K. Yoshimura, et al, IPAC'10

Beam in Gap

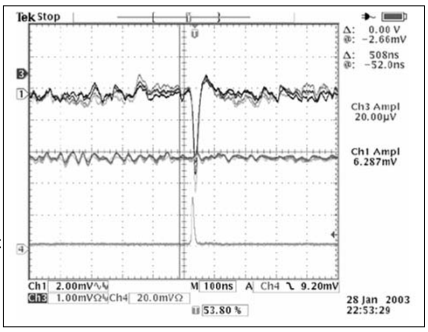
Using laser wire at SNS:

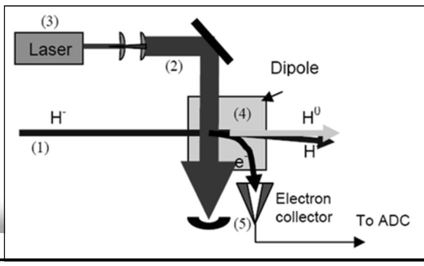


------→
In Gap

Delay
+ 20 dB
gain

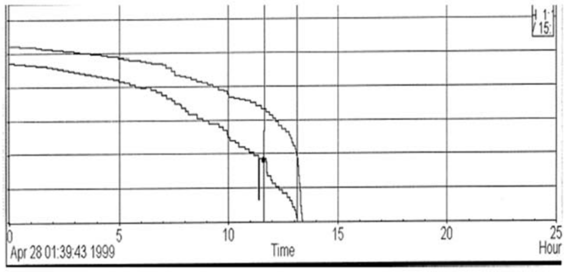
=>
dynamic
range
10^4





Beam in Gap Measurements at the SNS Front-End;
PAC 2003 , Aleksandrov, A; et al,

Coasting beam



HERAp:
Comparision
ACCT - DCCT

DC current (upper) and total bunch current (lower)

Tevatron: 980 GeV protons and antiprotons lose about 9 eV/turn due to the SR. For **uncaptured beam particles**, this energy loss is not being replenished by the rf system, so they **slowly spiral radially inward and die on the collimators**, which determine the tightest aperture in the Tevatron during collisions. The typical time for an uncaptured particle to reach the collimator is **about 20 minutes**. **The total uncaptured beam intensity is a product of the rate at which particles leak out of the main bunches and the time required for them to leave the machine**.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **11**, 051002 (2008), **Generation and diagnostics of uncaptured beam in the Fermilab Tevatron and its control by electron lenses, by** Xiao-Long Zhang et al

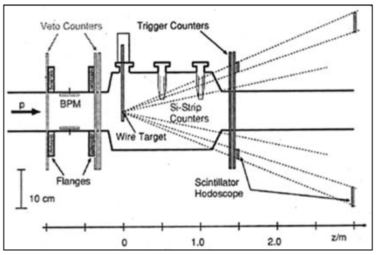
Coasting beam

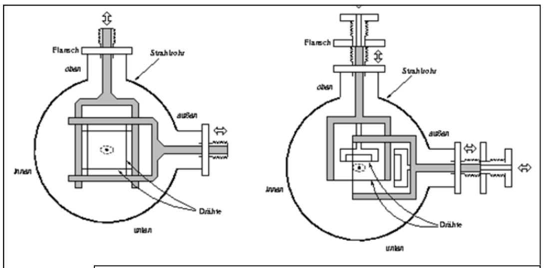
Measured by temporal beam loss distribution

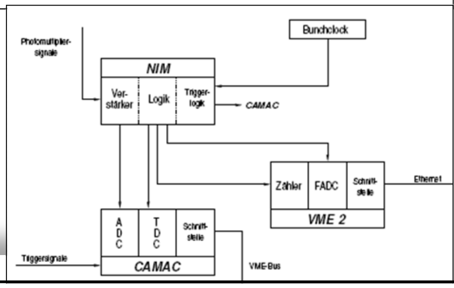
HERA-B: Wire scanners + Counters + TDC (only in beam tails)

Uncertainty due to meas. in halo!

Detection efficiency > 50%





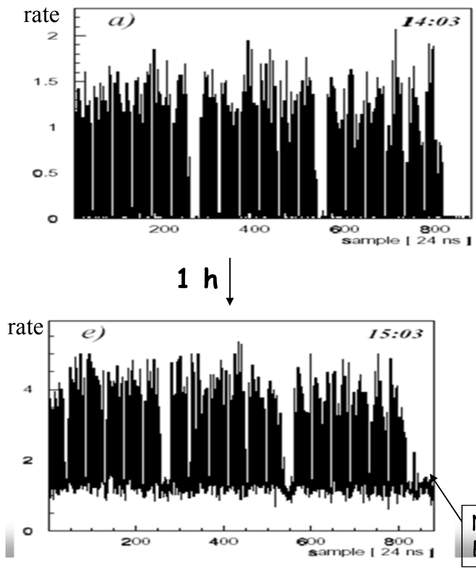


Observation of coasting beam at the HERA proton ring.
K. Ehret et al. NIM A456

Bestimmung der We hselwirkungsrate des HERA-B Targets und
PhD thesis. Universität Dortmund, Stefan Spratte

Coasting beam

Detection of coasting beam



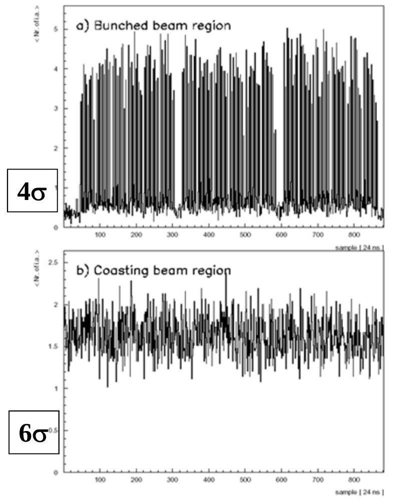
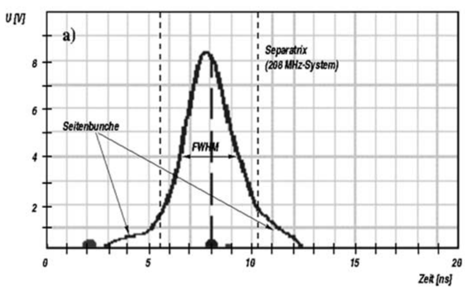


Figure 11.2: The time structure of the proton interaction for an outer target wire at different distances of the wire to the beam center: a) wire ≈ 4σ from the beam center and b) wire ≥ 6σ from the beam center.

Note the increased rate in the Bunch gaps (=coasting beam)

Coasting beam and bunch impurity



Fast wall current monitor
⇒ Low dynamic range for detection of neighbor buckets
⇒ Insensitive to DC beam

Bestimmung der We hselwirkungsrate des HERA-B Targets und Untersuchung des Coasting Beam am HERA Protonen-Ring
Fachbereich Physik d. Universität Dortmund
D I S S E R T A T I O N Diplom-Physiker Stefan Spratte, Juni 2000

Electron cloud diagnostic

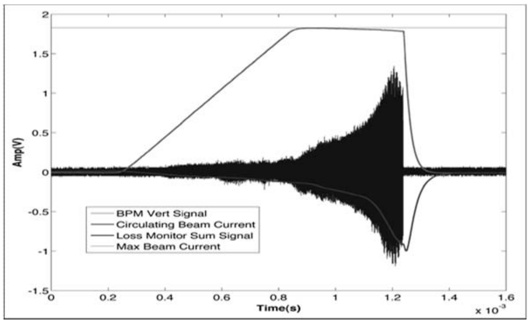
- BPMs
- Pressure rise
- Retarding Field Analyzer (RFA)
- Tracks
- Microwaves

Electron cloud diagnostic

What is an electron cloud

- Beam generates low energy electrons (synchrotron radiation, residual gas ionization, stray particles)
- electrons strike the wall -> multipactoring => quasi-stationary e-cloud
- => Beam interaction with e^- and gas
- Resonance with repetitive bunches, trapped in positive charged beam.
- Effects: Particle losses, faulty BPM readings, instabilities, => destructive interaction

Accelerators concerned:
SNS
J-PARC
LANL PSR
HCX
FNAL MI, Booster, recycler
RHIC
CERN SPS, LHC
KEKB
...

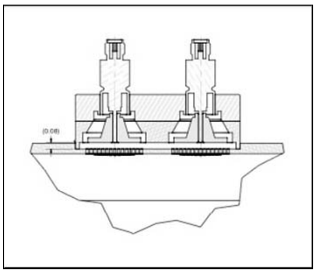


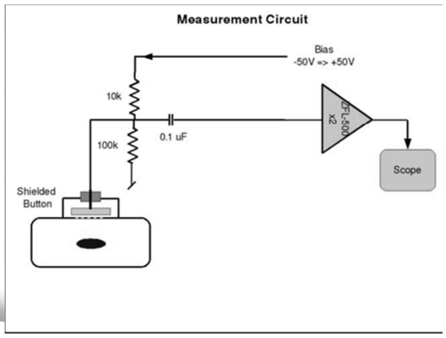
Recent studies of the electron cloud-induced beam instability at the Los Alamos PSR; R. Macek, ECLOUD10

Electron cloud diagnostic: Shielded BPM

Shielded BPMs:

- Shielded pick-up buttons are a relatively simple diagnostic device for obtaining time-resolved information on the electron cloud density.
- An SPU a biased electrode placed on the beampipe wall, shielded from the beam wakefield by a grounded grid.
- It collects low energy electrons present in that portion of vacuum chamber. A variable DC bias voltage enables to attract, or repel electrons depending on their energy.
- E-cloud line density λ: $I_{PU}=\lambda e f_b t A_{Pu}/A_{ch}$
  f_b = bunch frequency
  t = button transparency
  A_{pu} = Area of button
  A_{ch} = Inner area of chamber
  (assuming homogeneous distribution)

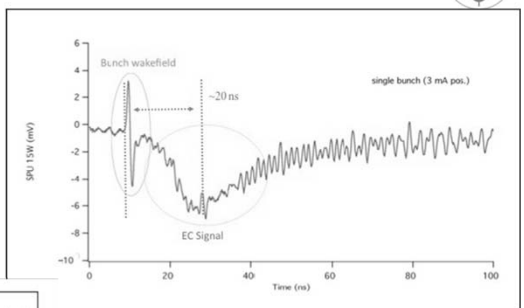


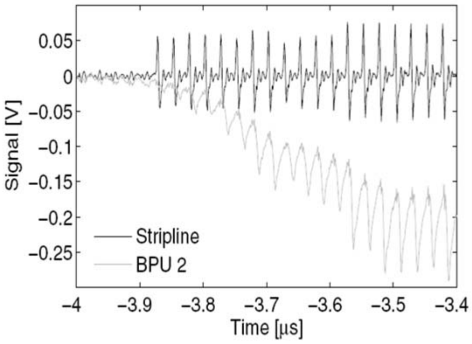


A SHIELDED PICK-UP DETECTOR FOR ELECTRON CLOUD MEASUREMENTS IN THE CESR-TA RING; J. Sikora, BIW2010

Electron cloud diagnostic: Shielded BPM

Single (positron) bunch. Wakefield and electron cloud signal on the SPU in the aluminum vacuum chamber (bias +50V).





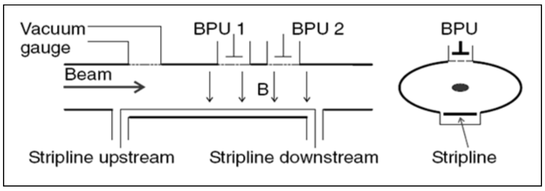
2-bunch measurement, with different distances between bunches (bias +50V) showing resonant effects of building up an electron cloud.

A SHIELDED PICK-UP DETECTOR FOR ELECTRON CLOUD MEASUREMENTS IN THE CESR-TA RING; J. Sikora, BIW2010

Bunch-to-bunch electron cloud buildup (25 ns bunch distance)

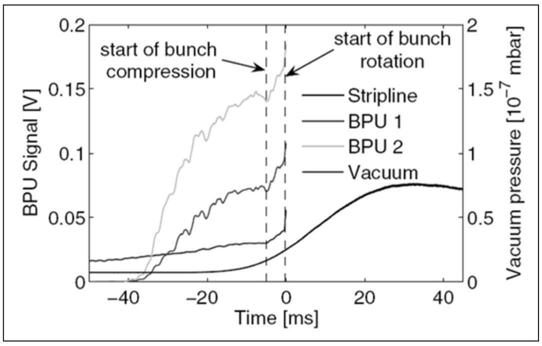
Electron cloud detection and characterization in the CERN Proton Synchrotron; E. Mahner et al, PRST-AB 11

Electron cloud diagnostic: Pressure rise



The pickup signals (BPU 1 and BPU2) and the stripline peak signal (in arbitrary units) and the vacuum pressure for the nominal LHC beam with 72 bunches. The EC becomes visible on the pickups about 40 ms before ejection, the vacuum gauge follows with a **delay of about 30 ms**.

Dynamic pressure rise due to desorption of molecules from wall by electron and ion impact (first seen in ISR).

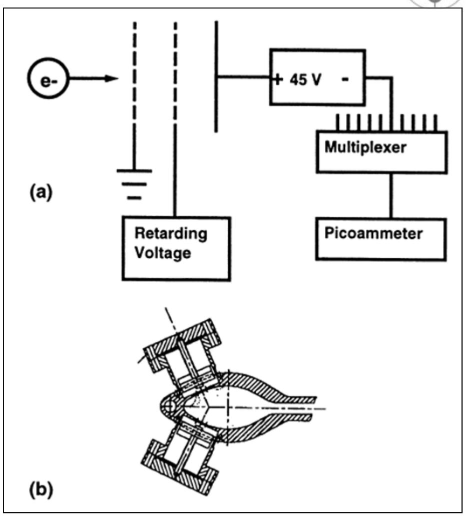


Electron cloud detection and characterization in the CERN Proton Synchrotron; E. Mahneret al, PRST-AB 11

Electron cloud diagnostic: RFA

Retarding Field Analyzer:

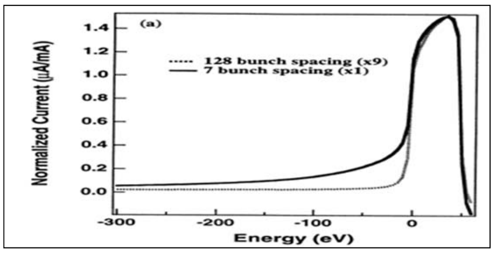
- The first grid is grounded to present a uniform field to the incoming electrons.
- The second grid is biased at a retarding potential (E_r) such that only electrons with kinetic energies greater than E_r are transmitted to the collector.
- The collector has a low SEY and is biased to increase the sensitivity.
- For weak signals a MCP or channeltron can be used. But usually electronic amplification is sufficient.
- Advantages:
    - Increased surface area.
    - Higher sensitivity
    - Energy separation



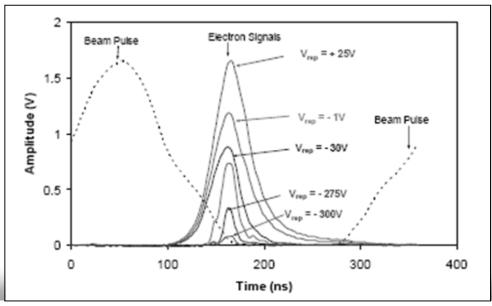
(a) Schematic diagram of the analyzer. (b) Cross-sectional view of a vacuum chamber

A rudimentary electron energy analyzer for accelerator diagnostics R.A. Rosenberg, NIM A 453

Electron cloud diagnostic: RFA



A rudimentary electron energy analyzer for accelerator diagnostics ; R.A. Rosenberg, NIM A 453

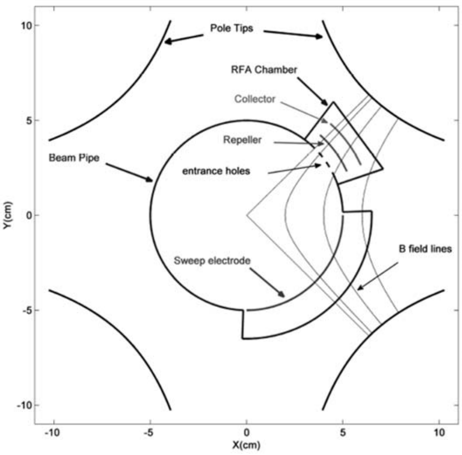


The Ecloud Measurement Setup in the Main Injector; C.Y. Tan, FERMILAB-CONF-10-508-AD

ELECTRON CLOUD DIAGNOSTICS IN USE AT THE LOS ALAMOS PSR; R.J. Macek, PAC03

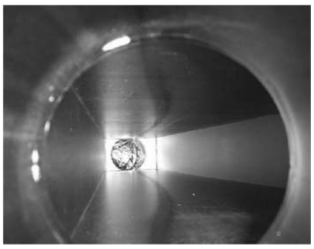
Electron cloud diagnostic: Tracks

Electrons follow magnetic lines

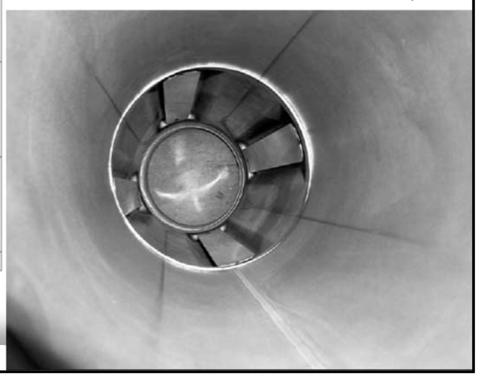


Electron cloud generation, trapping and ejection from quadrupoles at the Los Alamos PSR; Robert Macek, EC2010

Tracks in Dipole



in Quadrupole



Electron cloud diagnostic: Microwaves

So far, only localized measurements

Microwave transmission measurements are sensitive to the average e-cloud density over a long section:

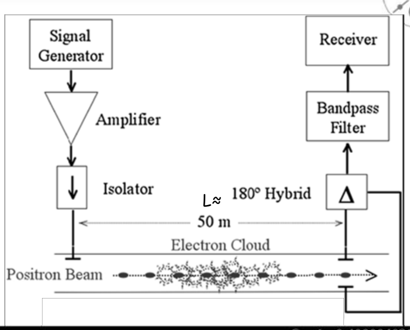
- Microwaves transmitted through a (not too dense) electron plasma (cloud) will undergo a phase shift $\Delta\phi$ (and a small attenuation).
- Changing the e-cloud density (e.g. by a cleaning gap between bunches) generates a phase modulation
- Appear as side bands to the carrier frequency ω.
- Frequency above cuttoff ω_c of the waveguide (= beam pipe)

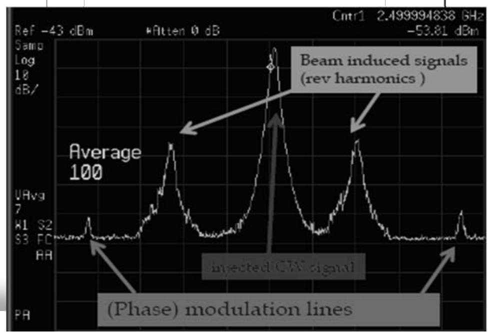
$$\Delta\phi \approx \frac{L\cdot\omega_p^2}{2c\cdot\sqrt{\omega^2-\omega_c^2}}$$

$$\omega_p = \sqrt{\frac{N_e e^2}{\varepsilon_0 m_e}} \quad \textit{plasma frequency}$$

$\Delta\phi \approx$ tens of mrad/m

$N_e \approx 10^{11}$-10^{12}/m^3



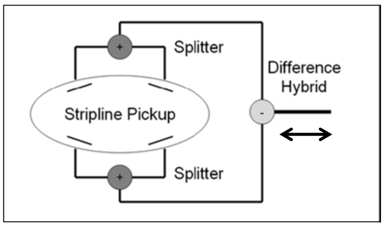


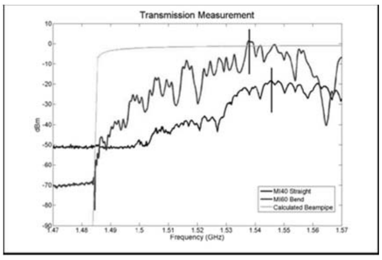
INTERACTIONS OF MICROWAVES AND ELECTRON CLOUDS
F. Caspers et al, PAC09

Electron cloud diagnostic: Microwaves

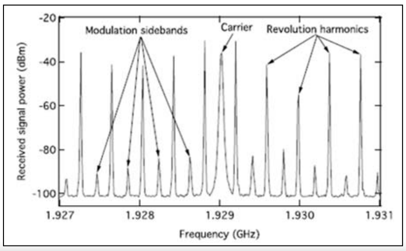
Practice:

- Use of BPMs as antennas
- Optimized for TE mode generation
- Care of common BPM signals (reversed) and at detector.
- Select right carrier frequency by transmission measurements
- Choice of good distance L
- Sidebands at $\omega\pm\omega_{rev}$.
- The amplitude of sidebands relative to carrier is prop. to phase shift $\Delta\phi$.





MEASUREMENT OF ELECTRON CLOUD DENSITY WITH MICROWAVES IN THE FERMILAB MAIN INJECTOR; J. Crisp et al, DIPAC09

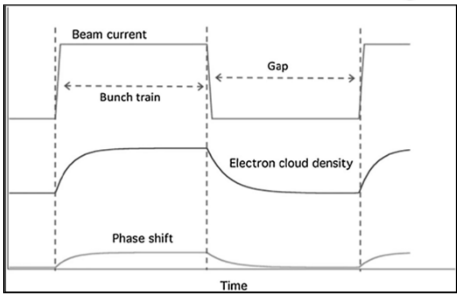


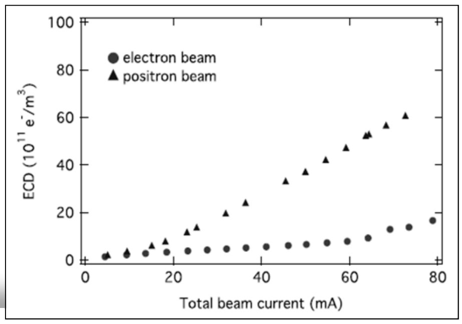
Characterization of electron clouds in the Cornell Electron Storage Ring Test Accelerator using TE-wave transmission; S. De Santis at al; PRST-AB 13

Electron cloud diagnostic: Microwaves

Problems:
- A LOT!
- Coupling efficiency of BPMs is small above cutoff, impedance not well matched (by design)
- Nonlinearities by reflections in generator and receiver (=> add. sidebands)
- Strong beam harmonics while weak EC sidebands
- AM modulation by resonant coupling to e^- trapped in magnetic field (near cyclotron freq. => add. Sidebands
- Due to reflections of the carrier, L can be underestimated.
- Ensure that clearing gap > decay time of cloud.
- Take into account EC rise and fall time.
- Where is the cutoff ω_c?

- **Although having a simple formulation, the practical application of the TE Wave method is not straightforward.** De Santis, ECLOUD10

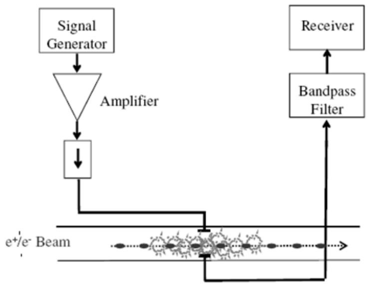




Characterization of electron clouds in the Cornell Electron Storage Ring Test Accelerator using TE-wave transmission; S. De Santis at al; PRST-AB 13

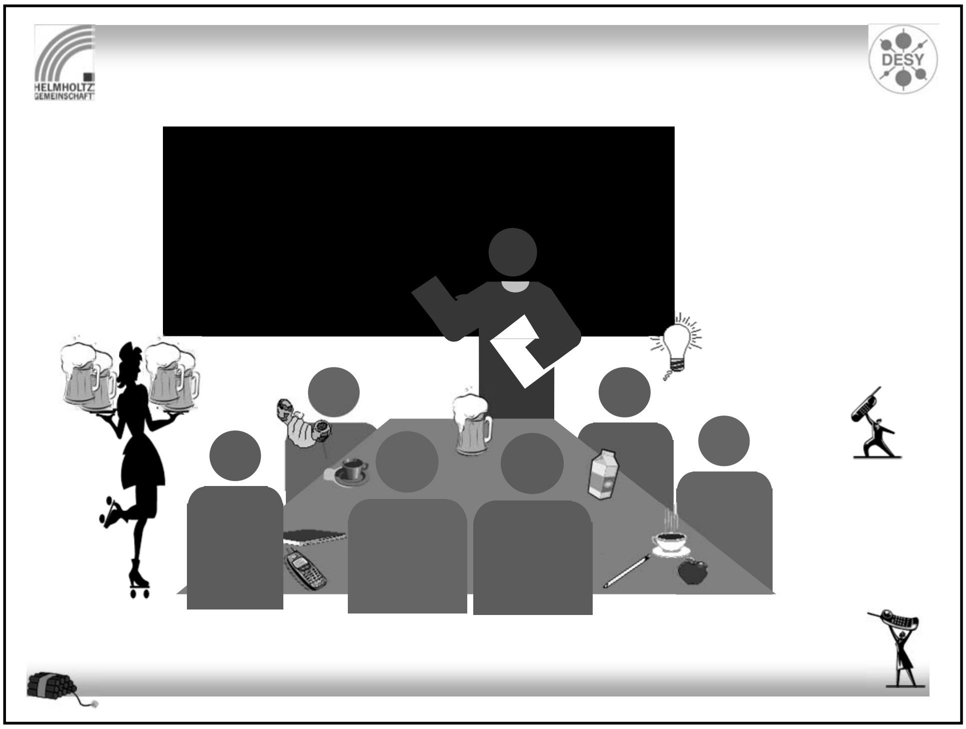
Electron cloud diagnostic: Microwaves

Do Not Transmit the Wave: the TE Resonant Method



The wave is excited slightly below cutoff so that there is no propagation, but only exponential attenuation, effectively obtaining a resonator. Selecting the frequency changes the resonator dimensions. Distant and unwanted parts of the accelerator do not affect the measurement.

De Santis, ECLOUD10 and
THE TE WAVE TRANSMISSION METHOD FOR ELECTRON CLOUD MEASUREMENTS AT CESR-TA*
S. De Santis et al, PAC09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