An overview on Beam Loss Monitoring

- The BLM business:
  - ‣ Definitions
  - ‣ Detector technologies
  - ‣ Machine protection
  - ‣ Location of BLMs
- Challenges on Beam Loss Monitoring

27-06-2014 BI seminar

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Some references

- "Beam Loss Monitors", K. Wittenburg. CERN Accelerator School 2008
- "Beam Loss Monitors", L. Froelich . ERL instrumentation workshop 2008 Accelerator School 2014
- "Beam instrumentation and diagnostics", P. Forck. Joint University 2014
- "Overview of BLM technology". K. Wittenburg. 3rd oPAC Topical Workshop on Beam Diagnostics 2014
- "Optical fiber based loss Monitors for electron storage rings". T. Obina. IBIC2013

- "Beam instrumentation and diagnostics. P. Strehl

- Particle Data Group (http://pdg.lbl.gov/)

- The Beam Loss/Beam diagnostics sessions of: IBICXX, iPACXX, HBXX, ...
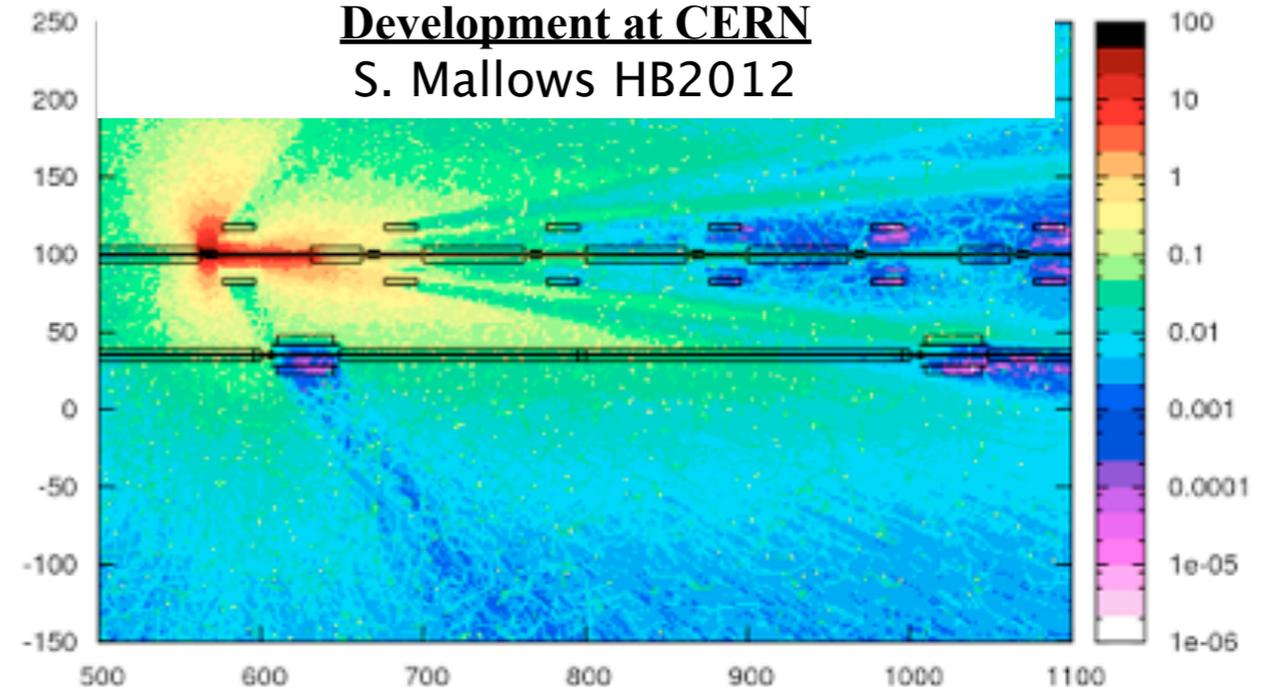
The BLM business

Definitions

QUASAR

- **Beam Losses:**
  - Particles deviating from the design orbit may eventually hit the aperture limit and be "loss" from the beam
  - The impact of particles in the vacuum chamber produces particle showers

Fiber Based BLM System Research and Development at CERN
S. Mallows HB2012

- **Beam Loss Monitoring system**
  - Ionizing radiation detectors located around the accelerator
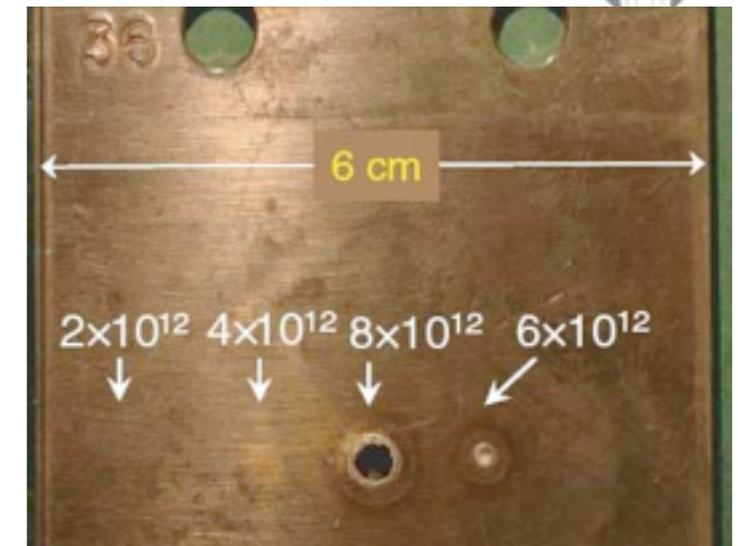 - What kind of detectors? Where do I put them? How do I extract/process the signals?

Main goals

- ## Machine protection
  - The impact of a high power beam into a single location may have catastrophic consequences on equipment.
  - Aborts (safely extracts from ring or inhibits further injections in a LINAC) the beam when the BLM signals exceed a predefined threshold
  - Thresholds established based on: Damage Level (Typically to vacuum chamber.beam pipe) or Quench levels in superconducting magnets
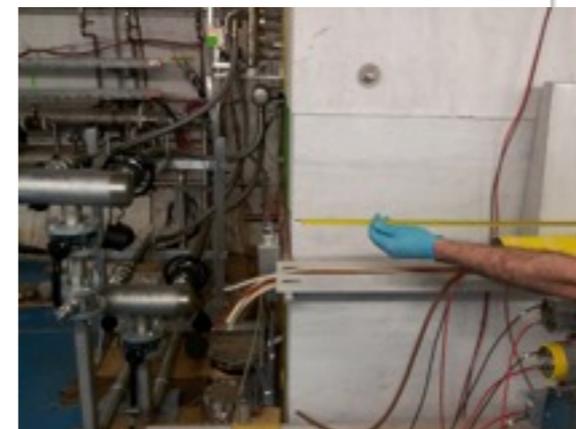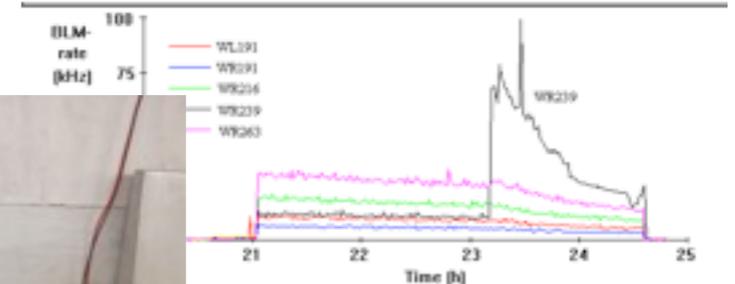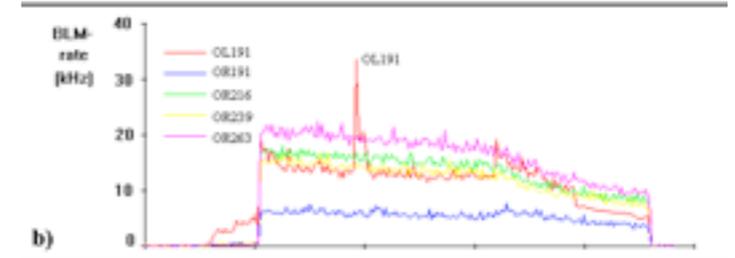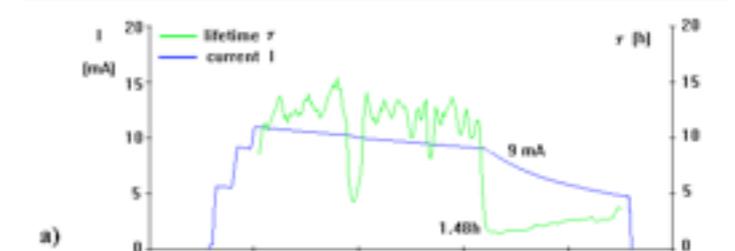
- ## Beam diagnostics
  - Beam tuning
  - Halo measurement

- ## Keep activation levels low
  - Production of "radioactive waste"
  - Protection against human hazard

Type of losses

- Beam Loss categorization

  - Irregular beam losses
    - They are avoidable but sometimes tolerated
    - RF trips
    - vacuum leaks
    - Injection losses
    - Obstacles in the beam

  - Regular beam losses: Normally there are controlled although not avoidable
    - Debris from interaction point (collider)
    - Intentionally produced losses (for beam setup)
    - Losses at aperture imitations (collimation)
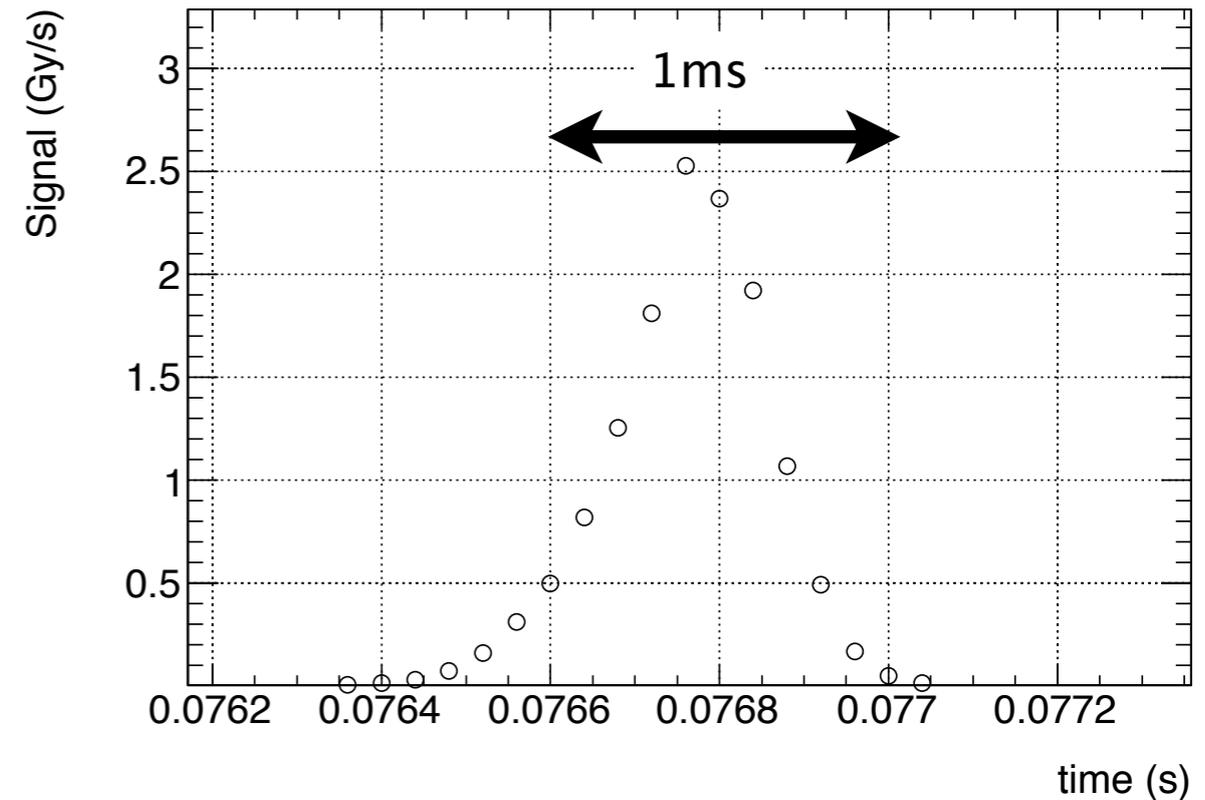
Type of losses

- Beam Loss categorization
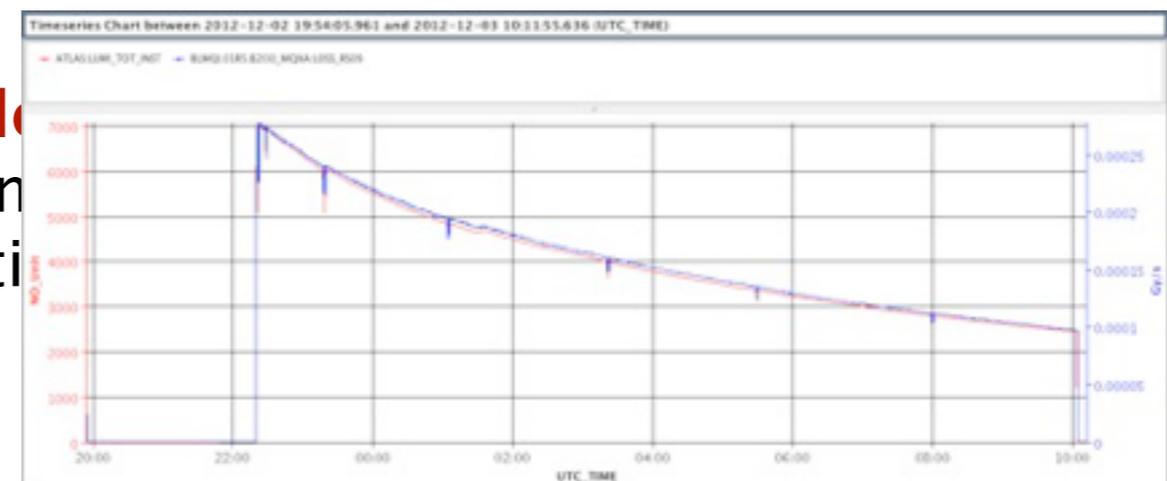
  - Irregular beam losses
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    - RF trips
    - vacuum leaks
    - Injection losses
    - **Obstacles in the beam**

  - Regular beam losses: Normally there are controlled although not avoidable
    - **Debris from interaction point (collide**
    - Intentionally produced losses (for beam
    - Losses at aperture imitations (collimati

Source of BLM signal

- ## Ionization
  - Energy loss by Ionization described by the Bethe–Bloch formula
  - Concept of Minimum Ionizing Particle

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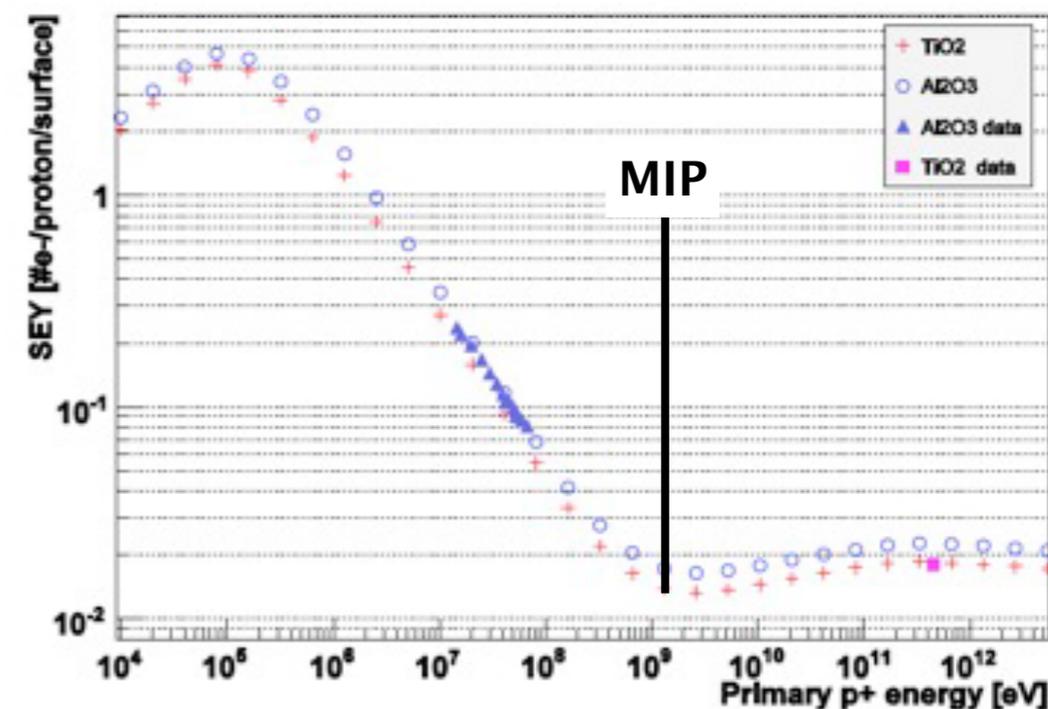
- ## Scintillation

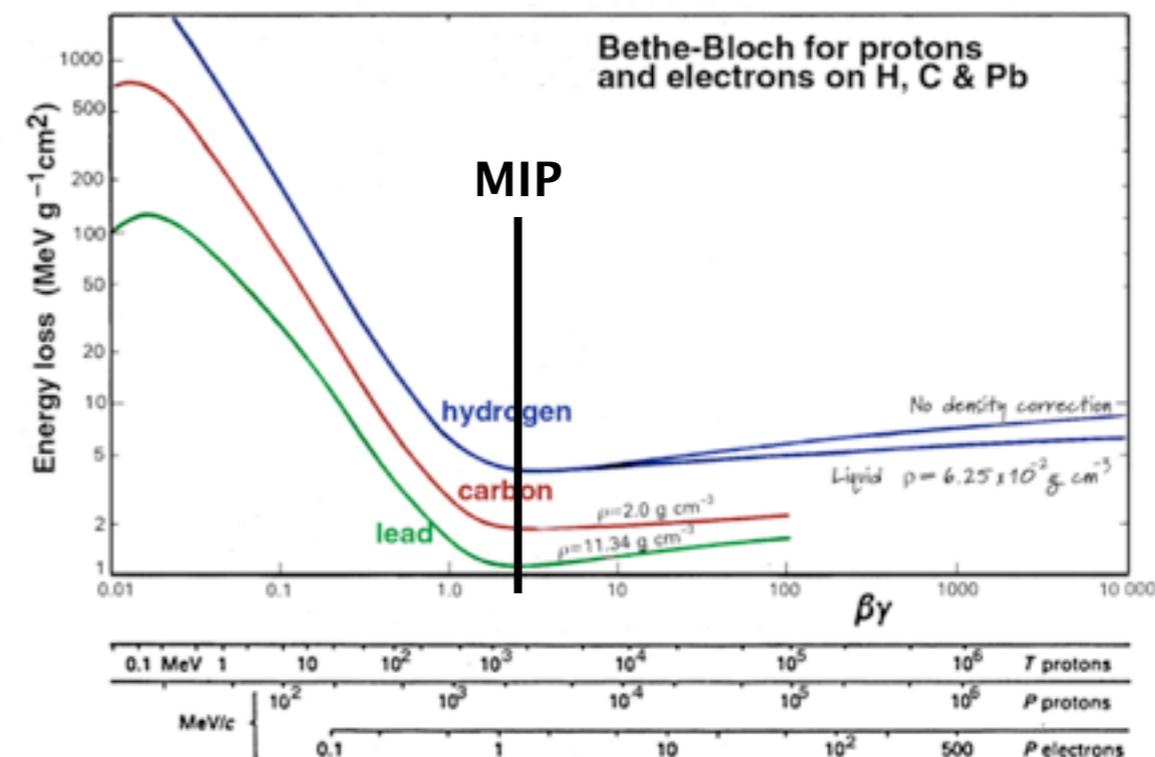$$Y = dL/dx = R \, dE/dx$$

- ## Secondary emission

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

- ## Cherenkov light

$$photon\ yield : \frac{dN}{dx} = 2 \cdot \pi \cdot \alpha \cdot \sin^2 \Theta \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2} \right)$$

$$\cos \Theta = \frac{1}{\beta \cdot n} \ with\ \beta > 1/n\, ;\, \alpha = 1/137.036\ and\ \lambda_{1,2} = \ \text{wavelength interval}$$

Some useful units and conversion numbers

You will need this for doing
BLM R&D....
... on a piece of paper

- With the assumption

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

a conversion between energy deposition
(dose) and number of crossing minimum
ionizing particles can be provided

Radiation units

1 Ci = 3.7×10^{10} decays per second
Marie and Pierre Curie

1 Bq = 1 decay per second
Henri Becquerel

Activity – how frequently
radioactive materials disintegrates.

1 R = 2.58×10^{-4} C/kg (radiation ionizing 1 kg
of dry air to this charge)
Wilhelm Röntgen
Exposure (how much of material was ionized)

1 Sv = 1 J/kg,
takes into consideration
biological impact (quality factor)

Louis Harold Gray $1 \text{ Gy} = 1 \frac{J}{kg} = 1 \text{ m}^2 \cdot \text{s}^{-2}$

1 Rad = 0.01 Gy
Dose (how much energy was deposited)

Rolf Maximilian Sievert
Dose equivalent (how much harm
the deposited energy caused
to human)
1 Rem = 0.01 Sv

21 Managed by UT-Battelle
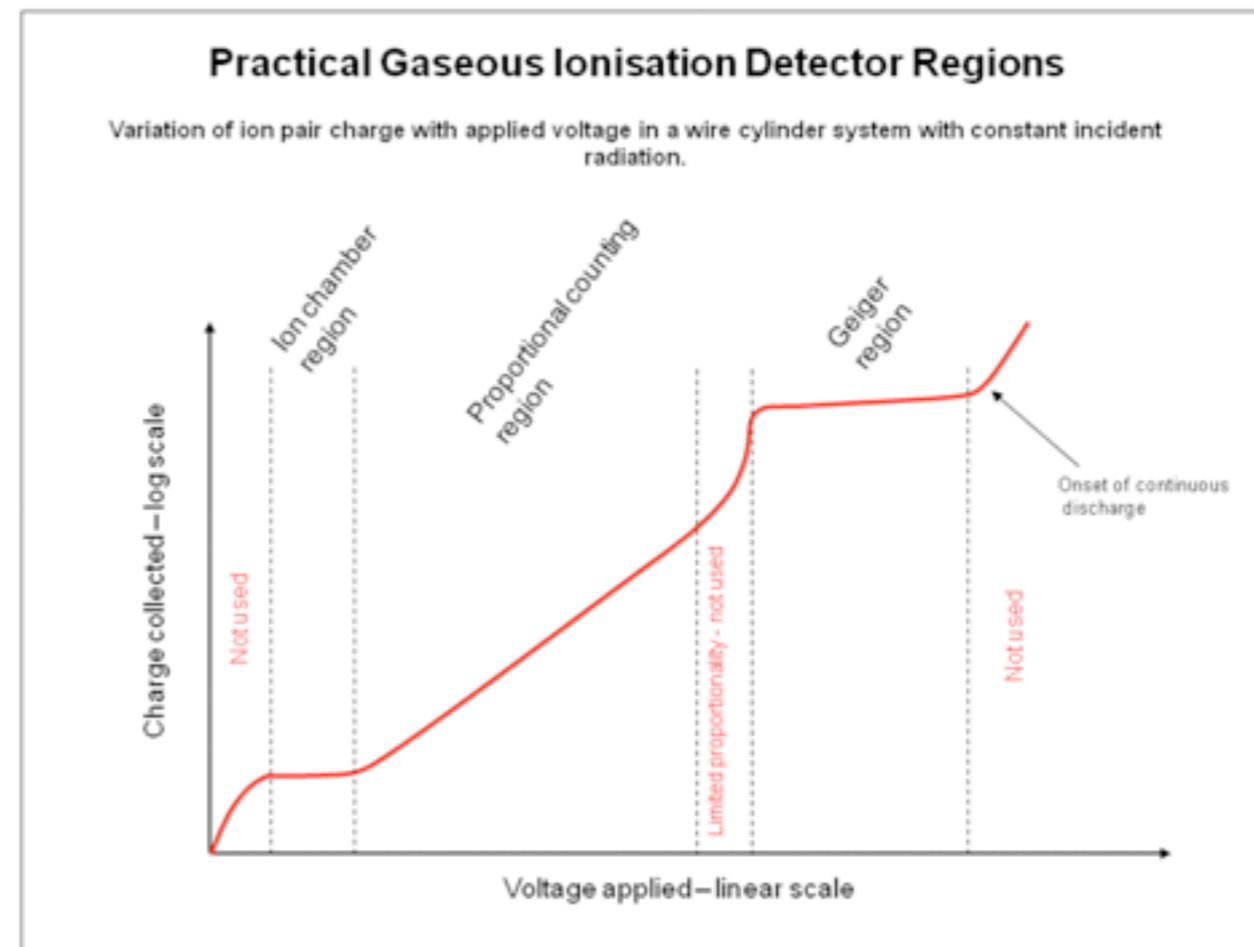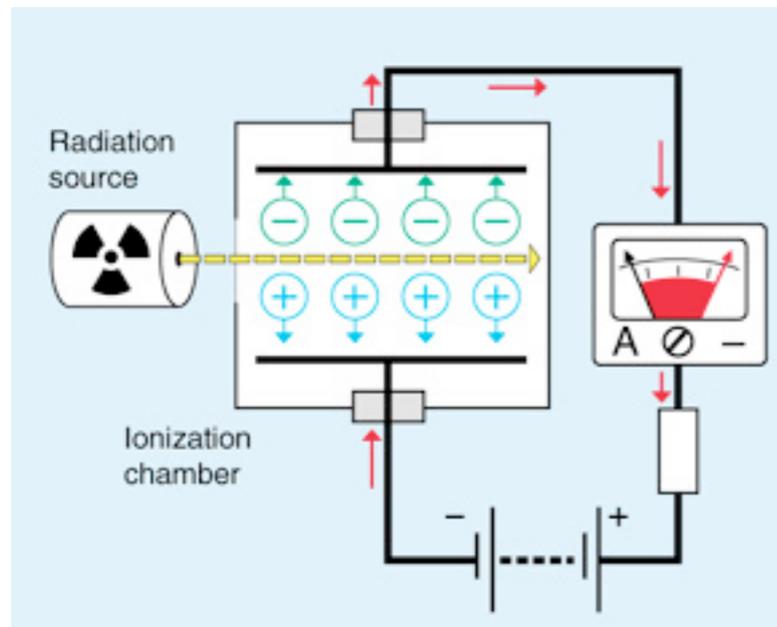for the U.S. Department of Energy

THTNB01 BIW2010

$$1\text{Gy} = 1\frac{J}{kg} \cdot \frac{MIP \cdot kg}{3.2 \cdot 10^{-10} \cdot J \text{ cm}^2} = 3.1 \cdot 10^9 \frac{MIP}{cm^2}$$

Ionization based BLMs

- ## Ionization Chamber
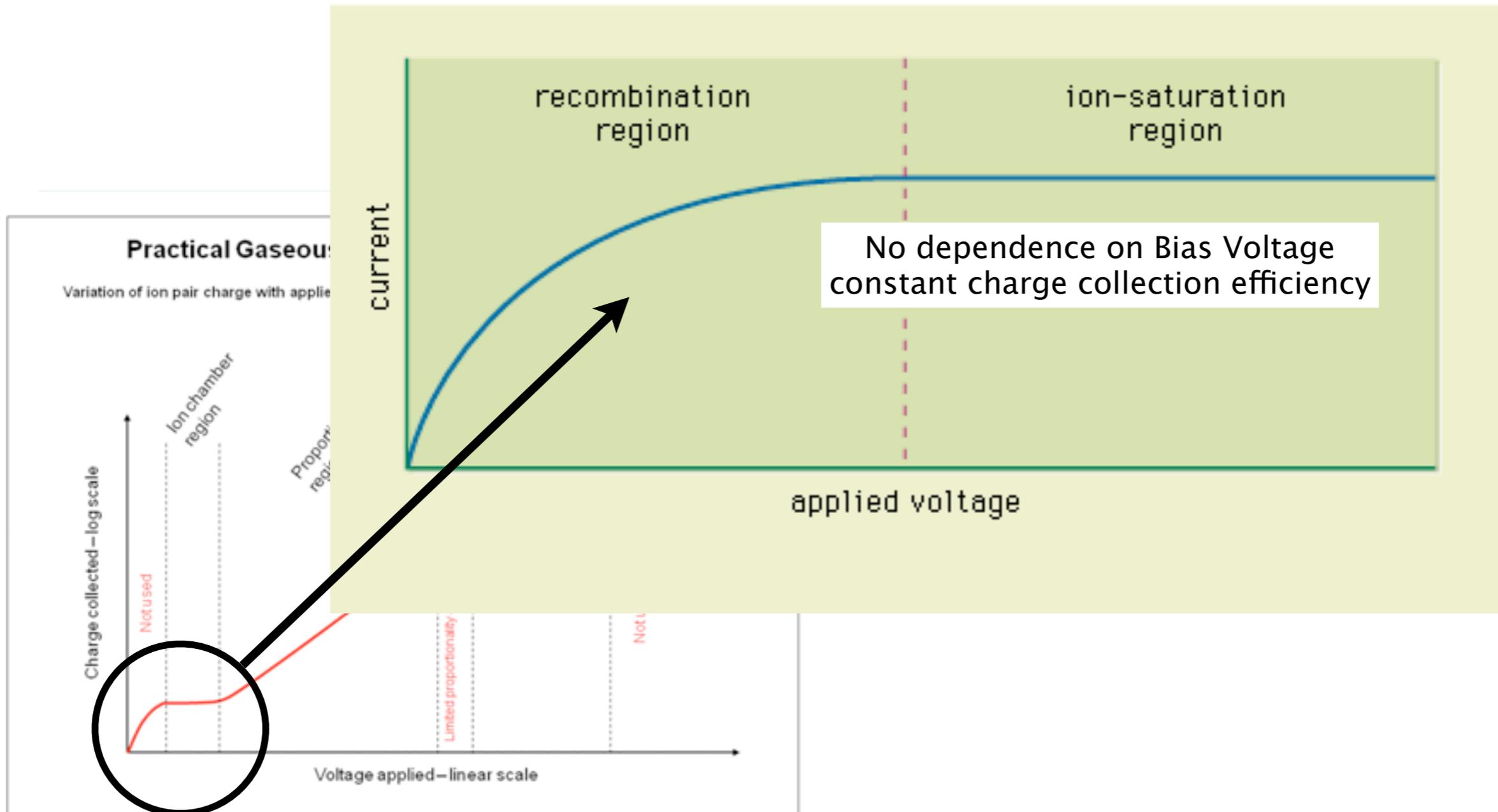 - Gas detector: Incident particle ionizes the active gas producing electrons (fast, a few ~100ns) and ions (slow, a few 100us) as charge carriers
  - (25–100) eV/pair depending on active gas

Practical Gaseous Ionisation Detector Regions

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

Ionization based BLMs

- Ionization Chamber

Practical Gaseous

Variation of ion pair charge with applied

recombination region

ion-saturation region

current

No dependence on Bias Voltage
constant charge collection efficiency

applied voltage

Charge collected—log scale

Not used

Ion chamber region

Propor...
regi...

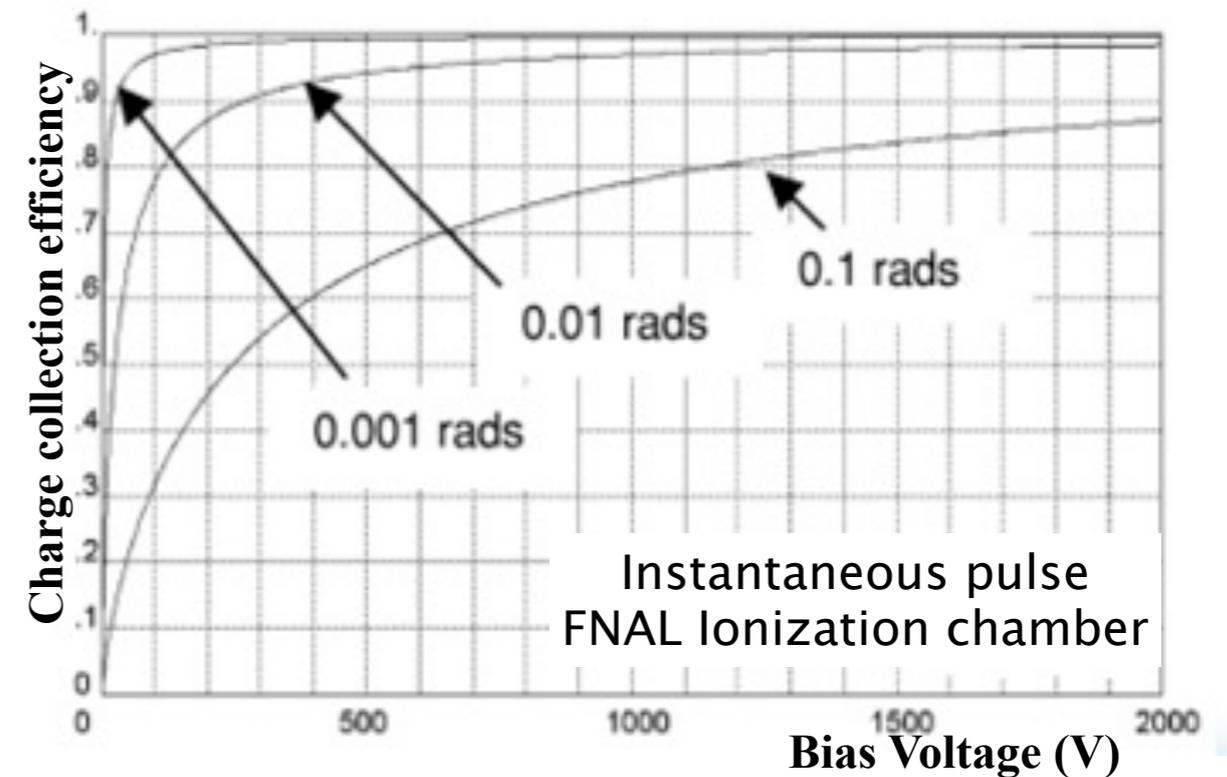Limited proportionality

Not u...

Voltage applied—linear scale

Ionization based BLMs

- Ionization Chamber: Saturation

  - Large number of e/ion pairs generated
  - The field generated by ions shields the Bias field
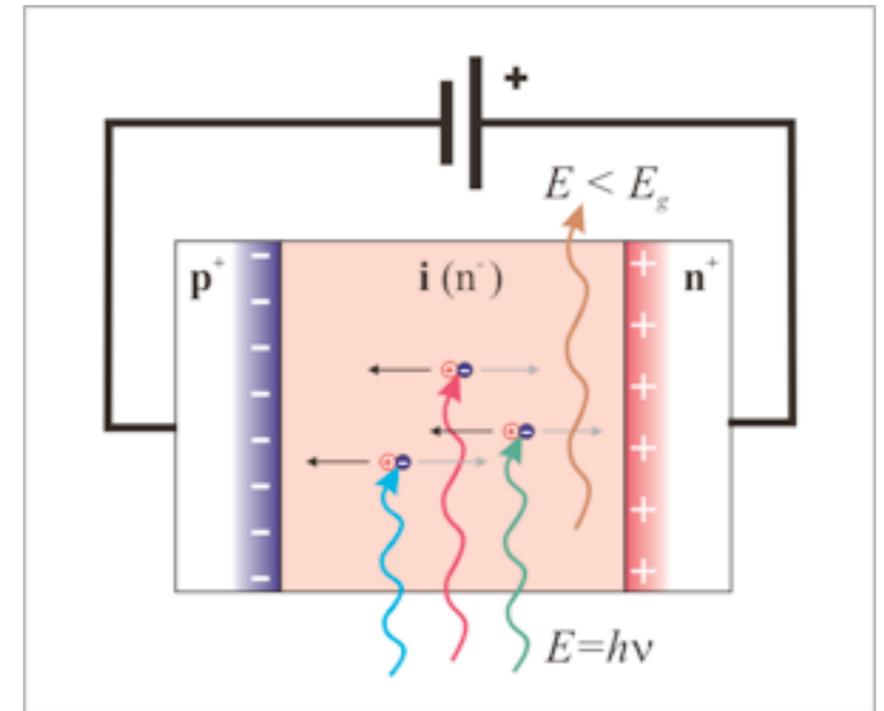 - Charge recombination

PRO/CONTs:
  - Very robust, radiation hard and require little maintenance
  - No dependence on Bias Voltage
  - Large dynamic range (up to 10^{+8}–10^{+9})
  - Slow (time resolution ~100us)
  - Saturation effects

Ionization based BLMs

- Semiconductor (PIN, diamond, Si,....). Solid state ionization chambers

  - Incident particles produce electron/ holes as charge carries (3–10eV/pair)
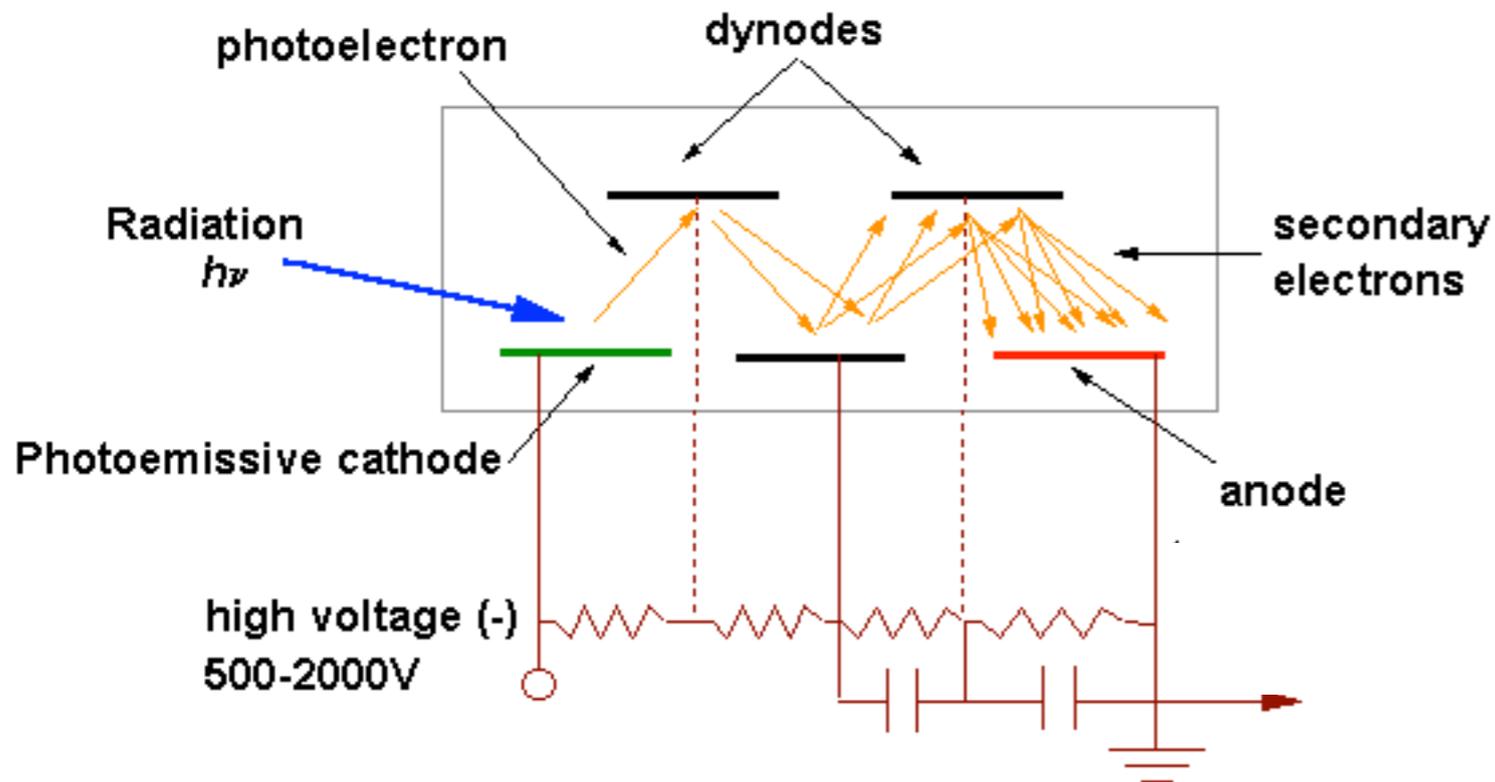 - $t_{hole} \gtrsim t_{electron} \sim$ 5–10 ns
  - smaller size

PRO/CONTs:
- No dependence on Bias Voltage
- Fast (er) response (5–10 ns)
- Radiation hardness (1 MGy)

Scintillation based BLMs

- Light produced by de-excitation of atomic/molecular levels
- Several types of scintillators
  - Inorganic crystals: NaI, CsI, ...
  - Organic (plastic): NE102, Antracene,...
  - Liquid

- Light directed (via Waveguides) to photomultiplier tube

Scintillation based BLMs

- **What needs to be considered**
  - Photon Yield
  - Collection Efficiency
  - Photocathode quantum efficiency
  - $G_{PMT} = \delta^n = (10^{+5} - 10^{+8})$ with:
    - δ (2–10) the number of secondary electrons
    - n (8–15) the number of dynodes

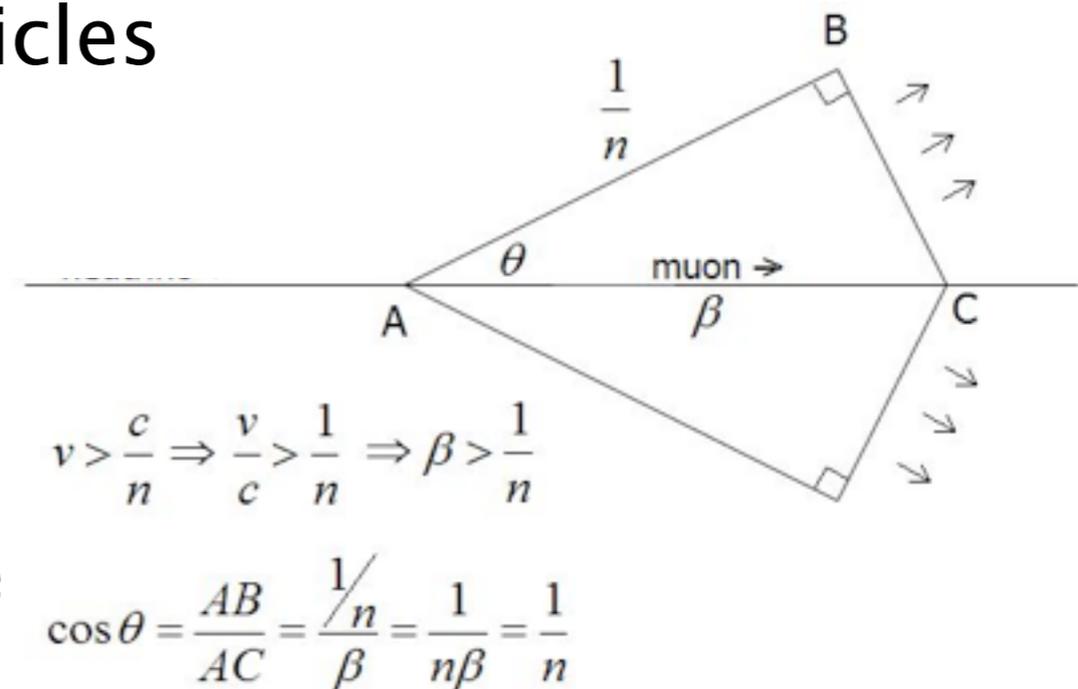| Material	R_S (γ/MeV)	ρ (g/cm³)
NaI	8 10^{+4}	3.7
PbWO$_4$	2 10^{+2}	8.3
NE102	2.5 10^{+4}	1.03
Antracene	4 10^{+4}	1.025

PRO/CONTs:
  - High sensitivity
  - Fast (5–10 ns) response (plastic/liquid)
  - Slow (100ns–1us) response (inorganic)
  - Limited radiation hardness (1MGy, 10MGy for liquids)
  - Gain control of PMT

Cherenkov light based BLMs

- Light produced by charged particles traveling at speed v>v$_{ligh}$

  - Photon Yield ~ 1000photons/mm (assuming quartz and a range 200–900nm)
  - Cherenkov spectrum proportional to λ–2. Only a small fraction on the light is usable

$$v > \frac{c}{n} \Rightarrow \frac{v}{c} > \frac{1}{n} \Rightarrow \beta > \frac{1}{n}$$

$$\cos \theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$$

- As for scintillators we need to consider collection efficiency and quantum efficiency of photosensor
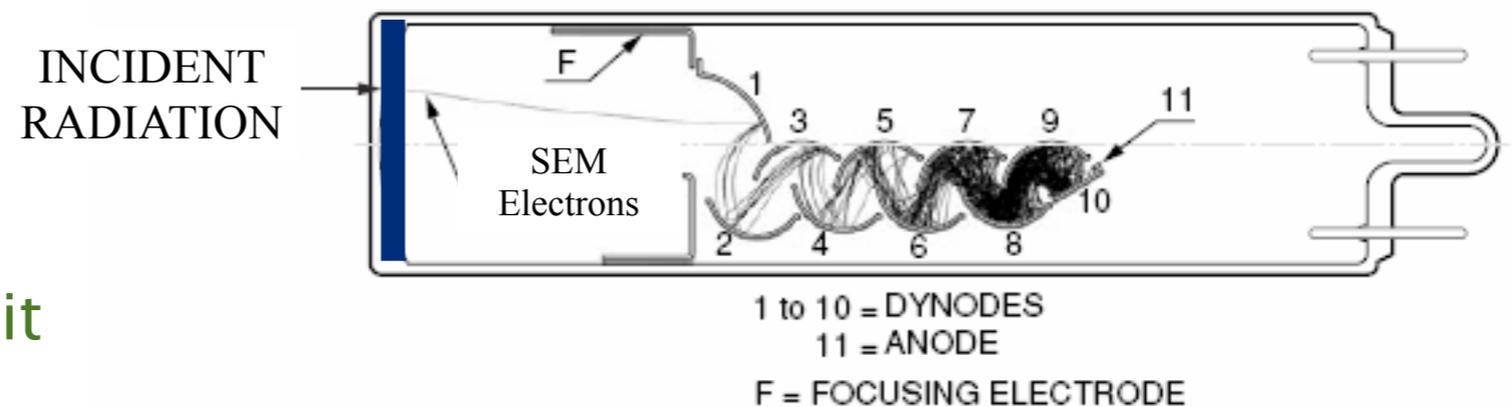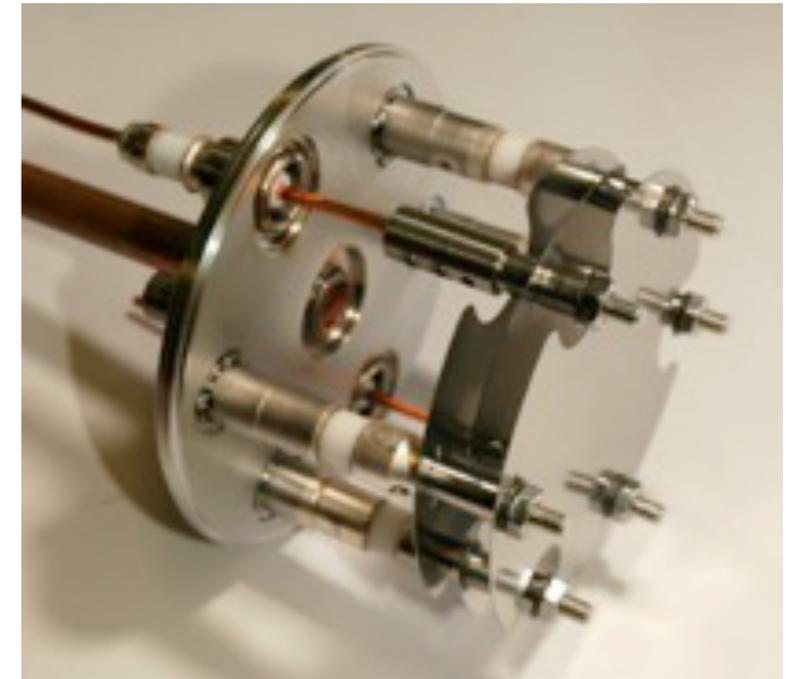
  PRO/CONTs:
  - Insensitive to neutral radiation
  - Fast (defined by your PMT or photosensor)
  - Low sensitivity
  - Limited radiation hardness (10–100MGy)

Secondary emission based BLMs

- Sensitivity defined by the (1–5)% charges produced per primary

- Tow possibilities:
  - With no amplification
    - Very low sensitivity
    - Needs current integration
  - With amplification
    - broadband current amplifiers
    - PMTs (sensitive to B fields)

PRO/CONTs:
  - Fast (<10ns). Electron transit
  - Very linear
  - Radiation hard (ideal for high radiation environments)
  - Very low sensitivity
  - Insensitive to neutral particles

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

Sensitivity summary

- **Ionization chamber:** **70 µC/Gy**
  1 liter argon
  $S \approx$ active mass · charge per ionization energy $\approx V \cdot \rho \cdot e / E_{ion} \approx 1\,l \cdot 1.8\,g/l \cdot e / 26\,eV$
- **Long ionization chamber:** **20 µC/Gy**
  1 meter length, 1 cm radius, argon
  $S \approx$ active mass · charge per ionization energy $\approx \pi r^2 \cdot L \cdot \rho \cdot e / E_{ion} \approx 314\,cm^3 \cdot 1.8\,g/l \cdot e / 26\,eV$
- **PIN diode:** **6 µC/Gy**
  1 cm² surface, 100 µm depletion depth
  $S \approx$ active mass · charge per excitation energy $\approx A \cdot d \cdot \rho \cdot e / E_{ion} \approx 10\,mm^3 \cdot 2.3\,g/cm^3 \cdot e / 3.6\,eV$
- **Secondary emission monitor:** **500 pC/Gy**
  100 cm² surface, 0.01 average secondary emission yield (SEY)
  $S \approx$ surface · SEY · electron charge · density of primaries per dose $\approx A \cdot SEY \cdot e \cdot (\rho/(dE/dx))$
  $\approx 100\,cm^2 \cdot 0.01 \cdot e \cdot 1/(2\,MeV \cdot cm^2/g)$
- **Aluminum cathode electron multiplier:** **5 µC/Gy**
  10 cm² surface, 0.01 average secondary emission yield (SEY), tube gain 10^5
  $S \approx$ surface · SEY · electron charge · density of primaries per dose · gain $\approx A \cdot SEY \cdot e \cdot (\rho/(dE/dx)) \cdot G$
  $\approx 10\,cm^2 \cdot 0.01 \cdot e \cdot 1/(2\,MeV \cdot cm^2/g) \cdot 10^5$
- **PMT with organic scintillator:** **200 C/Gy** ← Radiation damage problematic!
  1 liter scintillator, 60% collection efficiency, 30% photocathode efficiency, tube gain 10^5
  $S \approx$ active mass · photon yield per energy · collection efficiency · photocathode efficiency · gain · electron charge
  $\approx V \cdot \rho \cdot Y \cdot C \cdot P \cdot G \cdot e = 1\,l \cdot 1\,g/cm^3 \cdot 1/(100\,eV) \cdot 0.6 \cdot 0.3 \cdot 10^5 \cdot e$
- **Bare PMT (Čerenkov light):** **4 mC/Gy**
  10 cm² surface, 1 mm thick, 30% photocathode efficiency, tube gain 10^5
  $S \approx$ active volume · density of primaries per dose · photon yield per length · photocath. efficiency · gain · electron charge
  $\approx A \cdot d \cdot \rho \cdot (\rho/(dE/dx)) \cdot Y \cdot P \cdot G \cdot e \approx 1\,cm^3 \cdot 1/(2\,MeV \cdot cm^2/g) \cdot 260/cm \cdot 0.3 \cdot 10^5 \cdot e$
- **PMT with Cerenkov fiber:** **2 µC/Gy**
  1 meter length, 100 µm radius, 2% collection efficiency, 30% photocathode eff., tube gain 10^5
  $S \approx$ active volume · density of primaries per dose · photon yield per length · coll. eff. · photoc. eff. · gain · electron charge
  $\approx \pi r^2 \cdot L \cdot \rho \cdot (\rho/(dE/dx)) \cdot Y \cdot C \cdot P \cdot G \cdot e \approx 31\,mm^3 \cdot 1/(2\,MeV \cdot cm^2/g) \cdot 260/cm \cdot 0.02 \cdot 0.3 \cdot 10^5 \cdot e$

Flexible gain → linearity and calibration problematic!

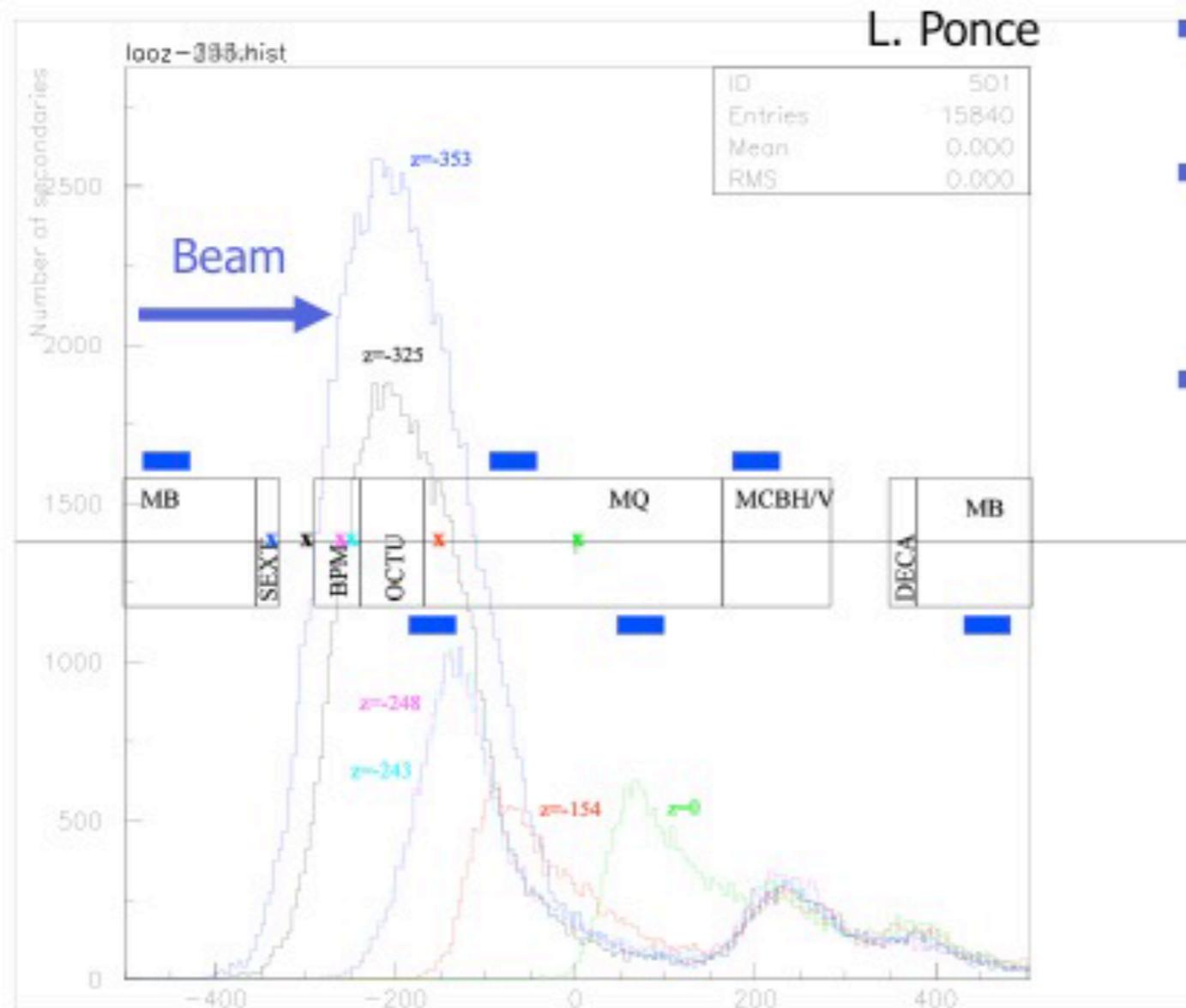| Detector material	Energy to create one electron [eV/e]	Number of [e / (cm MIP)] (depends on dE/dx and density)	Sensitivity S (for MIPs) [nC/rad]
Plastic scintillator	250–2500	$10^3 - 10^4$	$\approx 18 \cdot 10^3$ ($\cdot PMT_{gain}$) (1 ltr.)
Inorganic scint	50–250	$10^4 - 10^5$	$\approx 200 \cdot 10^3$ ($\cdot PMT_{gain}$) (1 L)
Gas ionization	22–95	≈ 100 (Ar,1 atm., 20°C)	≈ 600 ($\cdot Elec_{gain}$) (1 L)
Semiconductor (Si)	3.6	10^6	≈ 100 ($\cdot Elec_{gain}$) (1 cm² PIN diode)
Secondary emission	2–5%/MIP (surface only)	0.02–0.05 e/MIP	$\approx 2 \cdot 10^{-3}$ ($\cdot PMT_{gain}$) (8 cm²)
Cherenkov light	$10^5 - 10^6$	≈ 10 (H_2O)	≈ 270 ($\cdot PMT_{gain}$) (1 L)

BLM choice and design considerations

- No Universal rule!!!. Your BLM system will be designed for one particular machine
  - you CAN/SHOULD learn from BLM systems in previous machines but you won't be able to just copy any of them
  - Every accelerator is different: intensity, timing, radiation, length, normal conducting/superconducting ...

- To design a BLM system we need to consider:
  - Sensitivity
  - Dynamic range
  - Time response
  - Type of radiation
  - Shield-ability (from unwanted radiation)
  - Response to excessive radiation (saturation effects)
  - Physical size of BLMs
  - Test-ability
  - Calibration techniques
  - System end to end online test
  - Cost

Location of BLMs

- Where is the ideal location of a BLM? Everywhere!!!!

- What's the best "realistic" location of a BLM?

  - Beam Physics. Particles more likely to be lost at:
    - Beam envelope maxima
    - Aperture limitations
    - Both

  - Comprehensive study of possible failure cases and consequences on beam
    - Miss-alignments
    - Asynchronous firing of kicker magnets
    - Some surprises may come once your machine is running

  - Simulations
    - Tracking codes (MADX, SixTrack,.....)
    - Monte Carlo simulation codes (Geant4, FLUKA, EGS5, ...)
    - Benchmarking experiments (i.e. don't trust your simulations)

Location of BLMs

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
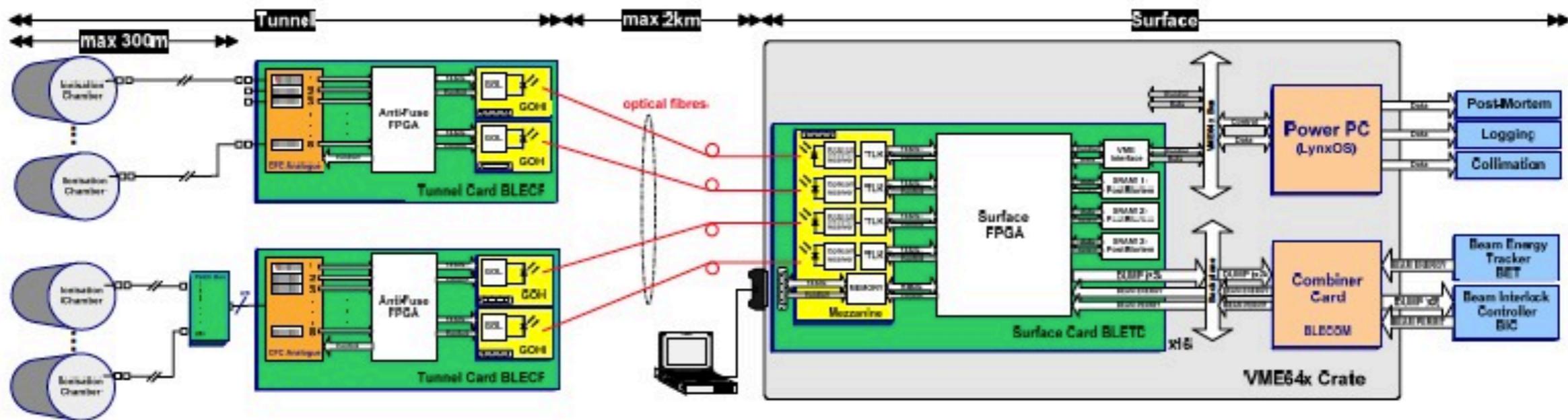 - to minimize uncertainty of ratio of energy deposition in coil and detector
  - Beam I – II discrimination

- Good probability that losses are seen by two BLM detectors
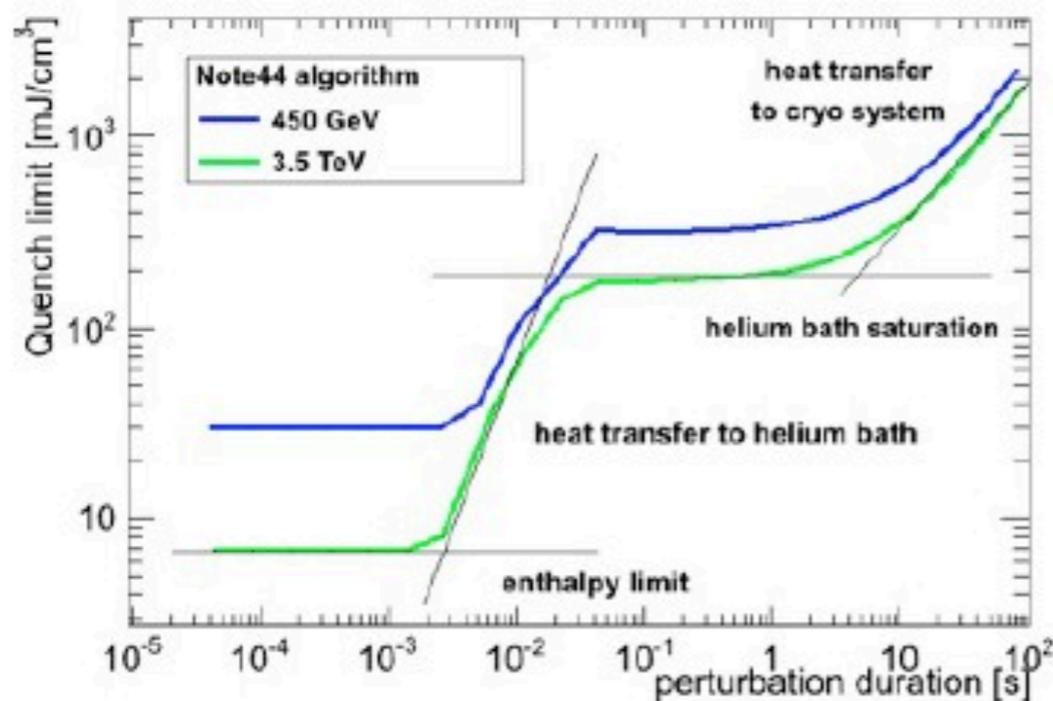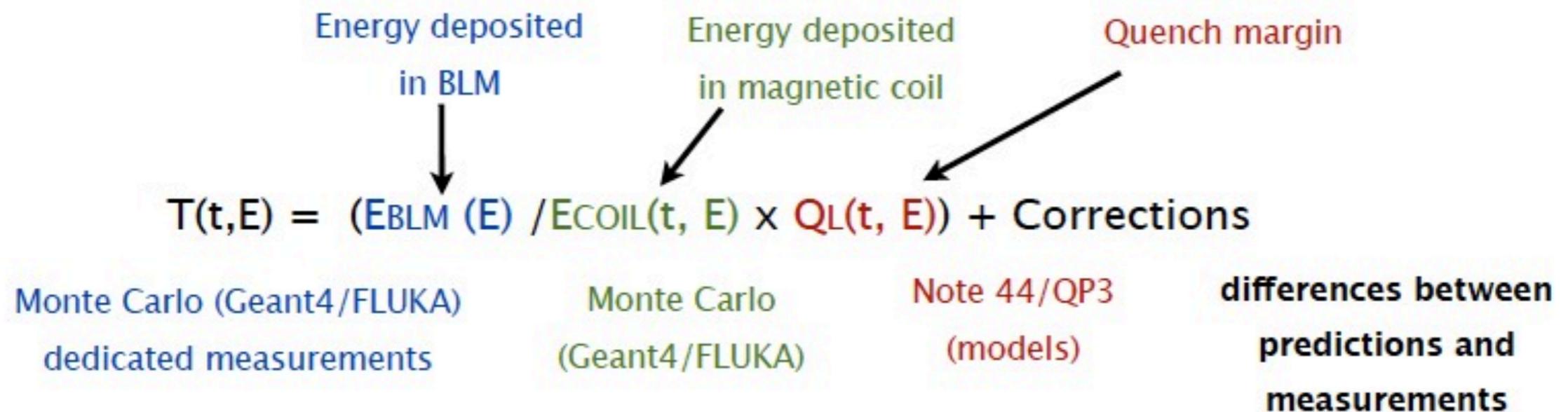
Machine Protection: the LHC case

- Avoid quench of superconducting magnets and any damage produced by beam losses.
  - About 3600 Ionization Chambers located around the LHC ring in likely-loss locations
  - The surface electronics cards receive the data for decoding and processing. The system computes the signals integrated in 12 different integration windows. These values are continuously compared to a set of predefined thresholds
  - The surface electronics cards receive the data for decoding and processing. The system computes the signals integrated in 12 different integration windows. These values are continuously compared to a set of predefined thresholds
  - Both the signals recorded by the BLMs and their abort thresholds are sent to Data Bases for offline analysis

Machine Protection: the LHC case

- In the LHC, the abort thresholds are mainly set to protect against "quench"

Energy deposited in BLM $\quad$ Energy deposited in magnetic coil $\quad$ Quench margin

$$T(t,E) = (E_{BLM}(E) / E_{COIL}(t, E) \times Q_L(t, E)) + \text{Corrections}$$

Monte Carlo (Geant4/FLUKA) dedicated measurements $\qquad$ Monte Carlo (Geant4/FLUKA) $\qquad$ Note 44/QP3 (models) $\qquad$ **differences between predictions and measurements**

- Each BLM has a 12 x 32 threshold table
  - 12 integration windows (40 us, ..., 83 s)
  - 32 energy levels (0 – 7TeV)

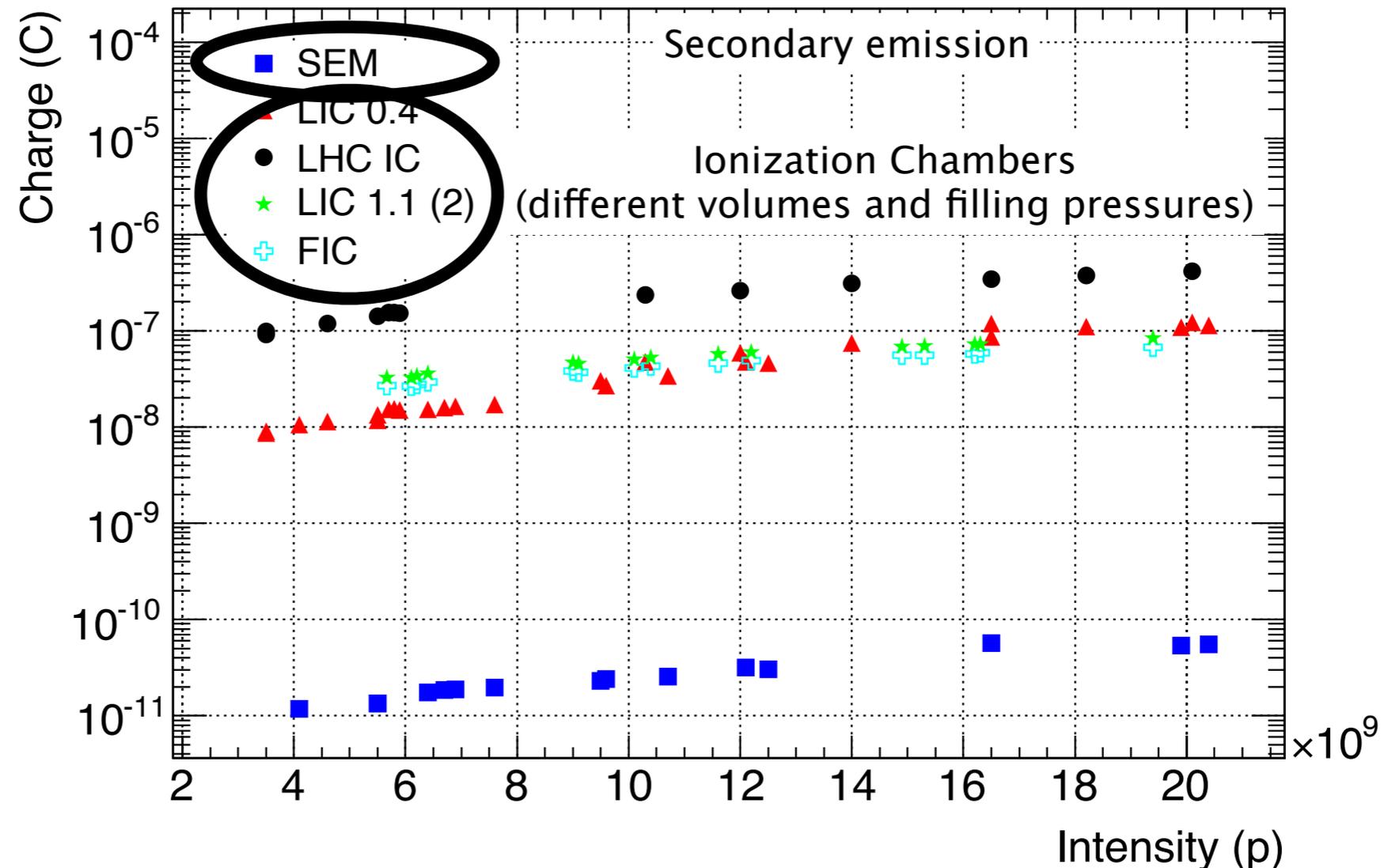- 4000 BLMs x 12 x 32 > 1.5 million thresholds

Challenges

Dynamic range

- New machines require BLMs covering Dynamic ranges $\gtrsim 10^{+6}$
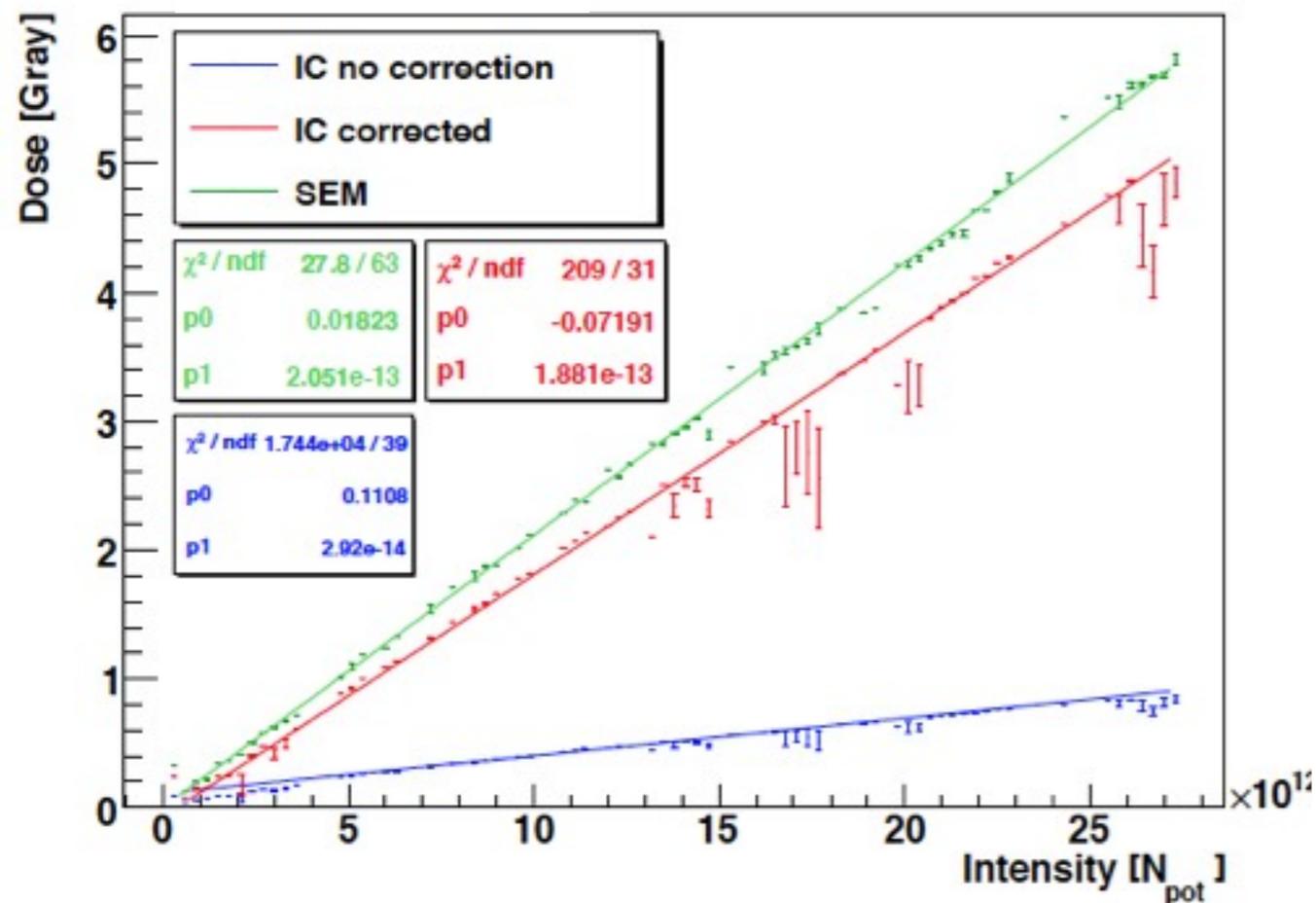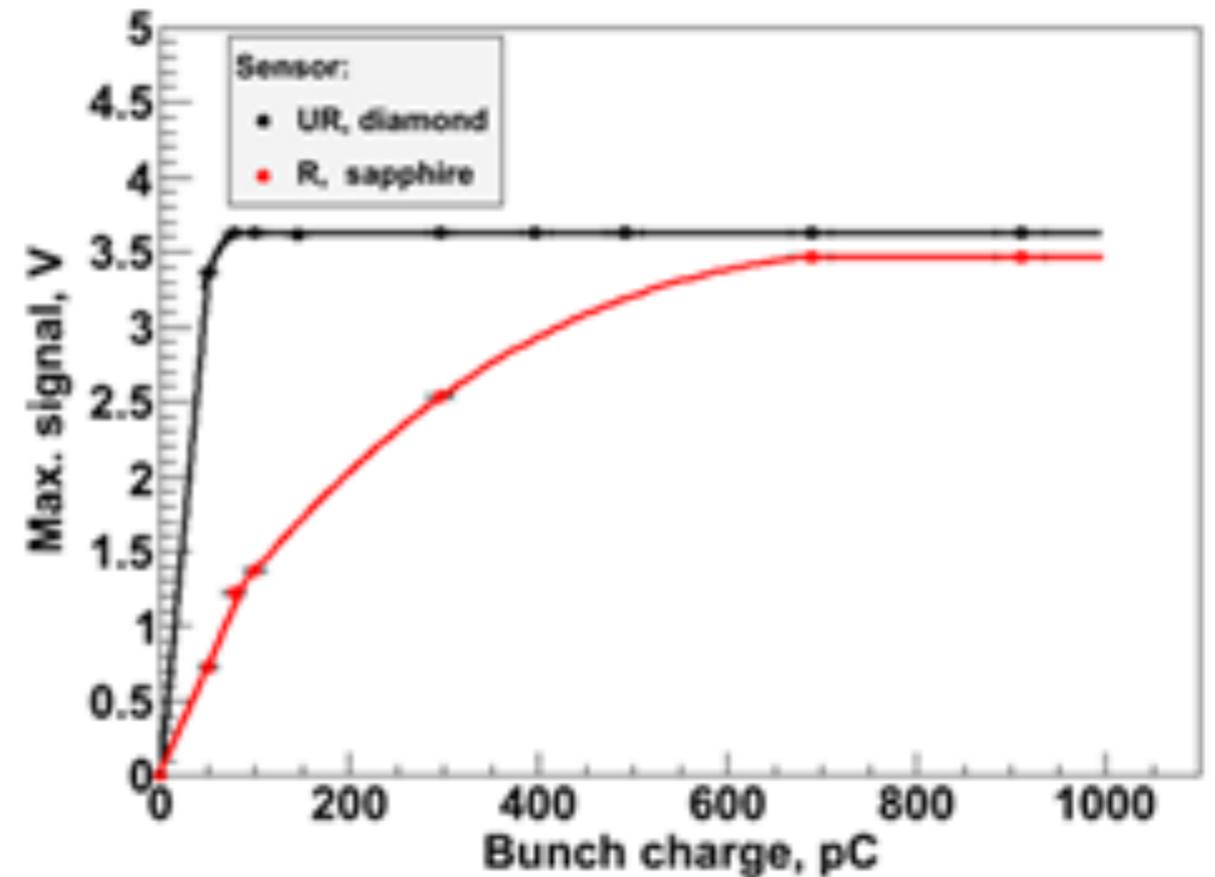- Various types of BLMs

High radiation environments

- In hard irradiation conditions most detectors and/or electronics will suffer saturation effects:
  - Understand/correct saturation effects
  - Develop insensitive detectors
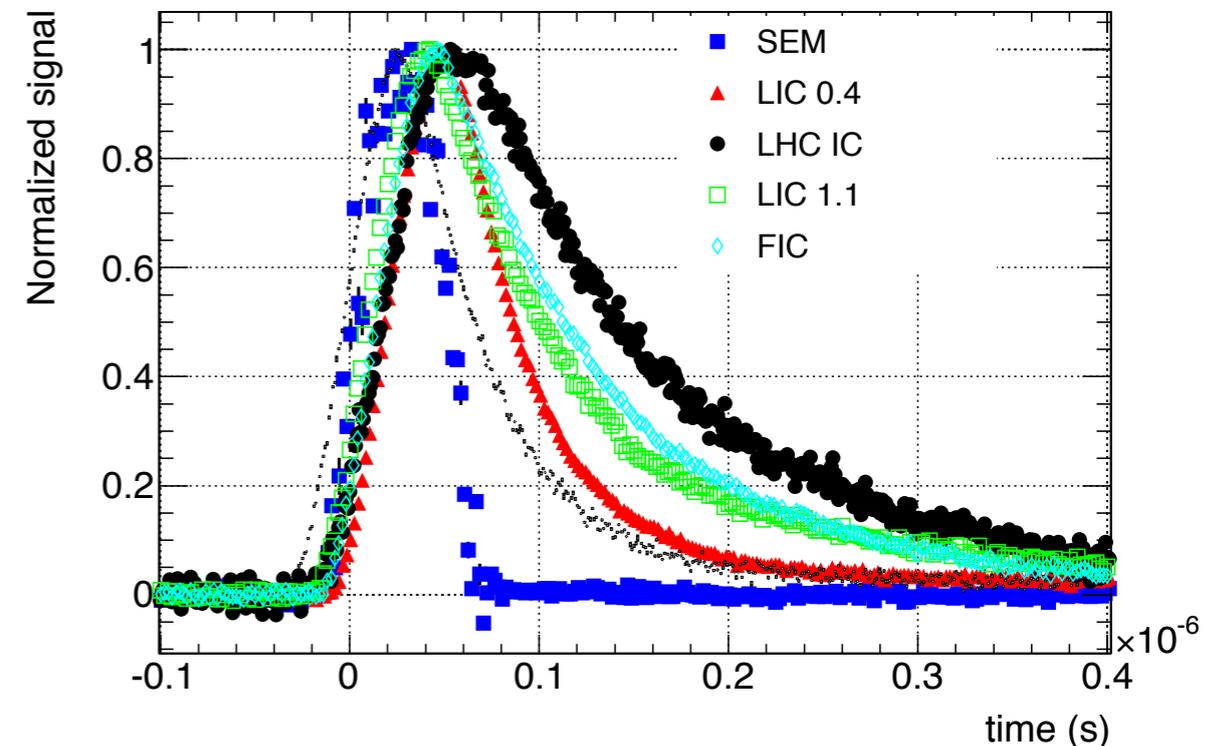
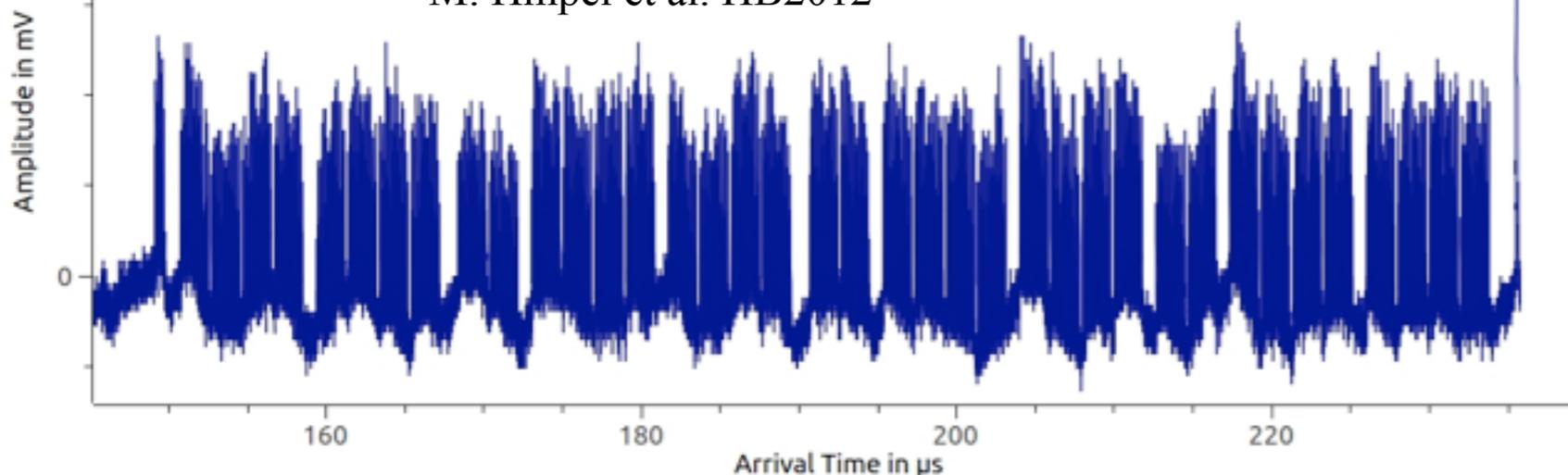D. Kramer Thesis

A. Ignatenko Thesis

Time resolution

- Determined by the need of measuring bunch by bunch "everything" (that includes beam losses)
- In hadron machines:

  - ICs are typical BLMs (radiation hard, reliable, ...)
  - But slow (~us). Can't see bunch spacing (~ 10–100 ns)
  - SEM are faster but very insensitive. (Broadband amplifiers for <10ns resolution BLMs??!!)

Bunch by bunch beam loss diagnostics with diamond detectors at the LHC
M. Hmpel et al. HB2012

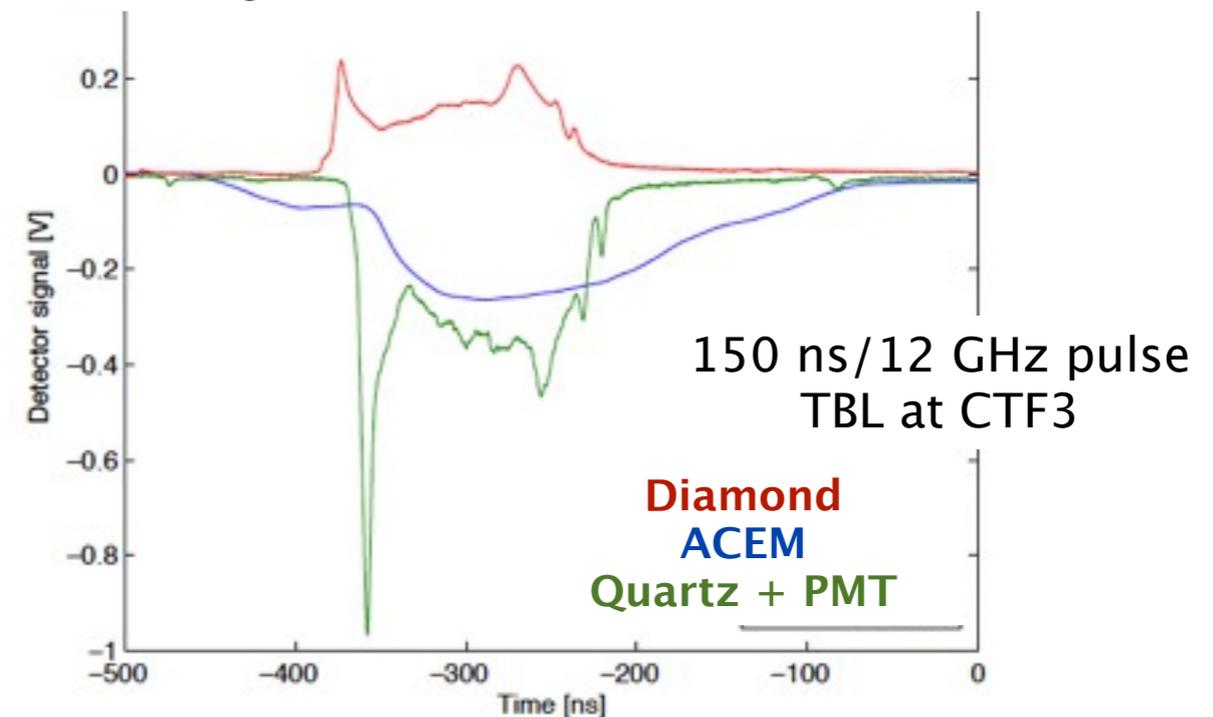 - Diamond detectors:
    - resolution ~ 1ns
    - radiation hard

Time resolution

- **In electron machines:**

  - The bunch spacing is pushing to unprecedented limits
  - E.g: CLIC: 0.6 – 0.083 ns

150 ns/12 GHz pulse
TBL at CTF3

Diamond
ACEM
Quartz + PMT

- **Cherenkov light (as prompt radiation) is currently the best candidate for fast BLMs**

  - Ultra fast photo sensor have been demonstrated to disentangle 12GHz bunch spacing
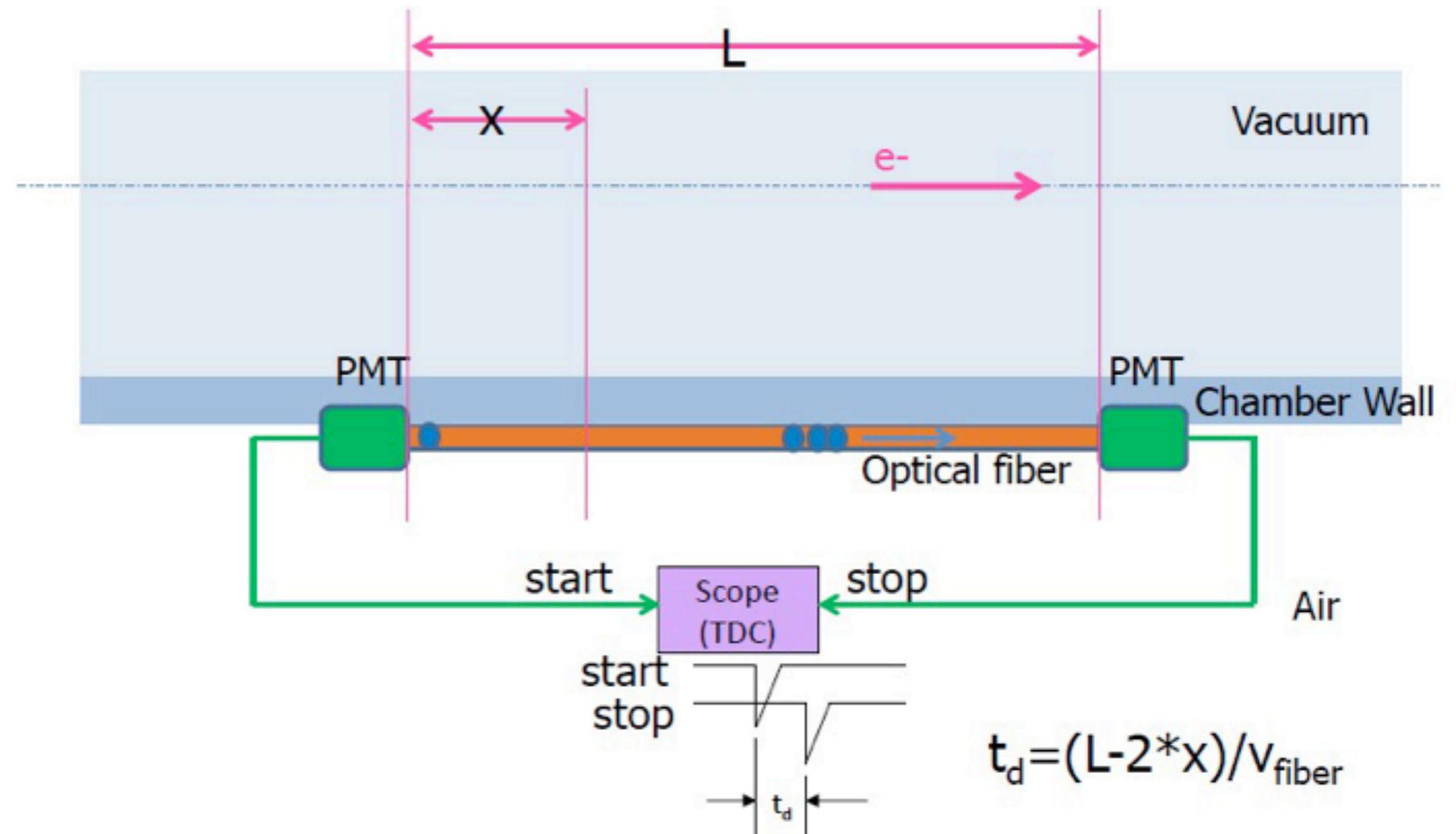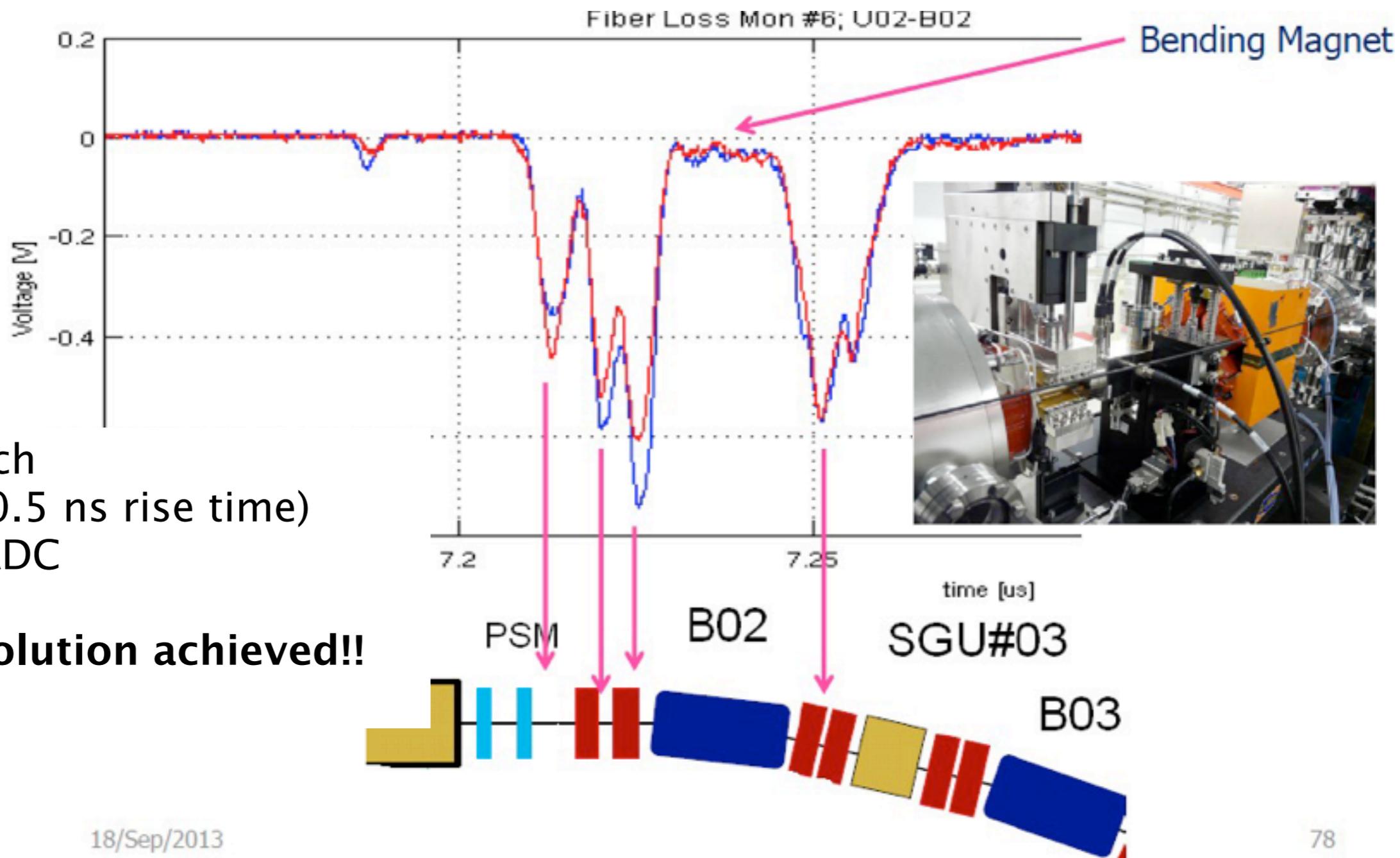
Position resolution

- It is defined by the granularity of the system, i. e. higher number of BLMs provides higher resolution

- Optical fibers provide position resolution by measuring signal delay

$$t_d = (L - 2*x)/v_{fiber}$$

Position resolution

- KEK–PF
- 2.5 GeV electrons
- single bunch

Single bunch
Fast PMT (0.5 ns rise time)
500 MHz ADC

30 cm resolution achieved!!

Position resolution

- ## What about machines with long pulses?
    - e.g CLIC/CTF3: 150 ns (30 m @2/3c) pulse with 12 GHz bunch spacing
    - Test setup at Test Beam Line (28 m)

High background environments

- Background = unwanted radiation
  - A BLM system should ideally measure beam losses. However, ionizing radiation can be generated by other mechanisms and detected by your BLMs:
    ‣ Electromagnetic noise
    ‣ RF cavities
    ‣ Synchrotron radiation

- Consequence
  - Dynamic range limitation

High background environments
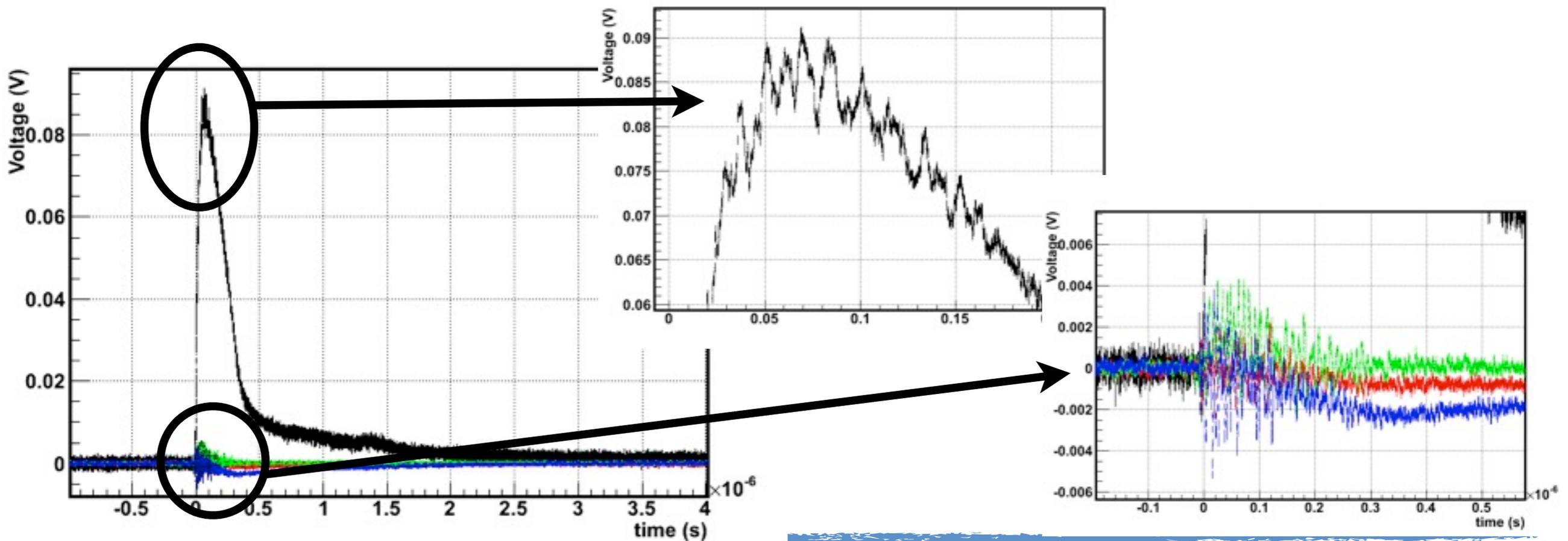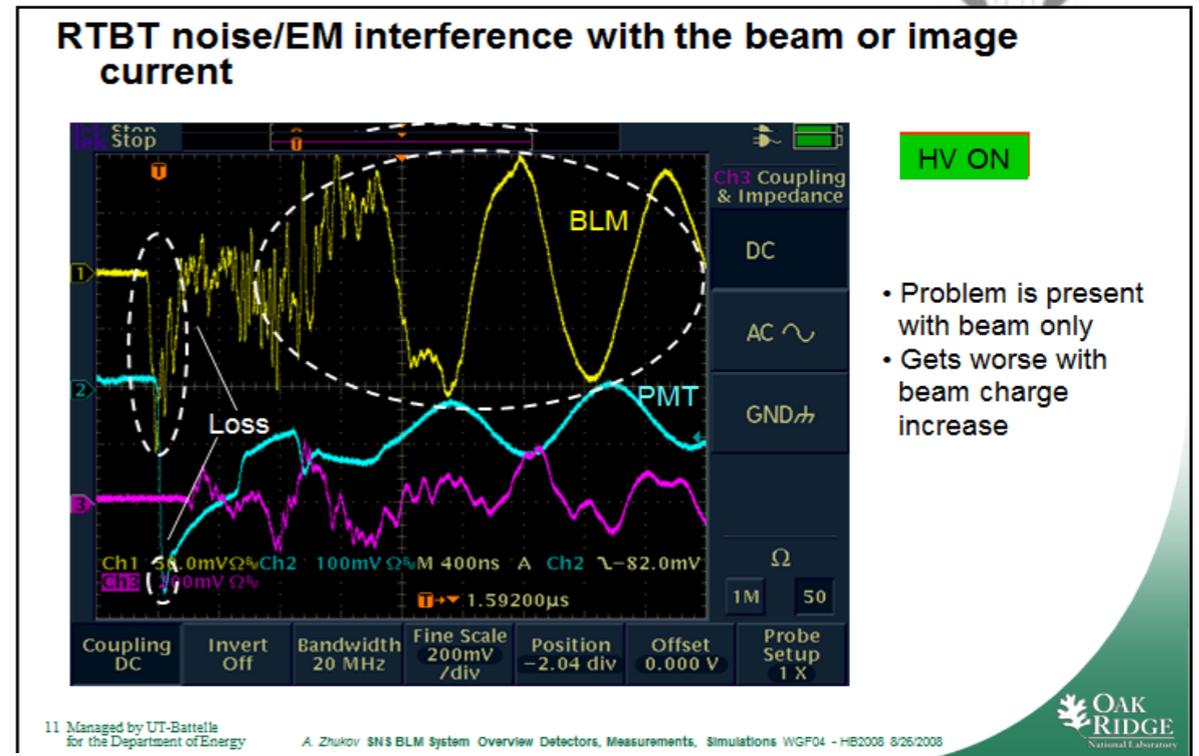
- **EM noise**
  - PS ripple
  - Neighboring magnets
  - Ground loops

- Provide the best shielding that you can .... and hope for the best!

RTBT noise/EM interference with the beam or image current

HV ON

- Problem is present with beam only
- Gets worse with beam charge increase

High background environments

- **RF cavities**
  - Electrons released (and escaping) in cavity
  - X rays

XFEL Beam Loss Monitor System
A. Kaukher, I. Krouptchenkov et al. IPAC12

Beam Loss Detected by Scintillation Monitor
Akihiko Miura, et al. **IPAC´11**

Figure 4: BLM signals from a single bunch and dark current at FLASH (April 2012): BLM with SQ1 synthetic fused silica (top, HV=700 V) and BLM with a scintillator (HV=550 V).

Figure 5: Signals from a gas proportional monitor (green) and plastic scintillation monitor (magenta) at SDTL13 section, during beam operation with chopped beam. The beam current signal with a current transformer is also shown (yellow).

- **Subtraction by software (no help on dynamic range) or detectors insensitive to X rays**

High background environments
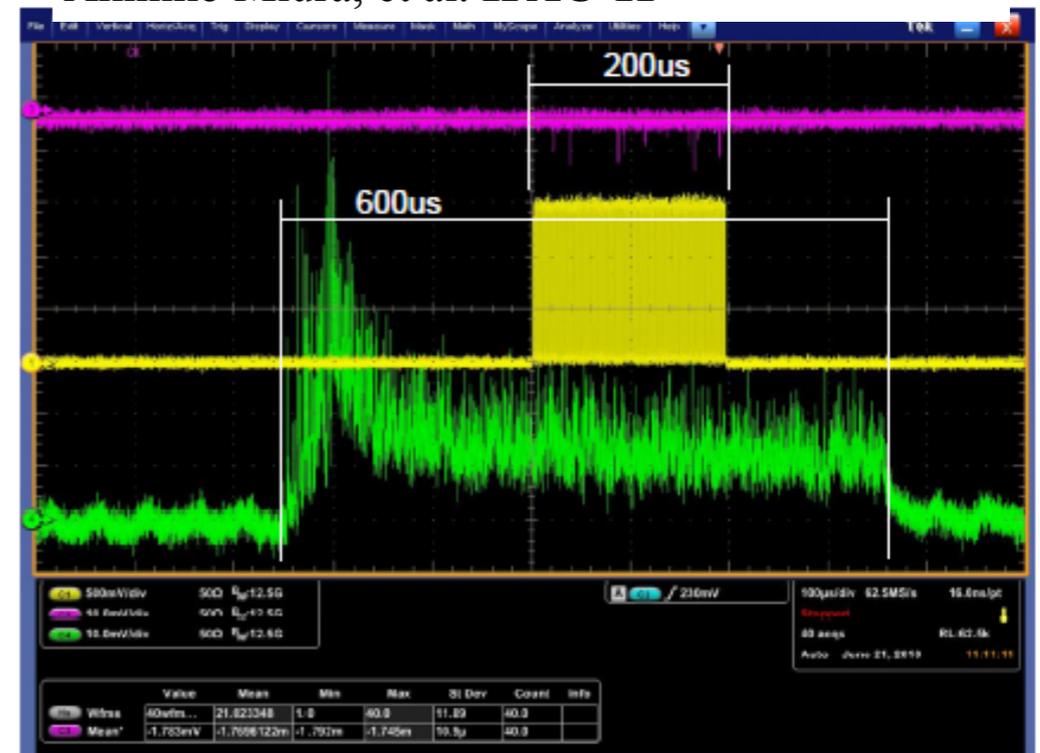
- Synchrotron radiation
  - X rays

- Subtraction by software (no help on dynamic range) or detectors insensitive to X rays

NSLS-II Beam Loss Monitor System
S. L. Kramer DIANET 2011

- Quartz rods and fibers (as Cherenkov light radiators) are insensitive to neutral radiation

- PIN diode "sandwiches" in coincidence

Operating principle

+ Bias   Photon

100μm

≤100ns

Coincidence

Charged particle

The charged particle crosses both PIN-diodes, causing a coincidence. Synchrotron radiation photons, if stopped by either PIN-diode, do not cause a coincidence

"Electron Beam Loss Monitors for HERA"
W. Bialowons et al.

Beam Losses at low energy

- Very few particles (secondaries) outside of the vacuum chamber

- Even fewer inside the active volume of the detector

Measurements and Simulations of Ionization Chamber Signals in Mixed Radiation Fields for the LHC BLM System

M. Stockner IEE-NSS 2006

LINAC2
50 MeV protons
I~3.5 10^{+3} p

ACEM

LHC-IC

BEAM CURRENT

PSI-PIF
120 MeV protons
copper collimator

3 orders of magnitude higher than IC leakage current

- – BLMs very close to beam pipe
- – neutron sensitive BLMs
- – Very sensitive BLMs (gain)
- – BLMs at aperture limitations (collimators)

Summary and conclusions

- You CANNOT just recycle an already designed BLM system for your own machine
  - Get as much information as possible from past experience
  - Define your specifications according to your accelerator needs
  - Stick with well known technologies if you can (they keep being used for a reason)

- TBL: Implement BLM system within the current operational instrumentation for machine tuning
  - Provide calibrated signals and display
  - Dedicated studies on position resolution with optical fibers

Thank you for your attention

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [μs]	Photons/MeV
NaI	3.7	1.78	303	0.06	$8 \cdot 10^4$
NaI(Tl)	3.7	1.85	410	0.25	$4 \cdot 10^4$
CsI(Tl)	4.5	1.80	565	1.0	$1.1 \cdot 10^4$
$Bi_4Ge_3O_{12}$	7.1	2.15	480	0.30	$2.8 \cdot 10^3$
CsF	4.1	1.48	390	0.003	$2 \cdot 10^3$
LSO	7.4	1.82	420	0.04	$1.4 \cdot 10^4$
$PbWO_4$	8.3	1.82	420	0.006	$2 \cdot 10^2$
LHe	0.1	1.02	390	0.01/1.6	$2 \cdot 10^2$
LAr	1.4	1.29*	150	0.005/0.86	$4 \cdot 10^4$
LXe	3.1	1.60*	150	0.003/0.02	$4 \cdot 10^4$

* at 170 nm

Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4 \cdot 10^3$
Antracene	1.25	1.59	448	30	$4 \cdot 10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2 \cdot 10^4$
NE102*	1.03	1.58	425	2.5	$2.5 \cdot 10^4$
NE104*	1.03	1.58	405	1.8	$2.4 \cdot 10^4$
NE110*	1.03	1.58	437	3.3	$2.4 \cdot 10^4$
NE111*	1.03	1.58	370	1.7	$2.3 \cdot 10^4$
BC400**	1.03	1.58	423	2.4	$2.5 \cdot 10^2$
BC428**	1.03	1.58	480	12.5	$2.2 \cdot 10^4$
BC443**	1.05	1.58	425	2.2	$2.4 \cdot 10^4$

Sensitivity S_{Ion} [C/rad] of Ion-chamber depends on geometry!

Example: 1 ltr. Argon filled chamber, 100% charge sampling efficiency:
$\rho = 1.661 \cdot 10^{-3}$ g/cm³ (20⁰C, 1 atm)

$$S_{Ion} = 100 \frac{erg}{g} \cdot \frac{1 eV}{1.6 \cdot 10^{-12} erg} \cdot \frac{1 e^-}{26 eV} \cdot \frac{1.66 \cdot 10^{-3} g}{cm^3} \cdot 1000 \, cm^3 \cdot \frac{1.6 \cdot 10^{-19} C}{e^-} = 638 \frac{nC}{rad}$$

1 rad   eV ---> erg   W   ρ   1 ltr.   e⁻ charge

Short Ionization Chamber
Calibration/Sensitivity

The number of electrons (n_e) produced in the gap by one minimum ionizing
Particles (MIPs) is:

$$n_e = \frac{D \cdot \rho}{W} \cdot \frac{dE}{dx} (Medium) \longleftarrow \text{Bethe-Bloch}$$

Note that the average energy needed to
produce an electron-ion pair (W-factor)
is larger than the ionization energy.
Is about constant for many gases
and radiations.

Example: Argon:
$\rho = 1.661 \cdot 10^{-3}$ g/cm³ (20⁰C, 1 atm)
dE/dx = 1.52 MeV/(g/cm²)

Gas	first ionisation potential	W [eV/e-] fast electrons
Ar	15.7	26.4
He	24.5	41.3
H₂	15.6	36.5
N₂	15.5	34.8
Air		33.8
O₂	12.5	30.8
CH₄	14.5	27.3

$n_e \approx 100/cm \cdot D$ [e/ MIP]

Note: Cross section for nuclear interaction is about $5 \cdot 10^{-6}$
times the ionization cross section (10^{-16} cm²). Cross section
for excitation is about 10^{-17} cm².
Rutherford (nuclear) scattering does not produce significant
energy transfer, but angular spread.