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.**

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 of Beam Loss Monitors

Basic idea for Beam Loss Monitors B LM:

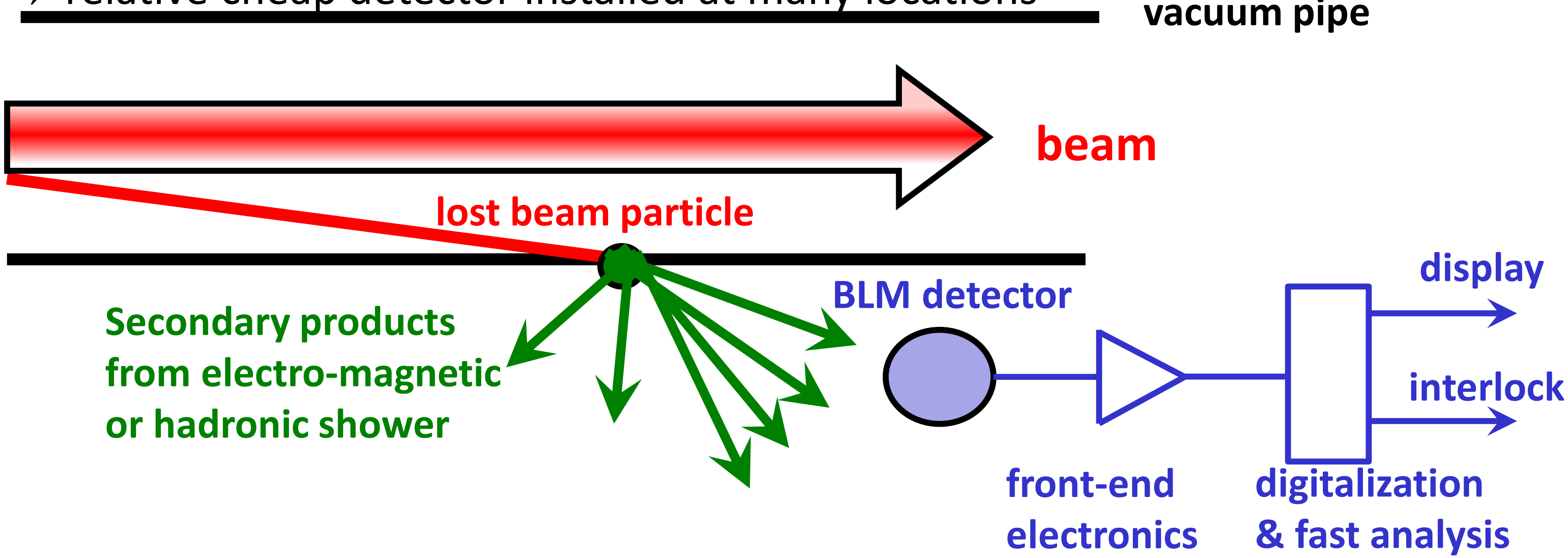
A loss beam particle must collide with the vacuum chamber or other insertions

⇒ 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



Secondary Particle Production for Electron Beams

Processes for interaction of electrons

For E_{kin} < 10 MeV:

⇒ only electronic stopping (x-rays, slow e^-).

For E_{kin}> 100 MeV:

Bremsstrahlungs-photon dominated

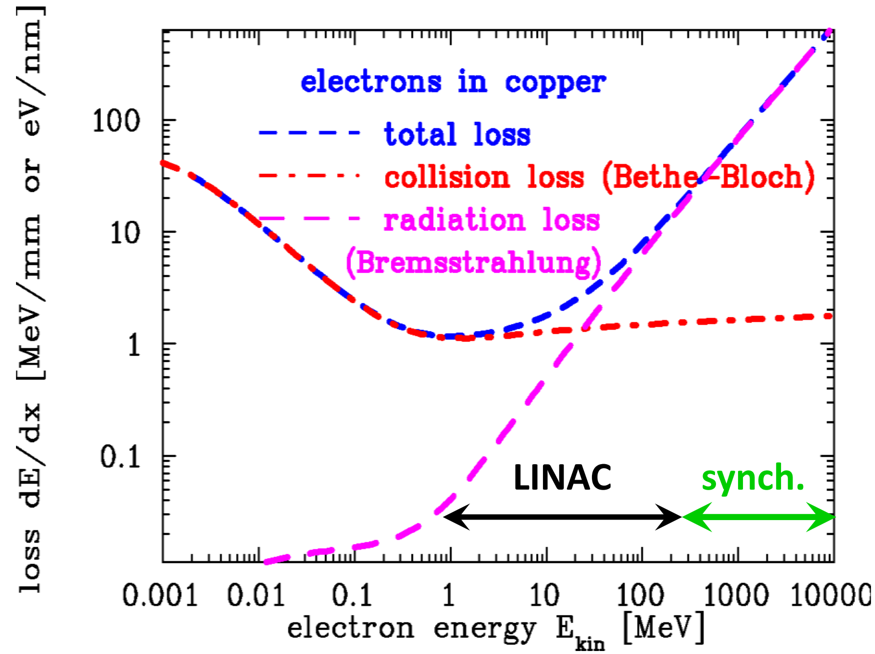
⇒ $\gamma \rightarrow e^+ + e^-$ or $\mu^\pm ... \rightarrow$ electro-magnetic shower

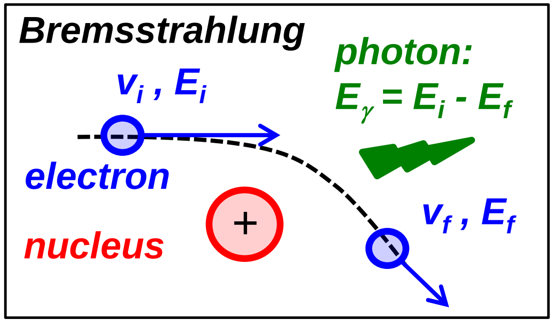
⇒ excitation of nuclear giant resonance $E_{res} \approx$ 6 MeV

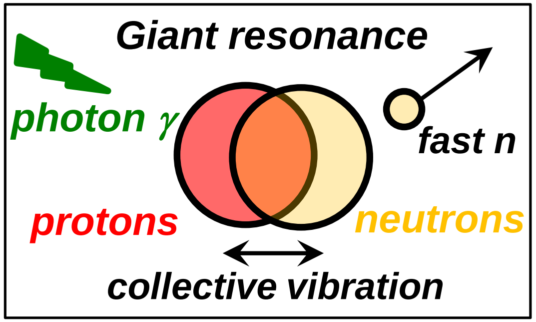
→ decay to neutrons via (γ, n), (γ, p) or (γ, np)

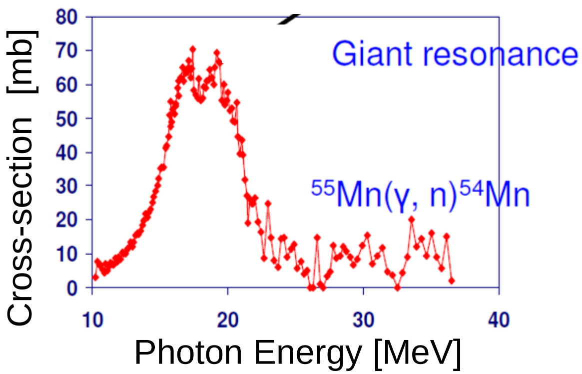
→ fast neutrons emitted

→ neutrons: Long ranges in matter due to lack of ele.-mag. interaction.



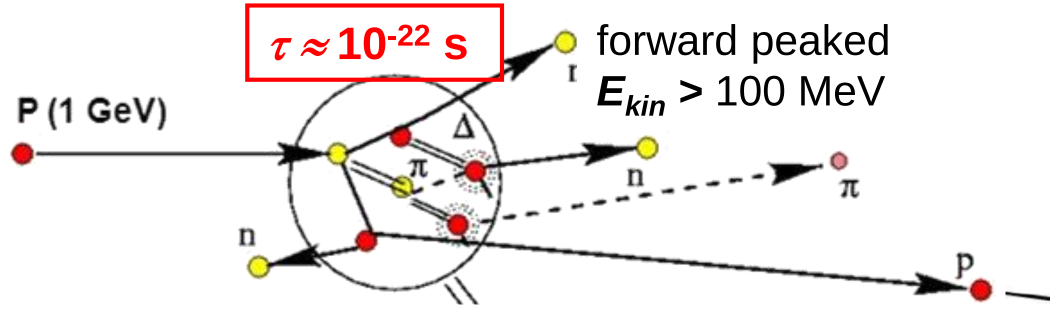






Nuclear reactions via spallation for protons with $E_{kin} \geq 1$ GeV (simplified):

- Pre-equilibrium phases: π-exchange within $\approx 10^{-22}$ s with $E_{kin} > 20$ MeV $\Rightarrow$ hadronic shower
- Inter-nuclear cascade: Evaporation of n, p, d, α within $\approx 10^{-18}$ s with $E_{kin} \approx 1 - 10$ MeV
- Fission for heavy nuclei



General properties:

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

D. Kiselev, CAS 2011

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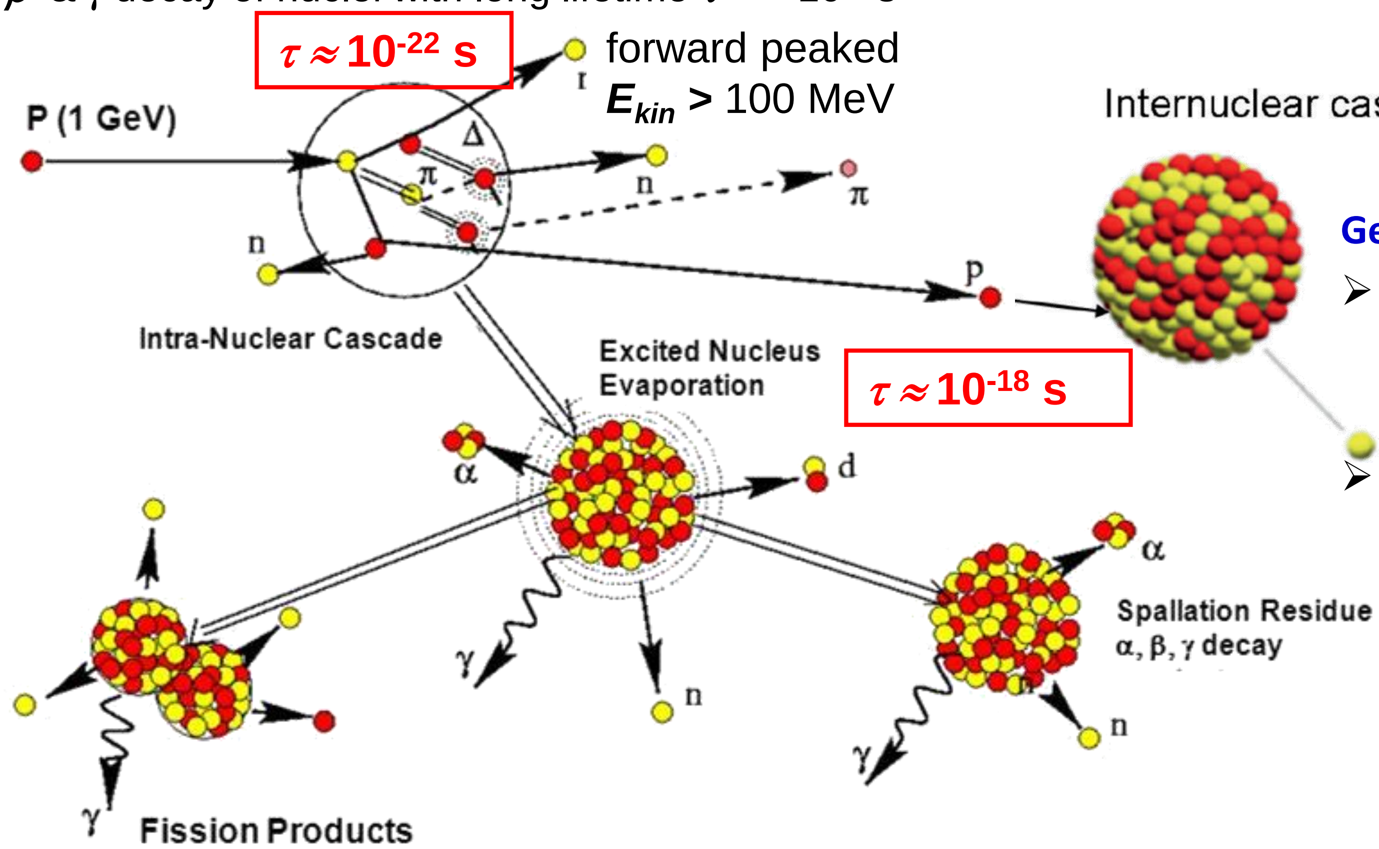
- Fission for heavy nuclei
- β & γ decay of nuclei with long lifetime $\tau >> 10^{-9}$ s



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

D. Kiselev, CAS 2011

Nuclear Physics Processes for Protons

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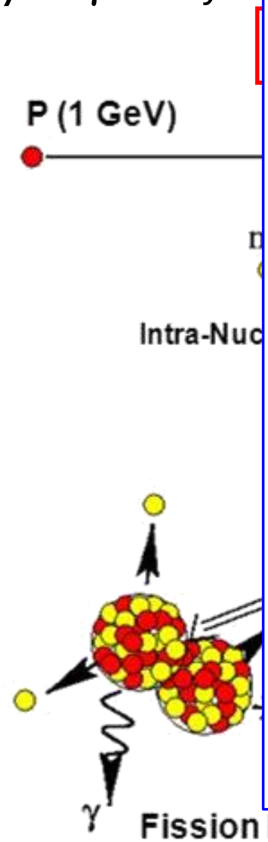
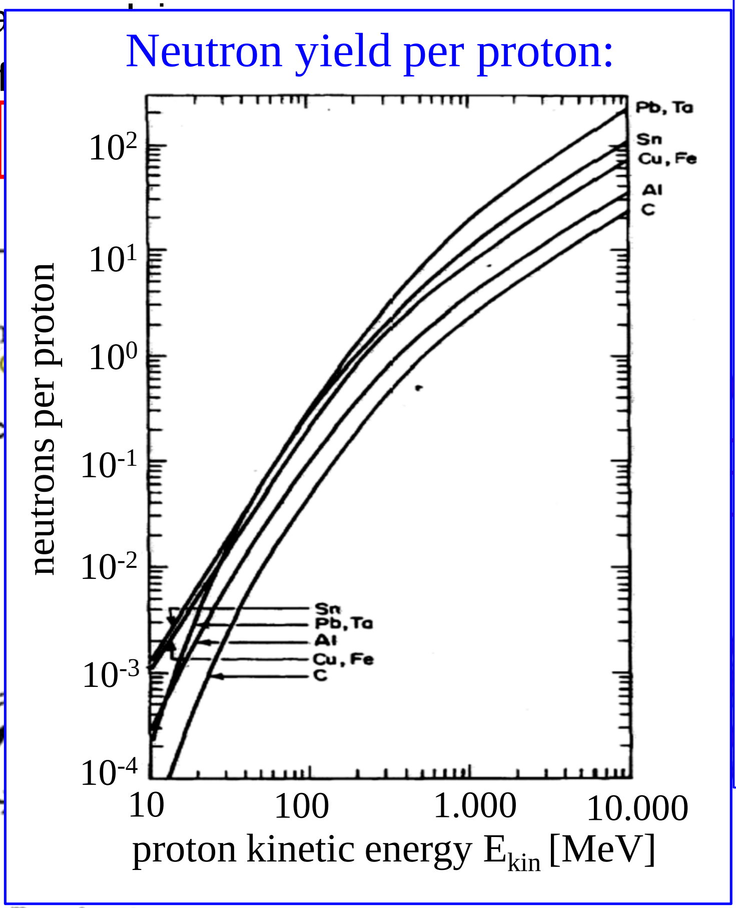
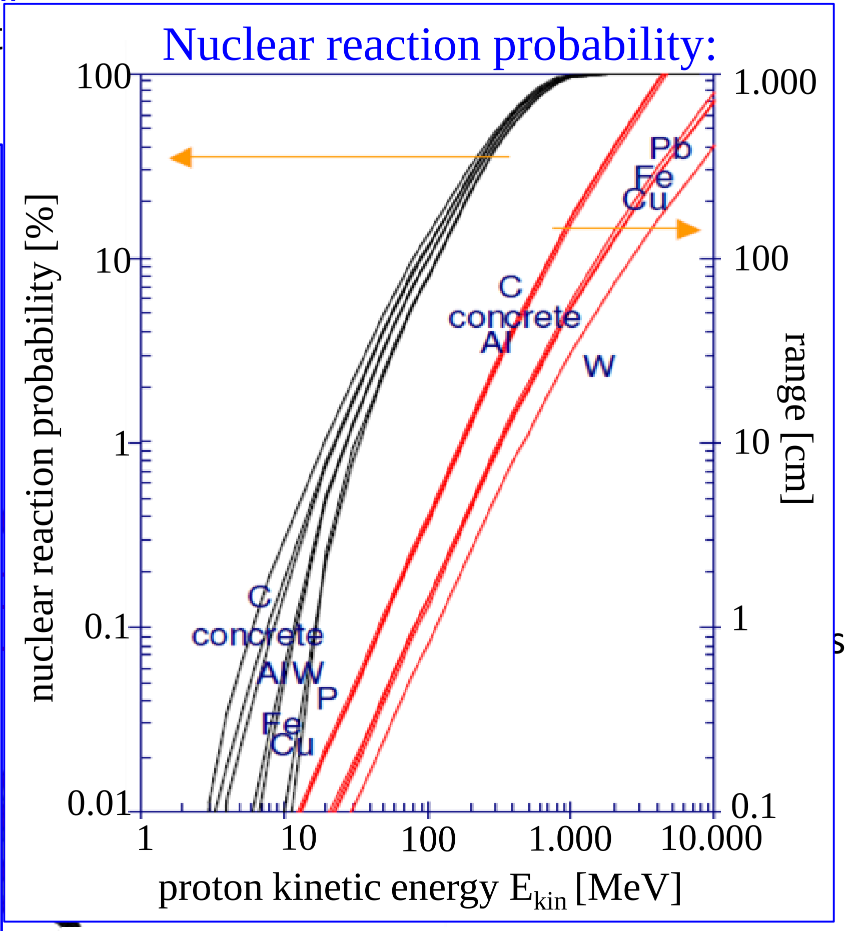






Thick target:

Penetration depth comparable to range

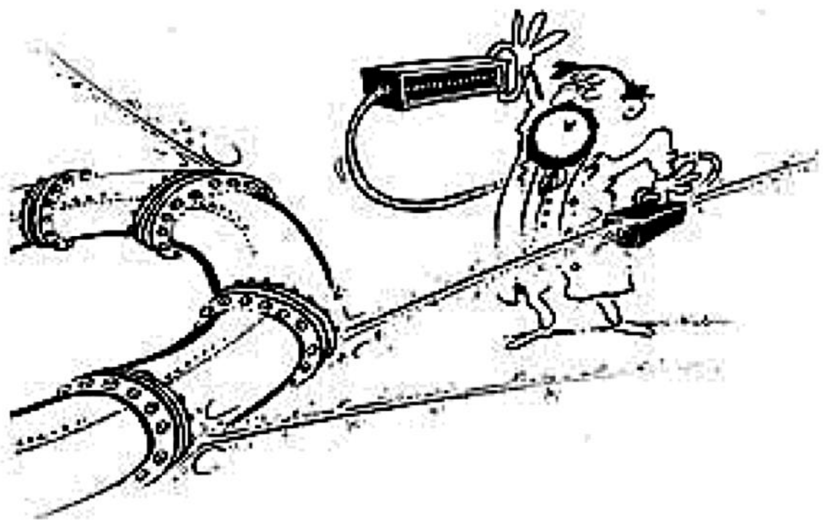
Result on long term ***t*** > 1 ms: Radioactive nuclei = activation

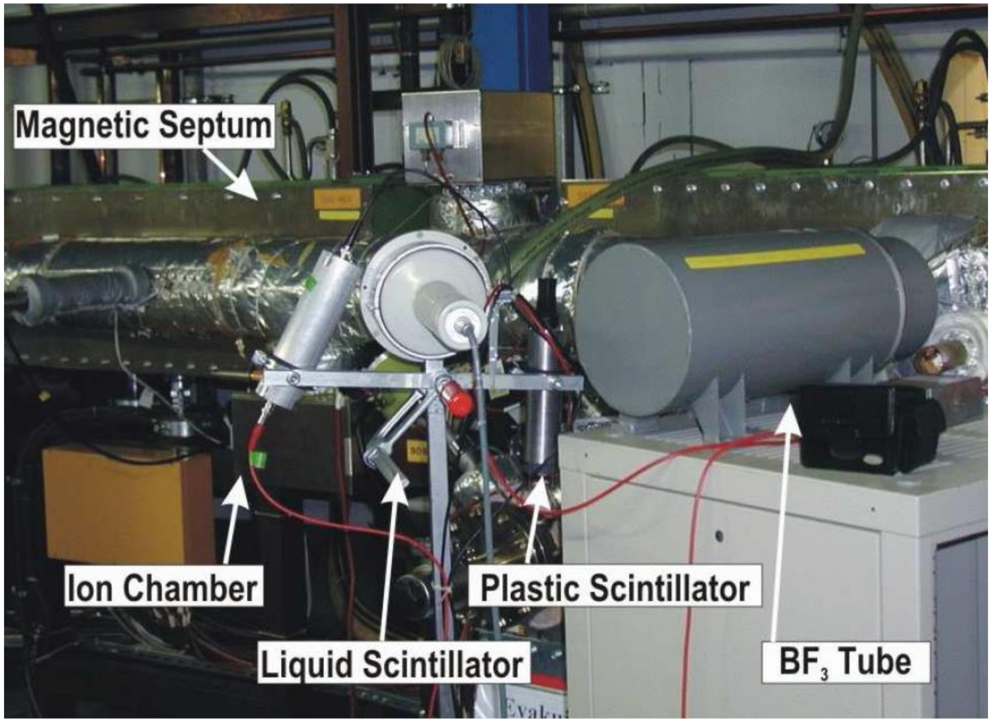
R.H. Thomas, in Handbook on Acc. Phy. & Eng.

Outline:

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

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





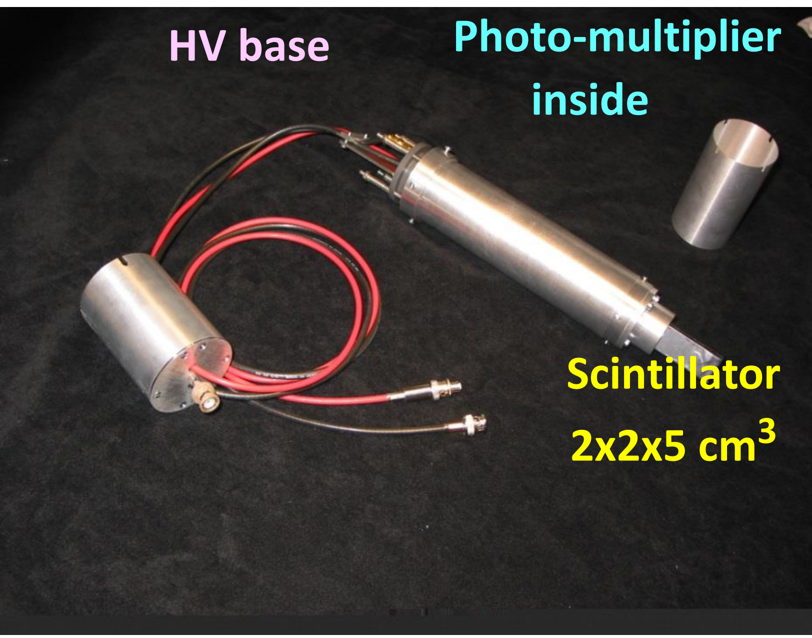
Plastics or liquids are used:

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

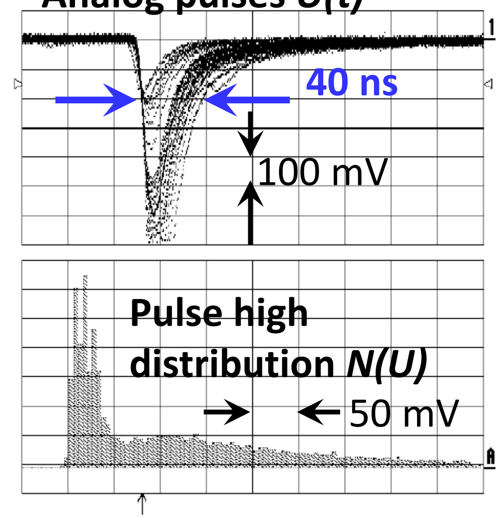
Scintillator + photo-multiplier:

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.



Analog pulses *U(t)*



20 ns/div and 100 mV/div

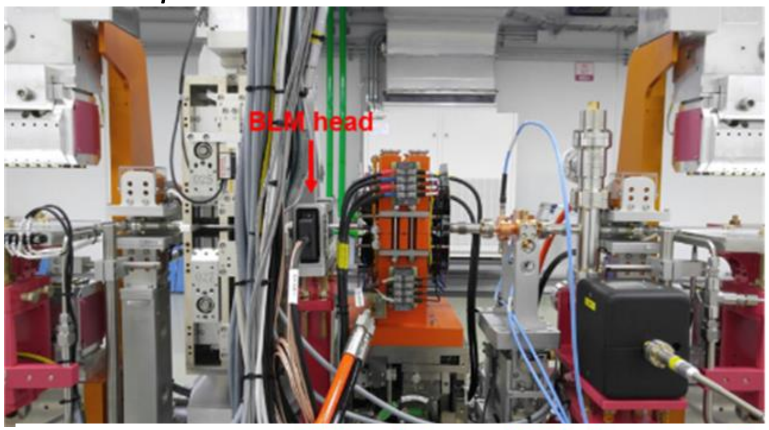
Cherenkov Light Detectors as Beam Loss Monitors

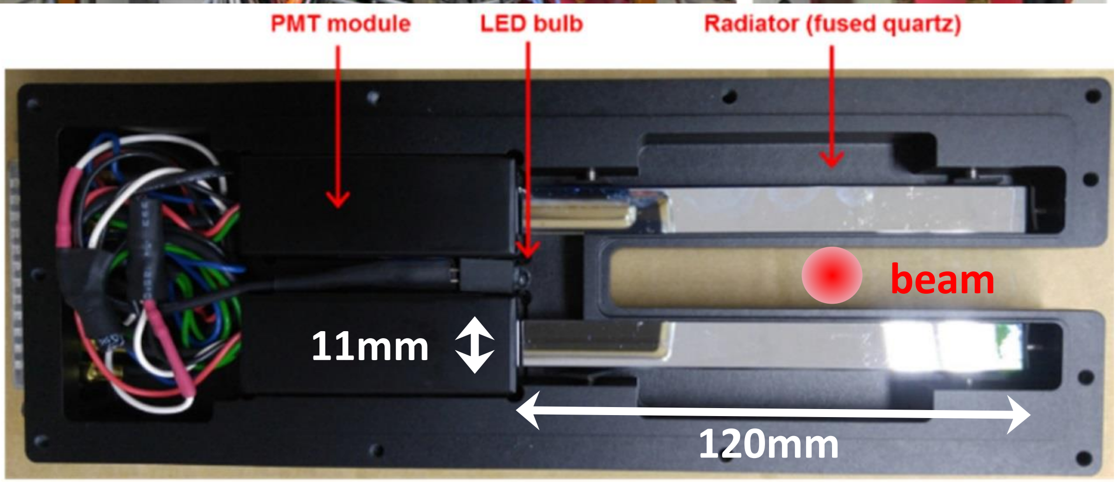
Cherenkov detectors:

Passage of a charged particle $\boldsymbol{v}$ faster than propagation of light $v > c_{medium} = c/n$

Technical: Quartz rod n**=1.5** & photomultiplier

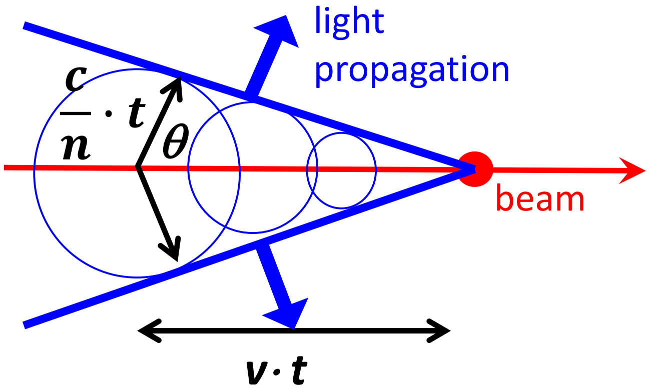
Example: Korean XFEL behind undulator





Cherenkov light emission:

For $v > c_{medium} = c/n$
light wave-front like a wake
broadband light emission



Advantage:

- Detection of fast electrons only
  not 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

PIN-Diode (Solid State Detector) as BLM

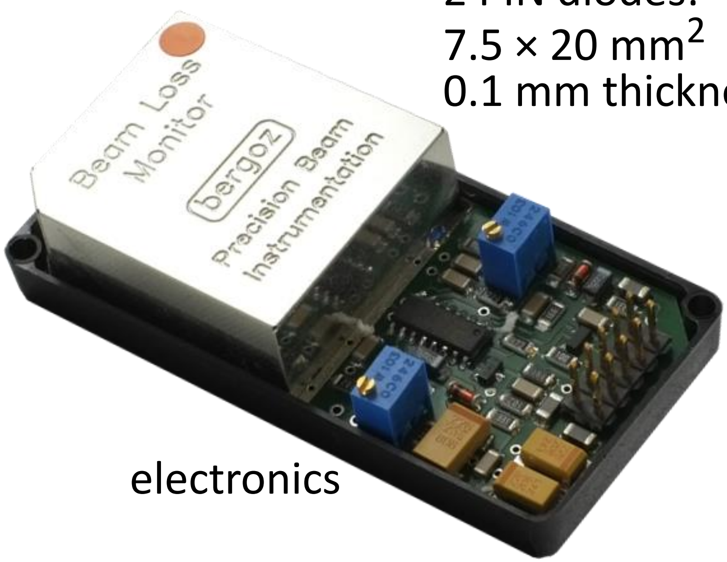
Solid-state detector: Detection of charged particles.

Working principle

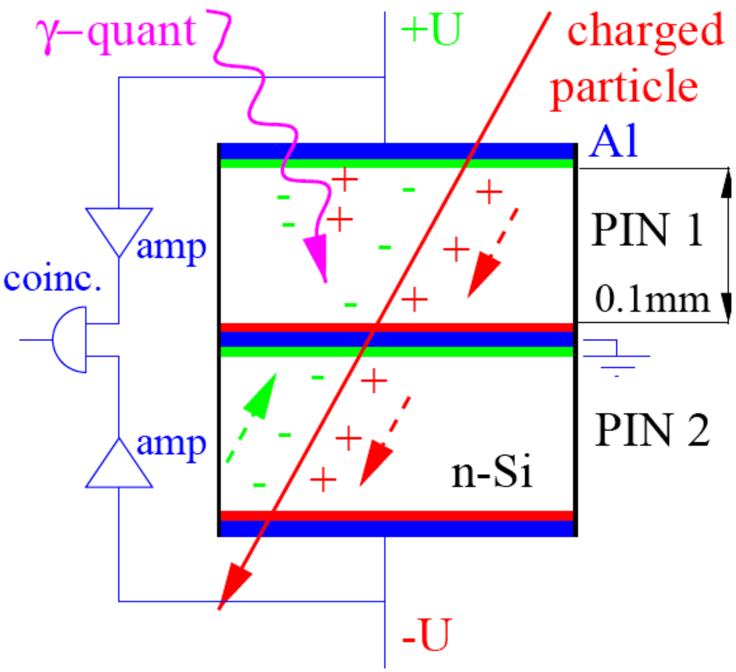
- About 10^4 e^--hole pairs are created by a Minimum Ionizing Particle (MIP).
- A coincidence of the two PIN reduces the background due to low energy photons.
- A counting module is used with threshold value comparator for alarming.

→ small and cheap detector.

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



electronics



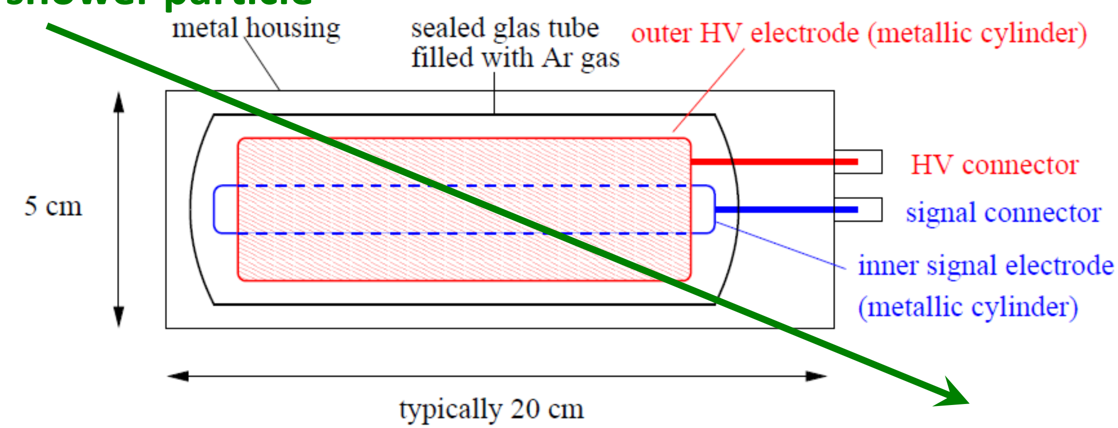
Ionization Chamber as BLM

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

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

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

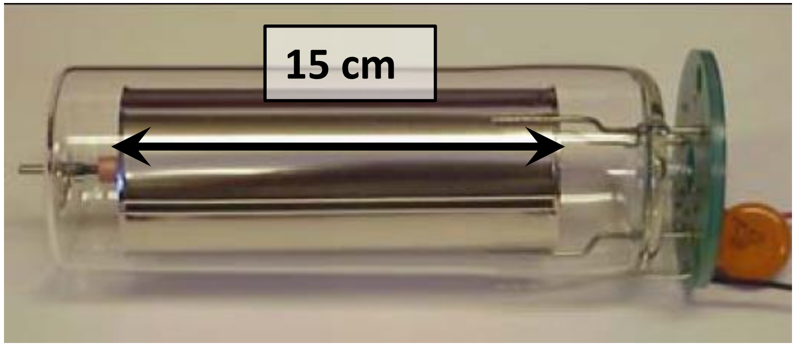
Gas	Ionization Pot. [eV]	W-Value [eV]
Ar	15.7	26.4
N_2	15.5	34.8
O_2	12.5	30.8
Air		33.8



Sealed tube Filled with Ar or N_2 gas:

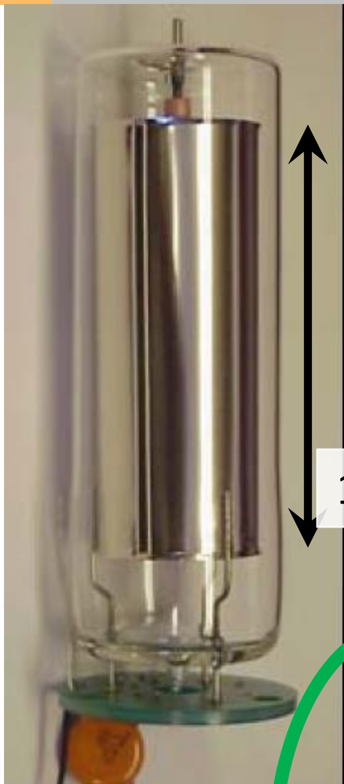
- Creation of Ar^+-e^- pairs,
  average energy ***W***=32 eV/pair
- Measurement of this current
- Slow time response

  due to ≈ 10 μs drift time of Ar^+.

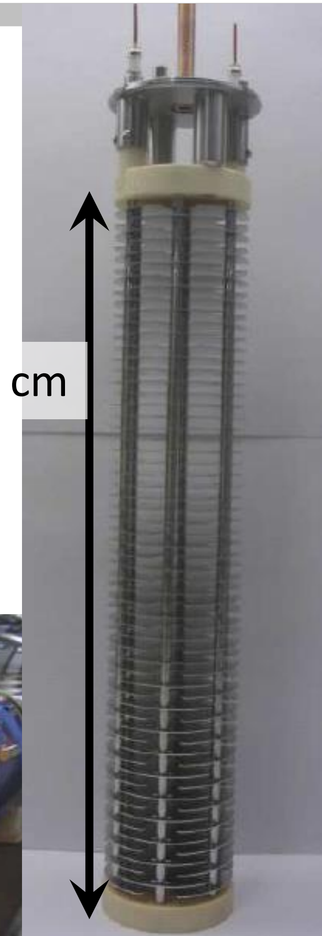


Per definition: Direct measurement of dose !

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



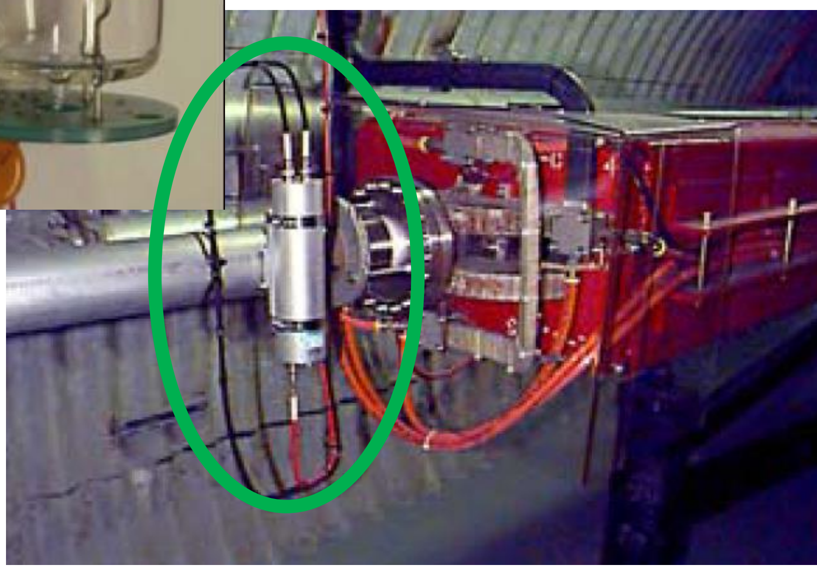
38 cm

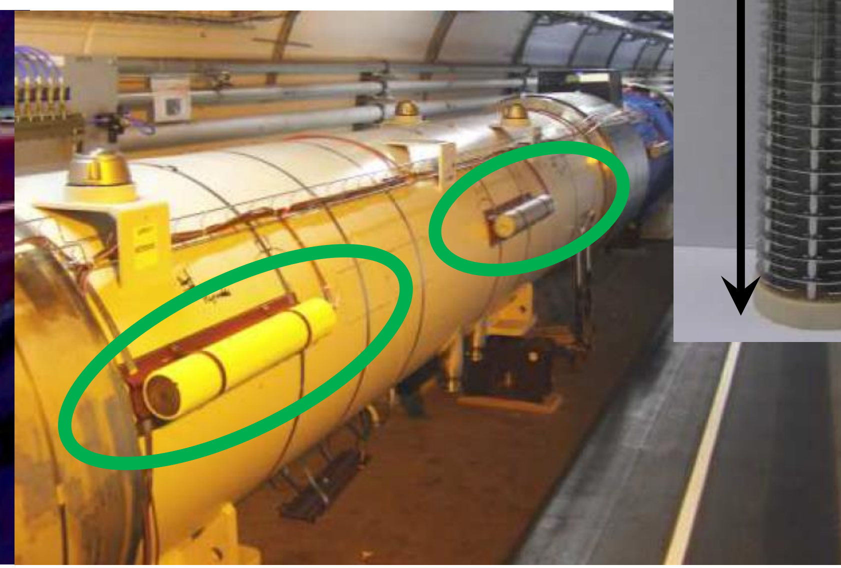
15 cm

4000 BLMs at LHC⇔ each ≈ 6m

TEVATRON, RHIC type

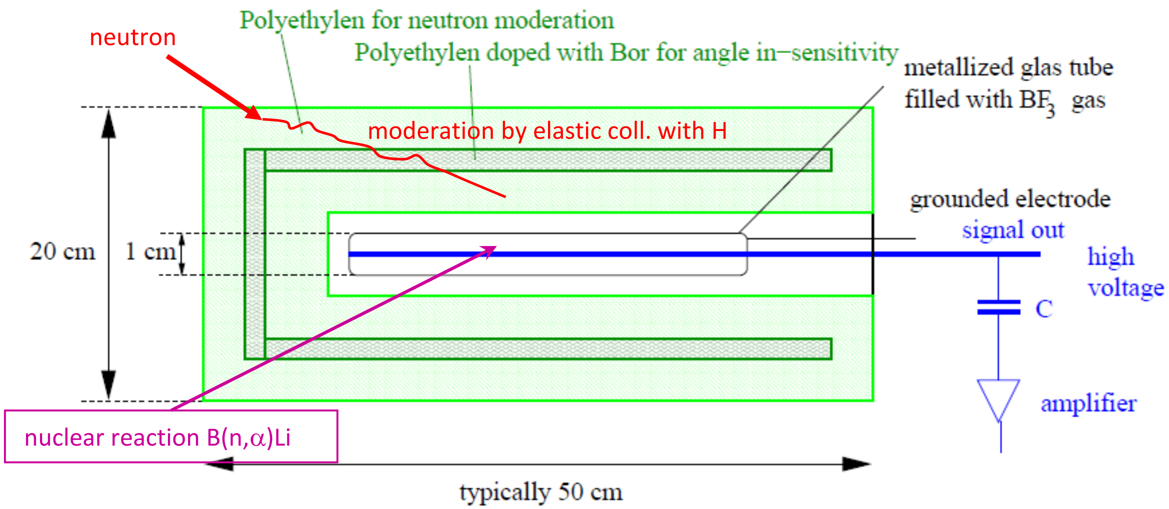
CERN type

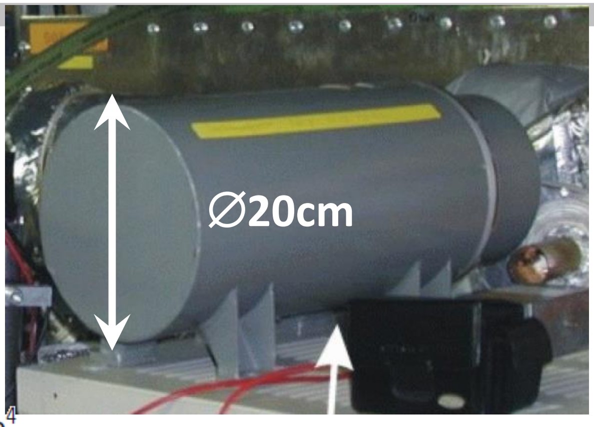


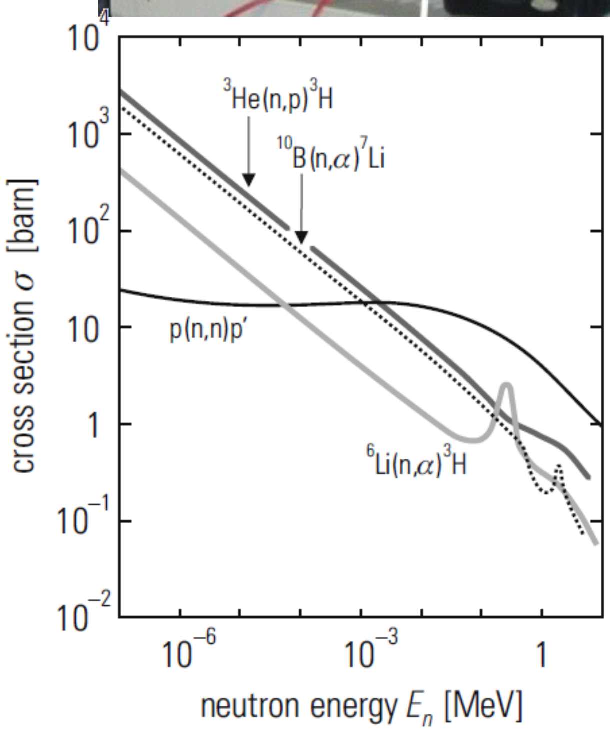


BF_3 Proportional Tubes as BLM

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







C. Grupen, Introduction to Radiation Protection

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:

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

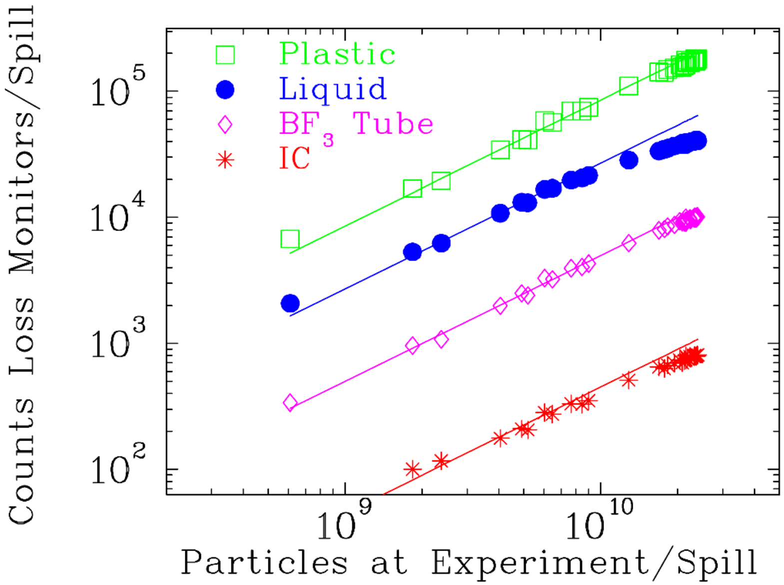
3. Electronic stopping of ^{7}Li and α leads to signal.

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:**

A

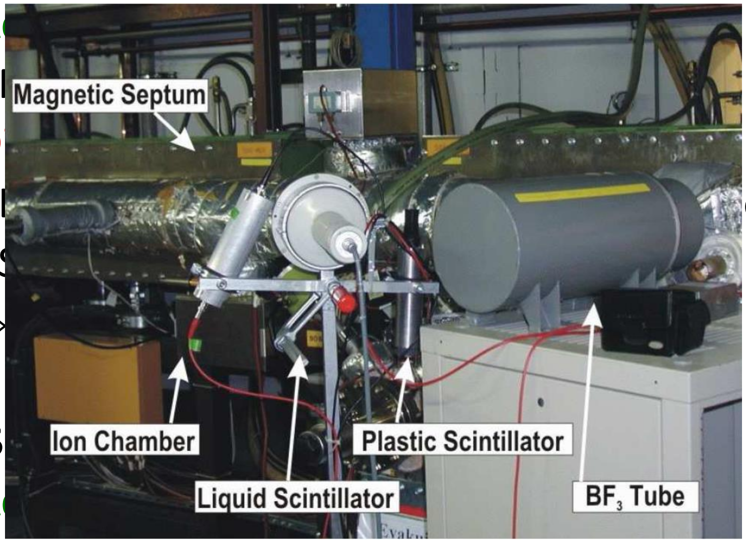
- I

D

- I on),

- S µs

⇒



➢ **S**

A

- 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

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.

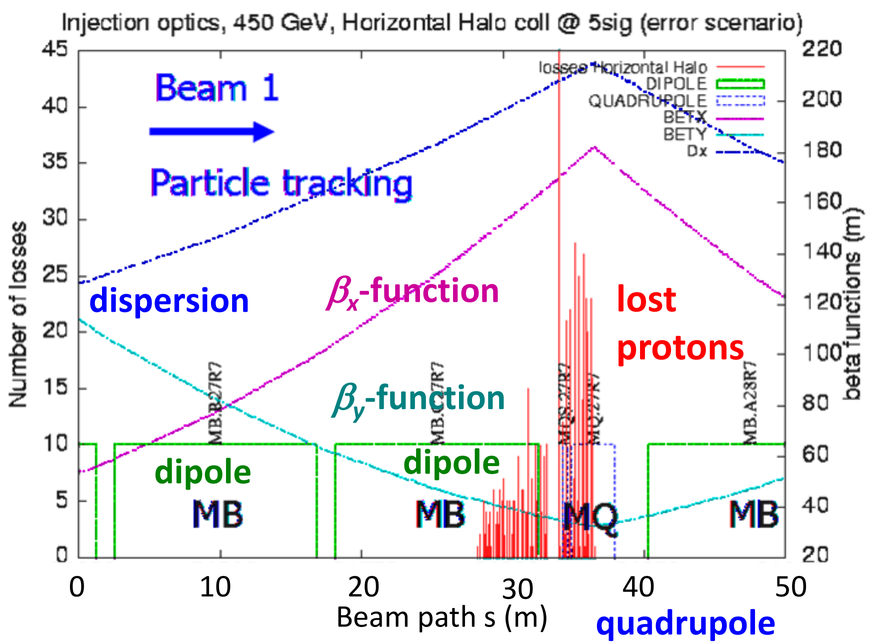
Monitoring of loss rate in control room ***and*** as interlock signal for beam abortion.

Application: BLMs for Quench-Protection

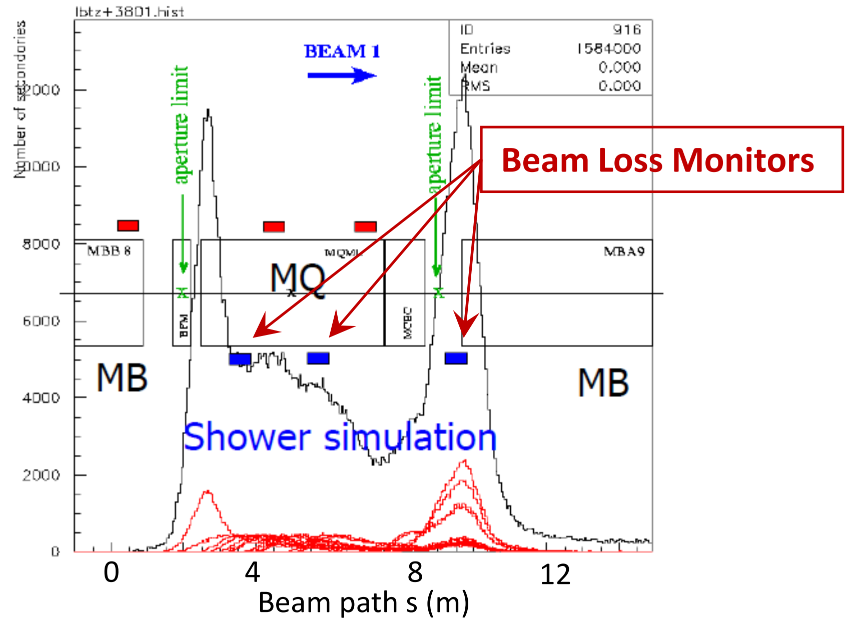
Super-conducting magnets can be heated above critical temperature T_c by the lost beam
⇒ breakdown of super-conductivity = ’quenching’.
⇒ Interlock within 1 ms for beam abortion generated by BLM.

Position of detector at quadruples due to maximal beam size.
High energy particles leads to a shower in forward direction → Monte-Carlo simulation.

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



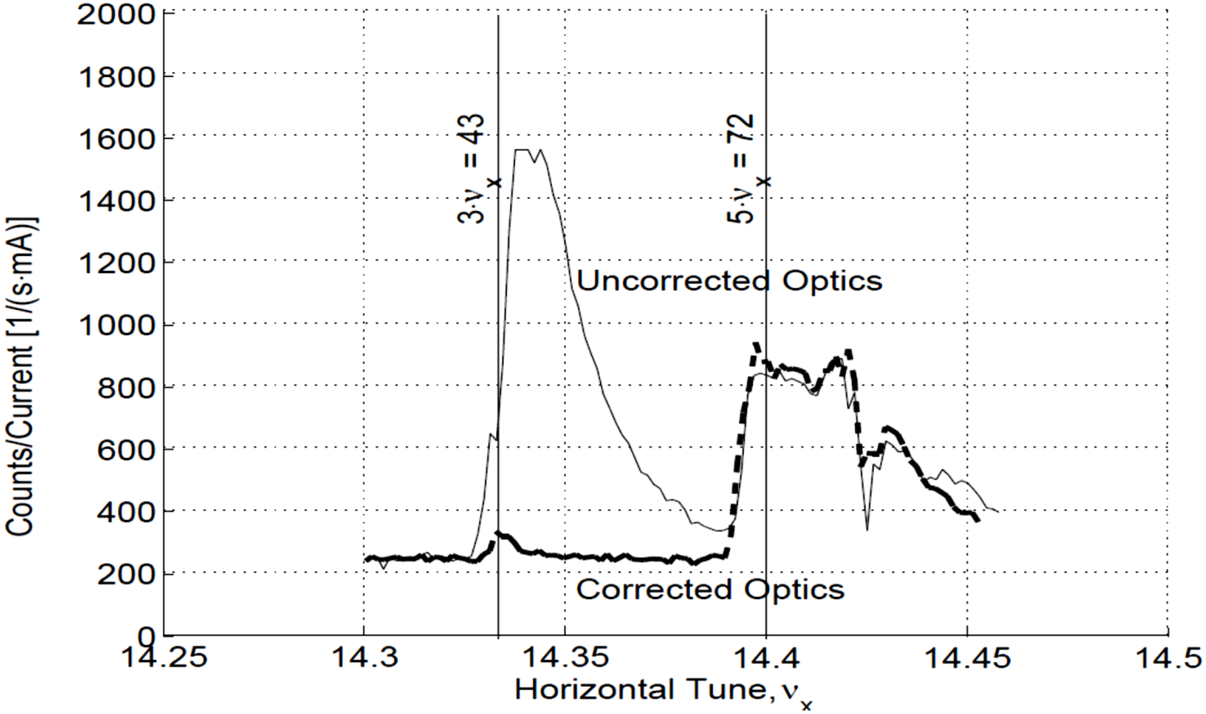
Example: Simulation of shower particles



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):

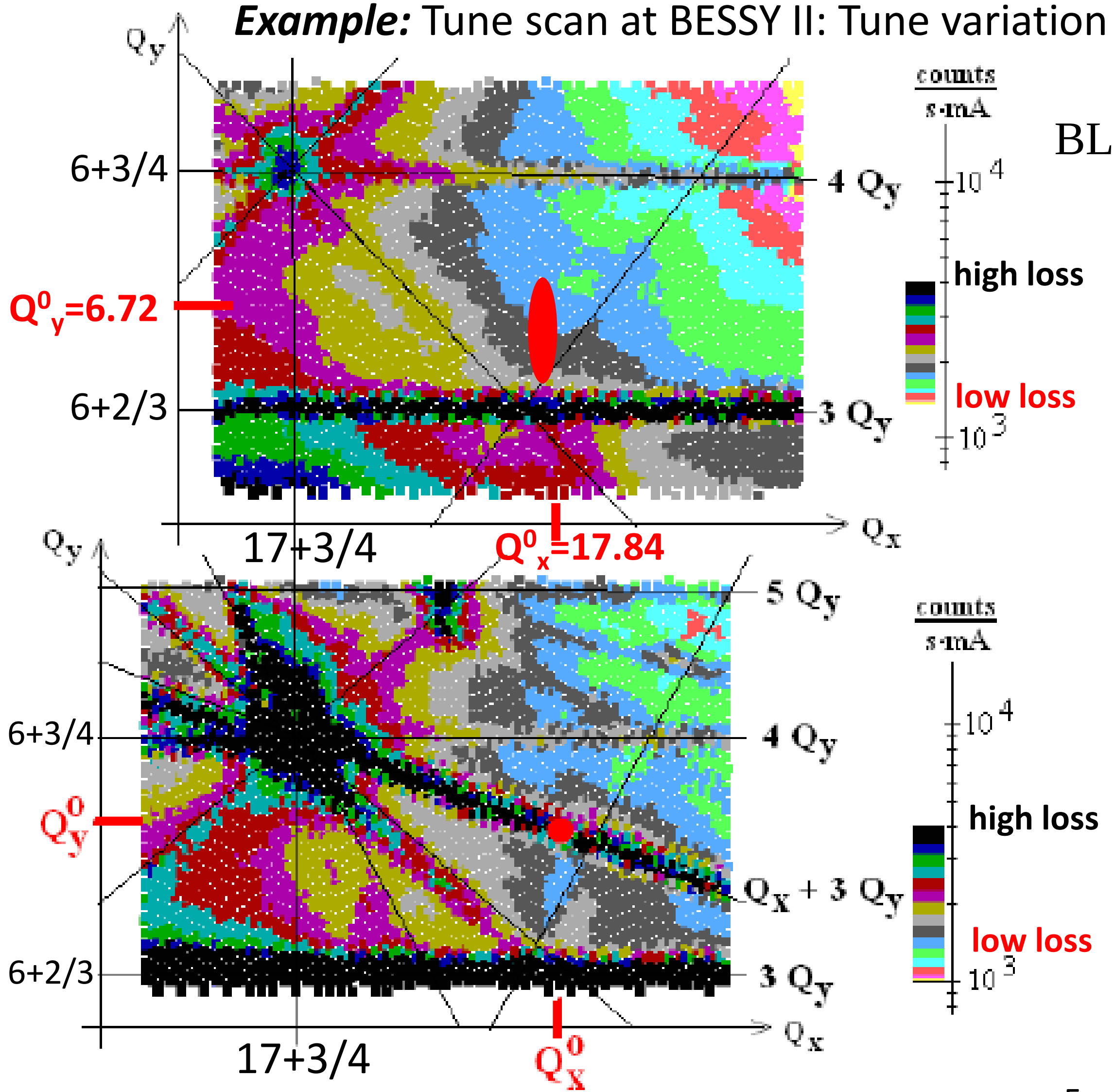


Beam blow-up by weak resonances can be avoided by proper tune value

$\rightarrow$ very sensitive device for optimization.

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

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:

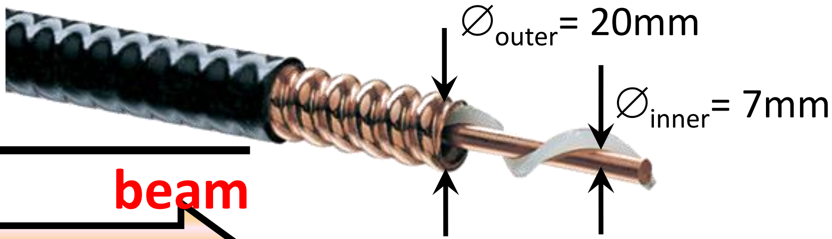
- **(Electron Multiplier**: medium sensitive, fast response, radiation hard)
- **BF_3 tube**: only neutrons, slow response, radiation hard, expensive
- **Optical fibers**: insensitive, very slow, radiation hard, very high spatial resolution.

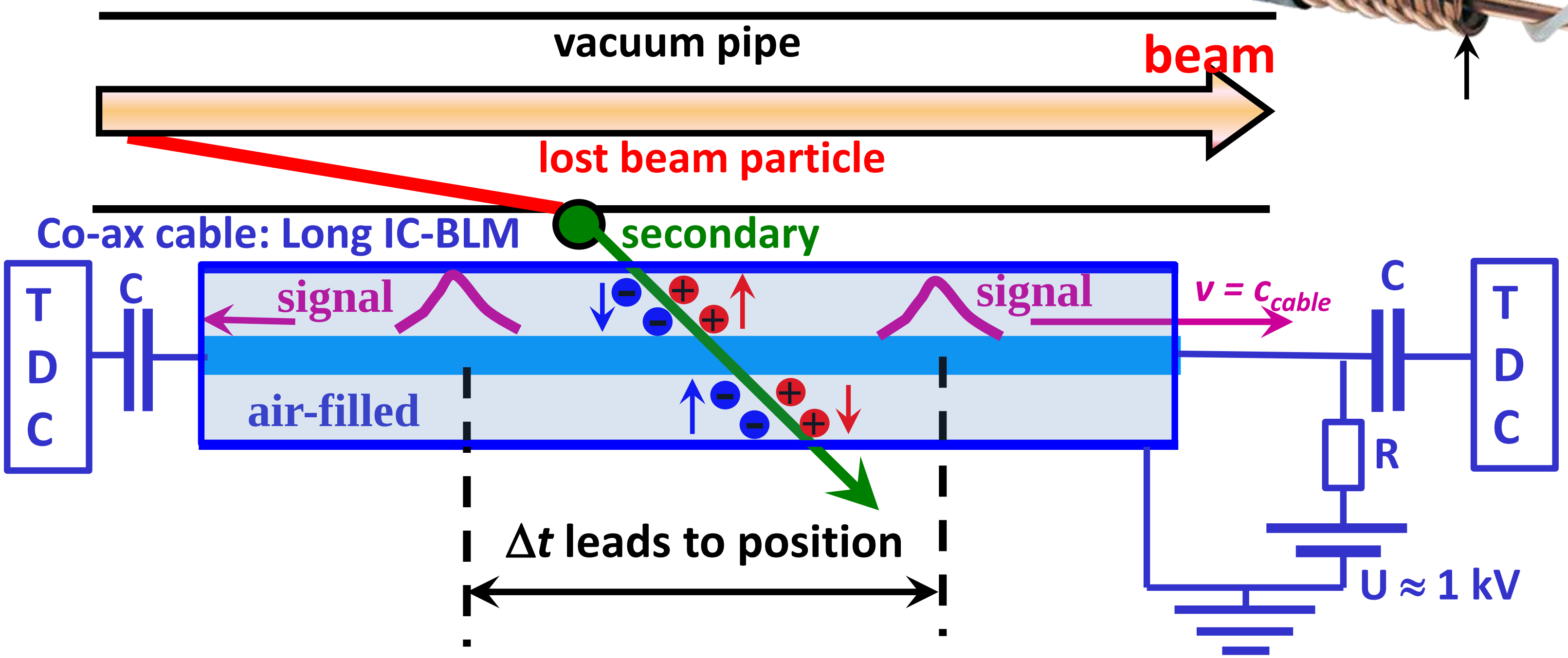
Backup slides

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

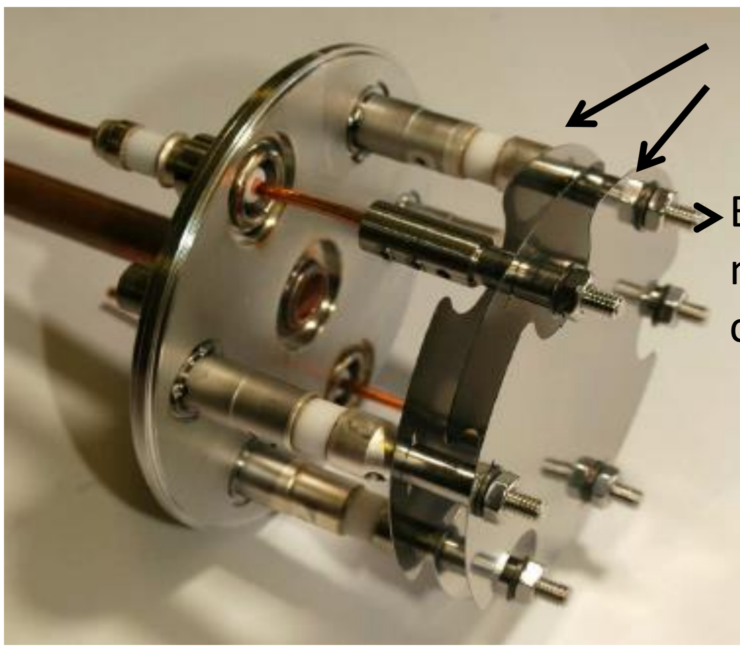
Secondary Electron Monitor as BLM

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)

$\rightarrow$ **small and cheap detector, very insensitive.**



HV electrodes

Electrode for measured current

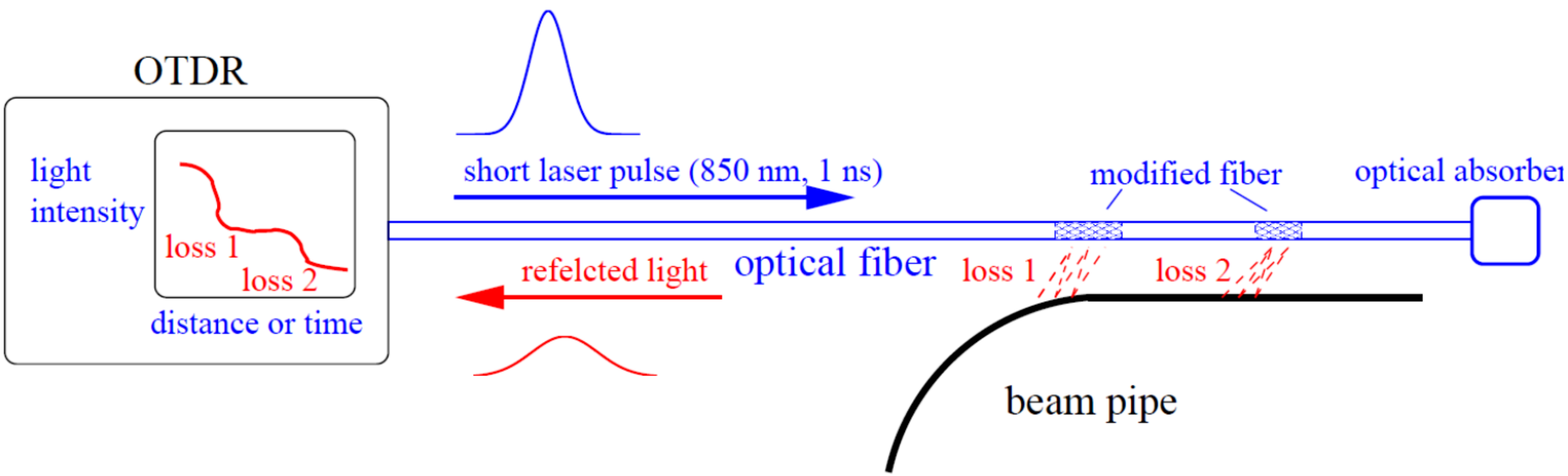
Detector with intrinsic amplification:

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

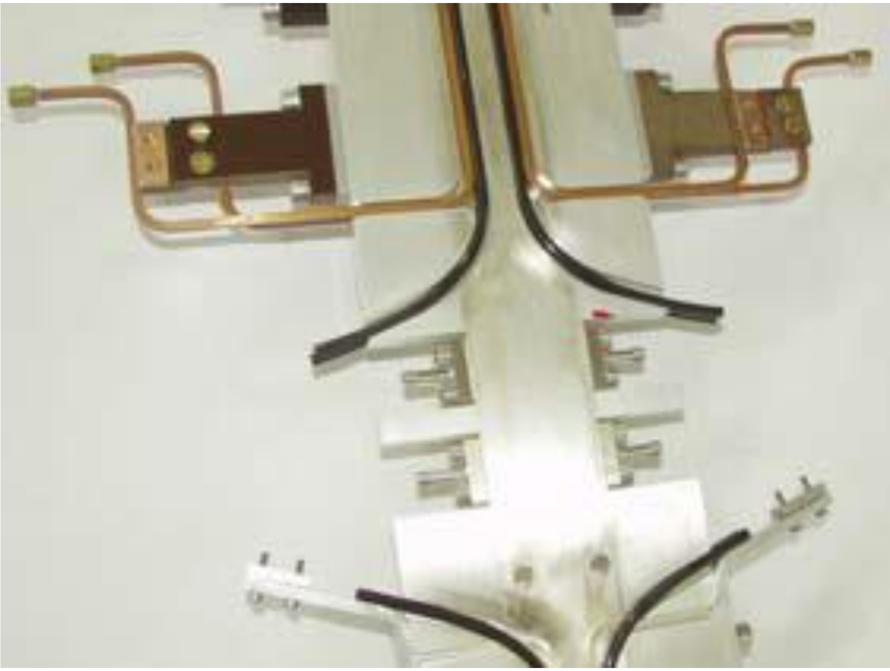
Advantage of optical fibers: Good spatial resolution with ***one*** detector

→ 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