When energetic beam particles penetrates matter, secondary particles are emitted: this can be e^-, γ, protons, neutrons, excited nuclei, fragmented nuclei...

⇒ Spontaneous radiation and permanent activation is produced.

⇒ Large variety of Beam Loss Monitors (**BLM**) depending on the application.

Protection: Sensitive devices e.g. super-conducting magnets to prevent quenching (energy absorption by electronic stopping)

→ **interlock signal for fast beam abortion.**

Beam diagnostics: Alignment of the beam to prevent for activation

→ **optimal transmission to the target.**

Accelerator physics: **using these sensitive particle detectors.**

- Several devices are used, depending on particle rate and required time resolution
- Some applications for usage

Basic idea for Beam Loss Monitors B LM:

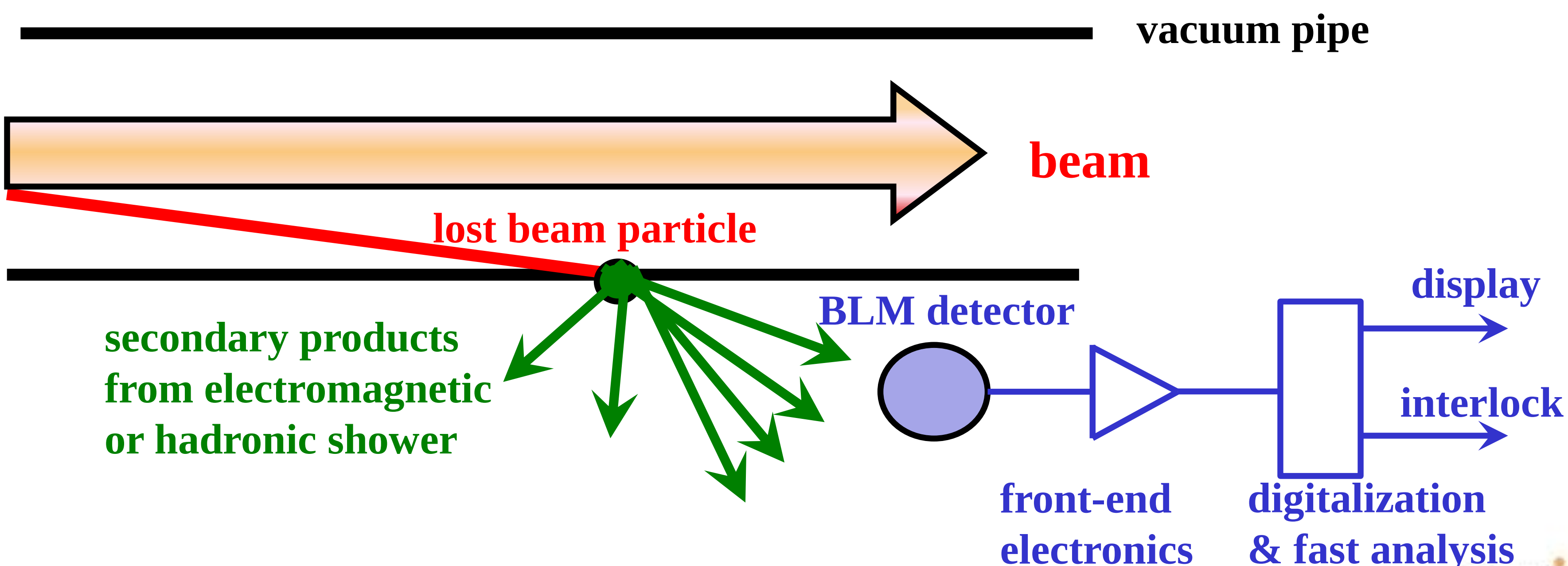
A loss beam particle must collide with the vacuum chamber or other insertions

⇒ Interaction leads to some shower particle:

e^-, γ, protons, neutrons, excited nuclei, fragmented nuclei

→ detection of these secondaries by an appropriate detector outside of beam pipe

→ relative cheap detector installed at many locations



Processes for interaction of electrons

For E_{kin} > 100 MeV:

Bremsstrahlungs-photon dominated

⇒ $\gamma \rightarrow e^+ + e^-$ or $\mu^\pm$, $\pi^\pm$ ....

→ electro-magnetic showers

⇒ excitation of

nuclear giant resonances $E_{res} \approx 6$ MeV

via (γ, n), (γ, p) or (γ, np)

→ fast neutrons emitted

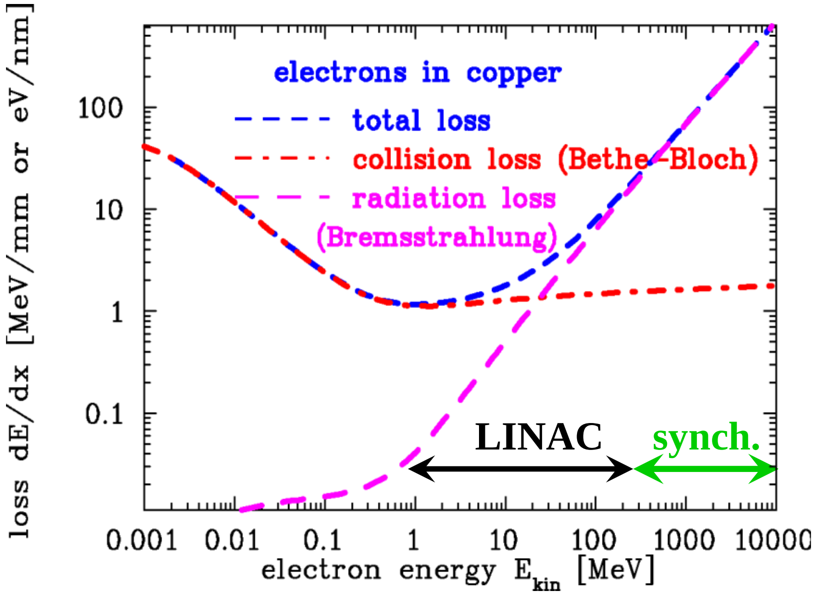
→ neutrons: Long ranges in matter

due to lack of ele.-mag. interaction.

For E_{kin} < 10 MeV:

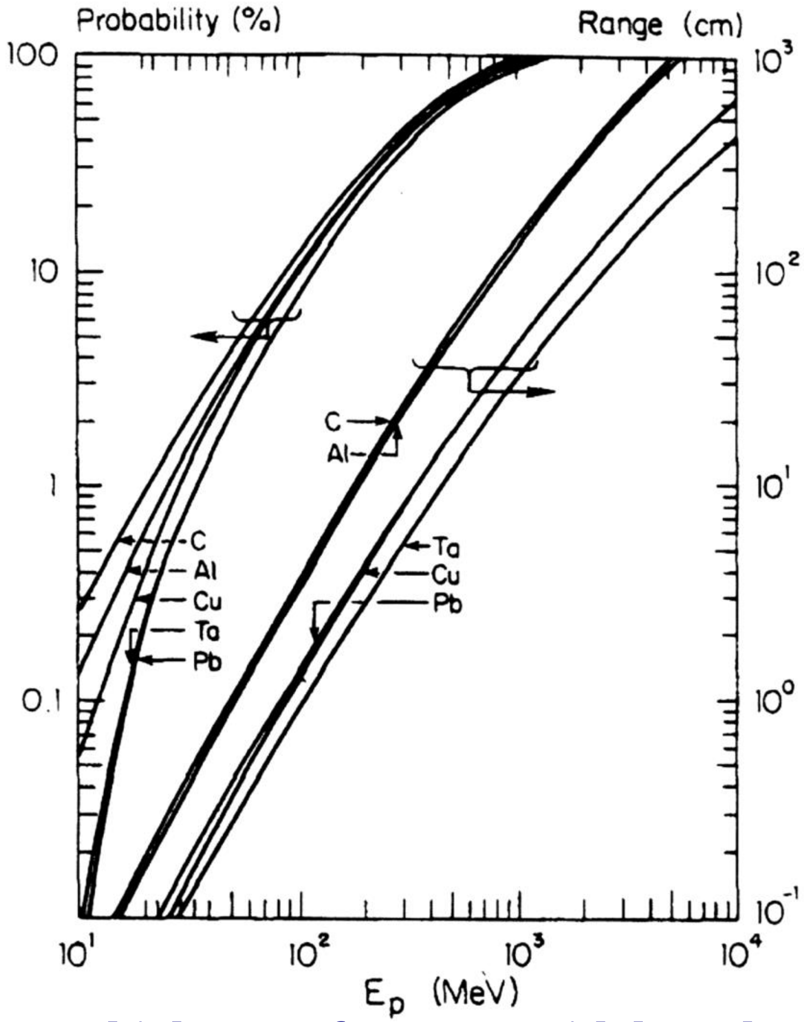
⇒ only electronic stopping

(x-rays, slow e^-).

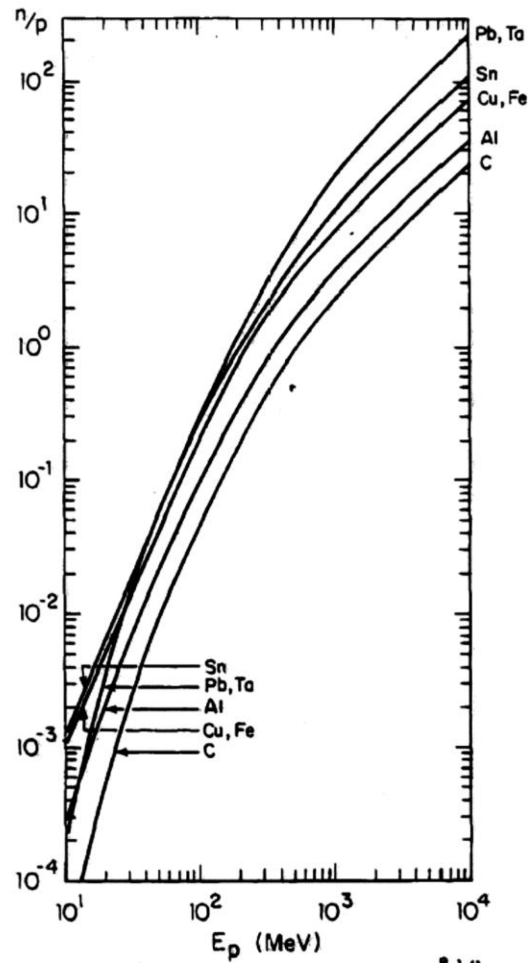


Secondary Particle Production for Proton Beams

Nuclear reaction probability:



Neutron yield per proton:

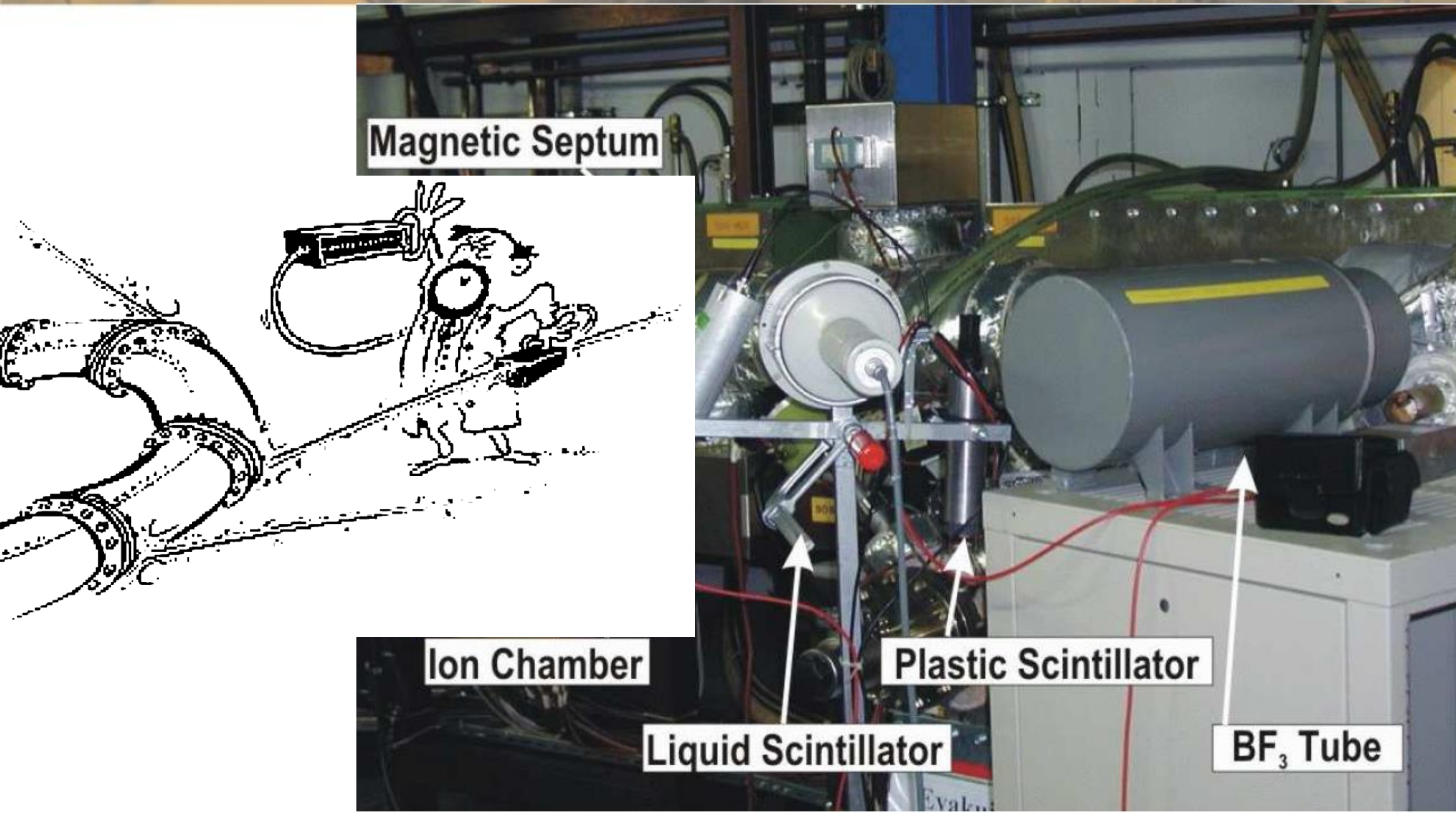


Thick target:

Penetration depth comparable to range → different types of nuclear reaction .

⇒ high rate of neutron with broad energy and angular distribution.

Various Beam Loss Monitors at the GSI-Synchrotron



Outline:

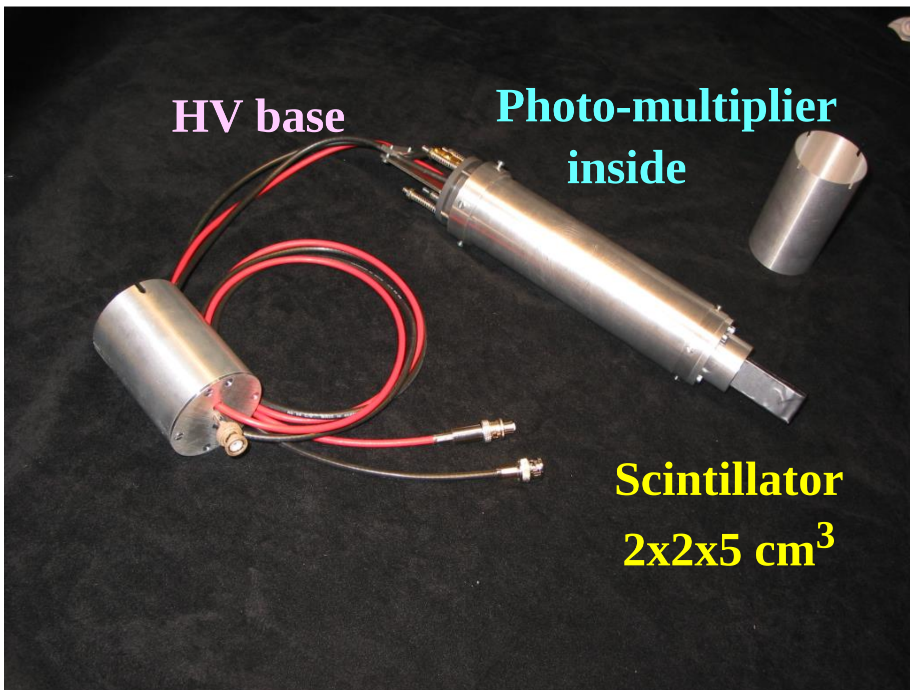
- Physical process from beam-wall interaction
- **Different types of Beam Loss Monitors**

  different methods for various beam parameters
- **Machine protection using BLMs**
- **Summary**

Scintillators as Beam Loss Monitors

Plastics or liquids are used:

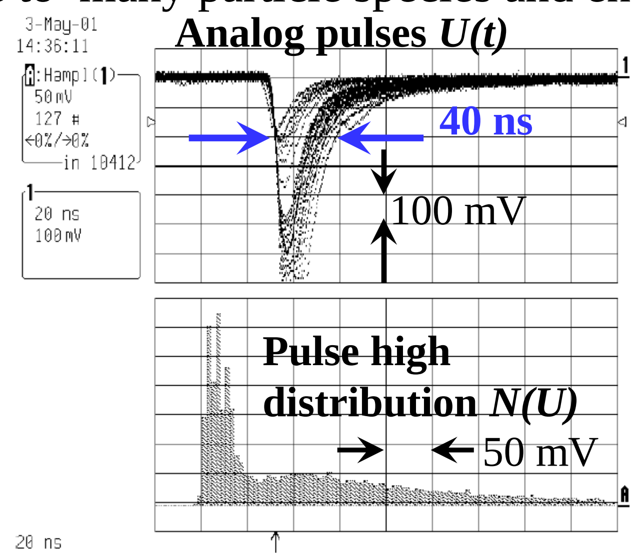
- detection of **charged particles**
  by electronic stopping
- detection of **neutrons**
  by elastic collisions n on p in plastics and fast p electronic stopping.



Scintillator + photo-multiplier:

counting (large PMT amplification)
or analog voltage ADC (low PMT amp.).
Radiation hardness:
plastics 1 Mrad = 10^4 Gy
liquid 10 Mrad = 10^5 Gy

Example: Analog pulses of plastic scintillator:
⇒ broad energy spectrum
due to many particle species and energies.



20 ns/div and 100 mV/div

Low Current Measurement: Particle Detectors

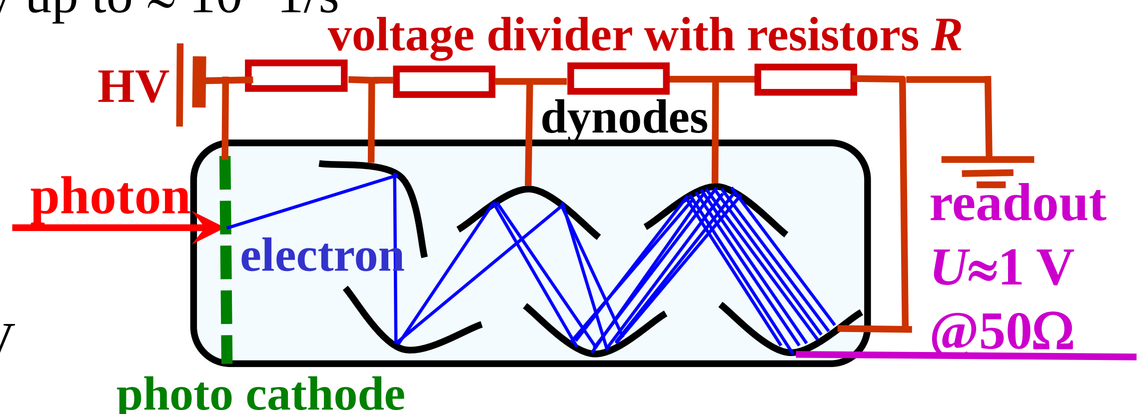
Electronic **solid state amplifier** have finite noise contribution

Theoretical limit: $U_{eff} = \sqrt{4k_B \cdot R \cdot \Delta f \cdot T}$

Signal-to-Noise ratio limits the minimal detectable current

Idea: Amplification of single particles with photo-multiplier, sec. e^- multiplier or MCPs and particle counting typically up to $\approx 10^6$ 1/s

Scheme of a photo-multiplier:



- Photon hits photo cathode
- Secondary electrons are acc. to next dynode $\Delta U \approx 100$ V
- Typ. 10 dynodes $\Rightarrow 10^6$ fold amplification

Advantage: no thermal noise due to electro static acceleration

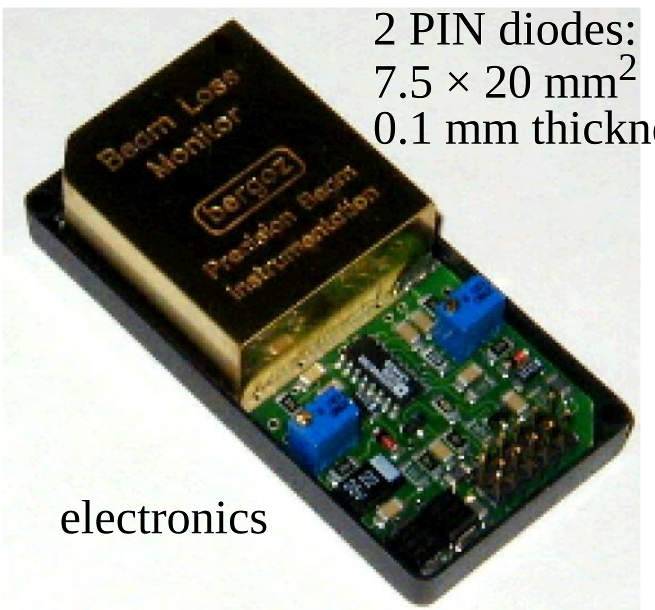
Typical 1 V signal output

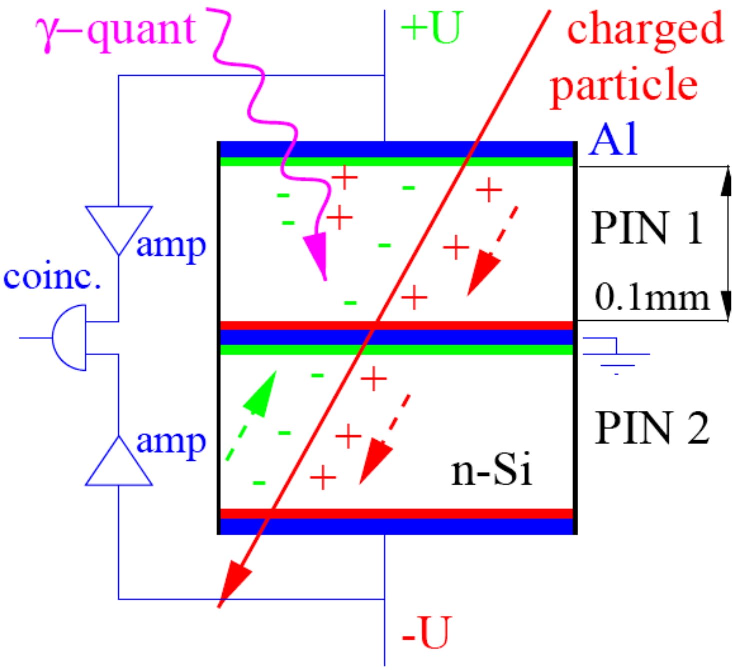
Solid-state detector: Detection of charged particles.

Working principle

- About 10^4 e^--hole pairs are created by a Minimum Ionizing Particle (MIP).
- A coincidence of the two PIN reduces the background due to low energy photons.
- A counting module is used with threshold value comparator for alarming.

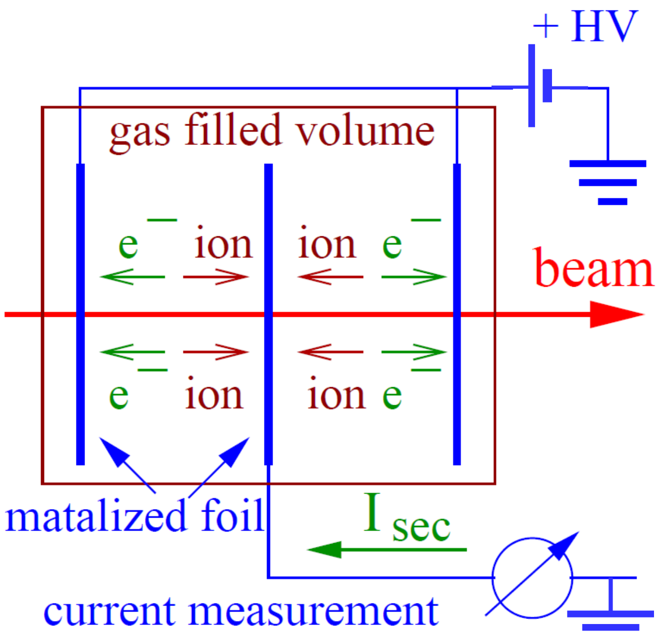
→ small and cheap detector.





Energy loss of charged particles in gases → electron-ion pairs → low current meas.

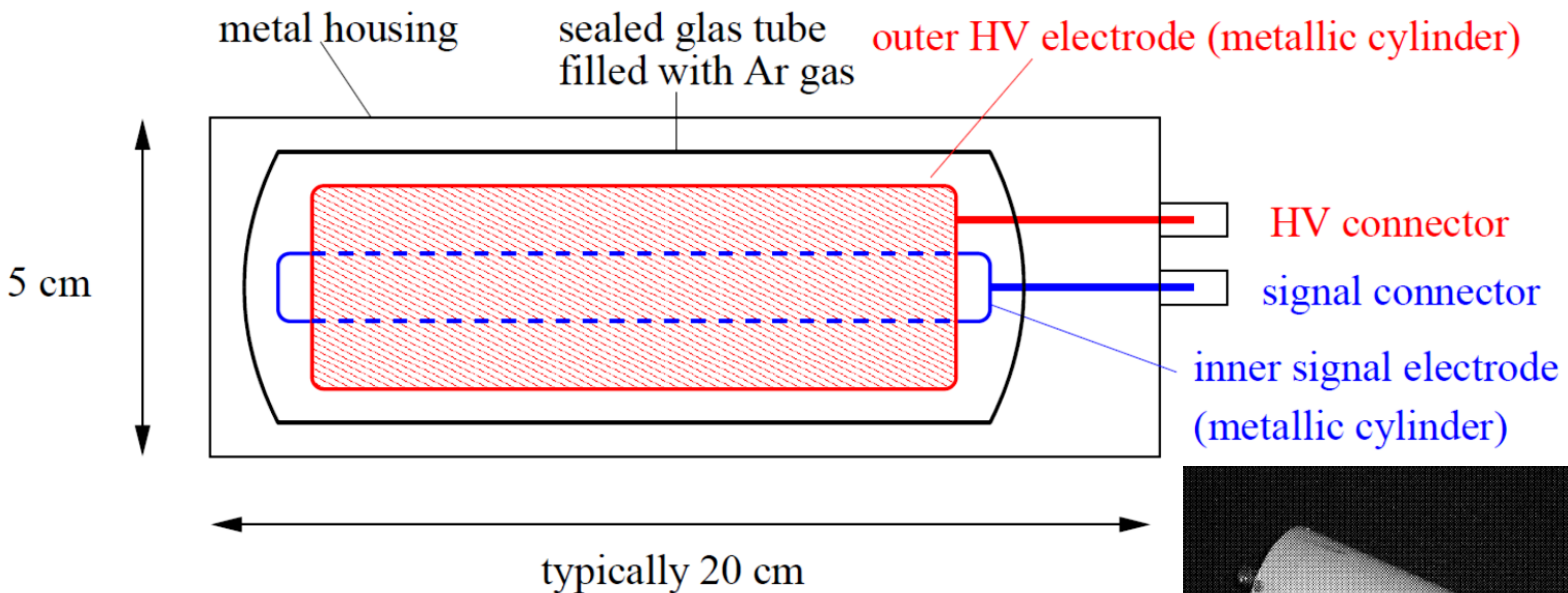
$$I_{sec} = \frac{1}{W} \cdot \frac{dE}{dx} \Delta x \cdot I_{beam}$$



W is average energy for one e$^-$ -ion pair:

Gas	Ionization Potential [eV]	W-Value [eV]
He	24.5	41.3
Ar	15.7	26.4
H_2	15.6	36.5
N_2	15.5	34.8
O_2	12.5	30.8
CH_4	14.5	27.3
Air		33.8

Main detection of charged particles



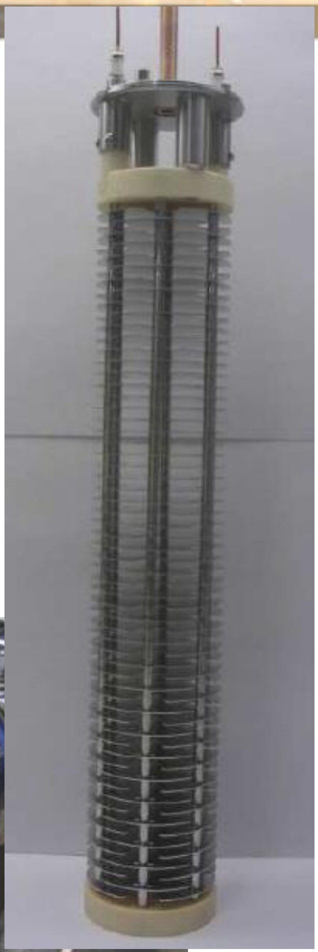
Sealed tube Filled with Ar or N_2 gas:

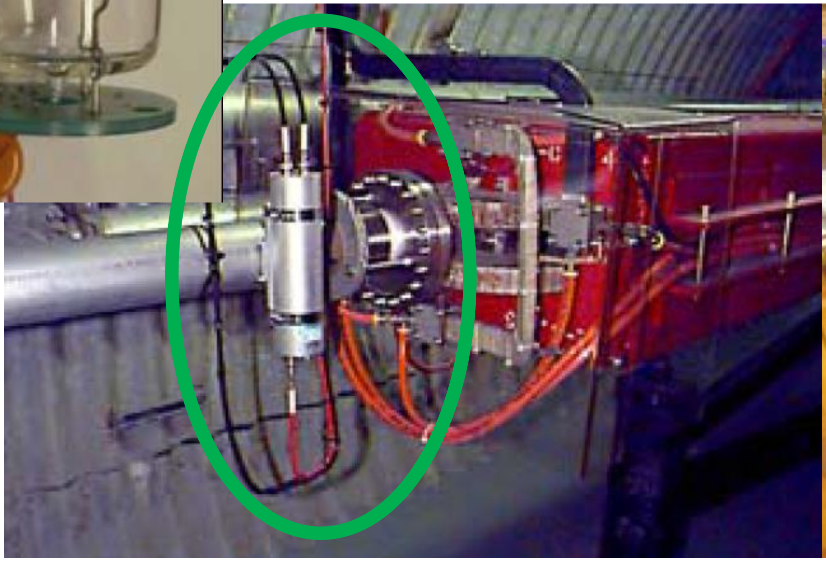
- Creation of Ar^+-e^- pairs, average energy W=32 eV/pair
- measurement of this current
- Slow time response due to 100 μs drift time of Ar^+.

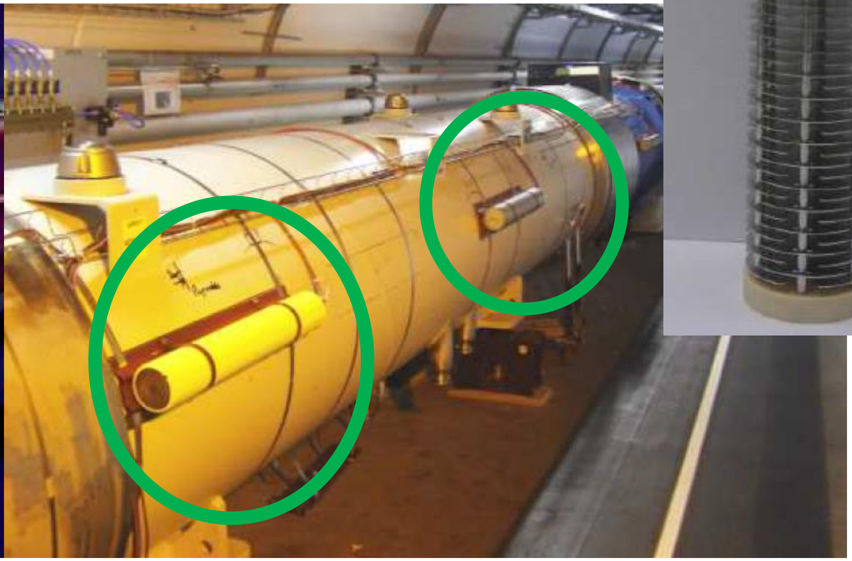
Per definition: direct measurement of dose.

Ionization Chamber as BLM: TEVATRON and CERN Type

TEVATRON, RHIC type		CERN type
20cm, ∅ 6 cm	**size**	50 cm, ∅ 9 cm
Ar at 1.1 bar	**gas**	N_2 at 1.1 bar
three	**# of electrodes**	61
1000 V	**voltage**	1500 V
3 μs	**reaction time**	0.3 μs
	# at the synchr.	4000 at LHC
	aver. distance	1 BLM each ≈ 6 m



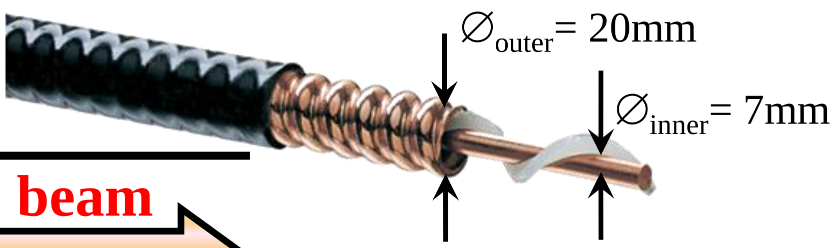


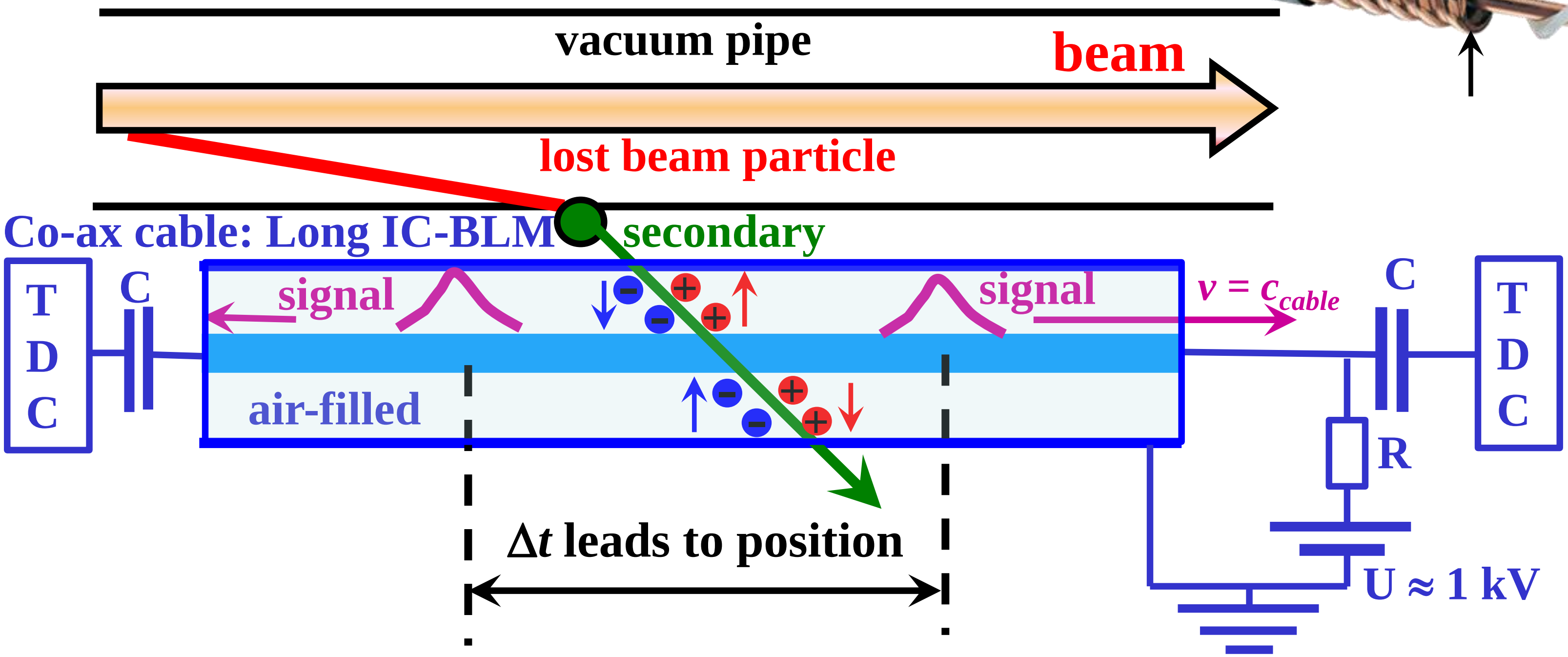


The long, cable-based Ionization Chamber

An air-filled ionization chamber IC can be realized by a cheap, air-filled co-axial cable:

Air-filled co-ax cable e.g. Andrew HJ4.5-50





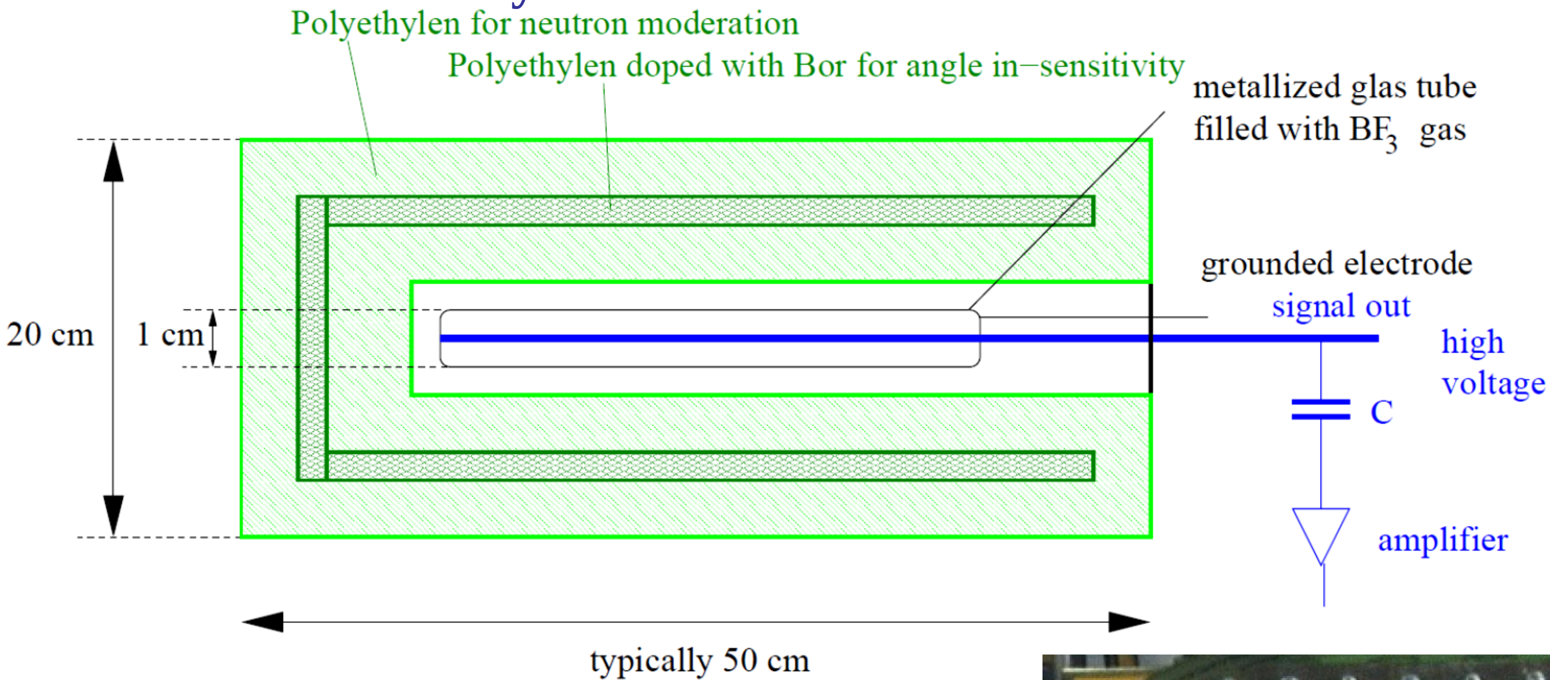
Realization: long cable along beam line ⇒ spatial resolution via time-of-flight measurement: determination of signal arrival at both ends leads to Δt

typical signal resolution of time-of-flight $\Delta t \approx 10$ ns ⇒ position resolution $\Delta x = c_{cable} \cdot \Delta t = 1.5$ m

Advantage of long IC: cheap, good spatial resolution

BF$_3$ Proportional Tubes as BLM

Detection of neutrons **only.**

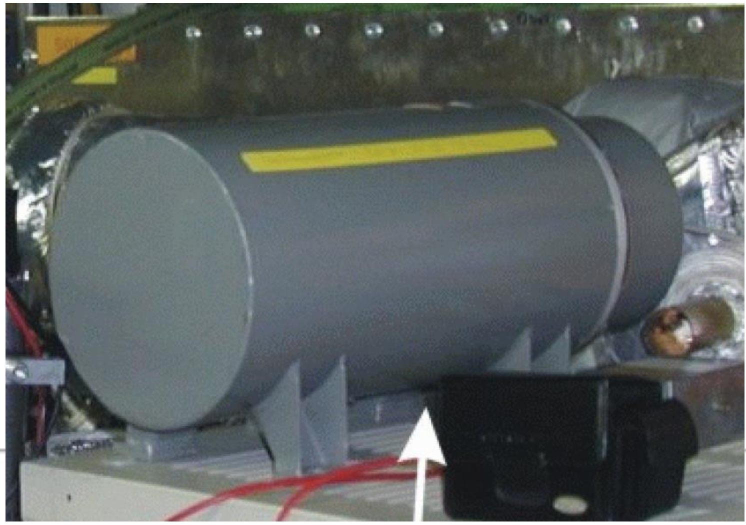


Physical processes of signal generation:

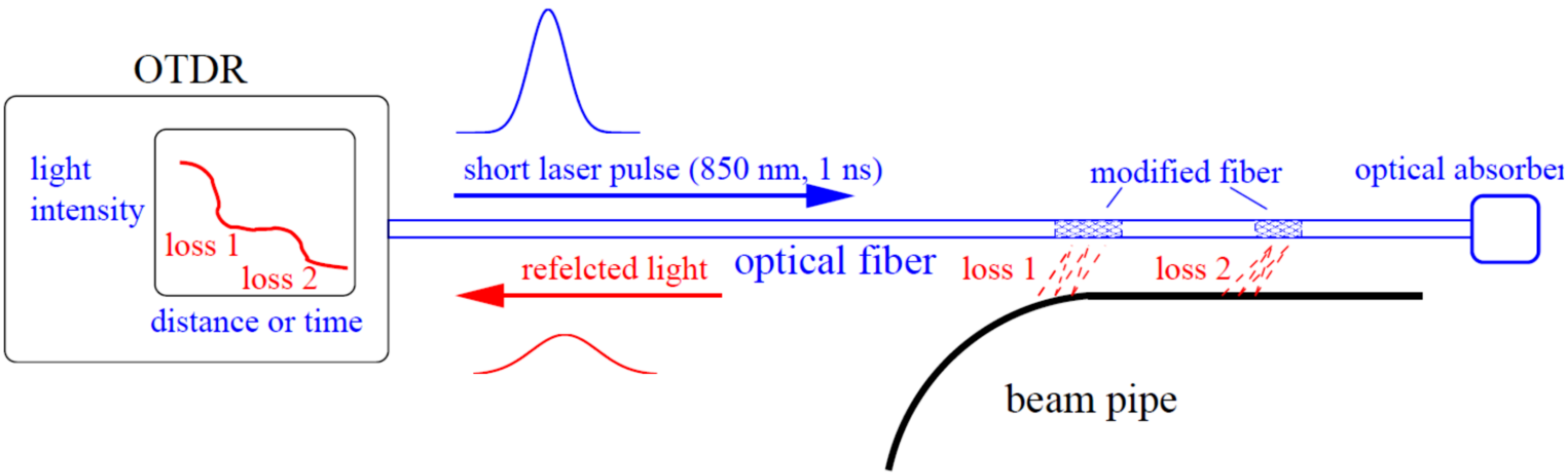
1. Slow down of fast neutrons by elastic collisions with p
2. Nuclear reaction inside BF$_3$ gas in tube:

   $$^{10}\mathbf{B} + \mathbf{n} \rightarrow {}^{7}\mathbf{Li} + \boldsymbol{\alpha} \quad \text{with} \quad Q = 2.3 \text{ MeV.}$$

3. Electronic stopping of ^{7}Li and α leads to signal.



Modification of fiber material is used as a measure of dose.



- several km long fibers (cheap due to use in tele-communication)
- 1 ns infra-red laser pulse
- OTDR (optical time domain reflector):

  time and amplitude of reflected light ⇒ location of modification.

Example for Optical Fibers BLM

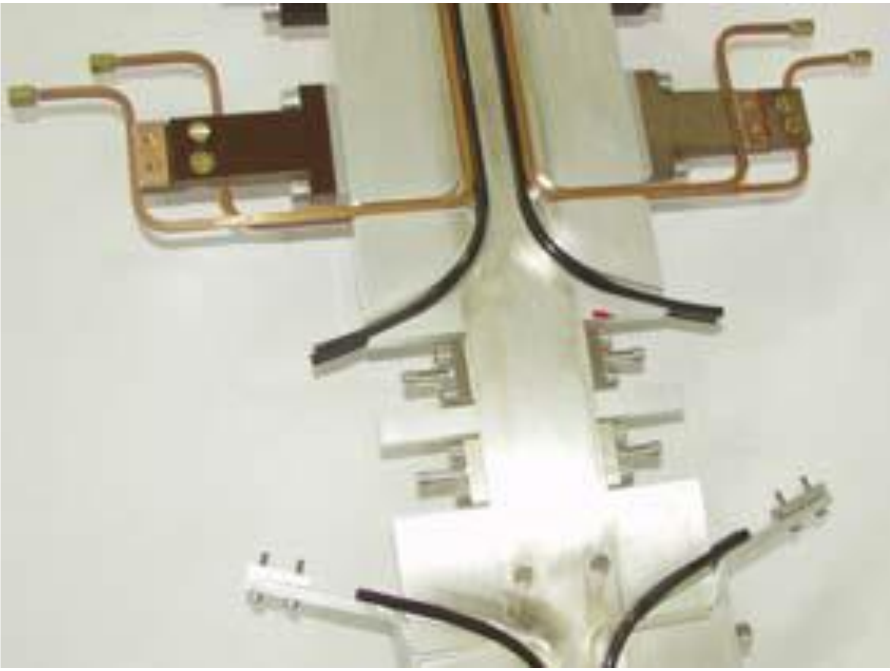
Advantage of optical fibers: Good spatial resolution with ***one*** detector

→ Installation parallel to beam pipe

→ low distance to loss

⇒ high solid angle for small volume

Example: Beam pipe of undulator at FLASH

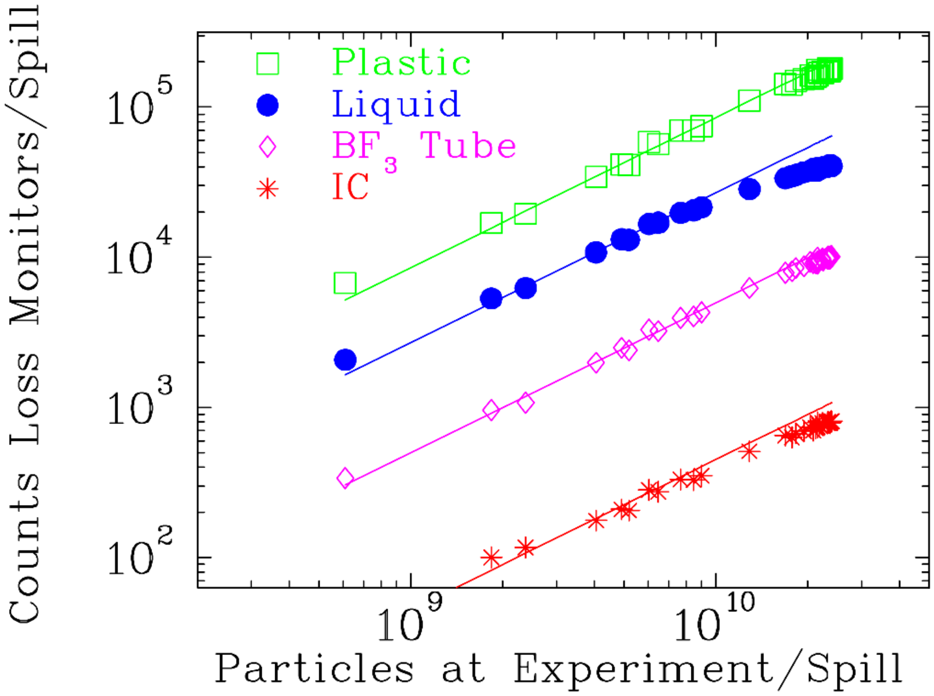


Alternative detection principle:
Cherenkov light by fast transversing particle

Comparison of different Types of BLMs

Different detectors are sensitive to various physical processes.

Example: Beam loss for 800 MeV/u O^{8+}
with different BLMs at GSI-synchr.:



⇒ Linear behavior for all detectors
but quite different count rate:

$r_{IC} < r_{BF3} < r_{liquid} < r_{plastic}$

Outline:

- Physical process from beam-wall interaction
- Different types of Beam Loss Monitors

  different methods for various beam parameters
- **Machine protection using BLMs**

  interlock generation for beam abort
- **Summary**

Machine Protection Issues for BLM

Losses lead to permanent activation $\Rightarrow$ maintenance is hampered

and to material heating (vacuum pipe, super-cond. magnet etc.) $\Rightarrow$ destruction.

Types of losses:

- ***Irregular*** or fast losses by malfunction of devices (magnets, cavities etc.)

  $\rightarrow$ BLM as online control of the accelerator functionality and **interlock generation**.
- ***Regular*** or slow losses e.g. by lifetime limits or due to collimator

  $\rightarrow$ BLM used for alignment.

Demands for BLM:

- **High sensitivity** to detect behavior of beam halo e.g. at collimator
- **Large dynamic range**:

  $\rightarrow$ low signal during normal operation, but large signal in case of malfunction

  $\rightarrow$ detectable without changing the full-scale-range

  e.g. scintillators from 10^2 1/s up to 10^7 1/s in counting mode.

Monitoring of loss rate in control room ***and*** as interlock signal for beam abortion.

Application: BLMs for Quench-Protection

Super-conducting magnets can be heated above critical temperature T_c by the lost beam

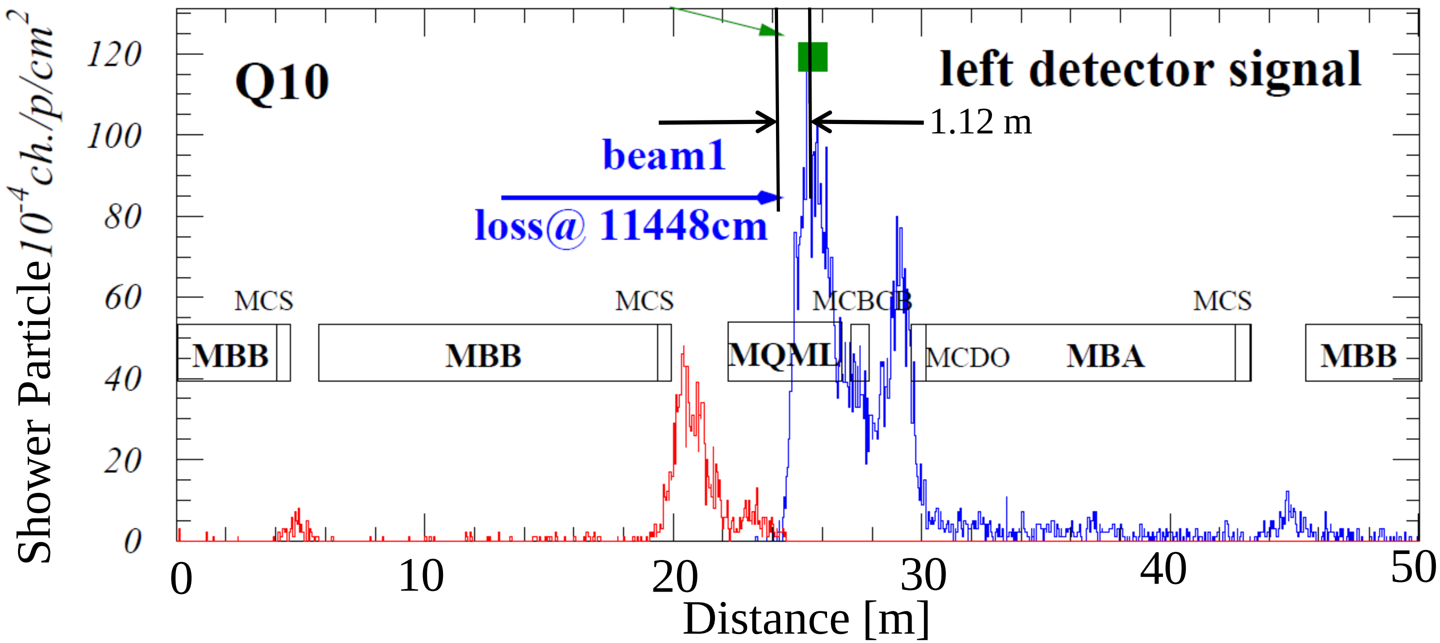
⇒ breakdown of super-conductivity = 'quenching'.

⇒ Interlock within 1 ms for beam abortion generated by BLM.

Position of detector at quadruples due to maximal beam size.

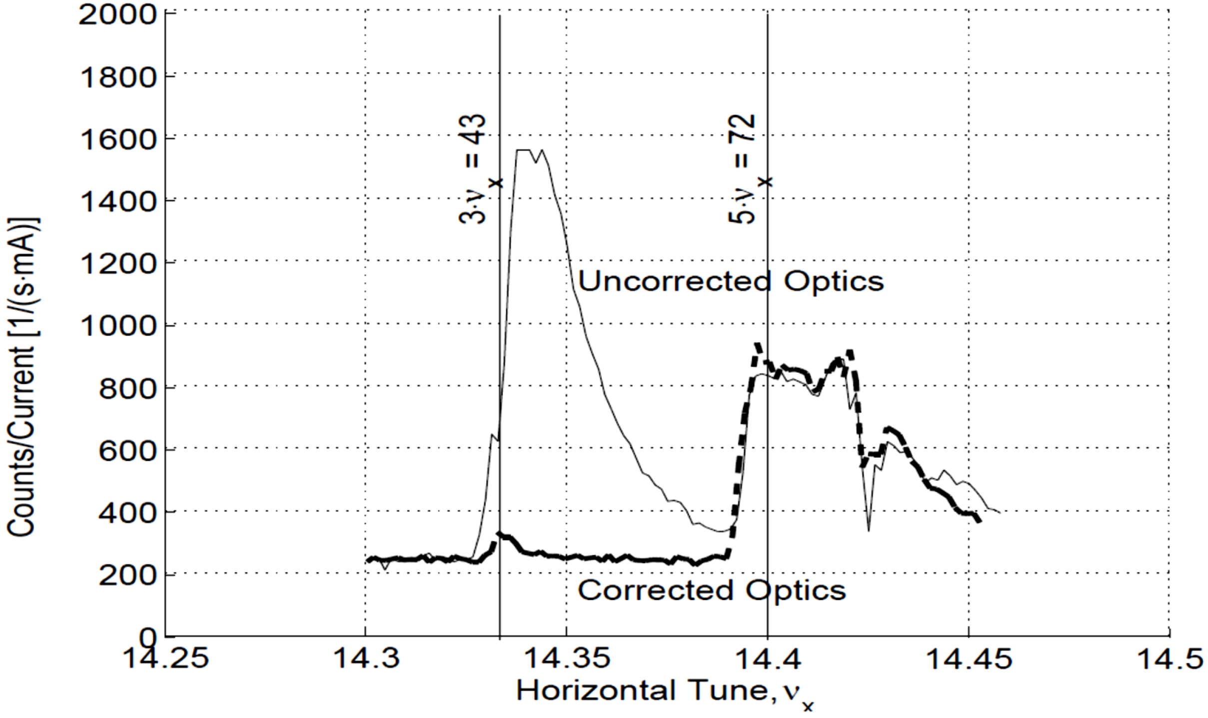
High energy particles leads to a shower in forward direction → Monte-Carlo simulation.

Example: LHC proton beam at 7 TeV: **shower maximum @ 11560cm**



Application: BLMs for optimal Tune Alignment

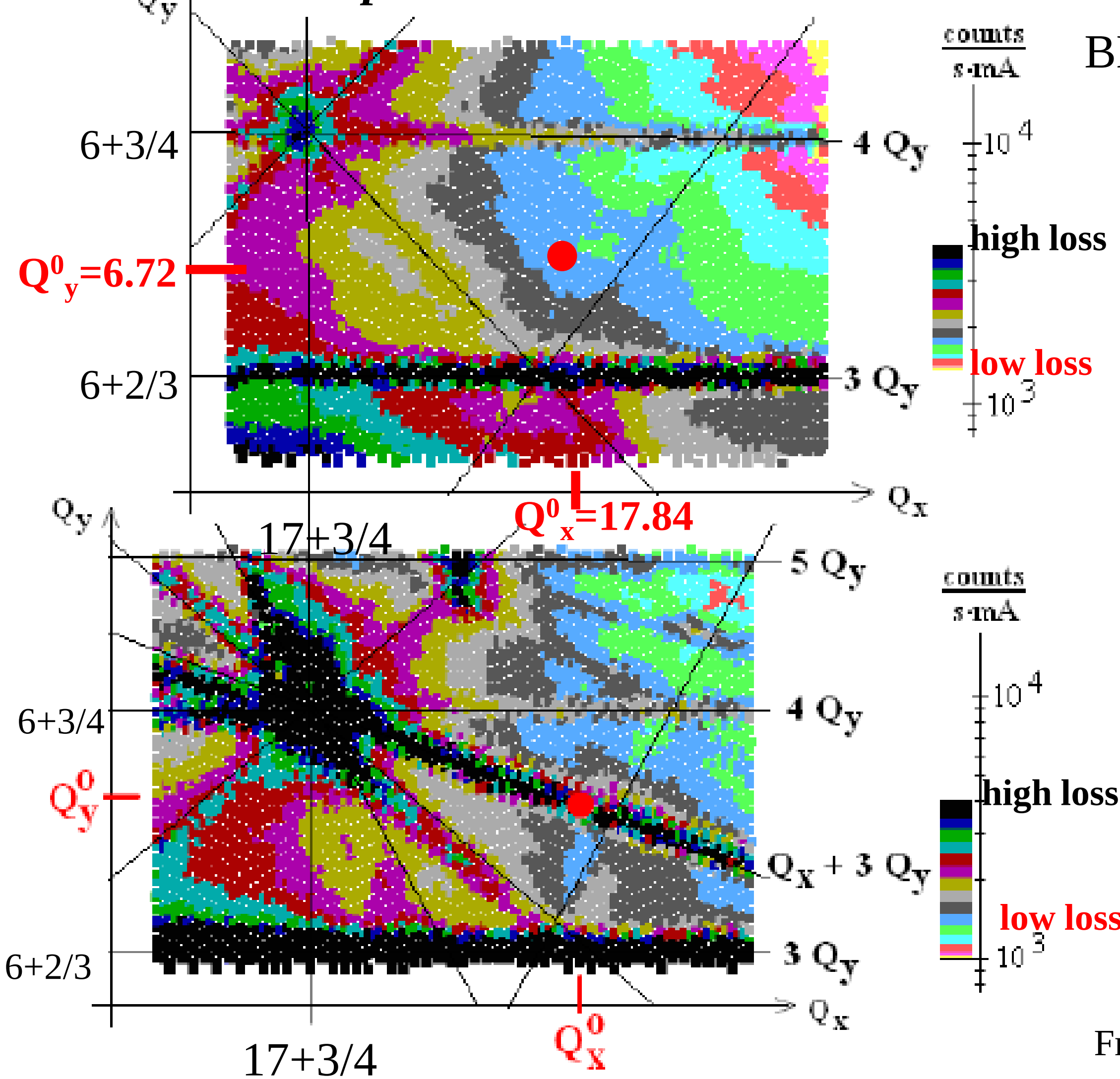
Example: Loss rate at a scraper inside the synchrotron as a function of the tune (i.e. small changes of quadrupole setting):



Beam blow-up by weak resonances can be avoided by proper tune value
→ very sensitive device for optimization.

Example: Tune scan at BESSY II: Tune variation & determination of losses

BLM: Plastic scintillator & PMT



Loss rate with **open** undulator
→ low loss (=long lifetime)
at working point Q^0_x , Q^0_y

Loss rate with **closed** undulator (16mm, 6T)
→high loss (=long lifetime)
→ excitation of coupling resonance
→ working point must be modified

From P. Kuske et al., DIPAC 2001 and PAC 2001

Measurement of the lost fraction of the beam:

- detection of secondary products
- sensitive particle detectors are used outside the vacuum
- cheap installations used at many locations

Used as interlock in all high current machines for protection.

Additionally used for sensitive 'loss studies'.

Depending on the application different types are used:

Frequently used:

- **Scintillators:** very sensitive, fast response, largest dynamics, not radiation hard
- **PIN diode:** insensitive, fast response, not radiation hard, cheap
- **IC:** medium sensitive, slow response, radiation hard, cheap, absolute measurement of dose

Used for special application:

- **(Electron Multiplier**: medium sensitive, fast response, radiation hard)
- **BF_3 tube**: only neutrons, slow response, radiation hard, expensive
- **Optical fibers**: insensitive, very slow, radiation hard, very high spatial resolution.