Beam Loss Technology

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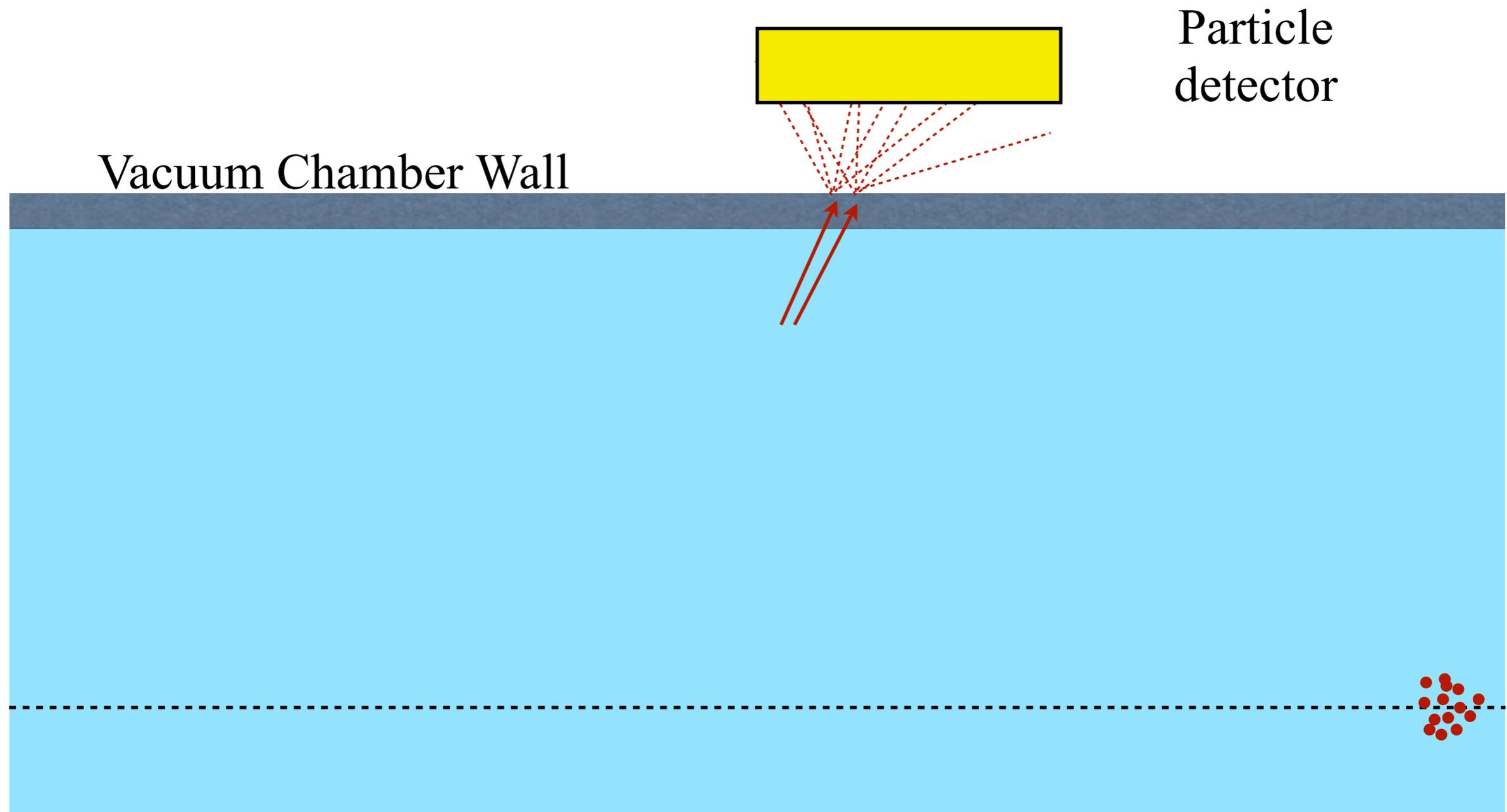**ACAS School for Accelerator Physics**

Outlook

- **Introduction**

- **Detector technologies**

- **Detector location**

- **Machine protection implementation**

- **State of the art**

- **Challenging environments**

A graphical introduction

Introduction

What are Beam Loss Monitors?

Particle detector

Vacuum Chamber Wall

Detector technologies

Sources of BLM signal

Ionization

- Energy loss described by Bethe-Bloch
- Concept of MIP

$$dE/dx_{MIP} = (1\text{-}5) \text{ MeV cm}^2 \text{ g}^{-1}$$

Scintillation

- Ionizing radiation detectors located around an accelerator
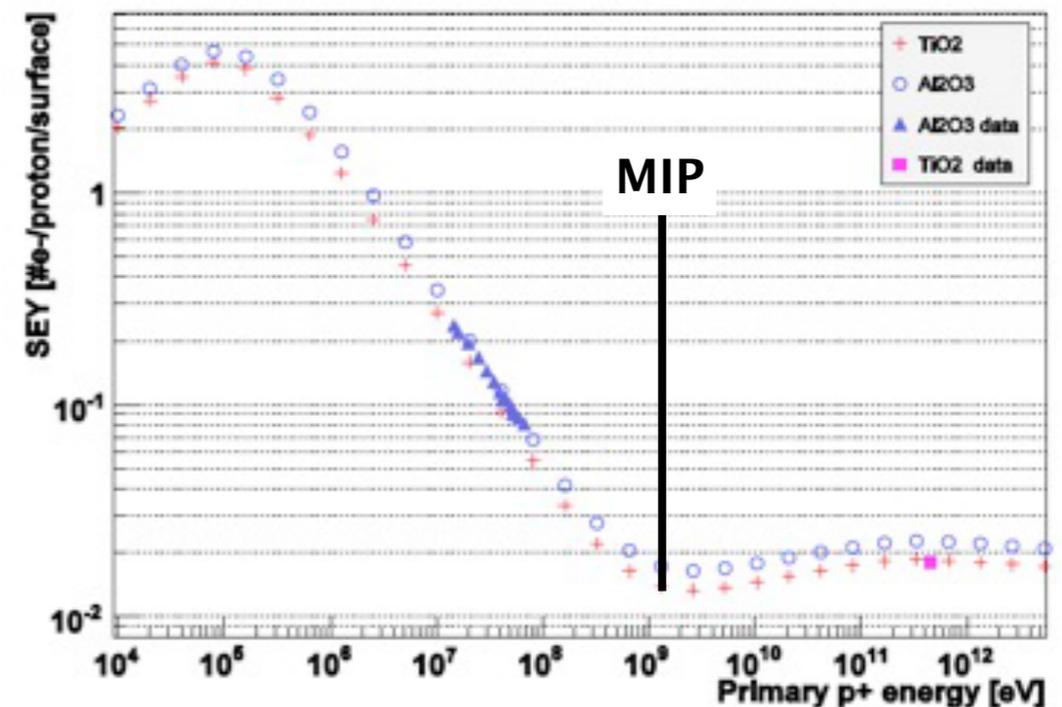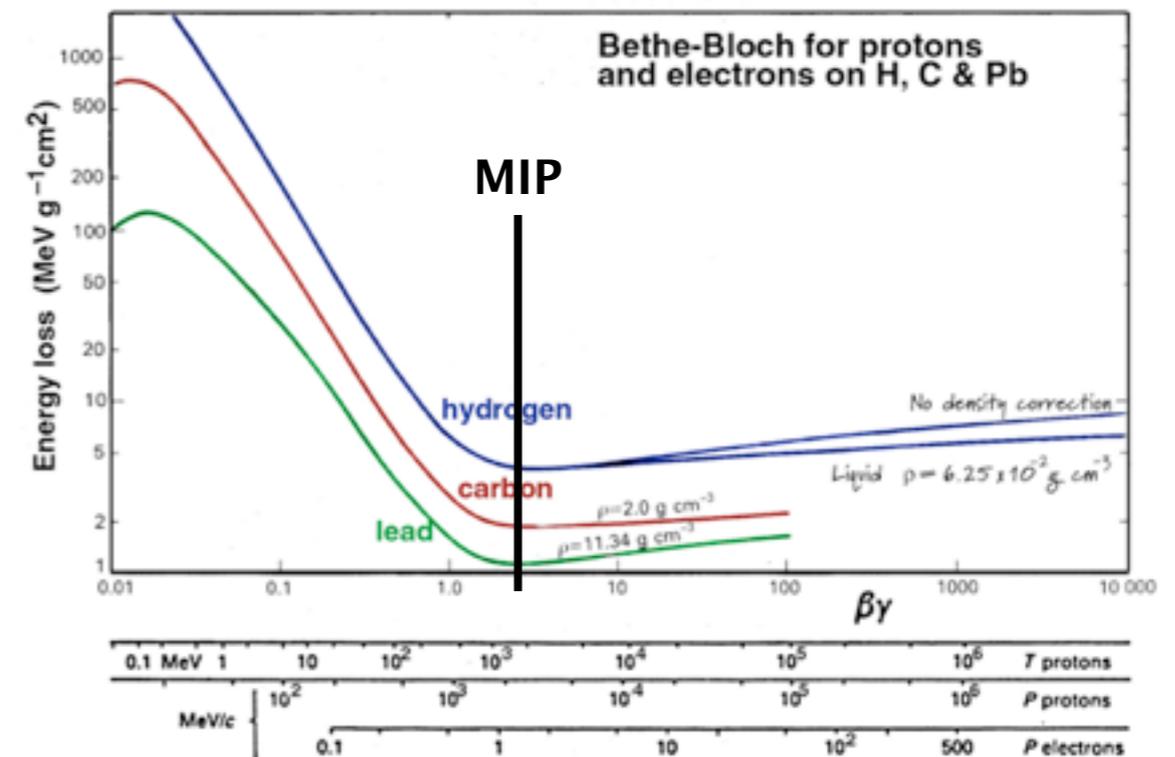
$$Y = dL/dx = R \, dE/dx$$

Secondary Emission

$$Y_{MIP} = (0.01\text{-}0.05) \text{ e/primary}$$

Cherenkov Effect

$$photon \; yield: \frac{dN}{dx} = 2 \cdot \pi \cdot \alpha \cdot \sin^2 \Theta \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$
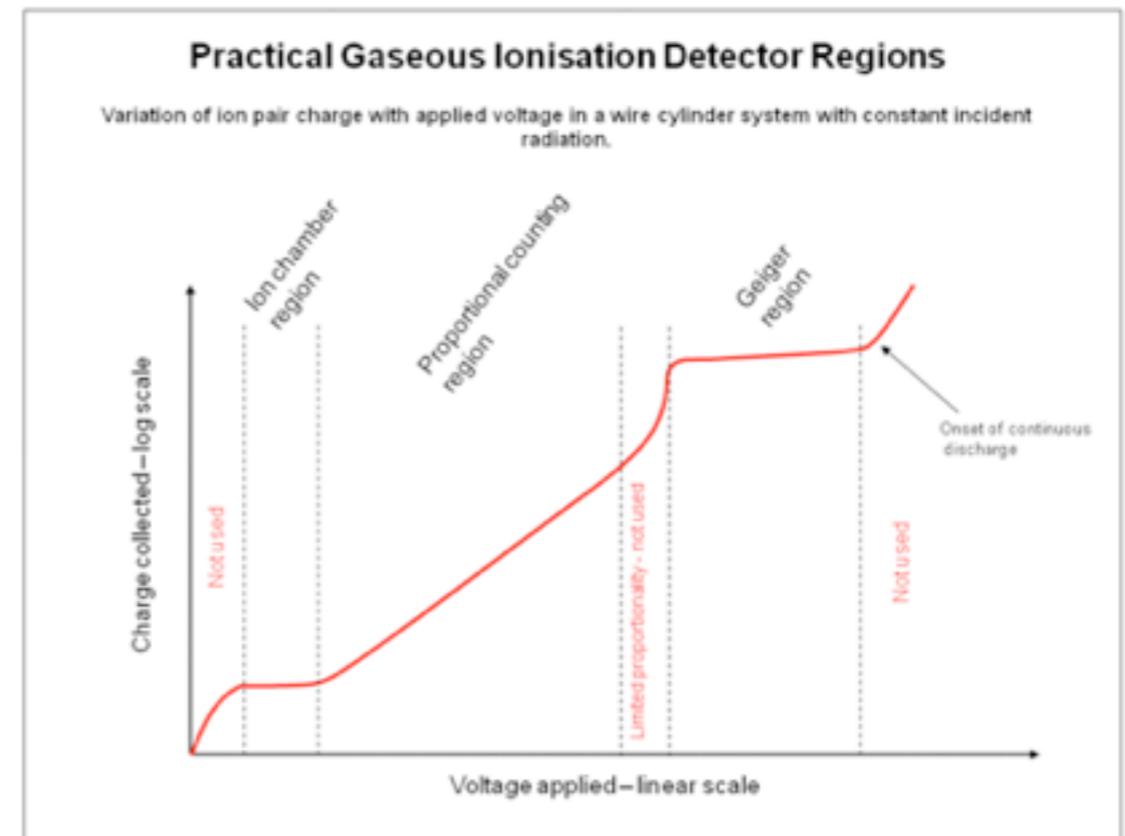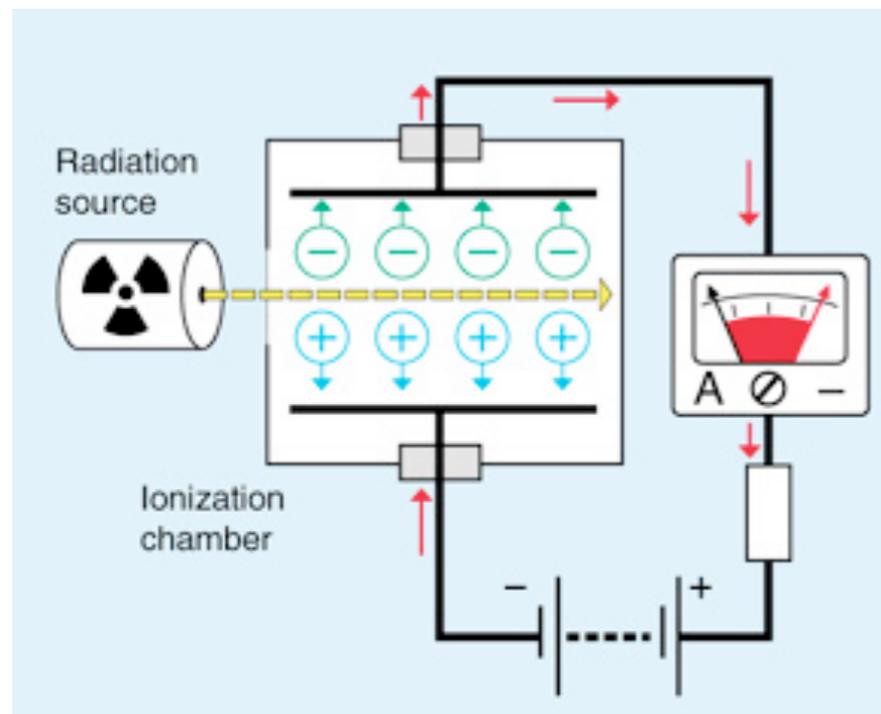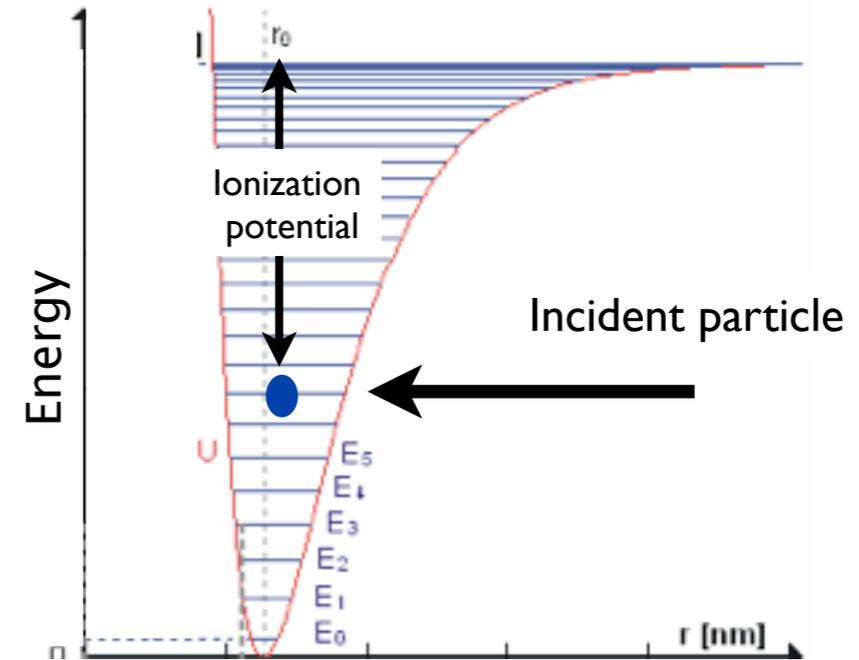
$$\cos \Theta = \frac{1}{\beta \cdot n} \; with \; \beta > 1/n \, ; \; \alpha = 1/137.036 \; and \; \lambda_{1,2} = \; \text{wavelength interval}$$
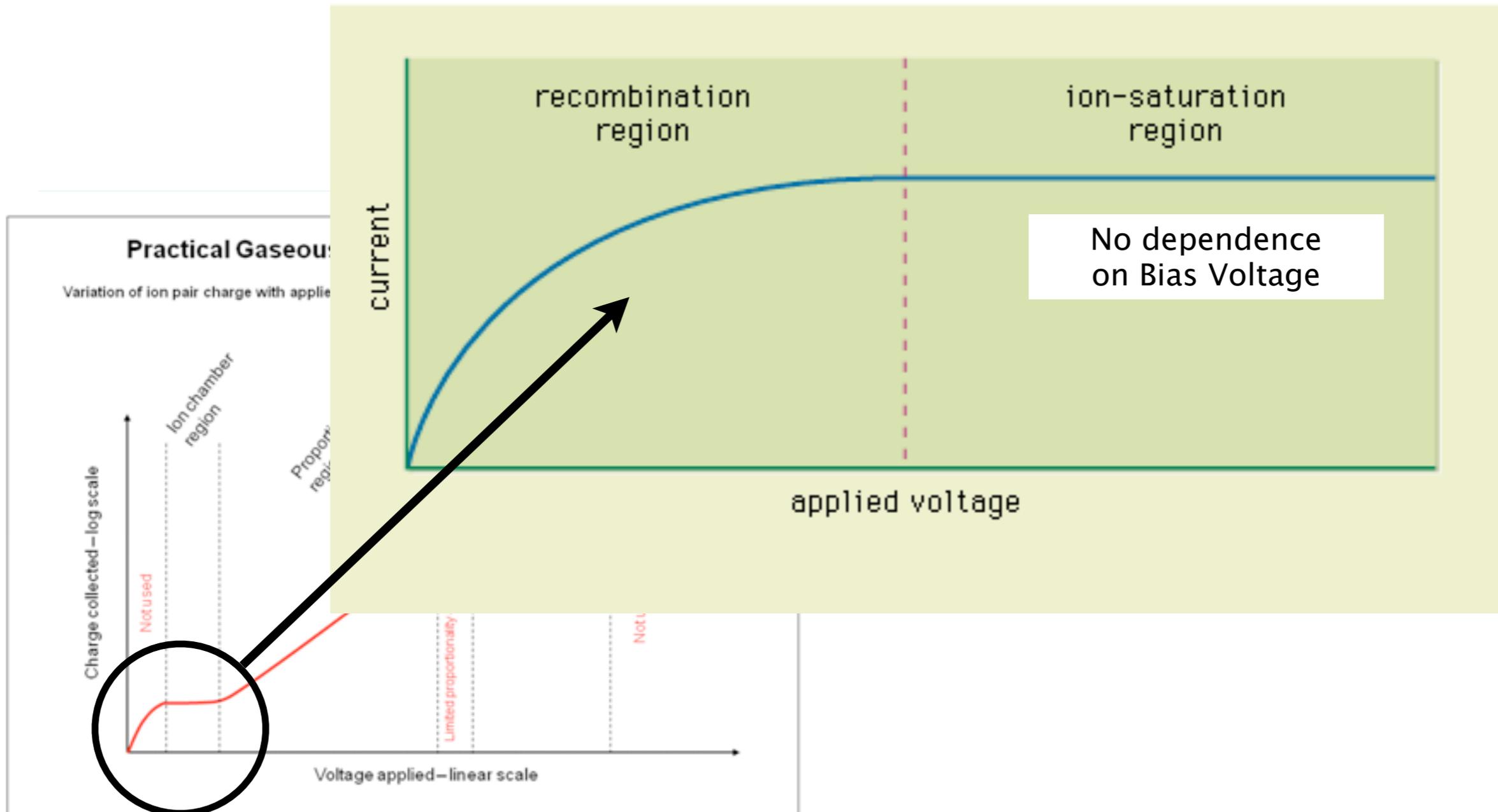
Ionization - Gas detectors

Incident particle produces e-/ion:

- Fast electrons and slow ions collected via Bias voltage to produce a measurable current
- Typical ionization potentials (25-100) eV/pair

Practical Gaseous Ionisation Detector Regions

Variation of ion pair charge with applied voltage in a wire cylinder system with constant incident radiation.

Ionization - Gas detectors

Ionization Chambers

recombination region | ion-saturation region

current

No dependence on Bias Voltage

applied voltage

Practical Gaseous

Variation of ion pair charge with applied

Ion chamber region

Proportional region

Charge collected – log scale

Not used

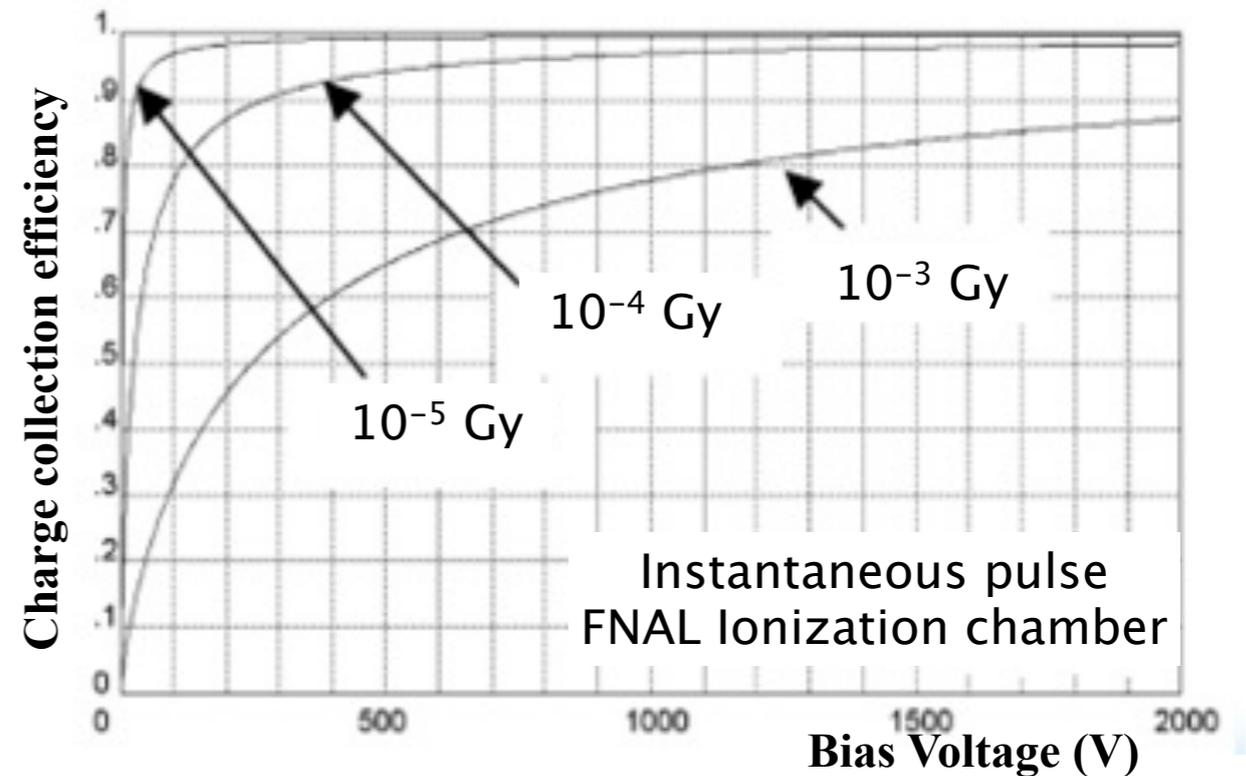Limited proportionality

Not used

Voltage applied – linear scale

Ionization - Gas detectors

Saturation effects:
- Large number of e/ion pairs generated
- Field generated by ions shields bias field
- Charge recombination

Plot: Charge collection efficiency vs Bias Voltage (V), with curves labeled 10^{-5} Gy, 10^{-4} Gy, 10^{-3} Gy. Instantaneous pulse FNAL Ionization chamber.

Ionization Chambers: PROs/CONs
- Very robust, radiation hard, require low mantainance
- No dependence on Bias Voltage
- Large Dynamic range
- Slow time response (~0.1 - 1 ms)

Ionization - Solid state detectors

- **Semiconductor based detectors (Si, Diamond, ...)**
  - Incident particles produce electron/holes as charge carriers (3-10eV/pair)
  - $t_{hole} \gtrsim t_{electron} \sim$ 1-10 ns
  - smaller size
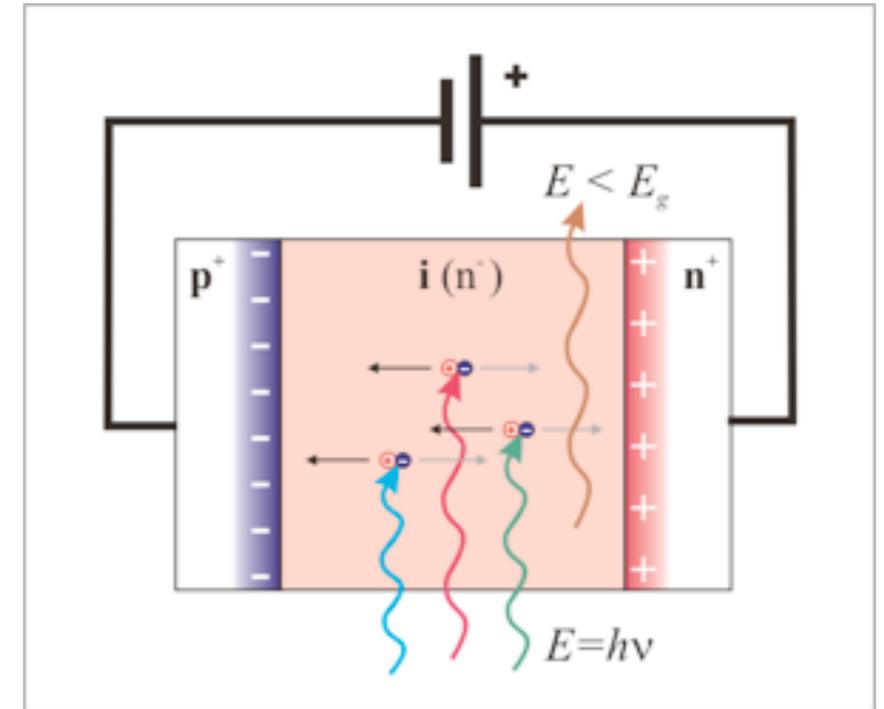
- **Solid state Ionization Chambers:** PROs/CONs
  - No dependence on Bias Voltage
  - Fast response (1-10 ns)
  - Radiation hardness (1 MGy)

Scintillators
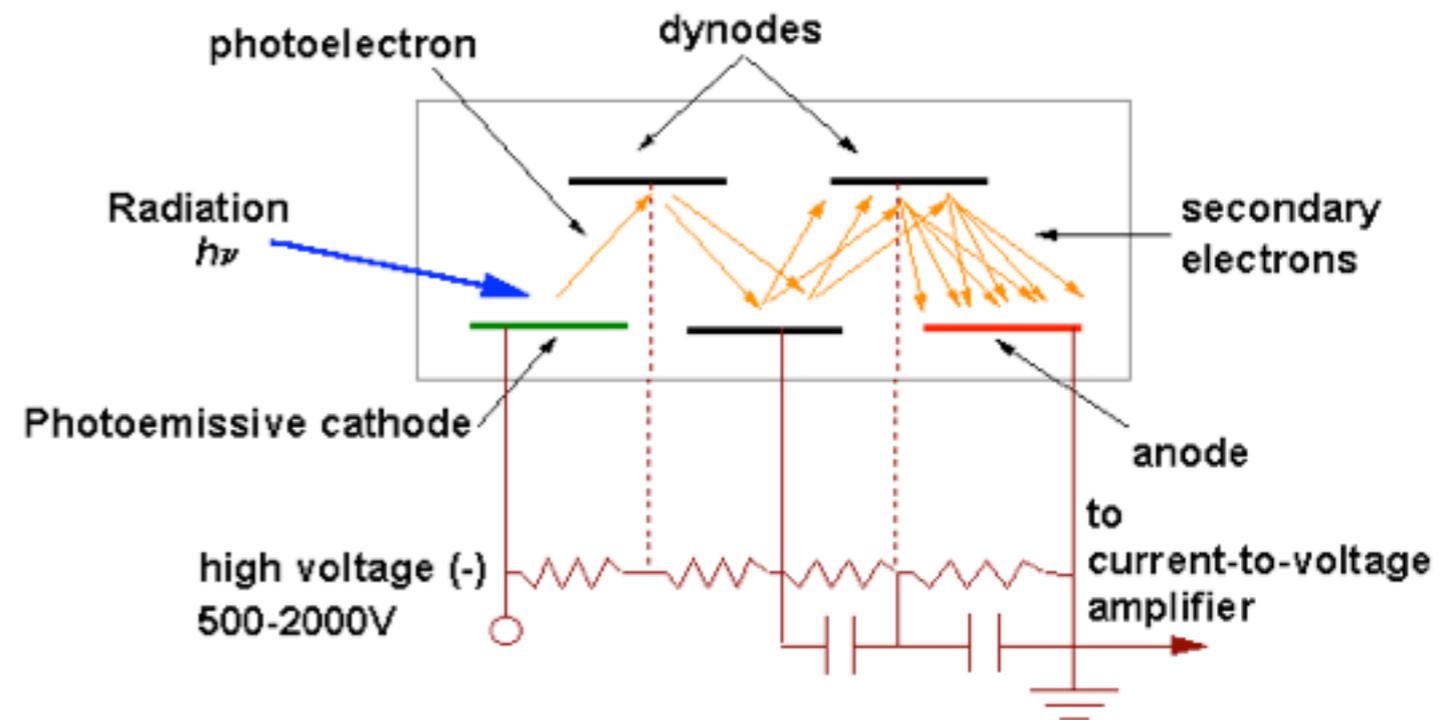
Light produced by de-excitation of atomic/molecular levels

Multiple types

- Inorganic crystals: NaI, CsI ...
- Organic (plastic): NE103, Antracene
- Liquid

Photo Multiplier Tube: active photon sensor

- Light from scintillator to PMT via waveguides

Scintillators

Considerations

- Photon Yield
- Collection efficiency
- Photocathode quantum efficiency
- PMT gain $G_{PMT} = \delta^n = (10^{+5} - 10^{+8})$
  - $\delta = (2\text{-}10)$ number of secondary electrons
  - $n = (8\text{-}15)$ number of dynodes

Material	R_s (γ/MeV)	ρ (g/cm³)
NaI	$8\ 10^{+4}$	3.7
PbWO$_4$	$2\ 10^{+2}$	8.3
NE102	$2.5\ 10^{+4}$	1.03
Antracene	$4\ 10^{+4}$	1.025

Scintillators: PROs/CONs

- High sensitivity
- Fast response: ~ (1-10) ns for plastic/liquid
- Slow response: ~ (0.1 - 1)µs for inorganic
- Limited radiation hardness (1-10 MGy)
- PMT gain control

Secondary Emission Monitors

- **Sensitivity defined by SEM Yield**
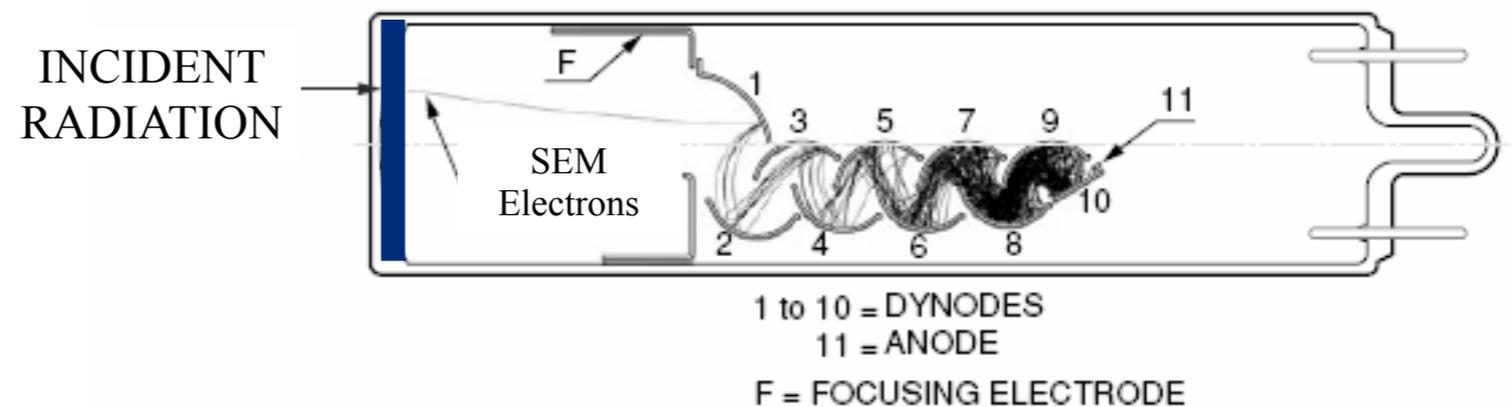 - 0.01- 0.05 e^-/primary

- **Two possible uses**
  - No amplification (needs current integration)
  - Amplification
    - broadband current amplifiers
    - PMT
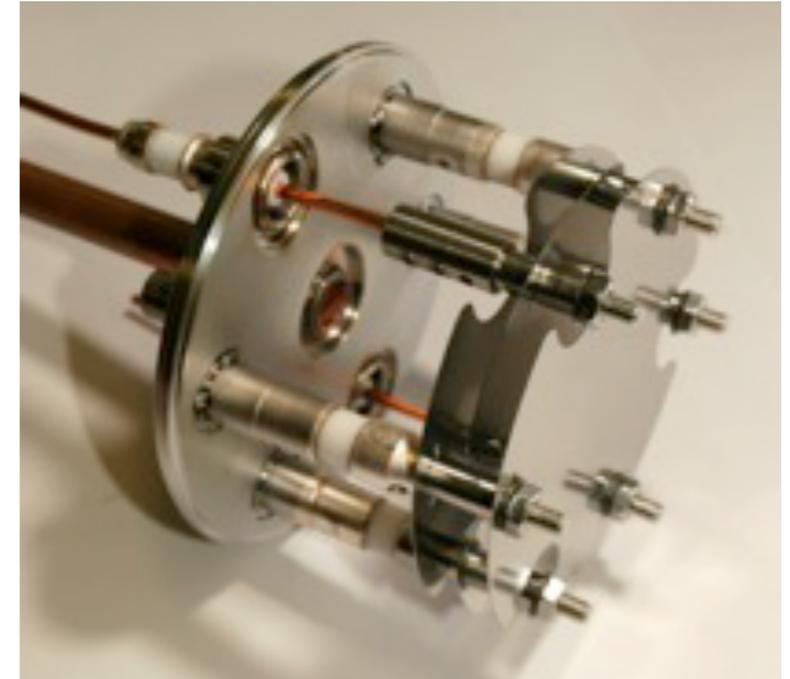
- **SEM:** PROs/CONs
  - Fast (< 10 ns) e transit
  - Very linear
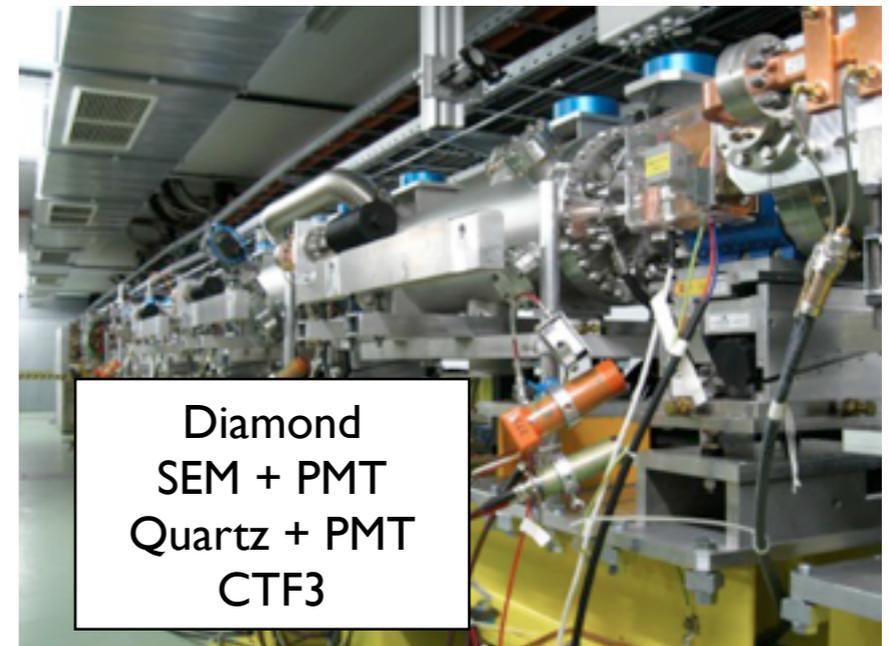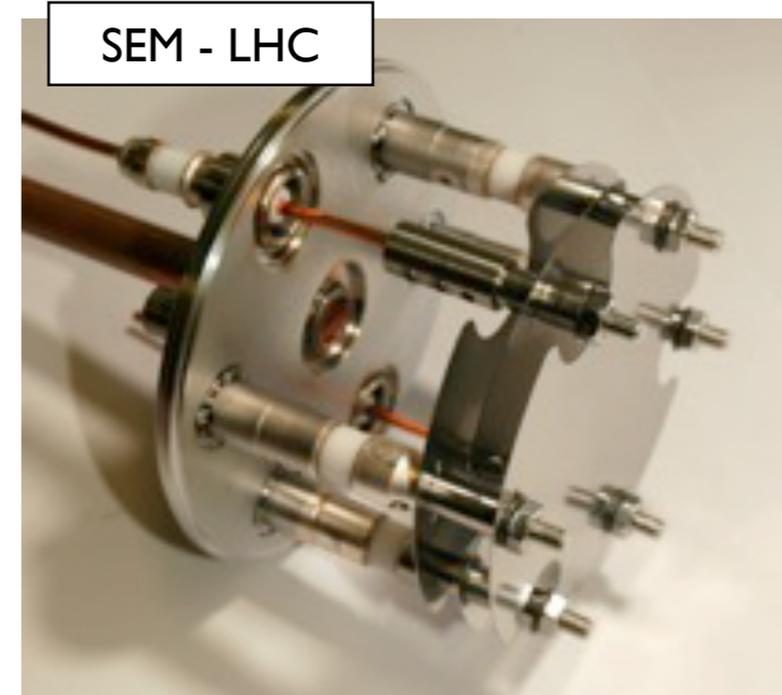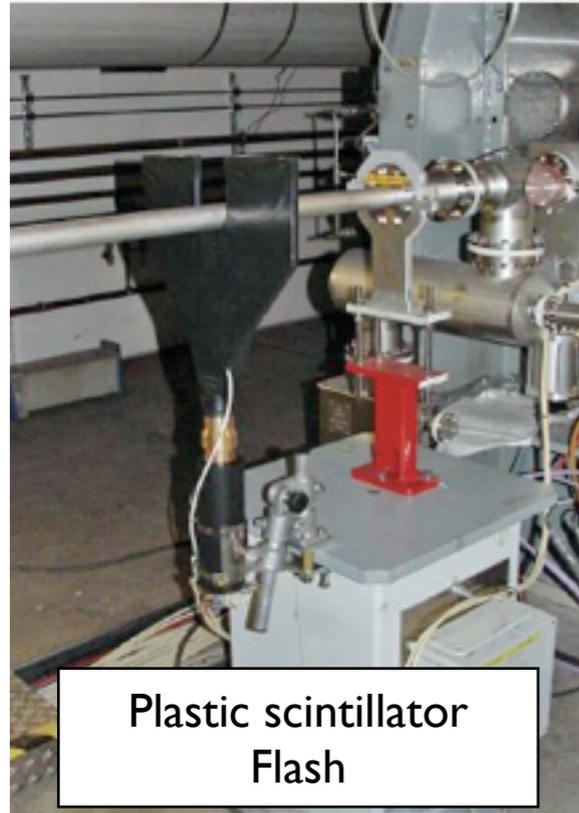 - Very radiation hard (no PMT)
  - Low sensitivity

INCIDENT RADIATION

SEM Electrons

F

1 3 5 7 9 11

2 4 6 8 10

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

Cherenkov detectors

Considerations (similar to scintillators)

- Photon Yield (continuous)
- Collection efficiency (**directionality**)
- Photocathode quantum efficiency (**match cherenkov spectrum**)
- PMT gain $G_{PMT} = \delta^n = (10^{+5} - 10^{+8})$
  - $\delta = (2\text{-}10)$ number of secondary electrons
  - $n = (8\text{-}15)$ number of dynodes

Cherenkov: PROs/CONs

- Fast (only limited by PMT response)
- Insensitive to neutral radiation
- Low sensitivity
- Limited radiation hardness (10 - 100 MGy)

Ion chamber
LHC

SEM - LHC

Plastic scintillator
Flash

Cherenkov radiator -
CEBAF

Diamond
SEM + PMT
Quartz + PMT
CTF3

Technology choice

No universal rule
- detector choice depends on main properties of the machine
- Intensity, energy, particle type, timing, length ...

Main considerations
- Sensitivity/Dynamic Range
- Time response
- Expected type of radiation
- Shield-ability (from unwanted radiation)
- Physical size
- Test ability
- Calibration techniques
- Cost

BLM location

Particle tracking codes (SixTrack, MadX, ...)**:**
- implementation of accelerator optics
- Mapping of the aperture limits along the machine

Trajectory of a halo particle

Magnets locations (*thin lenses*): $\Delta s \leq 100m$

Interpolation: Δs=10 cm (**270'000** points!)
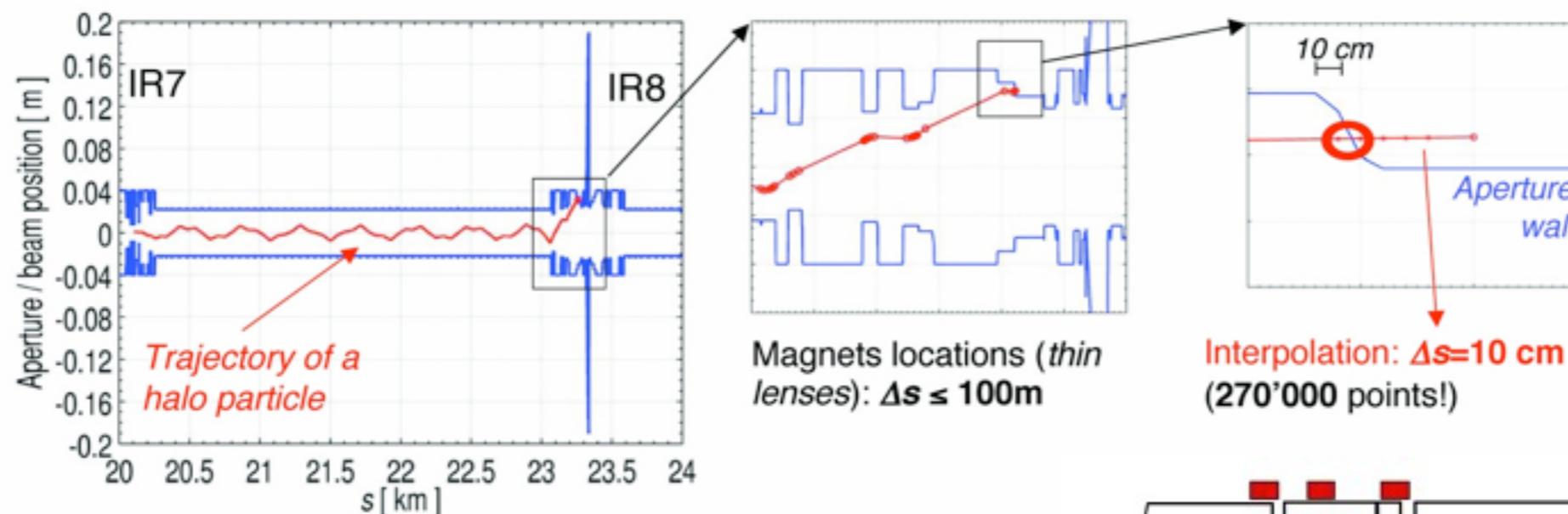
Monte Carlo simulation codes: (SixTrack, MadX, ...)**:**
- Geometry of accelerator components
- Mapping of the aperture limits along the machine
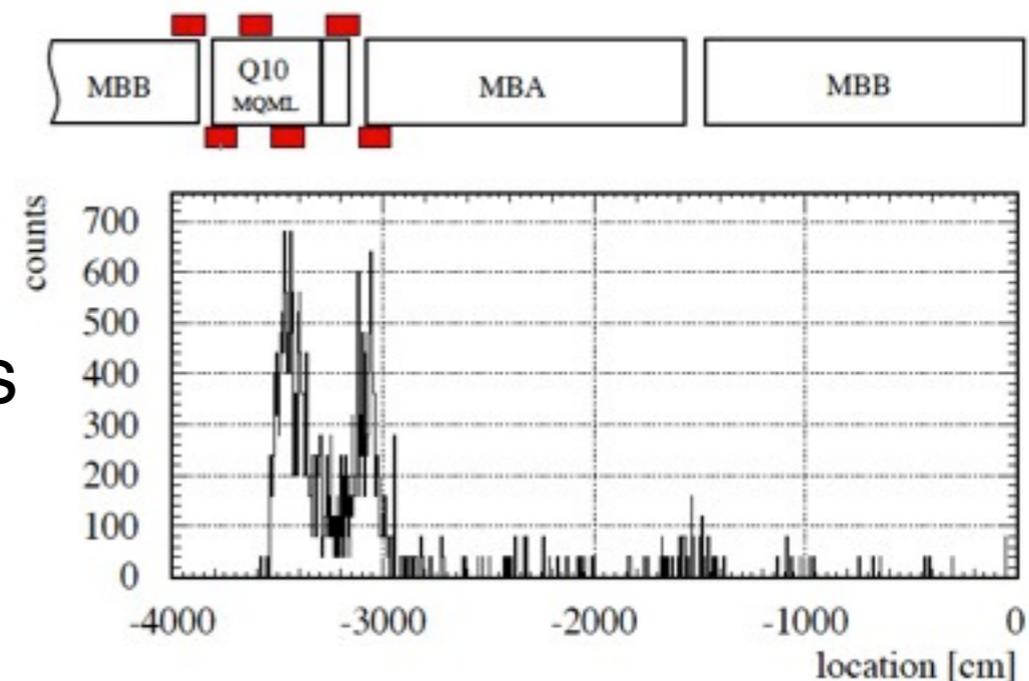
Particle Shower in the Cryostat

L. Ponce
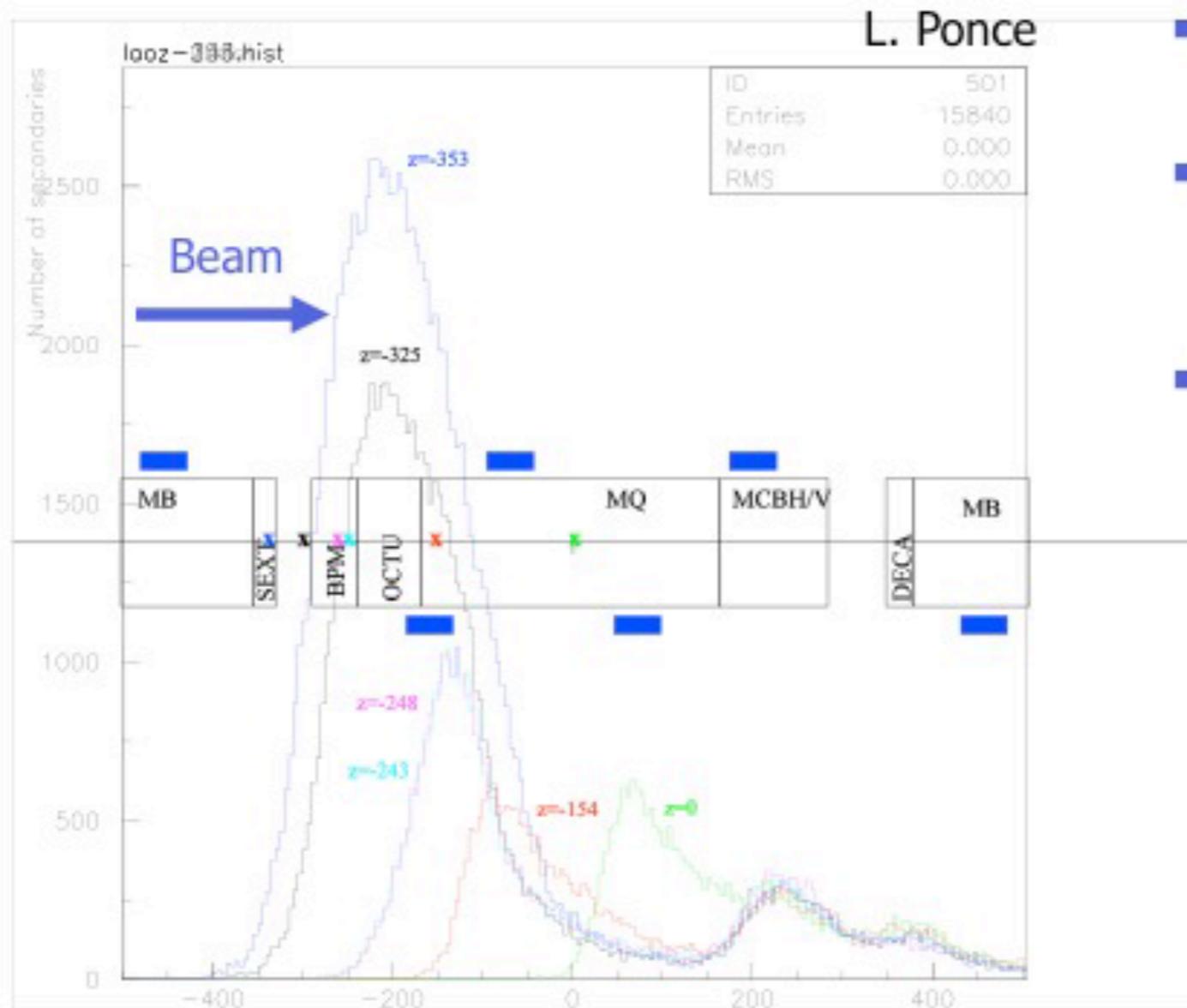
- Impact position varied along the MQ

- Black impact position corresponds to peak proton impact location

- Position of detectors optimized

  - to catch losses:
    - Transition between MB – MQ
    - Middle of MQ
    - Transition between MQ – MB

  - to minimize uncertainty of ratio of energy deposition in coil and detector

  - Beam I – II discrimination

- Good probability that losses are seen by two BLM detectors

E. Nebot del Busto   *ASAP 2016 - BLM Technology*   *15*

Machine Protection

BLM location

- 📌 **Depends on the technology of your magnets, cavities, ...**
  - Normal conducting. Damage of components
  - Superconducting. Quench protection ($T < T_C$)

- 📌 **Linear accelerators (Linac) vs storage ring**
  - Storage rings require protection for single turn/multi turn losses with different threshold level

- 📌 **How we protect**
  - Safe beam extraction (storage rings)
  - Subsequent injection inhibit (linac)

Abort thresholds calculations

- **Geant 4 simulation of horizontal losses in bending magnet**
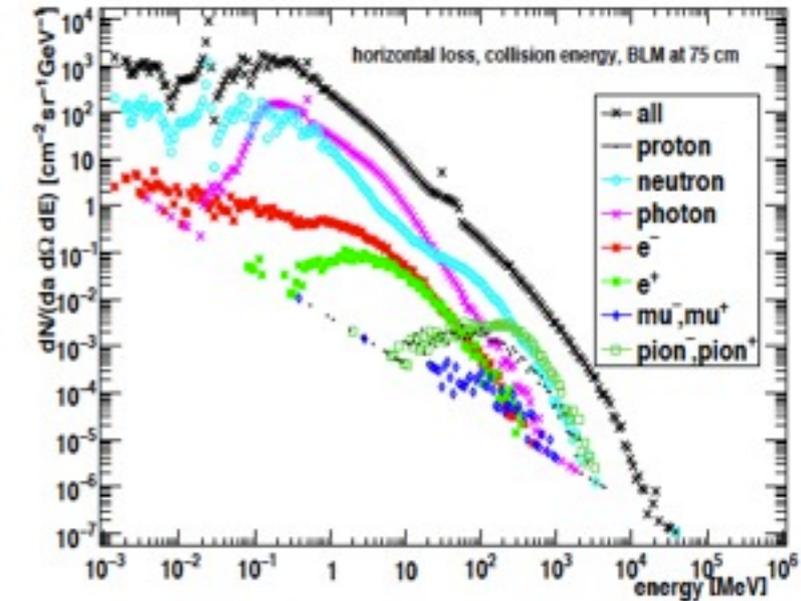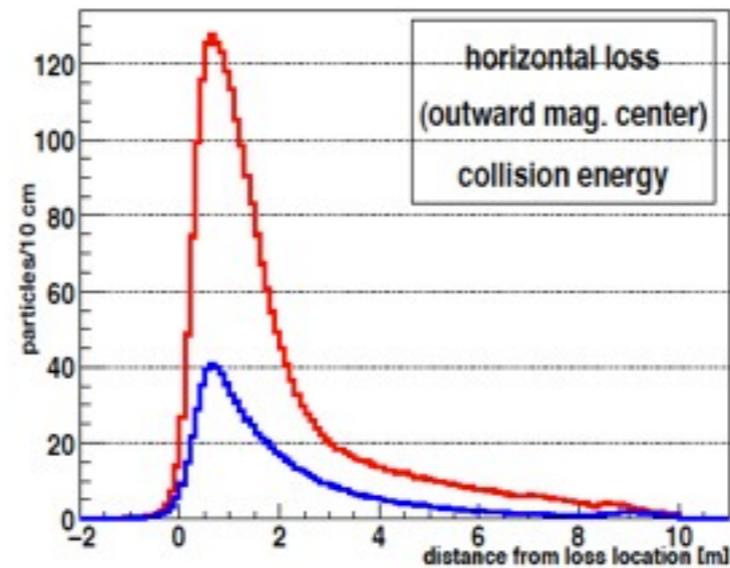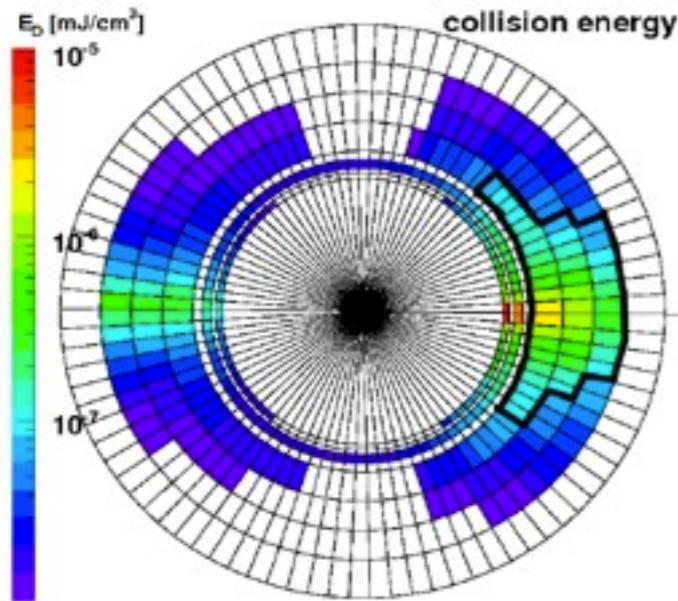
- **Complicated dependences with loss duration and beam energy**
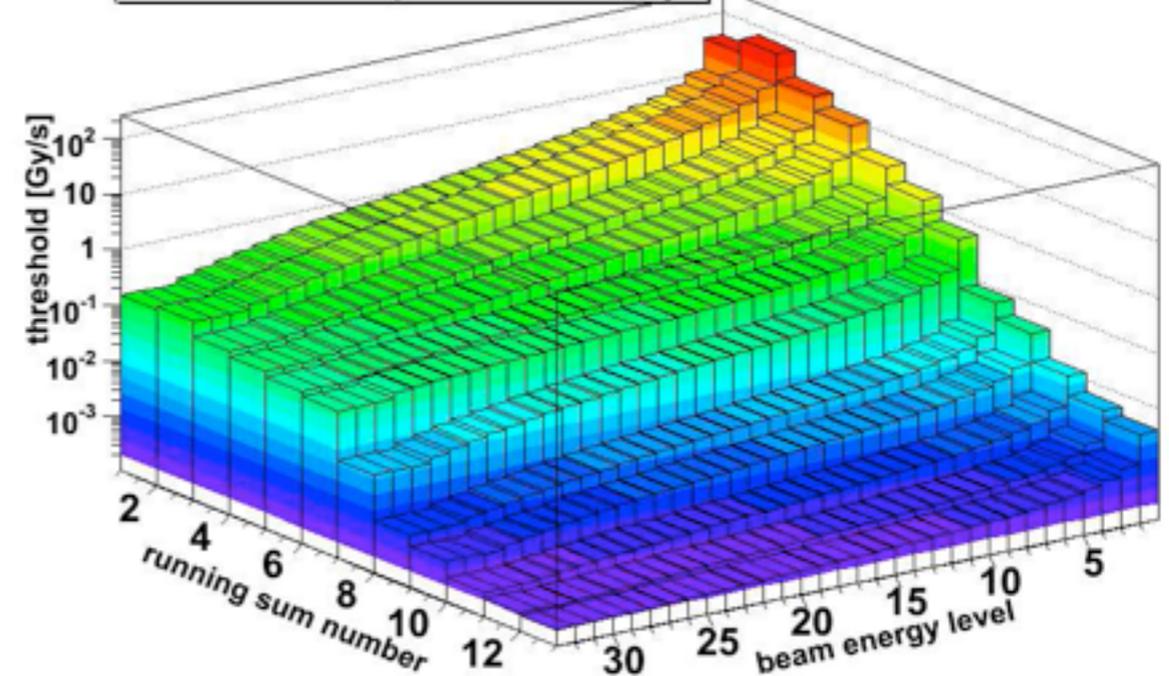
Read out and processing electronics

- **Complicated readout with multiple inputs and connected to interlock**
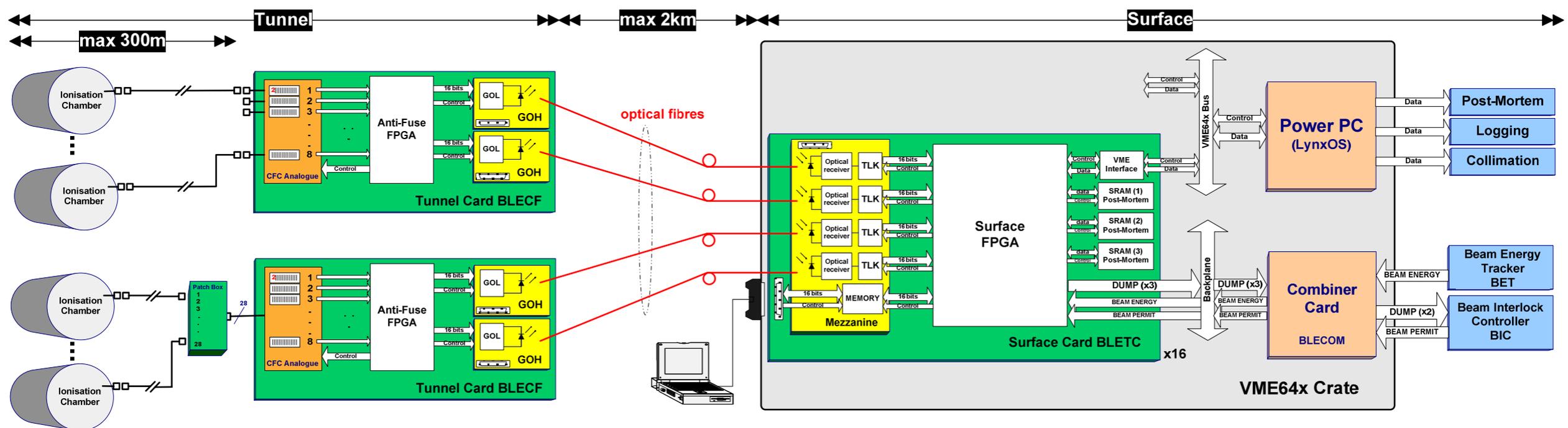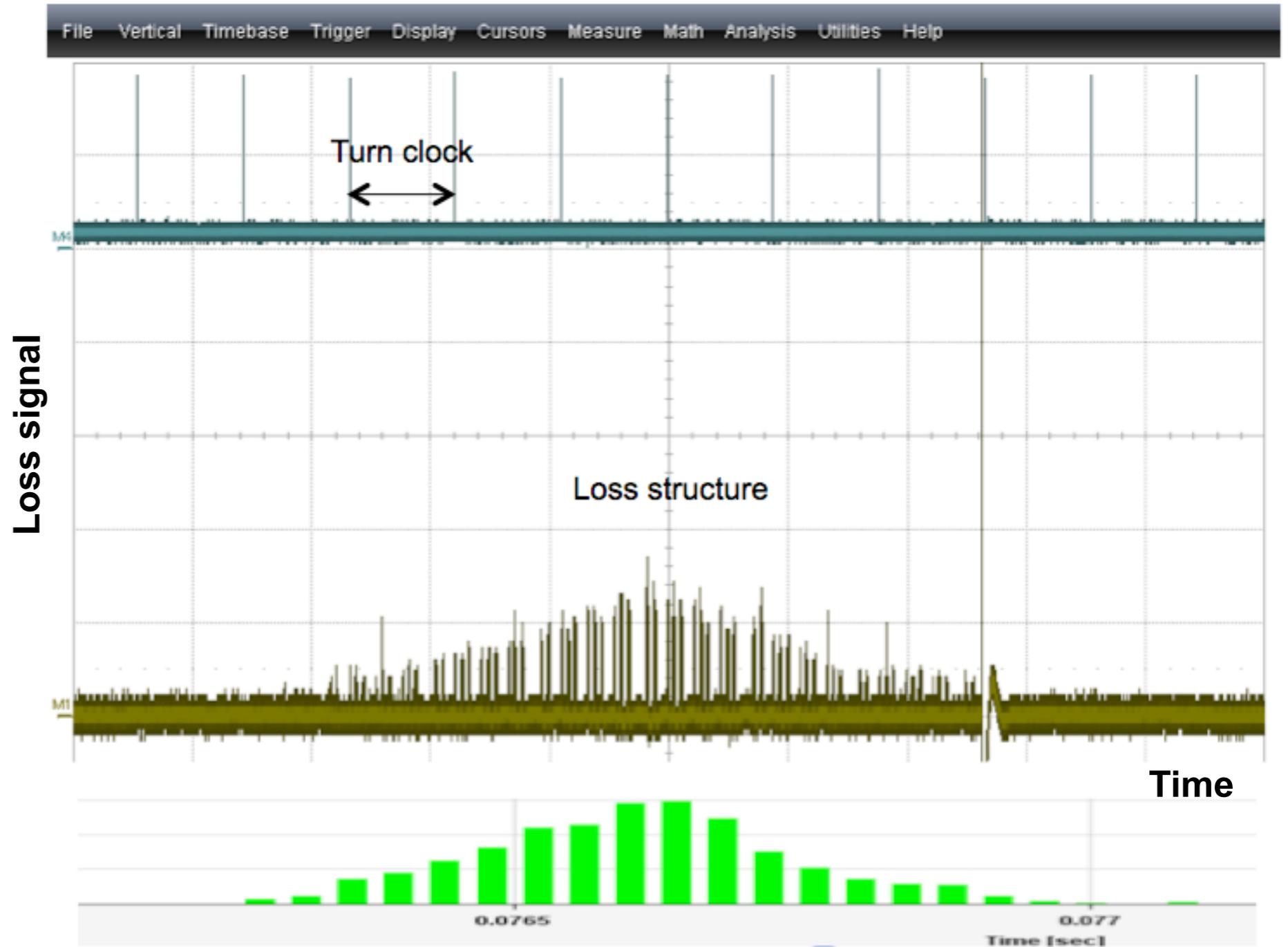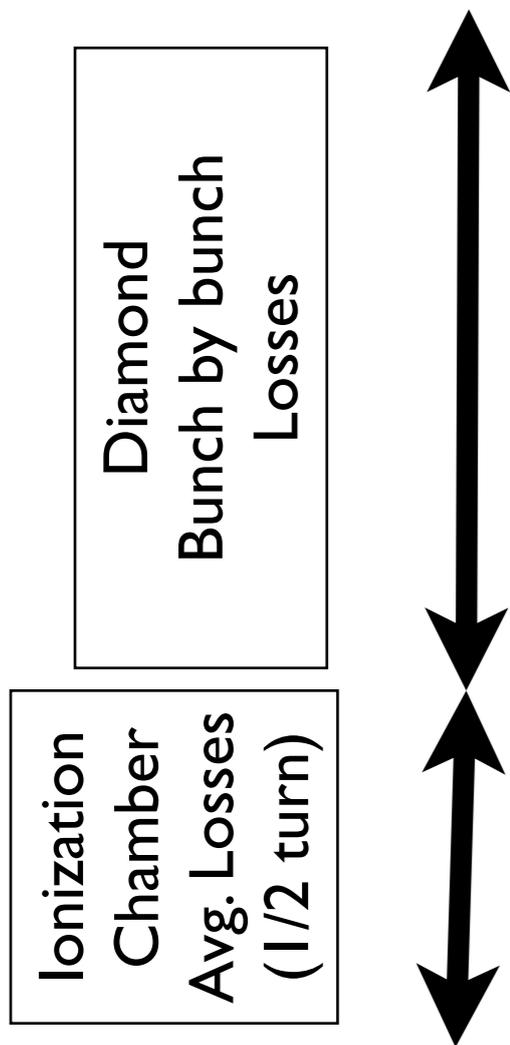
Data driven approach for threshold tuning
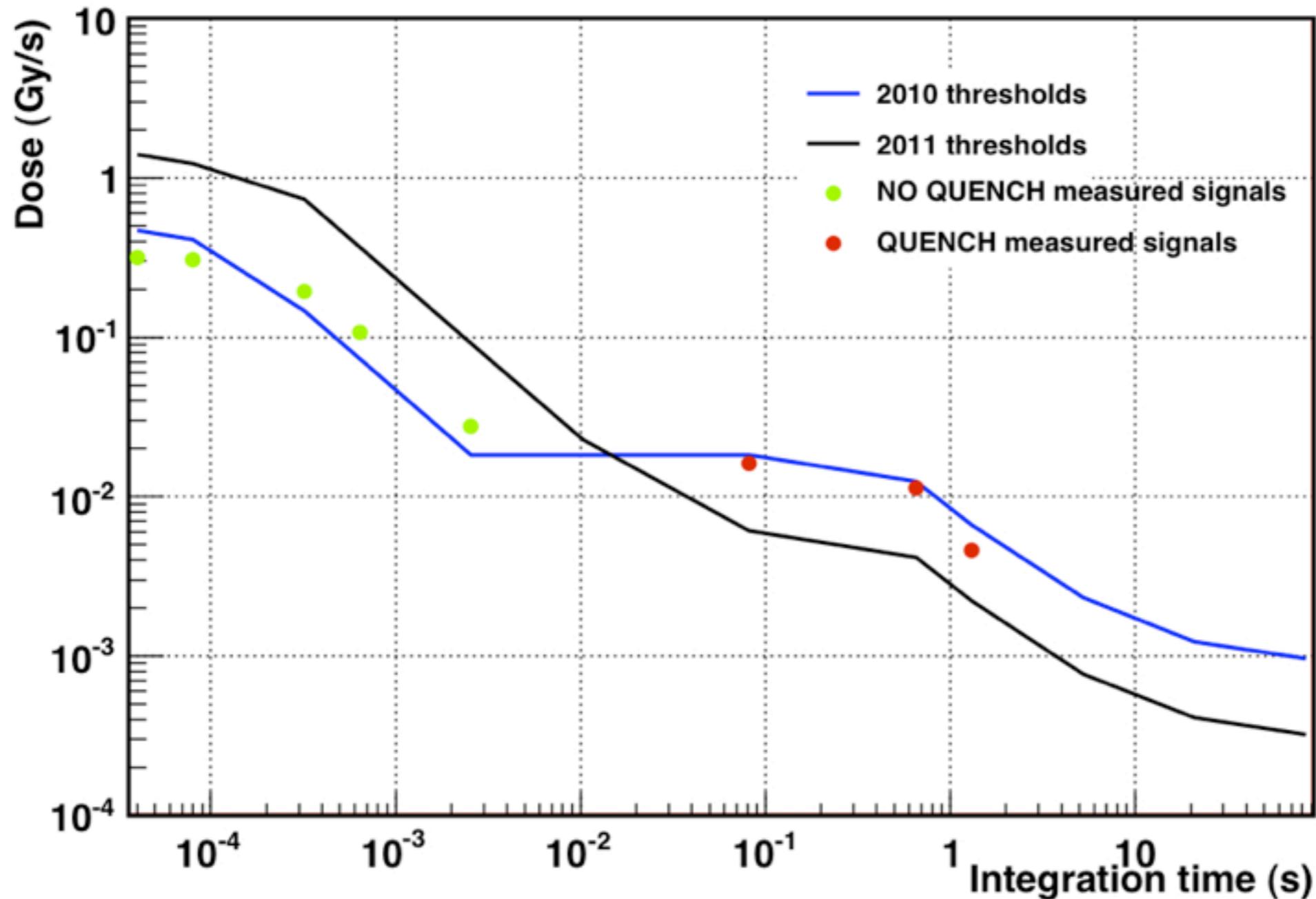
Threshold handling

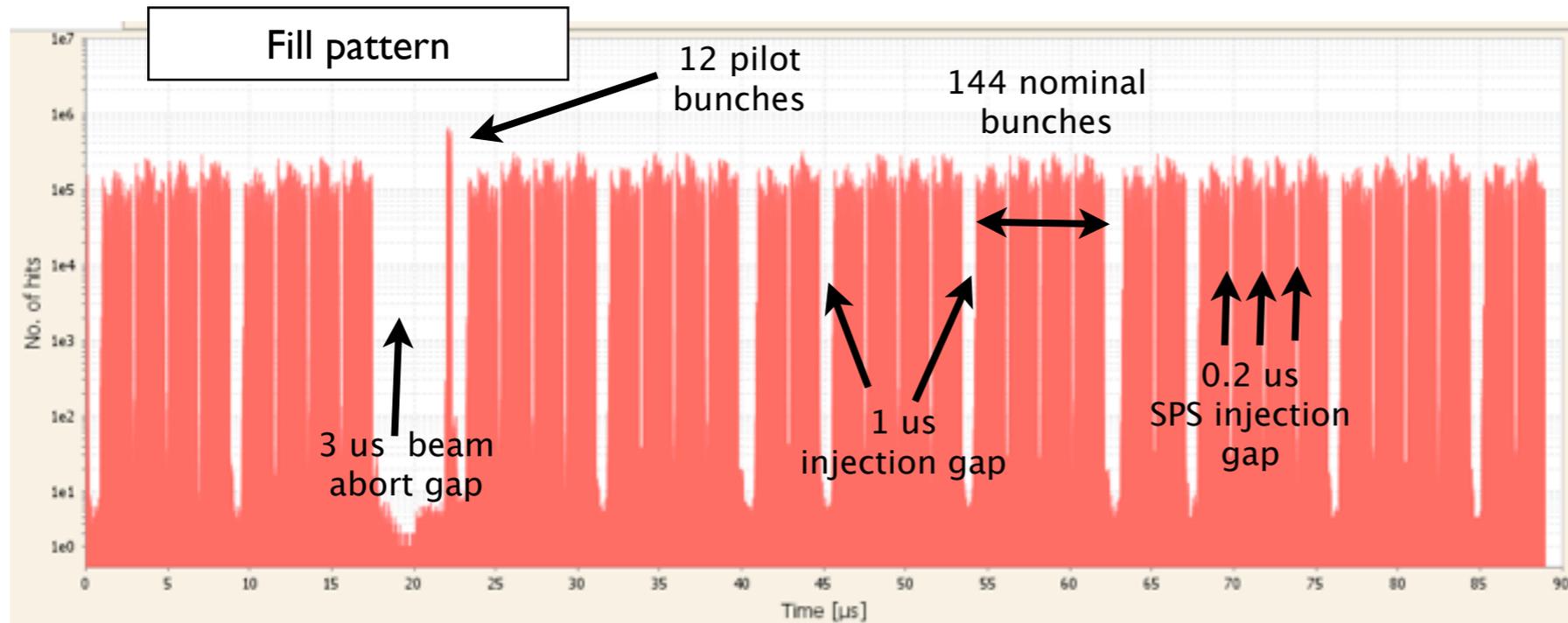- **Complicated applications for handling and monitoring of signals and thresholds**
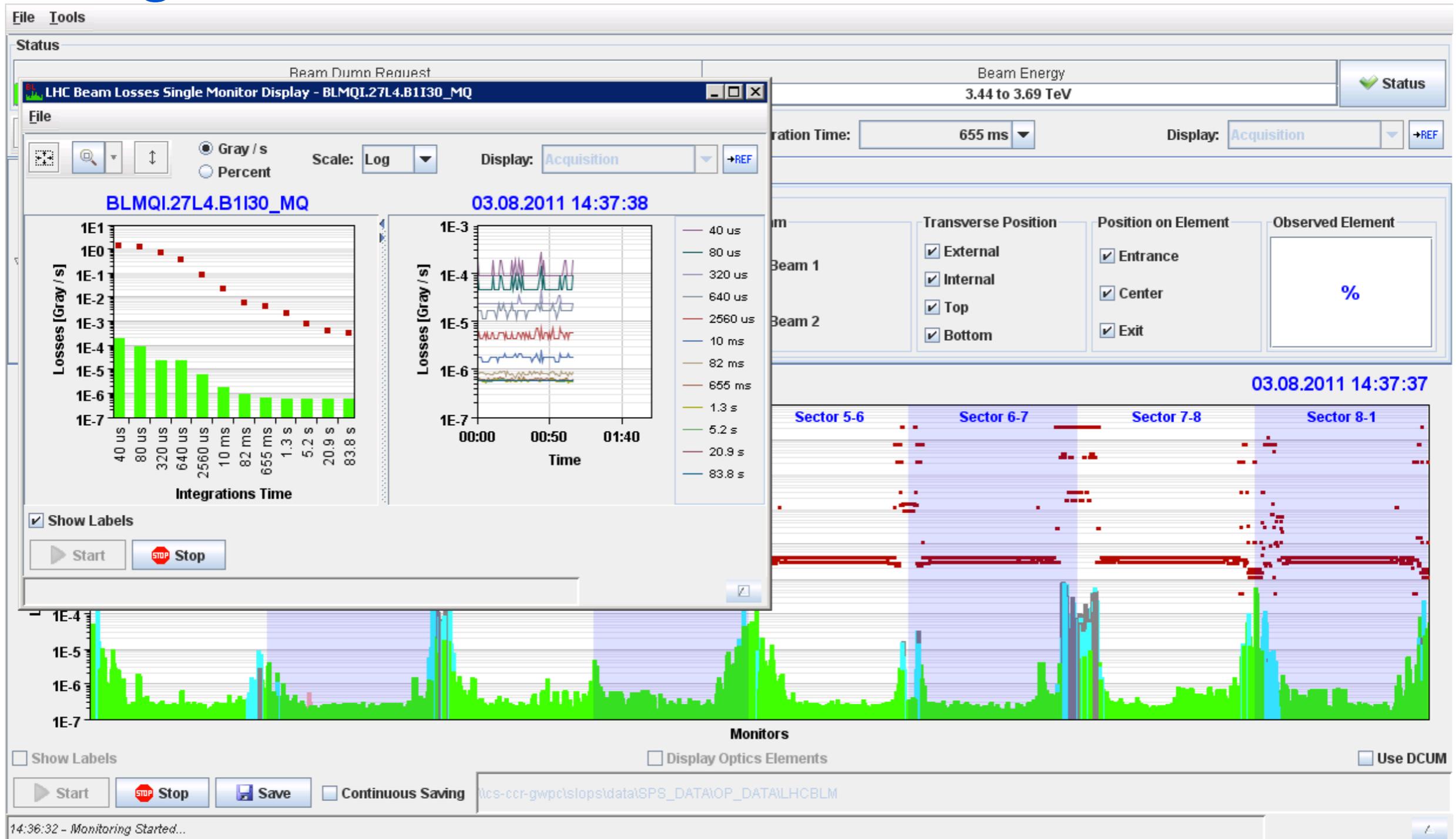
# State of the art: examples

Diamond detectors at the LHC

Diamond detectors at the LHC
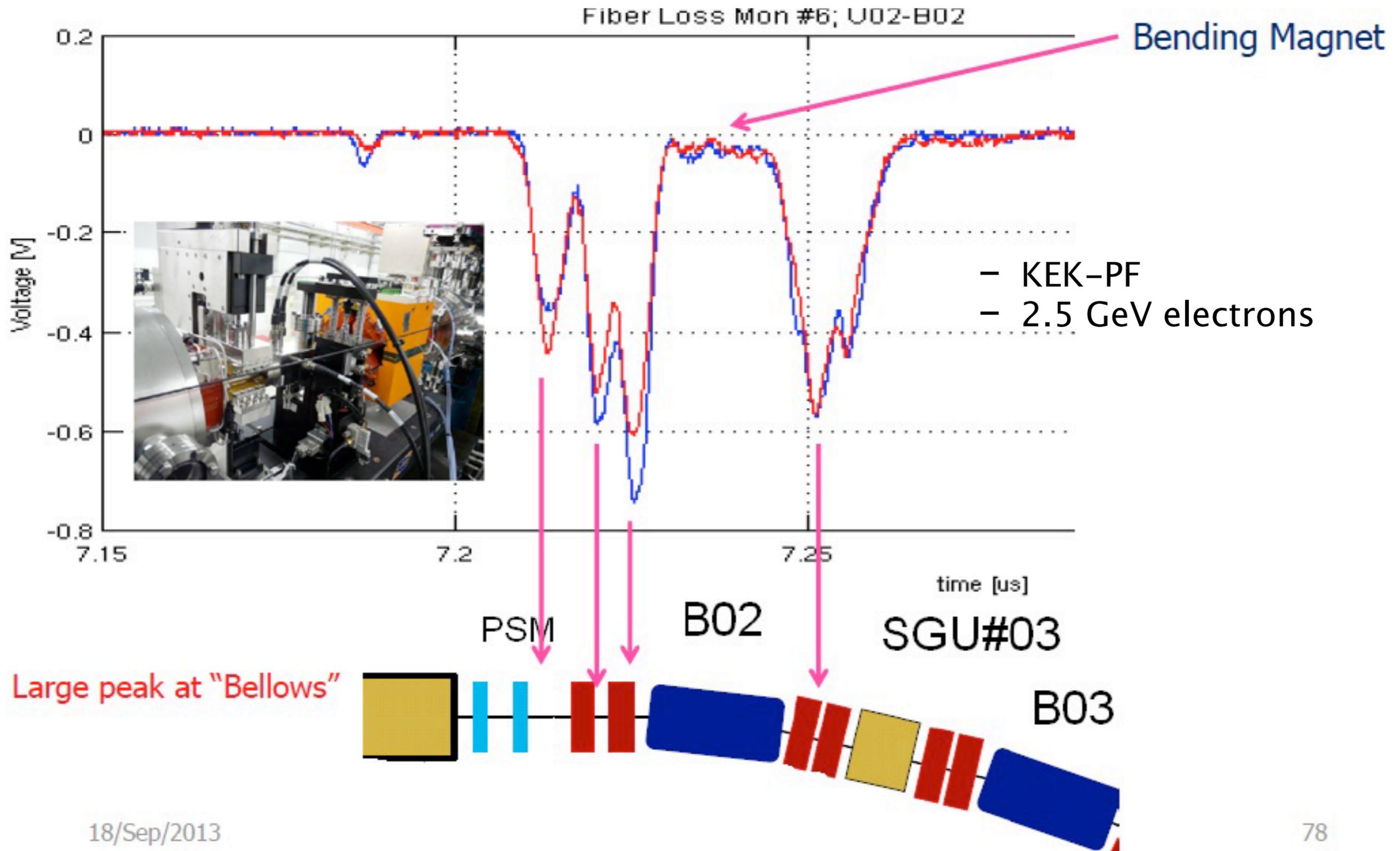

Fill pattern

12 pilot bunches

144 nominal bunches

3 us beam abort gap

1 us injection gap

0.2 us SPS injection gap

Single bunch instability

1 LHC Turn

Light (scintillation or Cherenkov) **generated in fiber core**
- Full coverage of beam lines
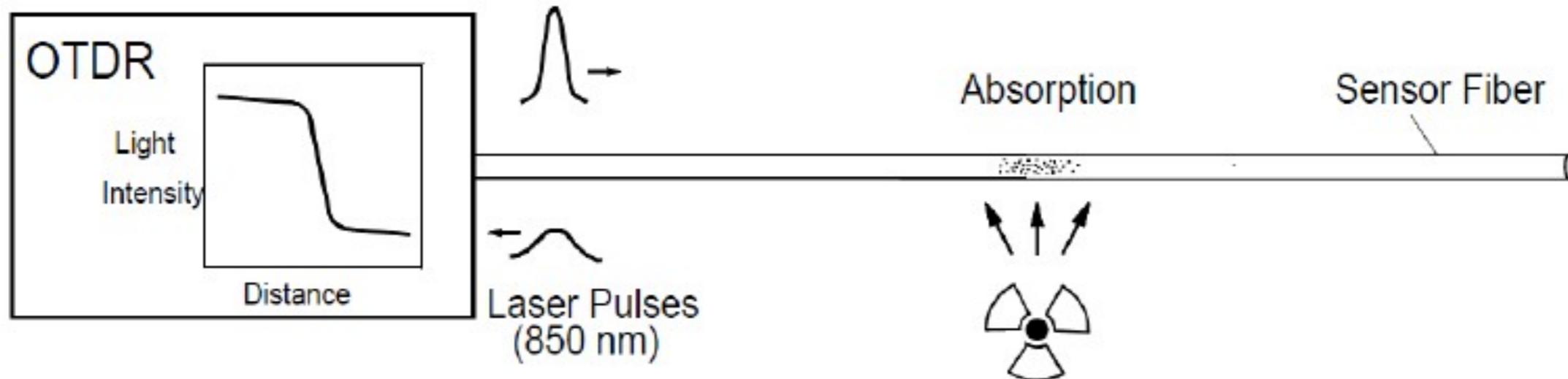- Potential position reconstruction via photon Time of Flight

$$t_d = (L - 2*x)/v_{fiber}$$
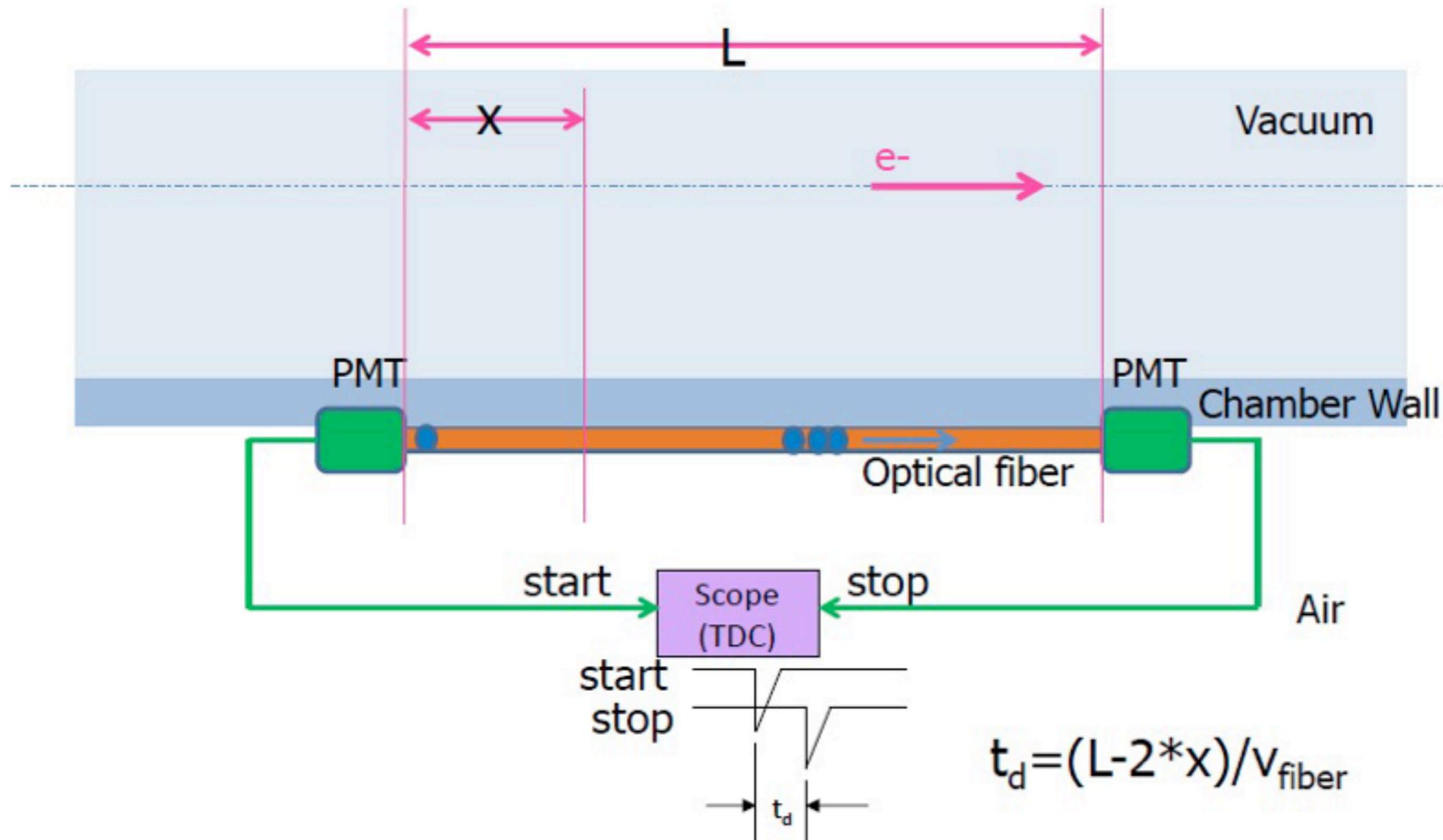
Optical fibre: Position reconstruction

Optical fibre: Dosimetry

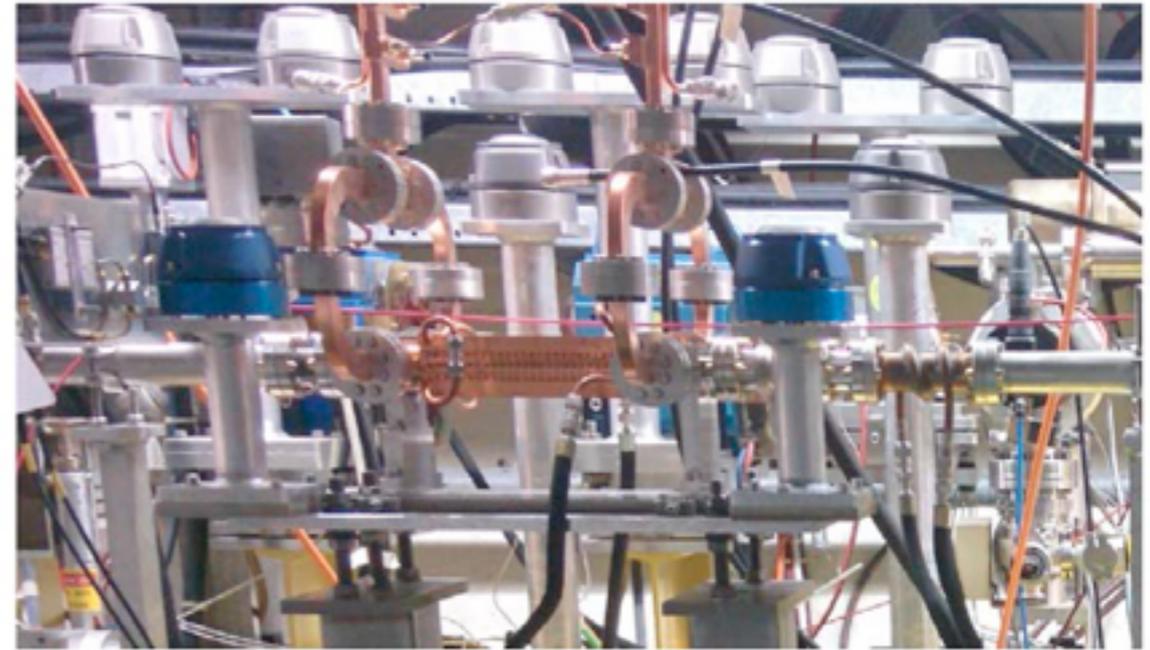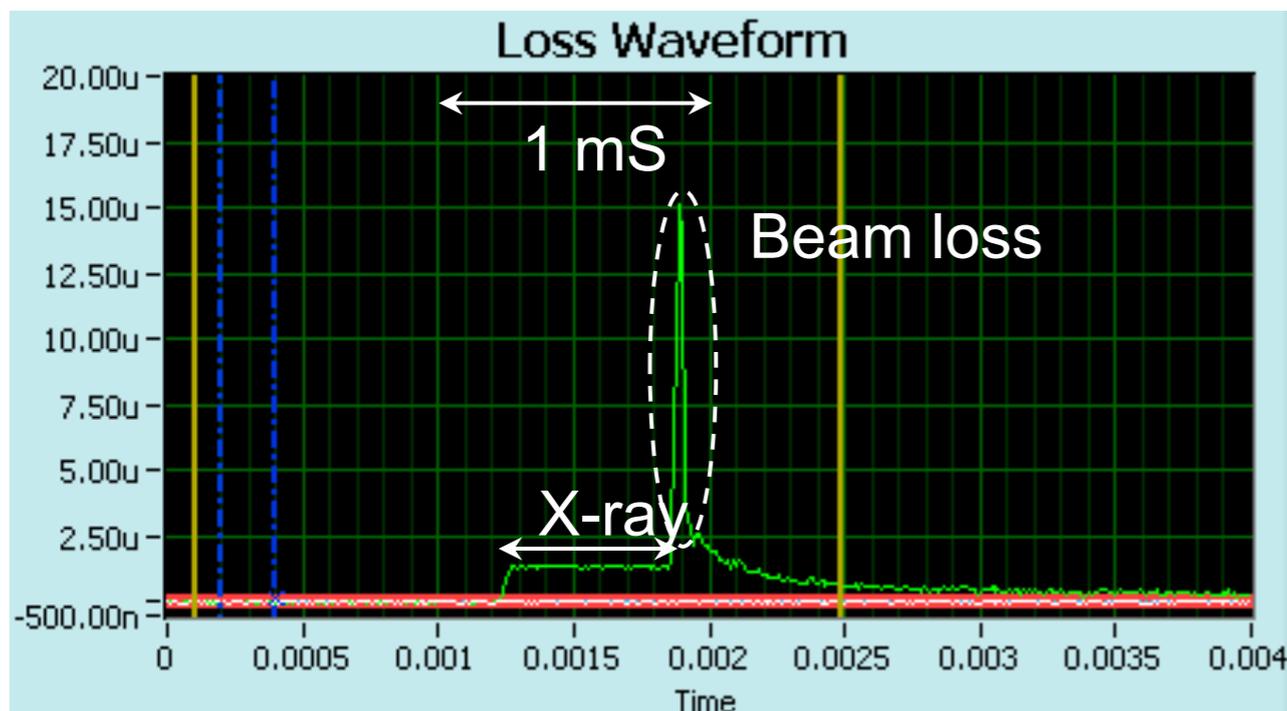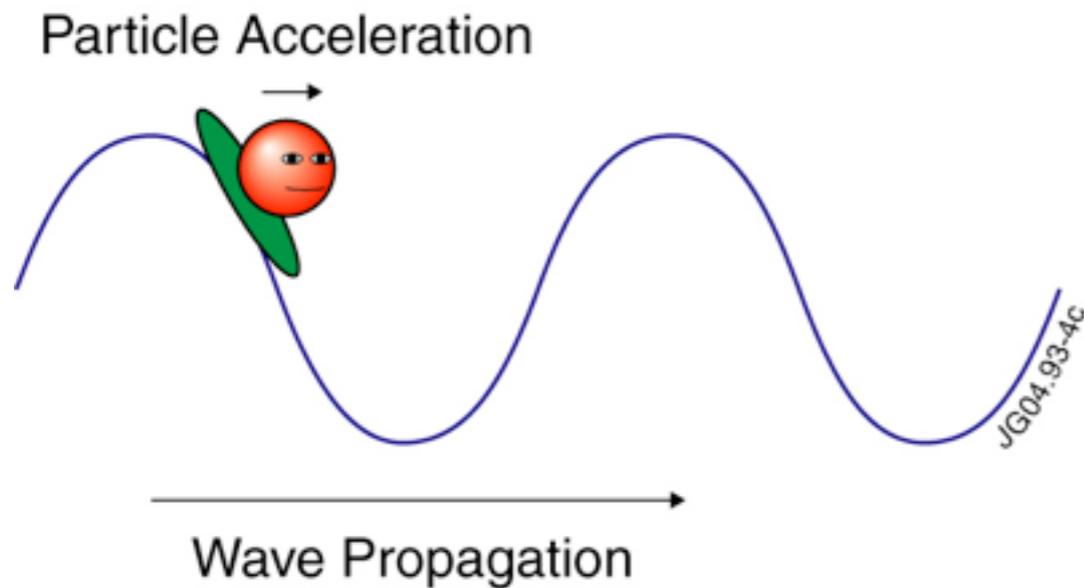- **Location vi Optical Time Domain Reflectometry**

- **Total dose via Radiation Induced Attenuation**
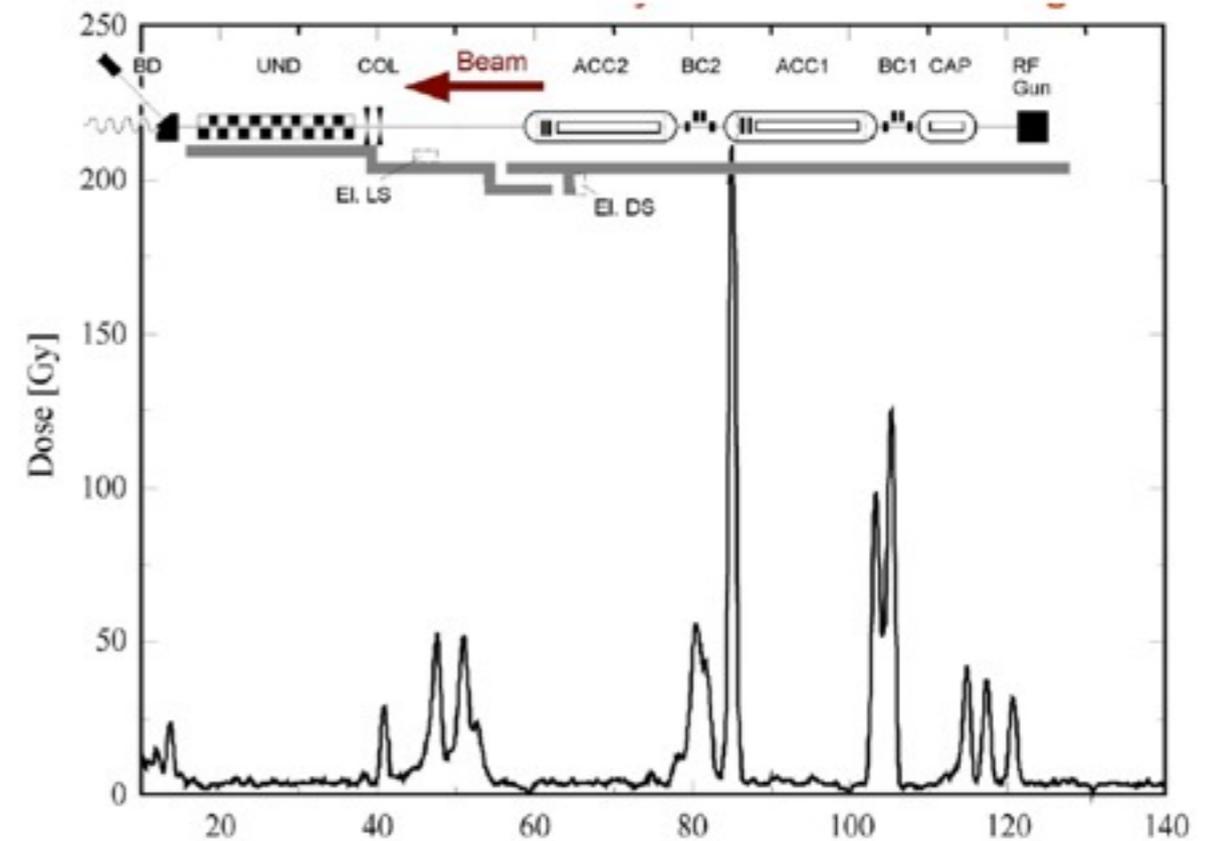
Beam Loss Monitors in high background environments

RF structure related background

- **Particles accelerated by surfing the wave**

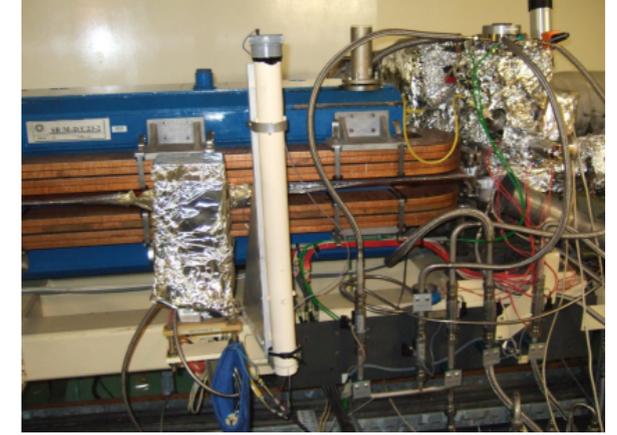(a) The BLM (red fibre) above the CLIC structure (in the middle)

- **Electrons released from inner surface of cavities**
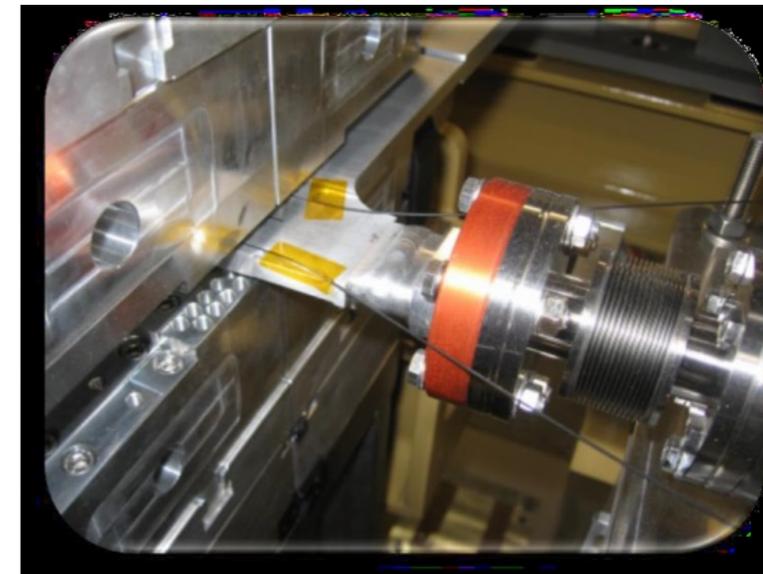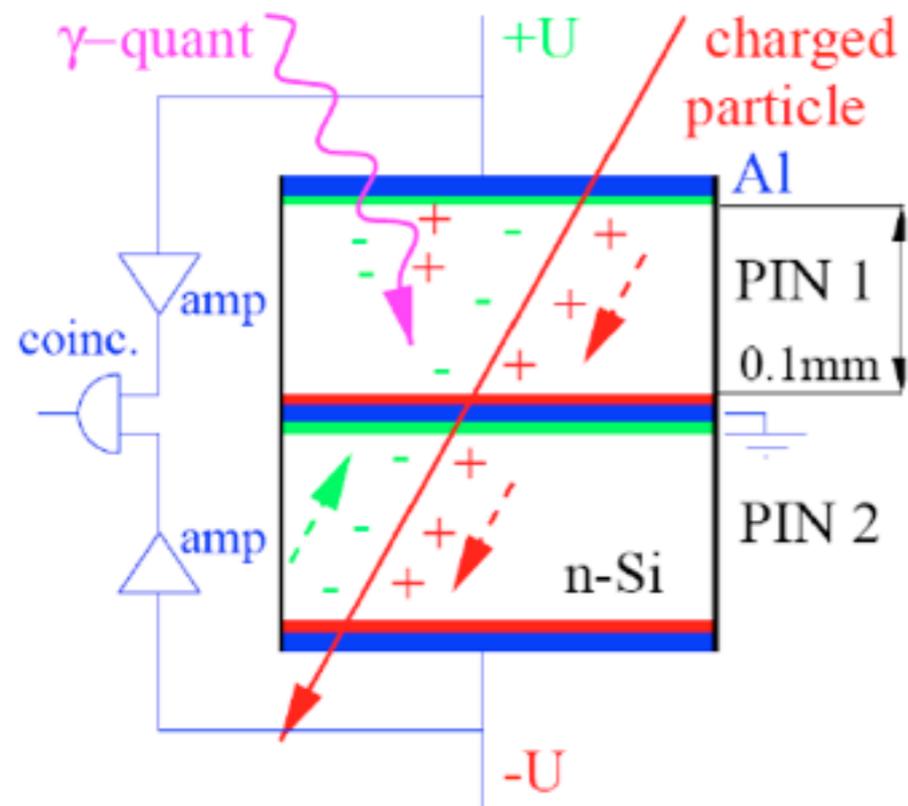 - Full coverage of beam lines

- **Xrays generated in the cavity may limit the BLM sensitivity**

Synchrotron radiation

- **Location vi Optical Time Domain Reflectometry**
- **Total dose via Radiation Induced Attenuation**

ESRF: Quartz rods as Cherenkov radiators

Fermi@Elettra
Quartz core optical fibers

Electromagnetic noise

High EM noise

- Ground Loop
- Bad shielding
- Ripple (power supplies, magnets...)

Electromagnetic noise

High EM noise

- Ground Loop
- Bad shielding
- Ripple (power supplies, magnets...)

MAGIC!
GHOSTS!!
SABOTAGE!!!

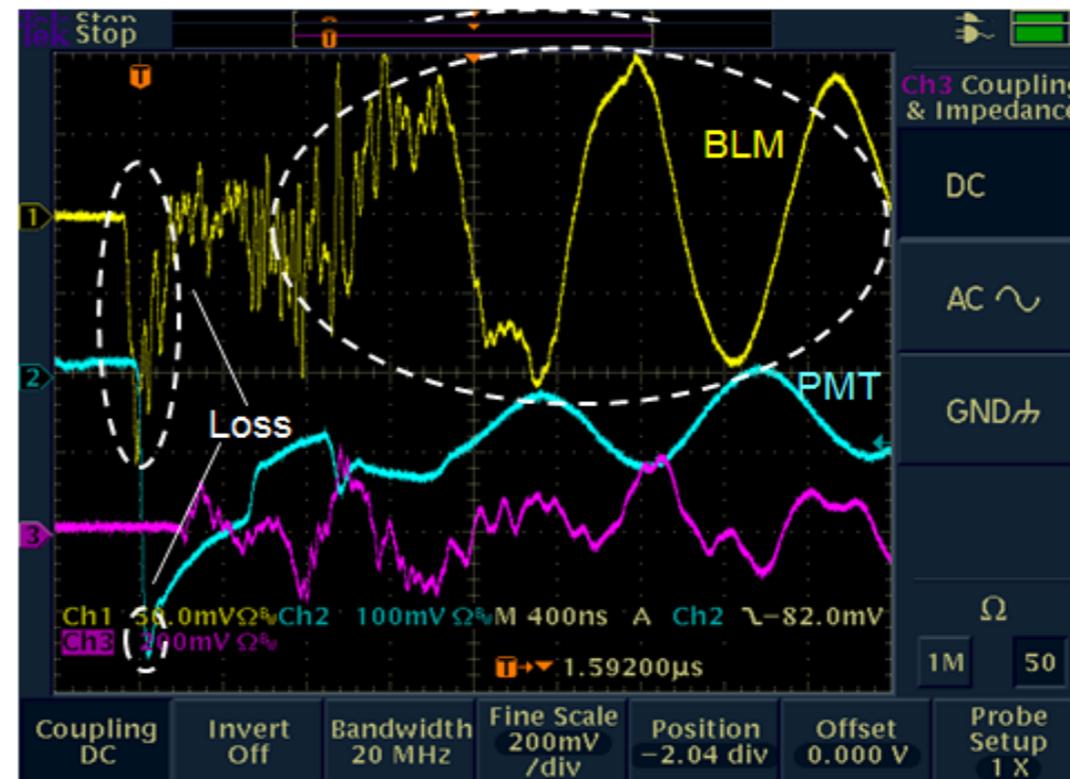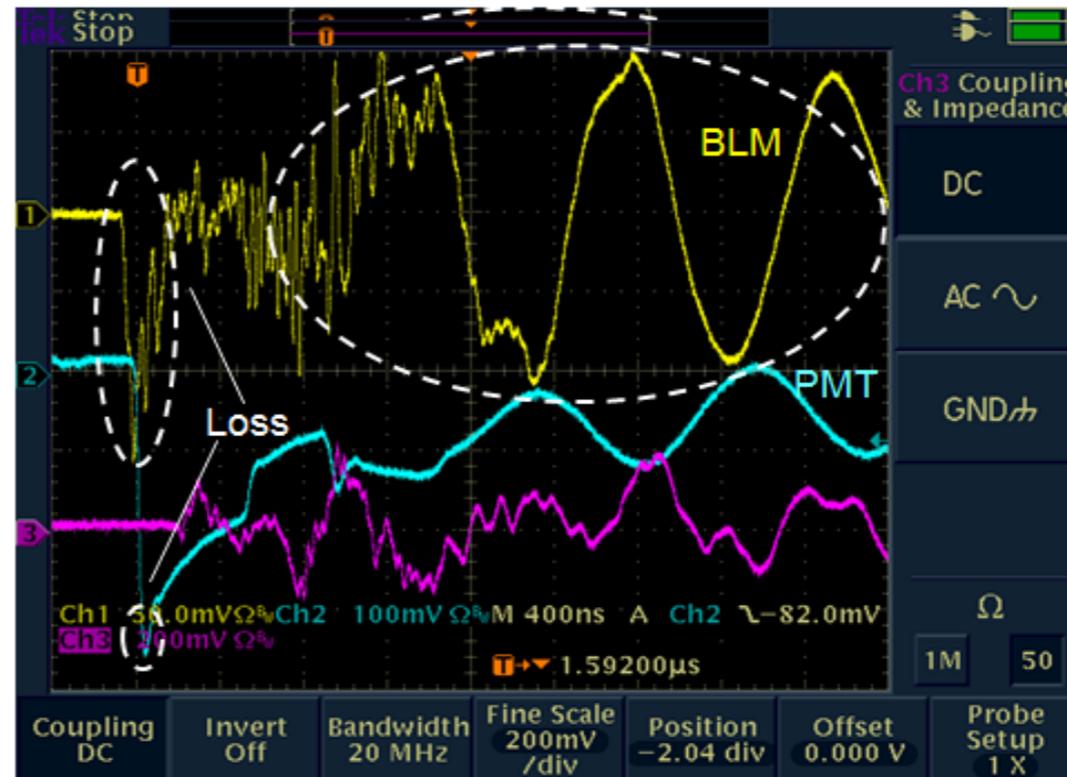RTBT noise/EM interference with the beam or image current

Electromagnetic noise

High EM noise

- Ground Loop
- Bad shielding
- Ripple (power supplies, magnets...)

MAGIC!
GHOSTS!!
SABOTAGE!!!

RTBT noise/EM interference with the beam or image current
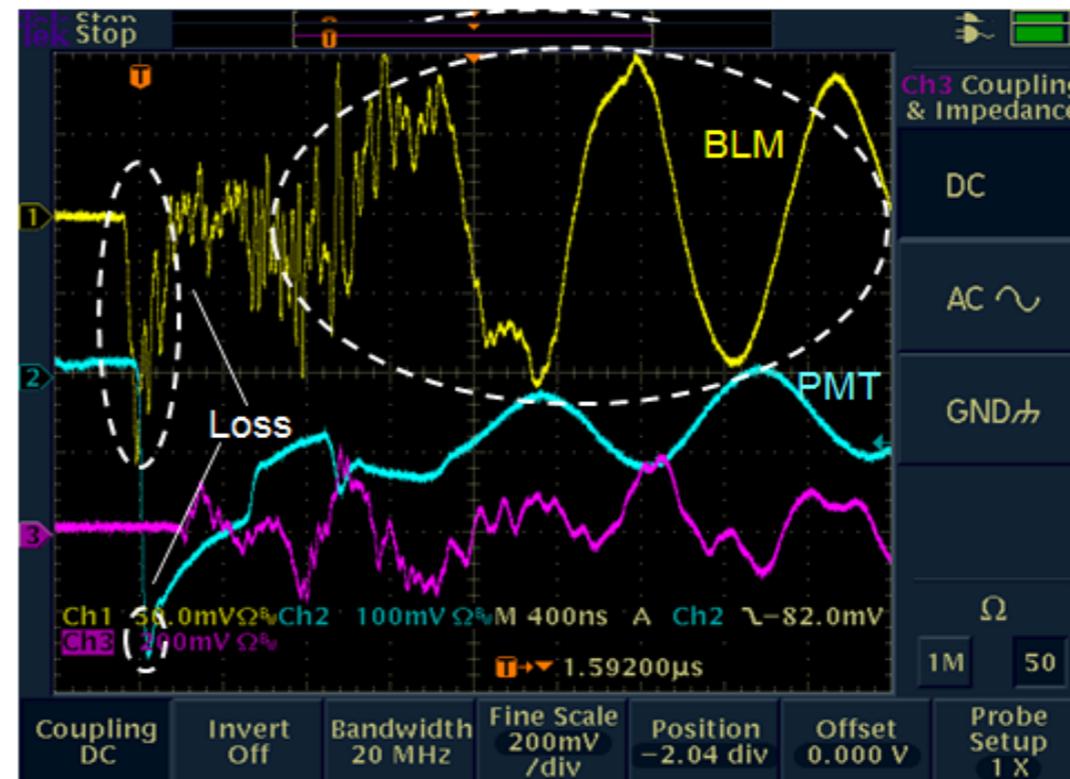
- Problem is present with beam only
- Gets worse with beam charge increase

11 Managed by UT-Battelle for the Department of Energy   A. Zhukov SNS BLM System Overview Detectors, Measurements, Simulations WGF04 – HB2008 8/26/2008

Keep scratching your head for days/months ..... and finally BLAME OTHERS!!!

References

(1) K. Wittenburg. "Beam Loss Monitors" CAS2008.

(2) A. Zukov. "Beam Loss Monitors: Physics, Simulations and Applications in accelerators". BIW2010.

(3) E. B. Holzer. "Beam Loss Monitoring for demanding environments". IBIC2015

(4) E. Nebot. "An overview on Beam Loss Monitoring". Advanced oPAC school on Acceleration optimization 2014.

(5) T. Obina. "Optical fiber based loss monitors for electron storage rings". IBIC2013.

(6) Particle data group:
   - "Review of particle physcis". Phys Rev. D 86. 010001 (2012) 30. Passage of Particles though matter
   - "Particle Physics Booklet". http://pdg.lbl.gov/