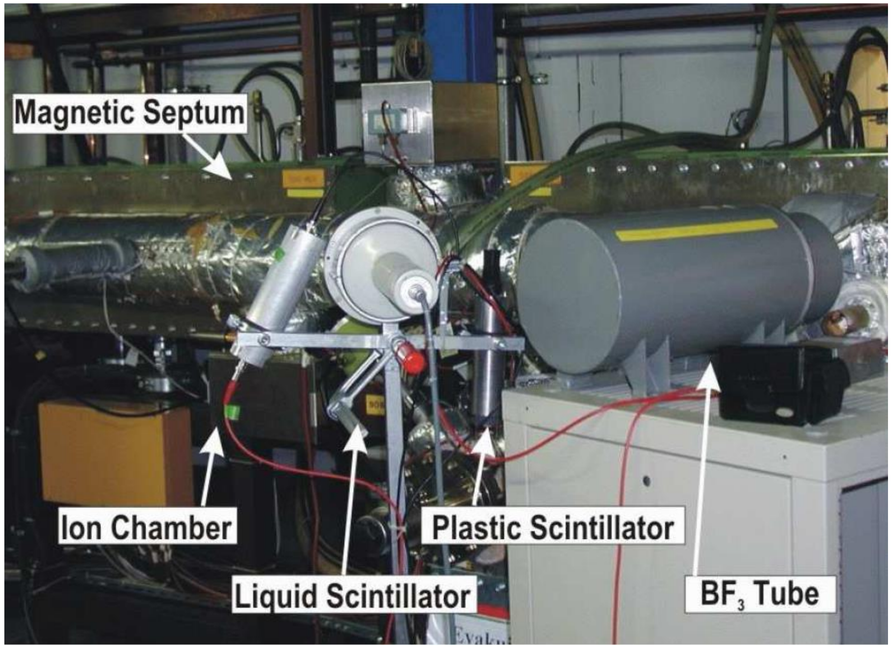
Beam Loss Monitors

JUAS 2025, ESI-Archamps at CERN

Peter Forck (GSI and University Frankfurt)



European Scientific Institute
Joint Universities Accelerator School

Beam Loss Monitors

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.**

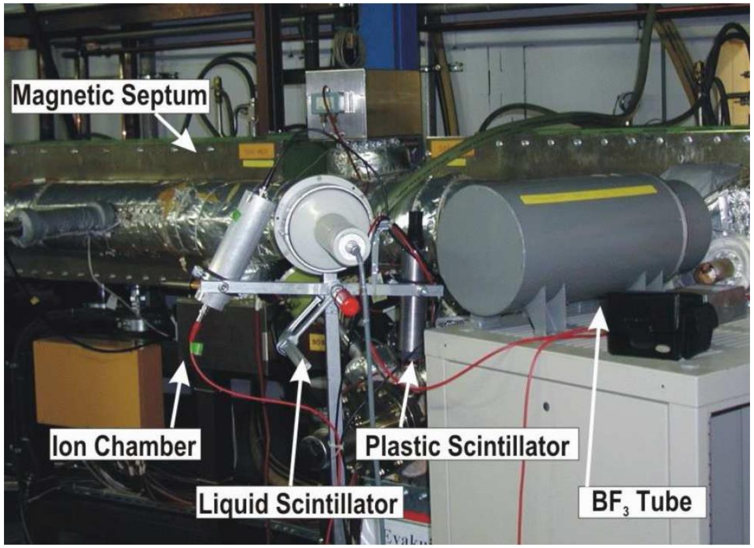
Operation: Alignment of the beam to prevent for activation

→ **optimal transmission to the target.**

Accelerator physics:

→ **sensitive detectors for accelerator development**

- Several loss monitors are used for various secondaries
- Different count rate & time resolution
- Some applications for usage



Basic Idea of Beam Loss Monitors

Basic idea for Beam Loss Monitors BLM:

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

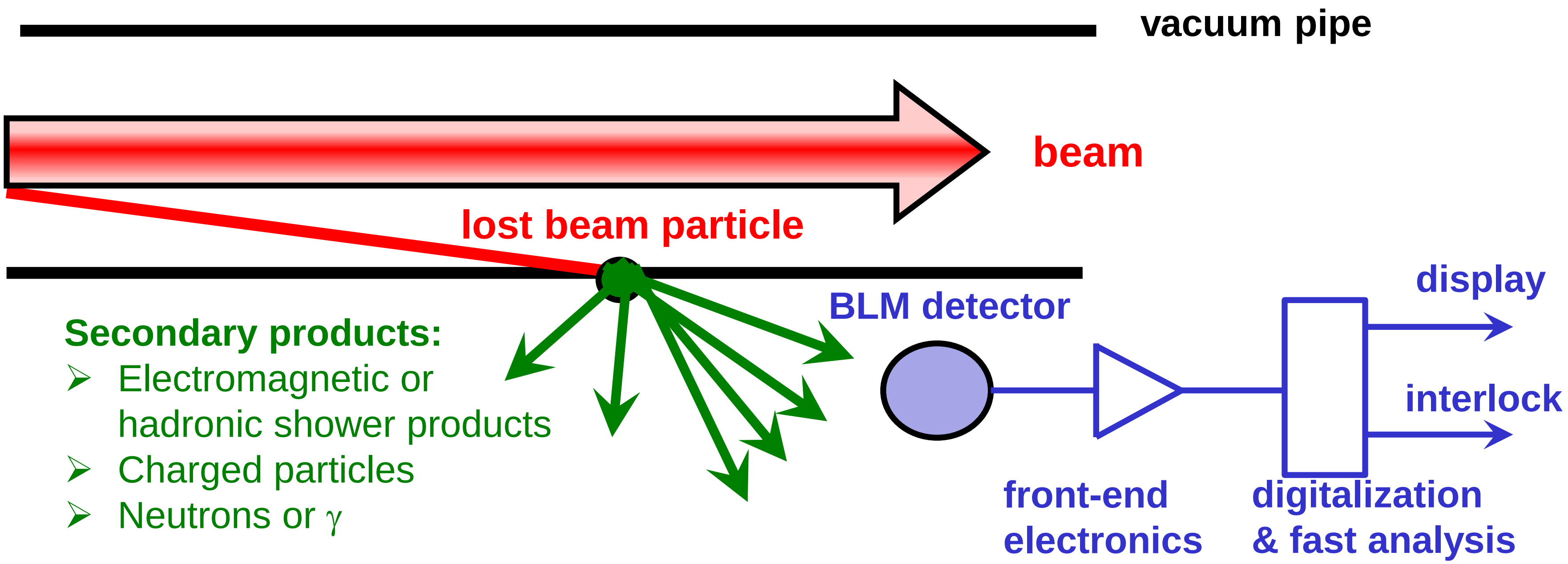
⇒ Interaction leads to some shower particle:

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

Remark: Due to grazing angle a thin vacuum chamber might be a ‘thick target’



Secondary products:
- Electromagnetic or hadronic shower products
- Charged particles
- Neutrons or γ

Secondary Particle Production for Electron Beams

Processes for interaction of electrons

For $E_{kin} < 10$ MeV:

$\Rightarrow$ only electronic stopping (x-rays, slow e^-).

For $E_{kin} > 100$ MeV:

Bremsstrahlungs-photon dominated

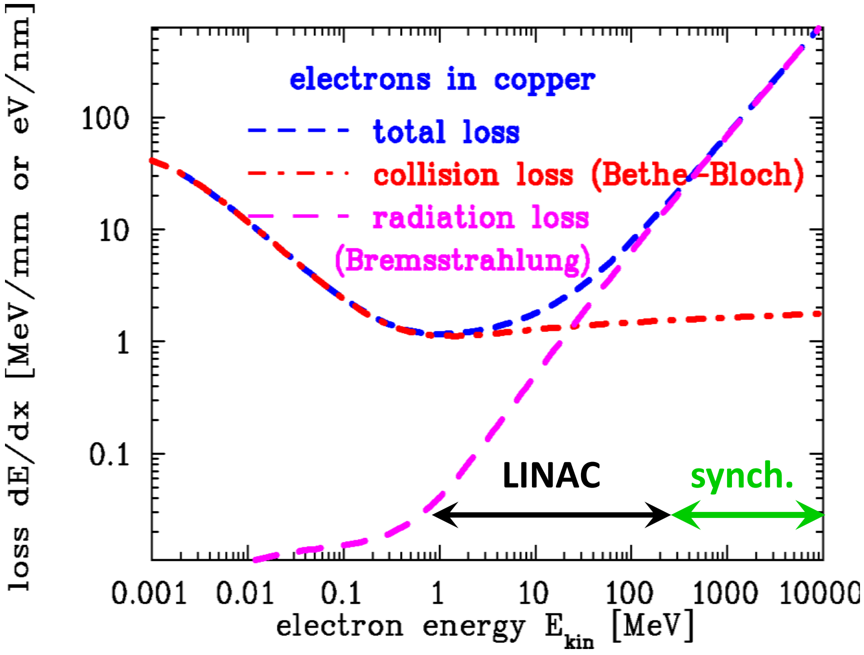
$\Rightarrow \gamma \rightarrow e^+ + e^-$ or $\mu^\pm ... \rightarrow$ electro-magnetic shower

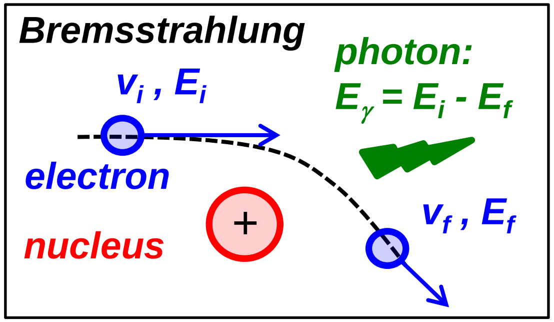
$\Rightarrow$ excitation of nuclear giant resonance $E_{res} \approx 10$ MeV

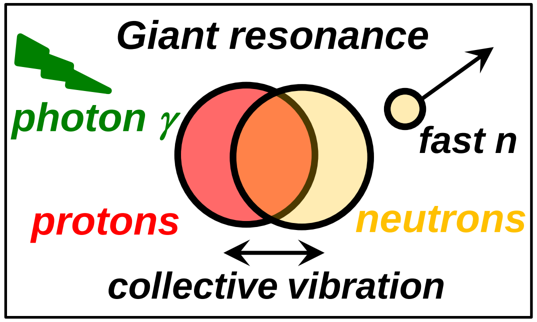
$\rightarrow$ decay to neutrons via (γ, n), (γ, p) or (γ, np)

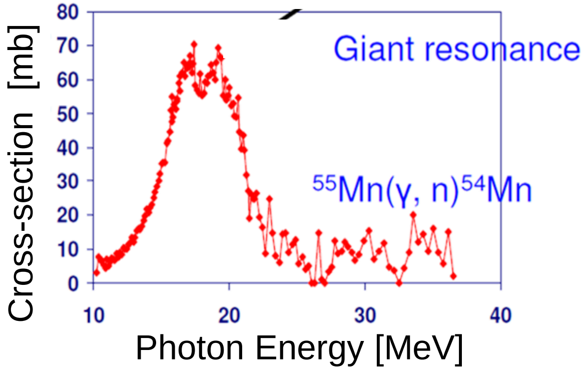
$\rightarrow$ fast neutrons emitted

$\rightarrow$ neutrons: Long ranges in matter due to lack of ele.-mag. interaction.





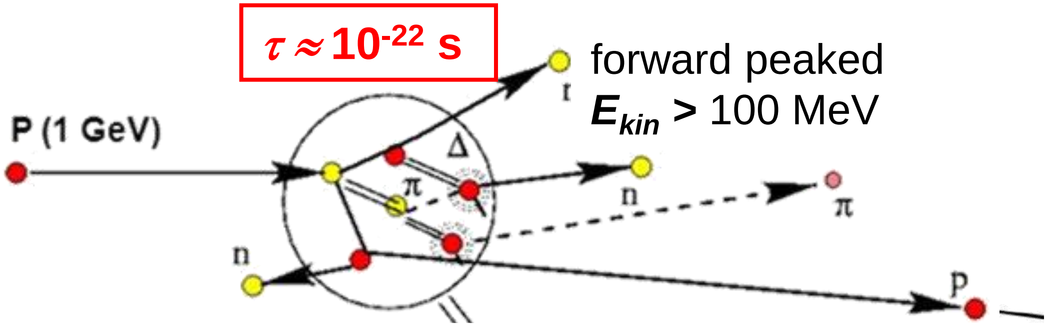




Nuclear Physics Processes for Protons

Nuclear reactions via spallation for protons with $E_{kin} \geq 1$ GeV (simplified):

- Pre-equilibrium phases: π-exchange within ≈ 10^{-22} s with $E_{kin} > 20$ MeV ⇒ hadronic shower



$\tau \approx 10^{-22}$ s

forward peaked
$E_{kin} > 100$ MeV

General properties:

- Binding energy:
  ≈ 5 MeV outer nucleons
  ≈ 50 MeV inner nucleons
- for $E_{kin} >> 100$ MeV
  comparable σ for n & p

D. Kiselev, CAS 2011

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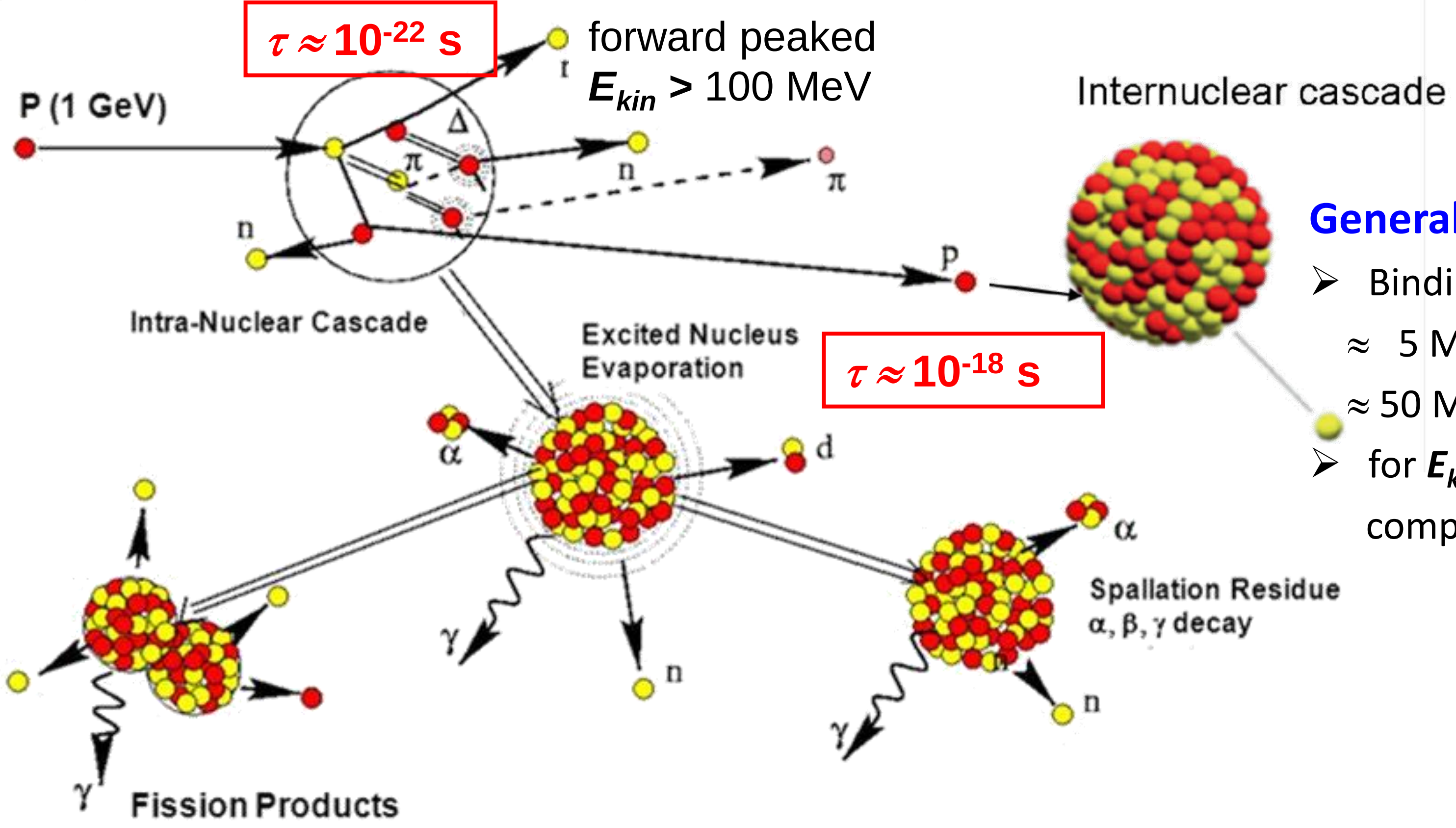
- Inter-nuclear cascade: Evaporation of n, p, d, α within ≈ 10^{-18} s with $E_{kin} \approx 1 – 10$ MeV
- Fission for heavy nuclei
- β & γ decay of nuclei with long lifetime $\tau >> 10^{-9}$ s



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Result on long term t > 1 ms: Radioactive nuclei = activation

D. Kiselev, CAS 2011

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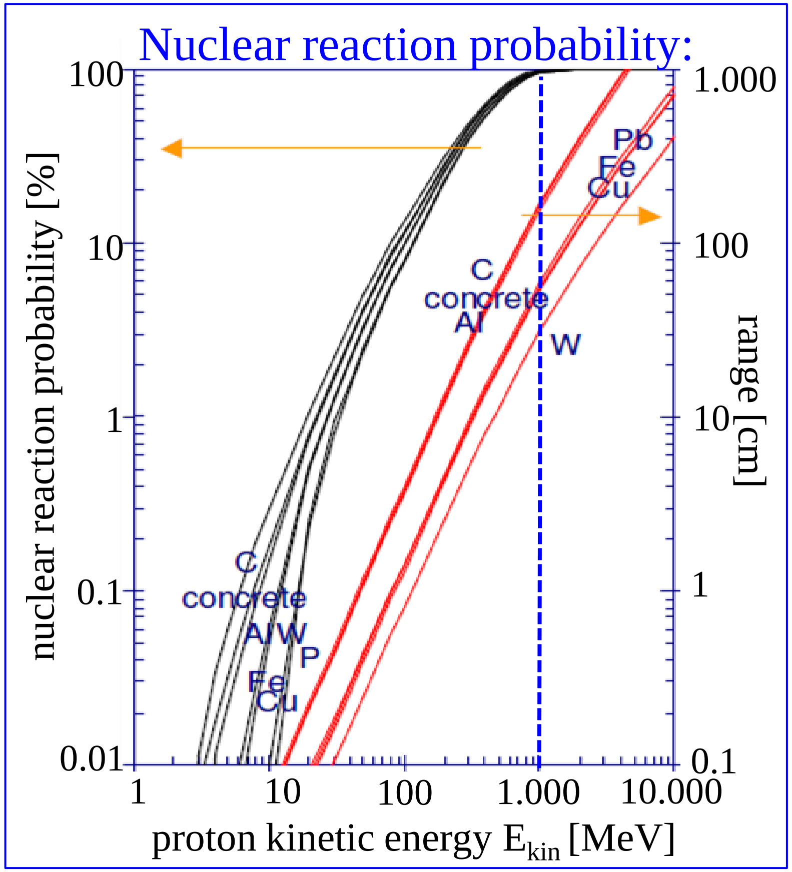
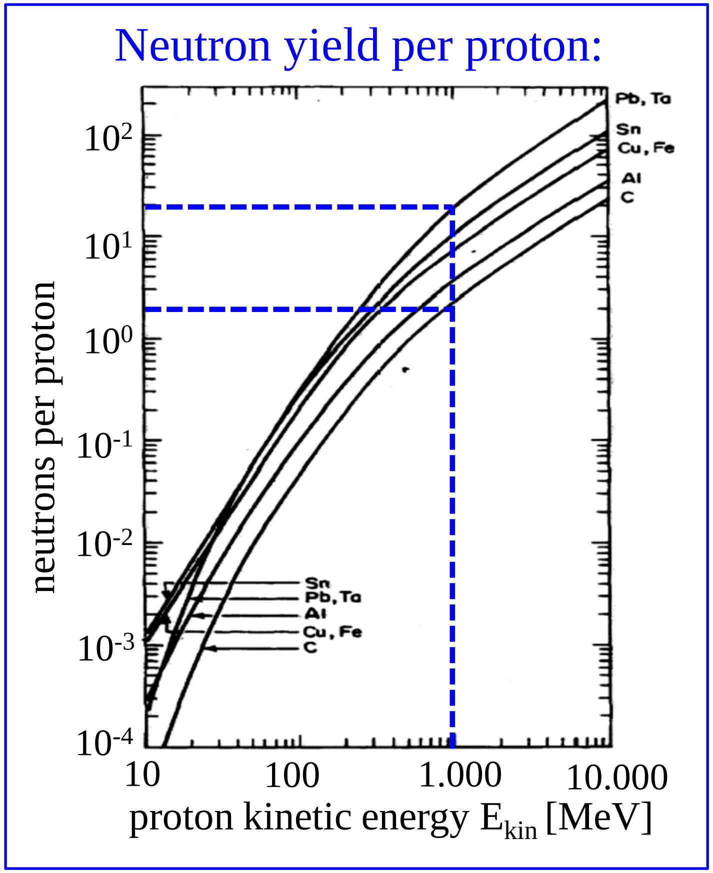




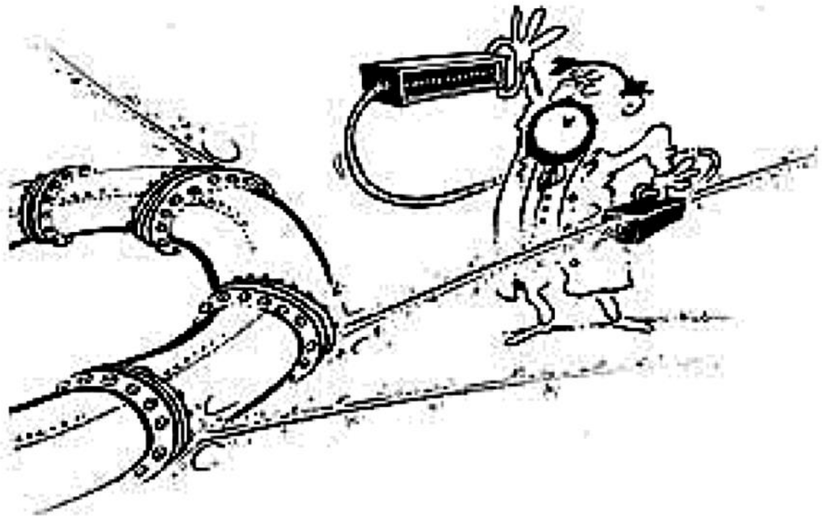
Thick target: Penetration depth comparable to range

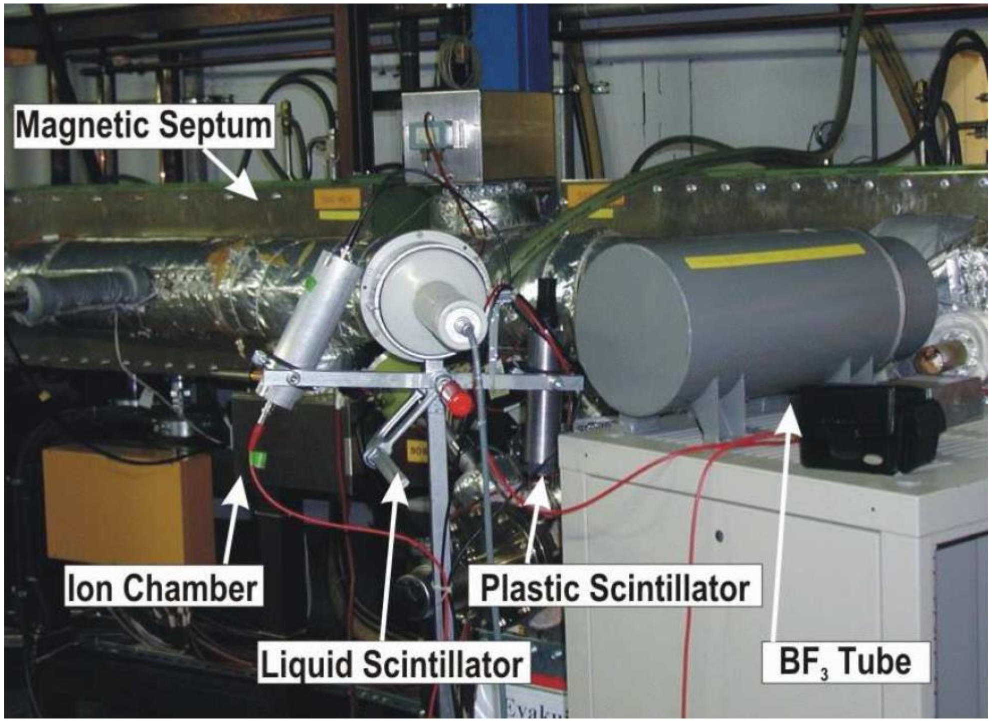
R.H. Thomas, in Handbook on Acc. Phy. & Eng.

Outline:

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

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

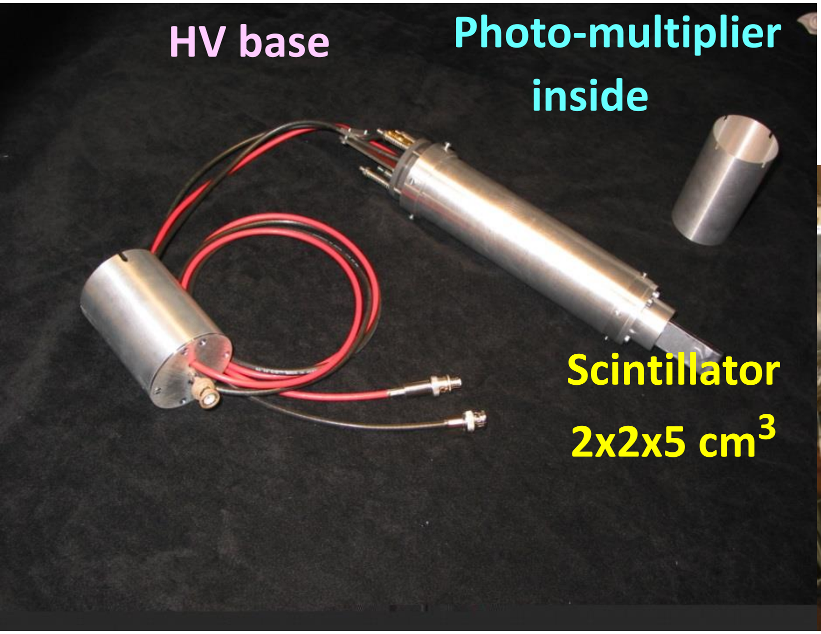




Scintillators as Beam Loss Monitors

Plastics or liquids are used:

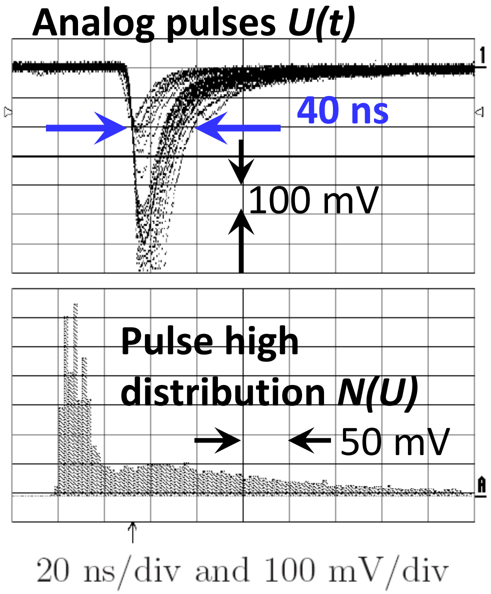
- detection of **charged particles** by electronic stopping
- detection of **neutrons** by elastic collisions n on p in plastics and fast p electronic stopping.



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:
$\Rightarrow$ broad energy spectrum
due to many particle species and energies.



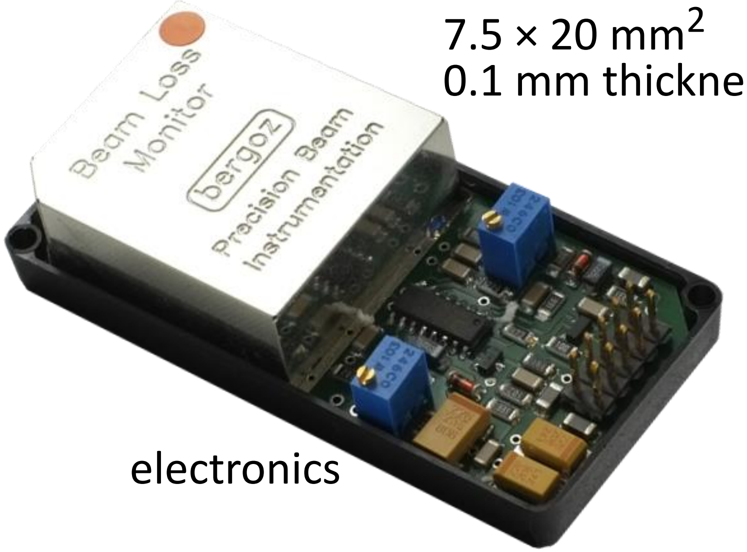
PIN-Diode (Solid State Detector) as BLM

Solid-state detector: Detection of charged particles.

Working principle

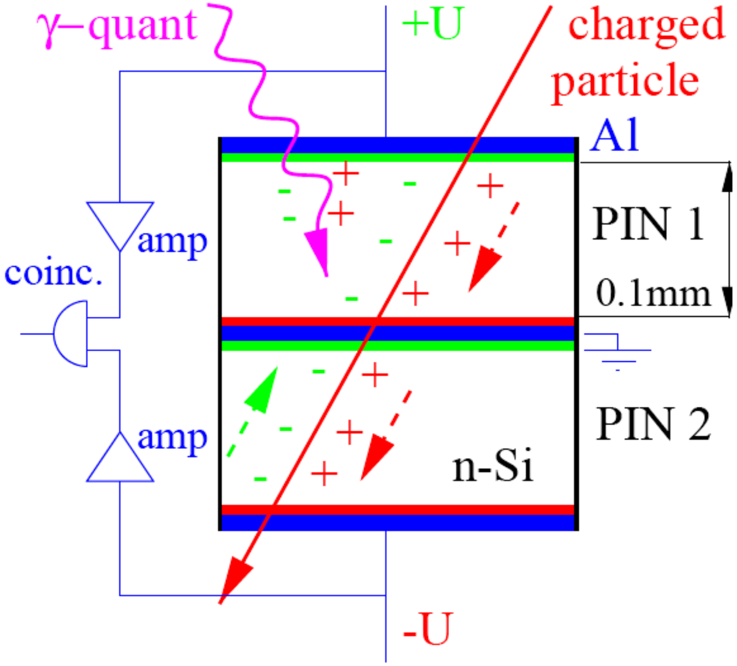
- About 10^4 e^--hole pairs are created by a Minimum Ionizing Particle (MIP).
- A coincidence of the two PIN reduces the background due to low energy photons.
- A counting module is used with threshold value comparator for alarming.

→ small and cheap detector.



2 PIN diodes:
7.5 × 20 mm^2
0.1 mm thickness.

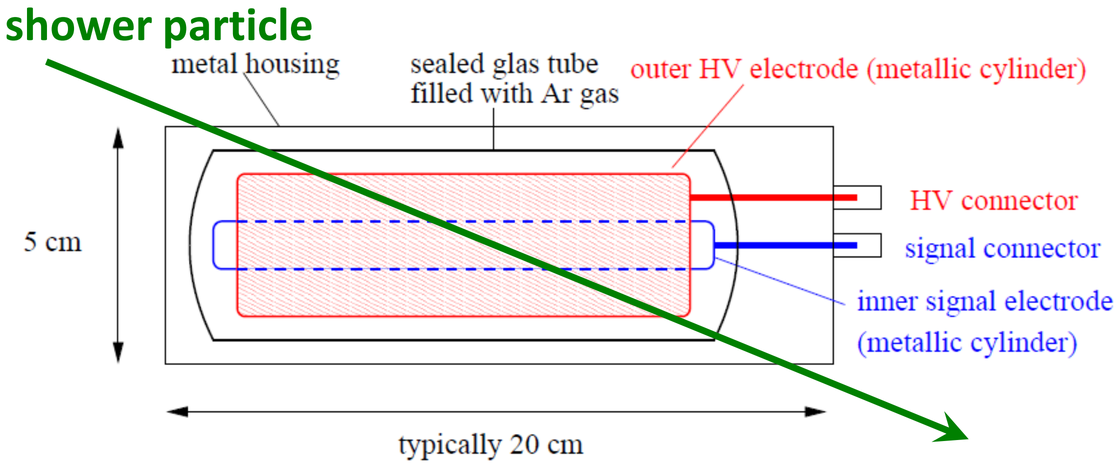
electronics



Ionization Chamber as BLM

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

$$I_{\text{sec}} \propto \frac{1}{W} \cdot \frac{dE}{dx} \Delta x$$



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

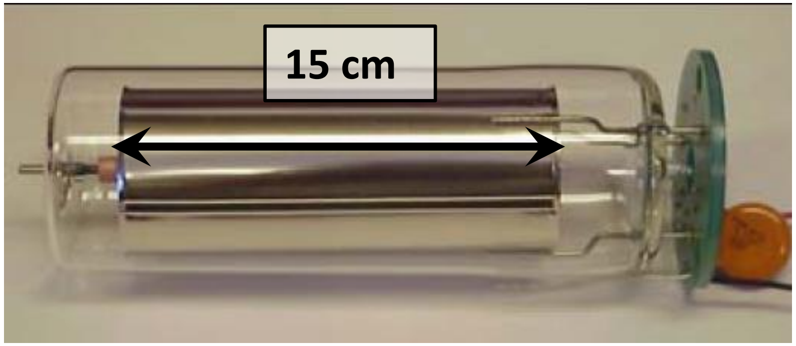
Gas	Ionization Pot. [eV]	W-Value [eV]
Ar	15.7	26.4
N_2	15.5	34.8
O_2	12.5	30.8
Air		33.8

Sealed tube Filled with Ar or N_2 gas:

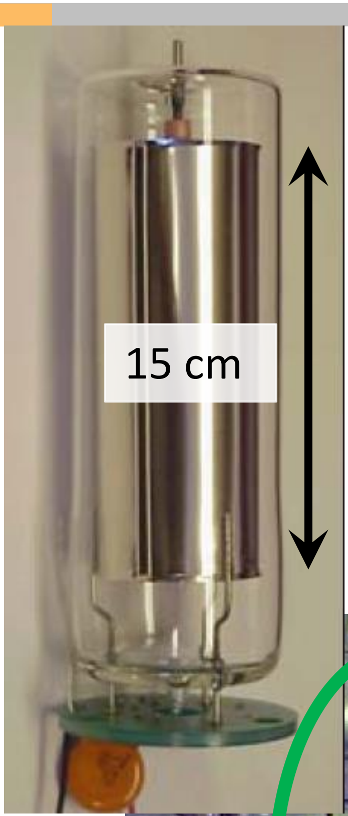
- Creation of Ar^+-e^- pairs,
  average energy ***W***=32 eV/pair
- Measurement of this current
- Slow time response

  due to ≈ 10 μs drift time of Ar^+.

Per definition: Direct measurement of dose !



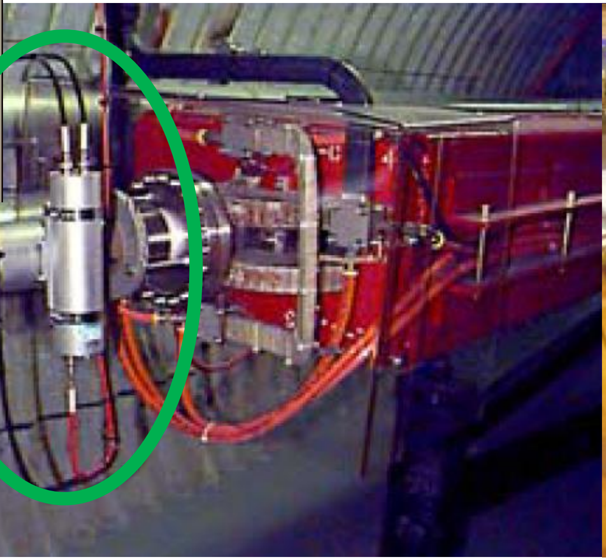
Ionization Chamber as BLM: TEVATRON and CERN Type



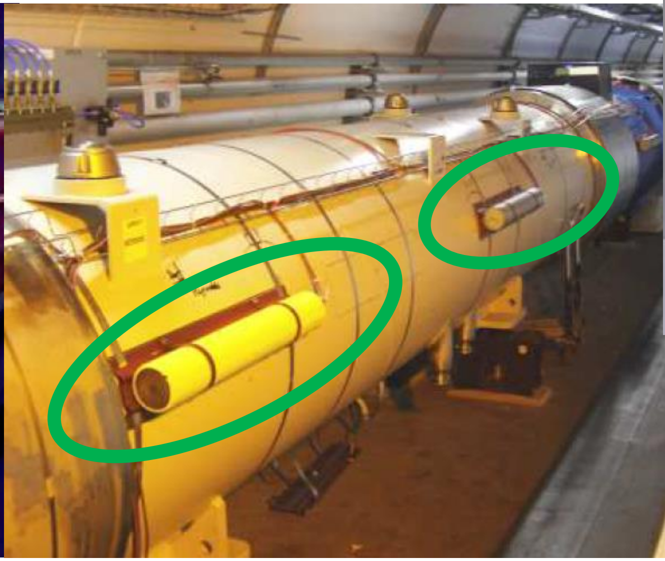
Parameter	TEVATRON, RHIC	CERN type
Size	15cm, ∅ 6 cm	50 cm, ∅ 9 cm
Gas	Ar at 1.1 bar	N_2 at 1.1 bar
# of electrodes	3	61
Voltage	1000 V	1500 V
Reaction time	3 μs	0.3 μs

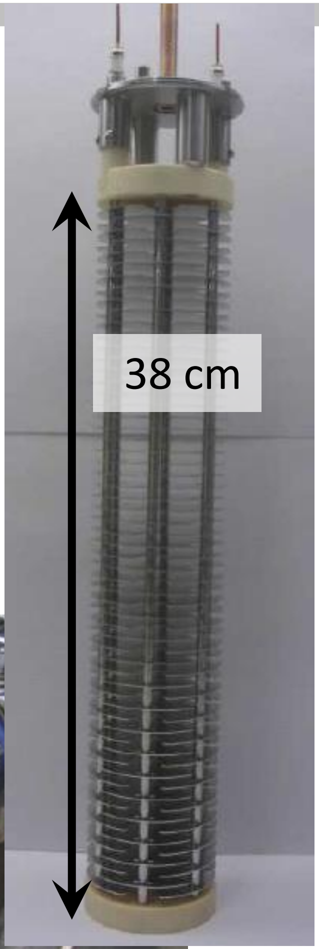
4000 BLMs at LHC⇔ each ≈ 6m

TEVATRON, RHIC type



CERN type





Cherenkov Light Detectors as Beam Loss Monitors

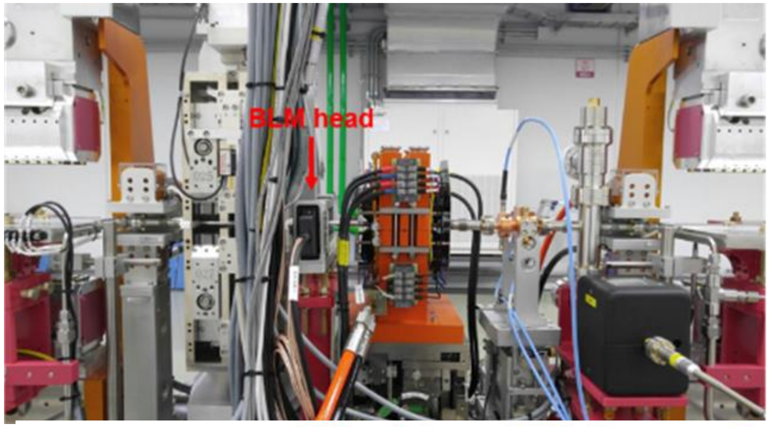
Cherenkov detectors → direct observation of lost electron:

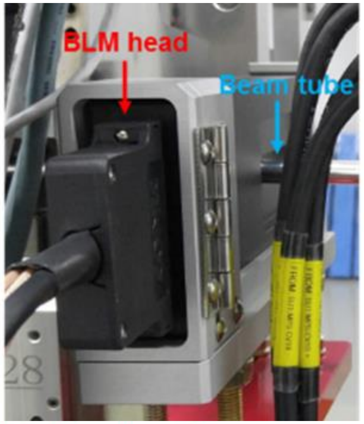
Passage of a charged particle faster than propagation of light

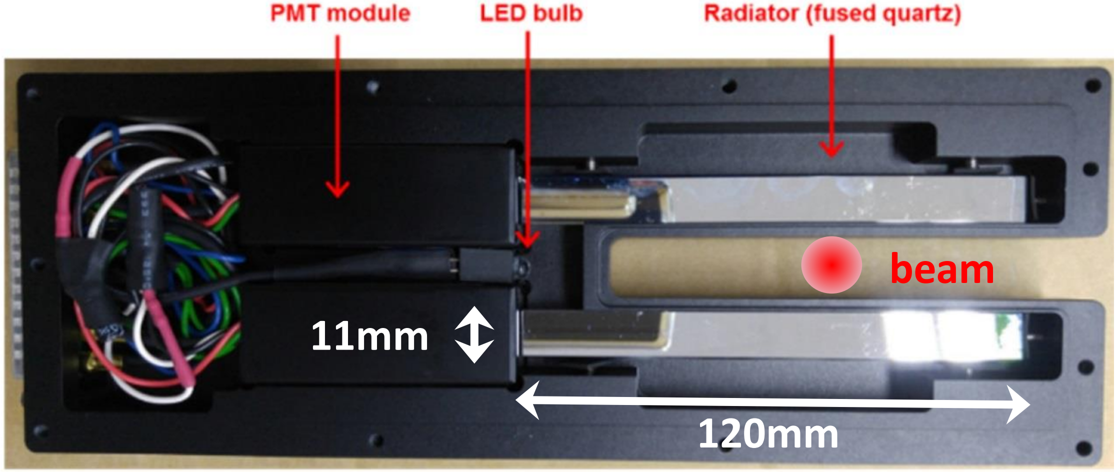
$v > c_{medium} = c/n$

Technical: Quartz rod $n=1.5$ & photomultiplier

Example: Korean XFEL behind undulator





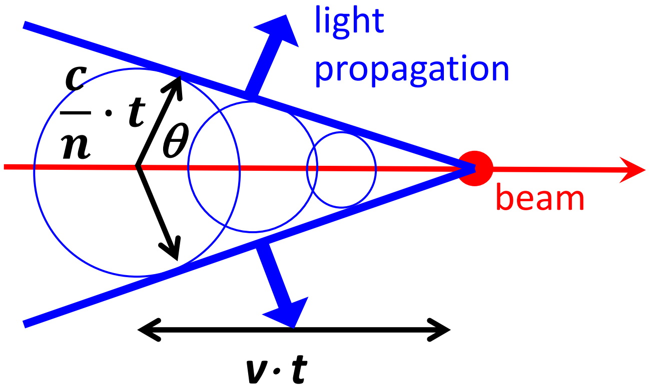


Cherenkov light emission:

For $v > c_{medium} = c/n$

light wave-front like a wake

broadband light emission



Advantage:

- Detection of fast electrons only
- Low sensitive to γ & synch. photons
- No saturation effects
- Prompt light emission

Usage: Mainly at FELs for short and intense pulses

H. Yang, D.C. Shin, FEL Conf. 2017

Comparison of different Types of BLMs

Different detectors are sensitive to various physical processes very different count rate, but basically proportional to each other

Typical choice of the detector type:

- **Ionization Chamber:**

  Advantage:

  - Measurement of absolute dose

  Disadvantage:

  - Low signal (low γ, eff, no neutron detection),
  - Sometimes slow, ion drift time 10 ... 100 µs

  ⇒ Often used at proton accelerators

- **Scintillator, Cherenkov detector:**

  Advantage:

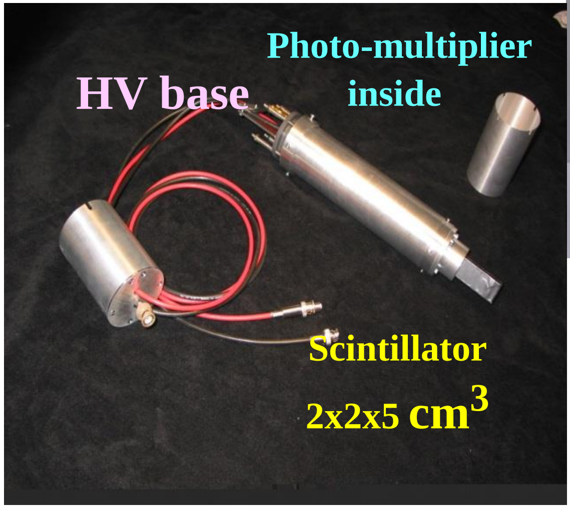
  - Fast current reading or particle counting
  - Can be fabricated in any shape, cheap

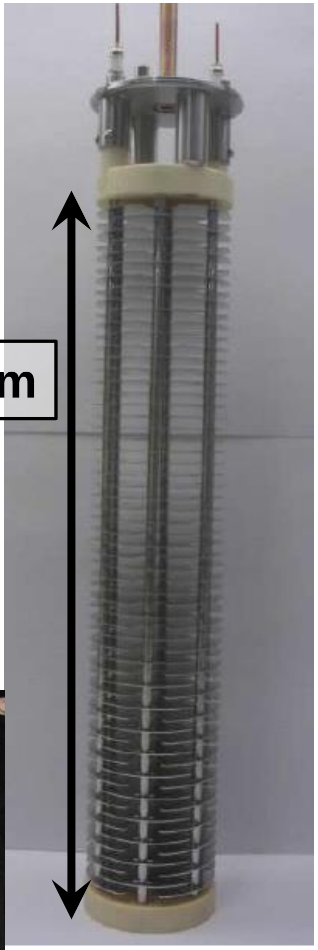
  Disadvantage:

  - Need calibration in many cases
  - Scint.: Might suffer from radiation

  ⇒ Often used at electron accelerators

  ⇒ Proton accel. at sensitive locations





Poll concerning BLM Types

Poll 7.1:

Which type of BLM measures the dose directly?

1) Scintillator
2) Ionization chamber
3) Solid state diodes
4) Cherenkov detectors

Poll 7.2:

Which type of BLM is most sensitive to neutrons?

1) Scintillator
2) Ionization chamber
3) Solid state diodes
4) Cherenkov detectors

Poll 7.3:

Which type of BLM can distinguish between beam particles and secondaries?

1) Scintillator
2) Ionization chamber
3) Solid state diodes
4) Cherenkov detectors

www.menti.com

code: 1208 6026

→ conclusion

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 ⇒ maintenance is hampered

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

Types of losses:

- ***Irregular*** or fast losses by malfunction of devices (magnets, cavities etc.)
  → BLM as online control of the accelerator functionality and **interlock generation**.
- ***Regular*** or slow losses e.g. by lifetime limits or due to collimator
  → BLM used for alignment.

Demands for BLM:

- **High sensitivity** to detect behavior of beam halo e.g. at collimator
- **Large dynamic range**:
  → low signal during normal operation, but large signal in case of malfunction
  → 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*** by the lost beam

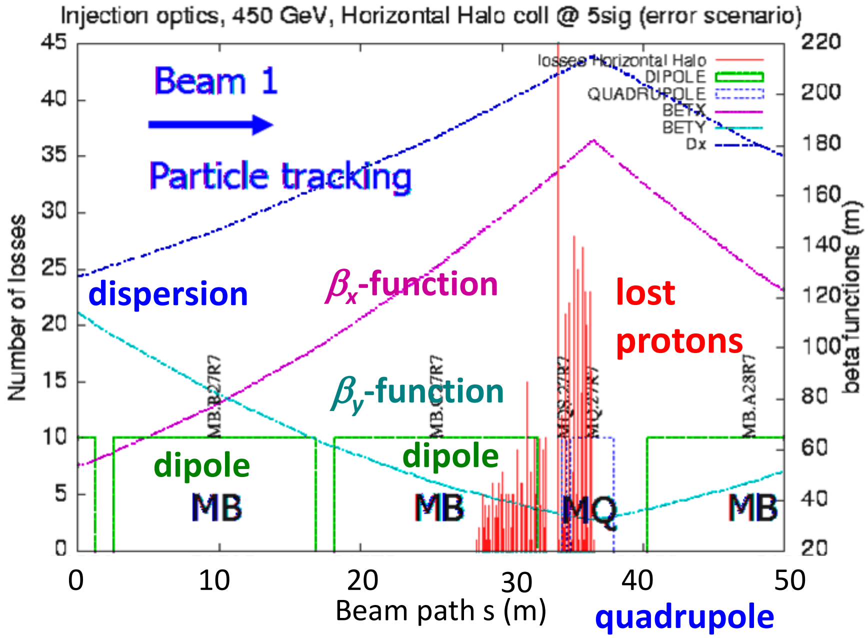
⇒ breakdown of super-conductivity = ’quenching’.

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

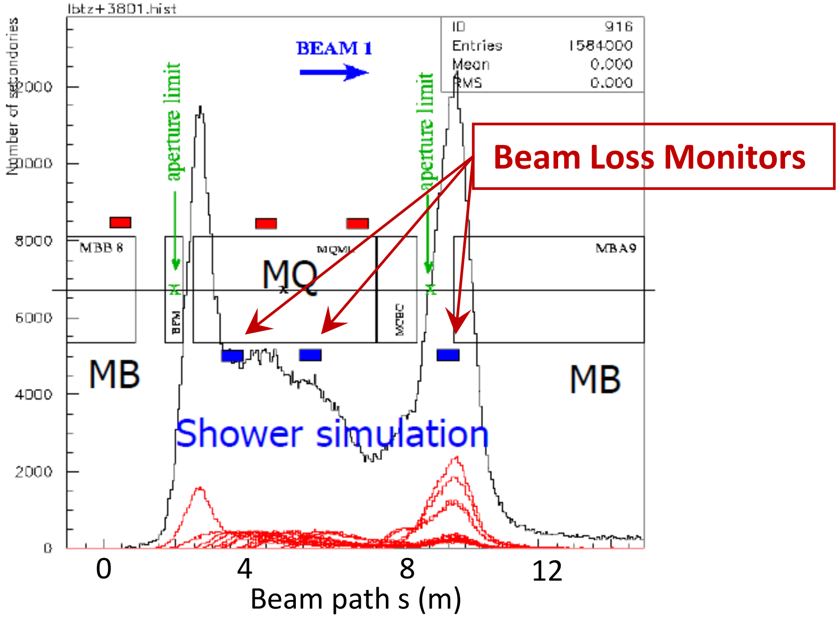
Position of detector at quadruples due to maximal beam size.

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

Example: Simulation of lost protons at LHC at 450 GeV → at focusing quad. ***D*** & β_x maximum



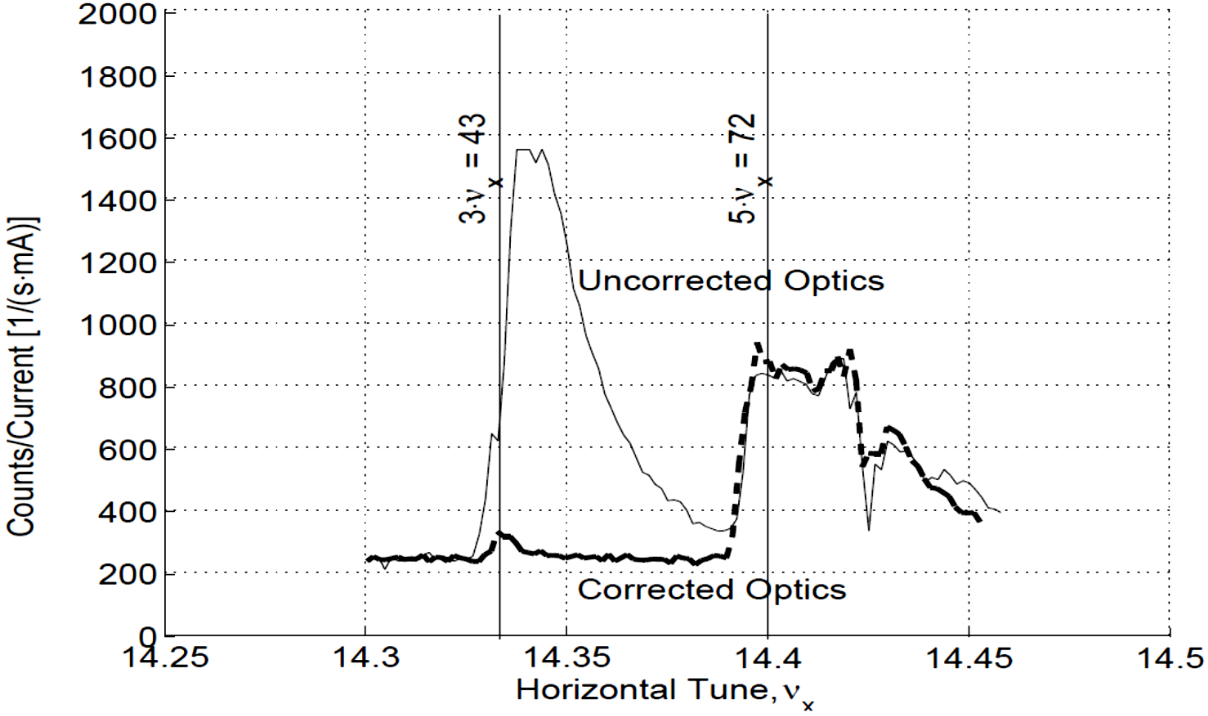
Example: Simulation of shower particles



B. Dehning, JAS 2014, CERN-2016-002

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.

Poll concerning Usage of BLMs

Poll 7.4:

Which answer is **wrong**? Beam loss monitors are used …

1) to prevent for unnecessary activation
2) as a system to restrict people access outside of the accelerator shielding
3) for quench protection for super-conducting components
4) for beam alignment

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Summary Beam Loss Monitors

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

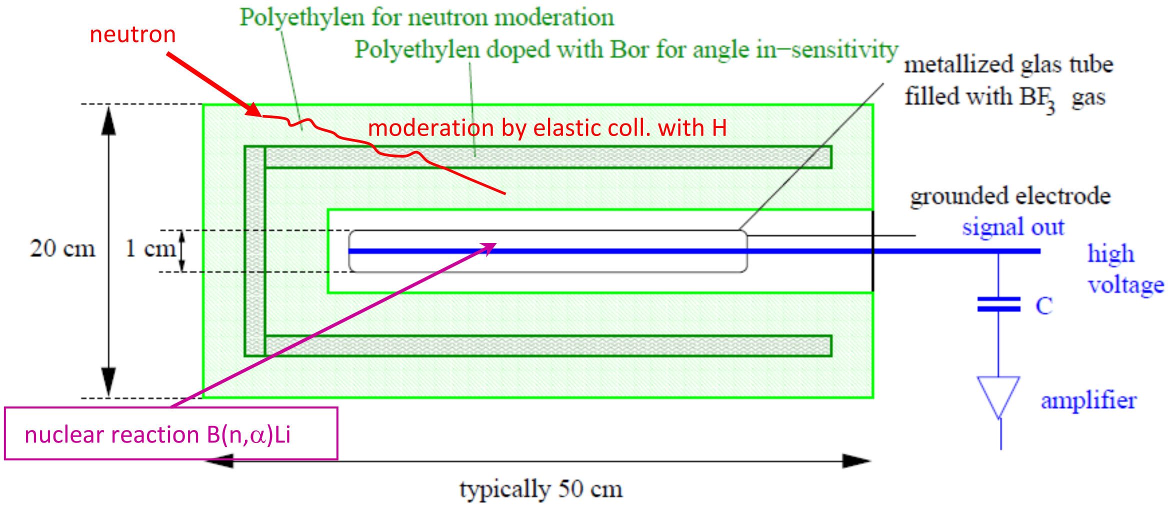
Used for special application:

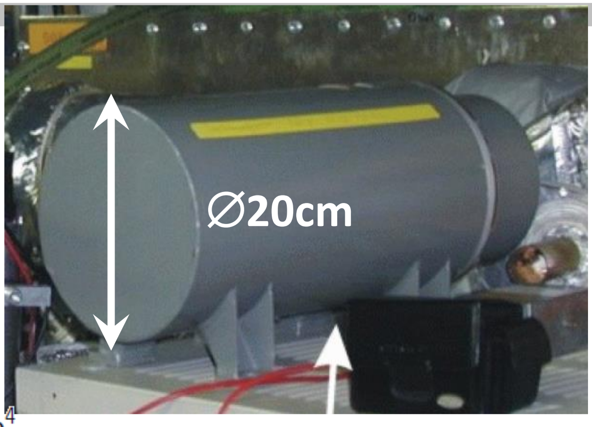
- **Electron Multiplier**: medium sensitive, fast response, radiation hard
- **BF_3 tube**: only neutrons, slow response, radiation hard, expensive
- **Optical fibers**: insensitive, very slow, radiation hard, very high spatial resolution.

Backup slides

BF_3 Proportional Tubes as BLM

Detection of neutrons **only** with a 'REM-counter':



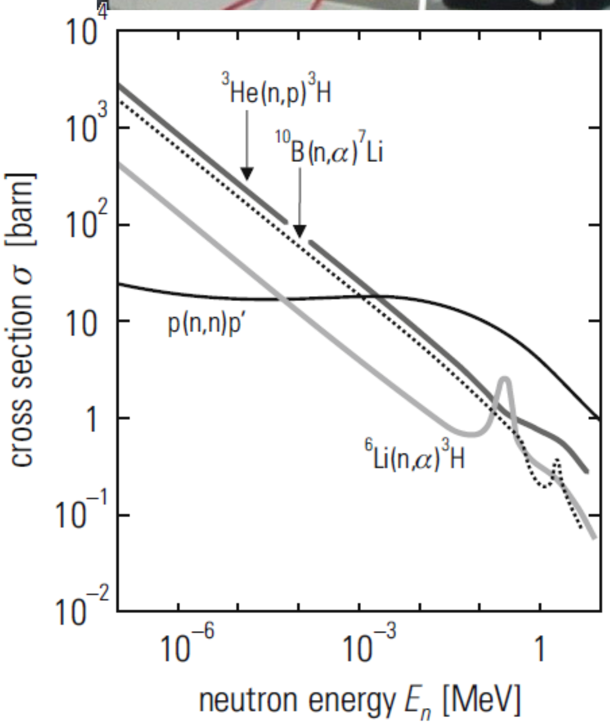


Physical processes of signal generation:

1. Slow down of fast neutrons by elastic collisions with p
2. Nuclear reaction inside BF_3 gas in tube:

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

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



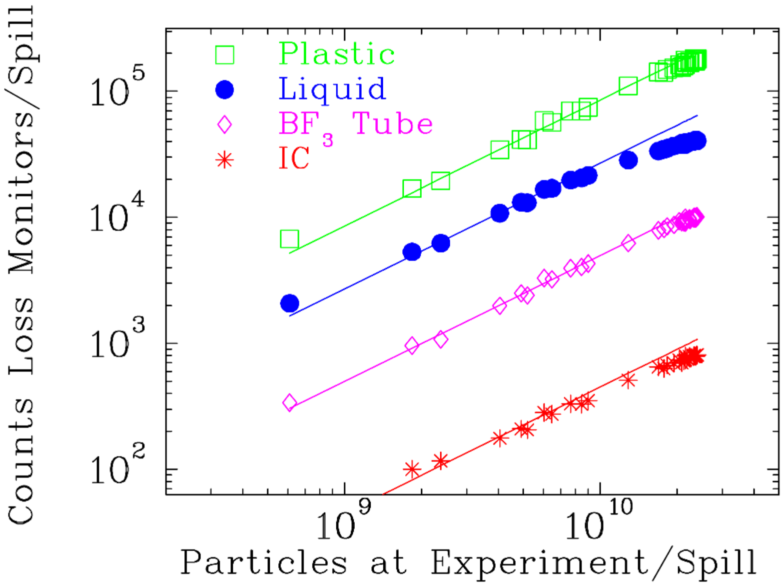
C. Grupen, Introduction to Radiation Protection

Remark: 'REM-counters' are frequently used for neutron detection outside of the concrete shield & in nuclear power plants

Comparison of different Types of BLMs

Different detectors are sensitive to various physical processes
very different count rate, but basically proportional to each other

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



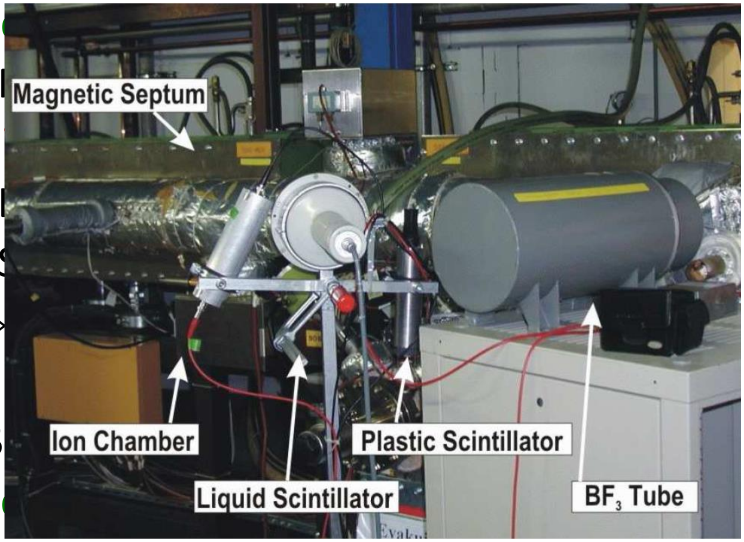
⇒ Linear behavior for all detectors

⇒ Quite different count rate:

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

Typical choice of the detector type:

- **Ionization Chamber:**



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⇒

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- Fast current reading or particle counting
- Can be fabricated in any shape, cheap

Disadvantage:

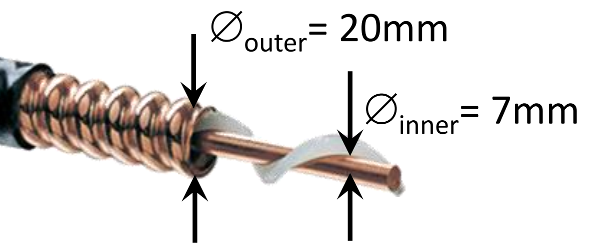
- Need calibration in many cases
- Might suffer from radiation

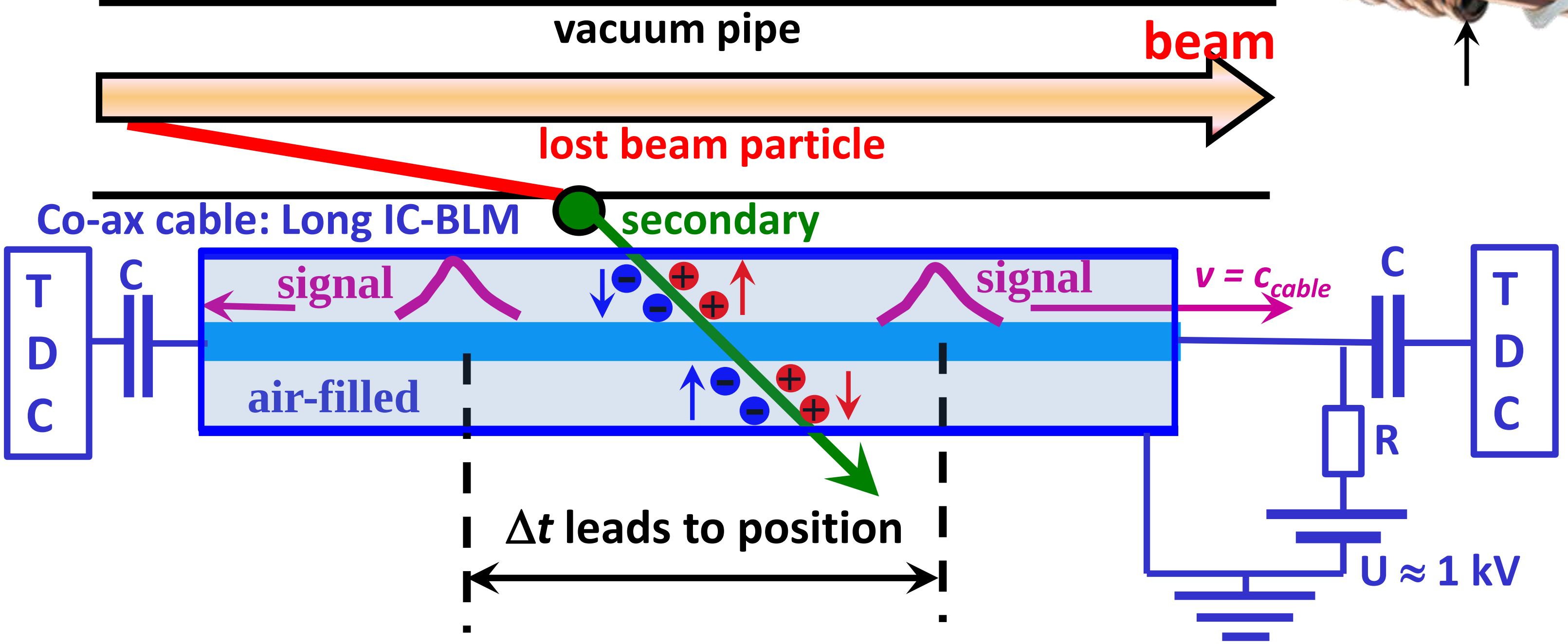
⇒ Often used at electron accelerators

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

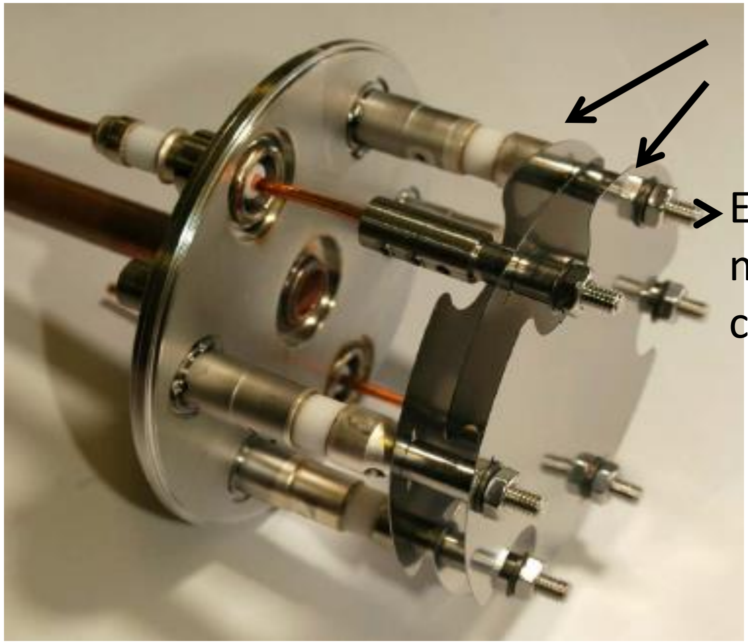
Secondary Electron Monitor as BLM

Ionizing radiation liberates secondary electrons from a surface.

Working principle:

- Three plates mounted in a vacuum vessel (passively NEG pumped)
- Outer electrodes: biased by $\boldsymbol{U} \approx +1$ kV
- Inner electrode: connected for current measurement (here current-frequency converter)

→ **small and cheap detector, very insensitive.**



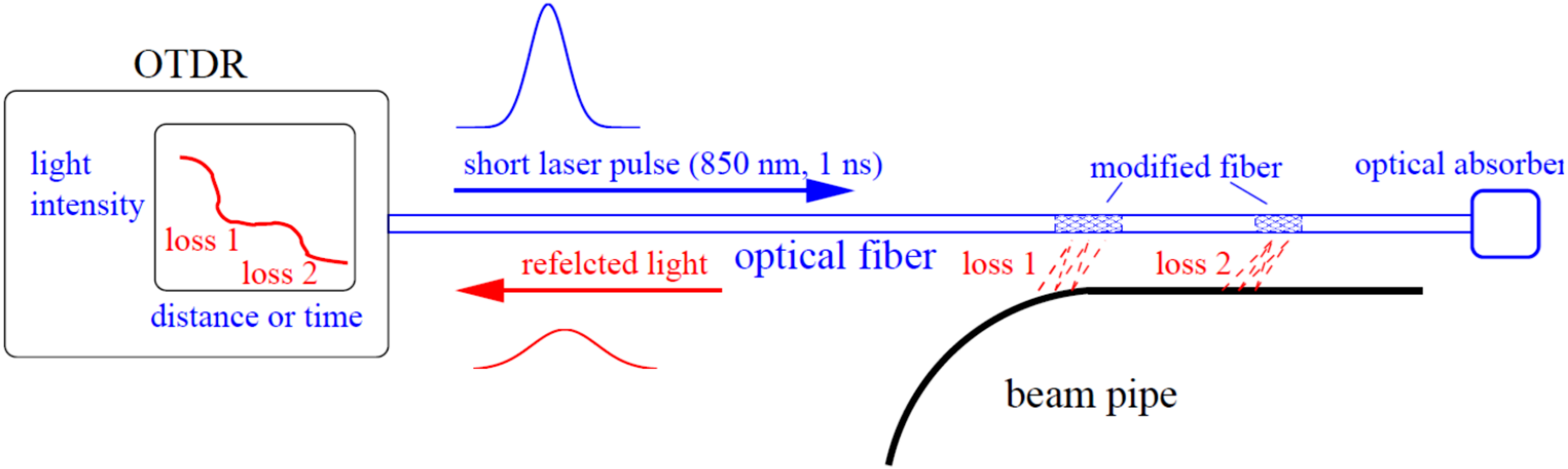
Detector with intrinsic amplification:

Secondary electron multiplier

i.e. a ‘photo-multiplier without photo-cathode’

Optical Fibers as BLM

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 $\Rightarrow$ location of modification.

Example for Optical Fibers BLM

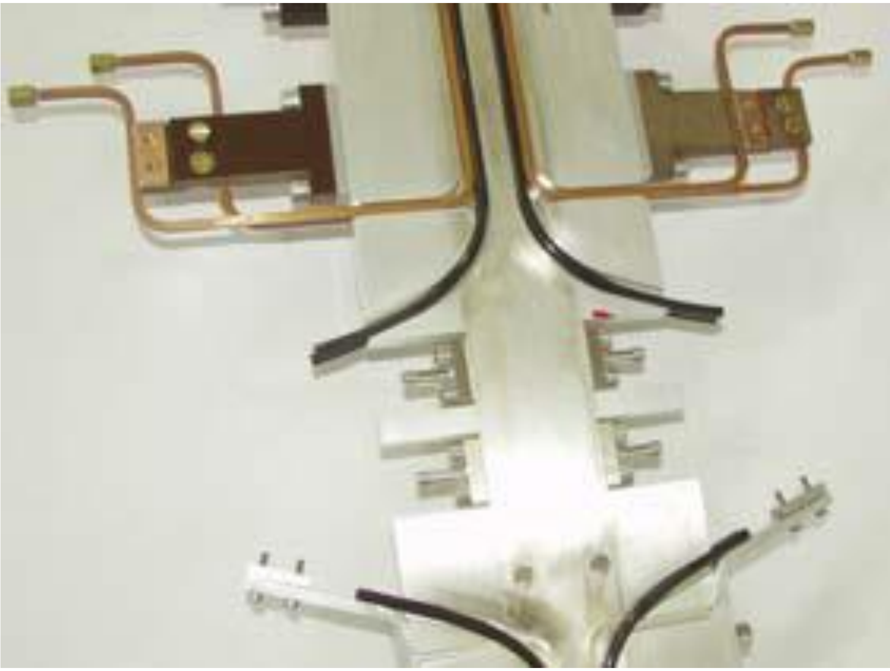
Advantage of optical fibers: Good spatial resolution with ***one*** detector

→ Installation parallel to beam pipe

→ low distance to loss

⇒ high solid angle for small volume

Example: Beam pipe of undulator at FLASH

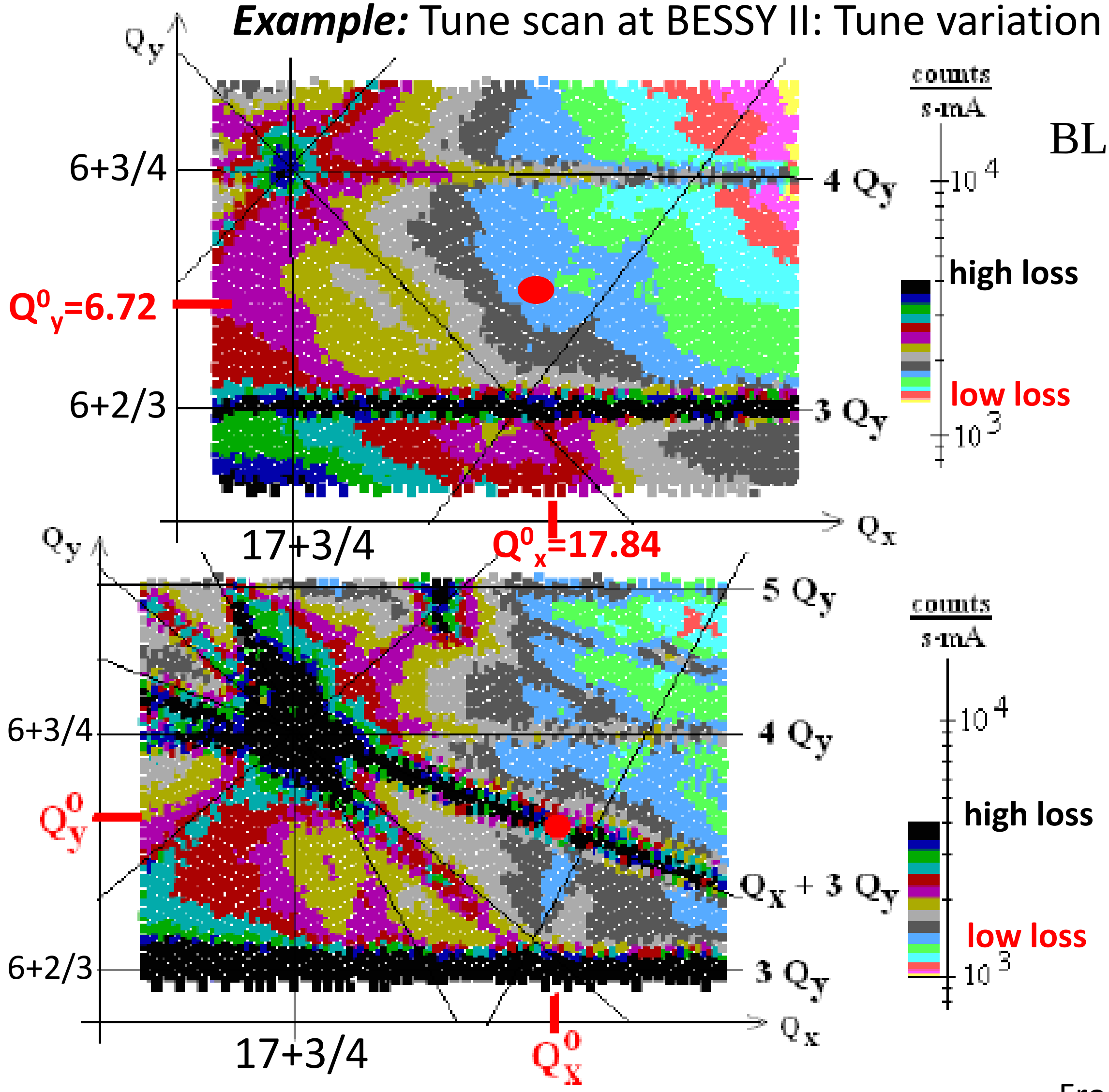


Alternative detection principle:

Cherenkov light by fast transversing particle

Application: BLMs for optimal Tune Alignment

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 at Q^0_x , Q^0_y

Loss rate with **closed** undulator (16mm, 6T)

→high loss (= short lifetime)

→ excitation of coupling resonance

→ working point must be modified

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