An overview on Beam Loss Monitoring

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

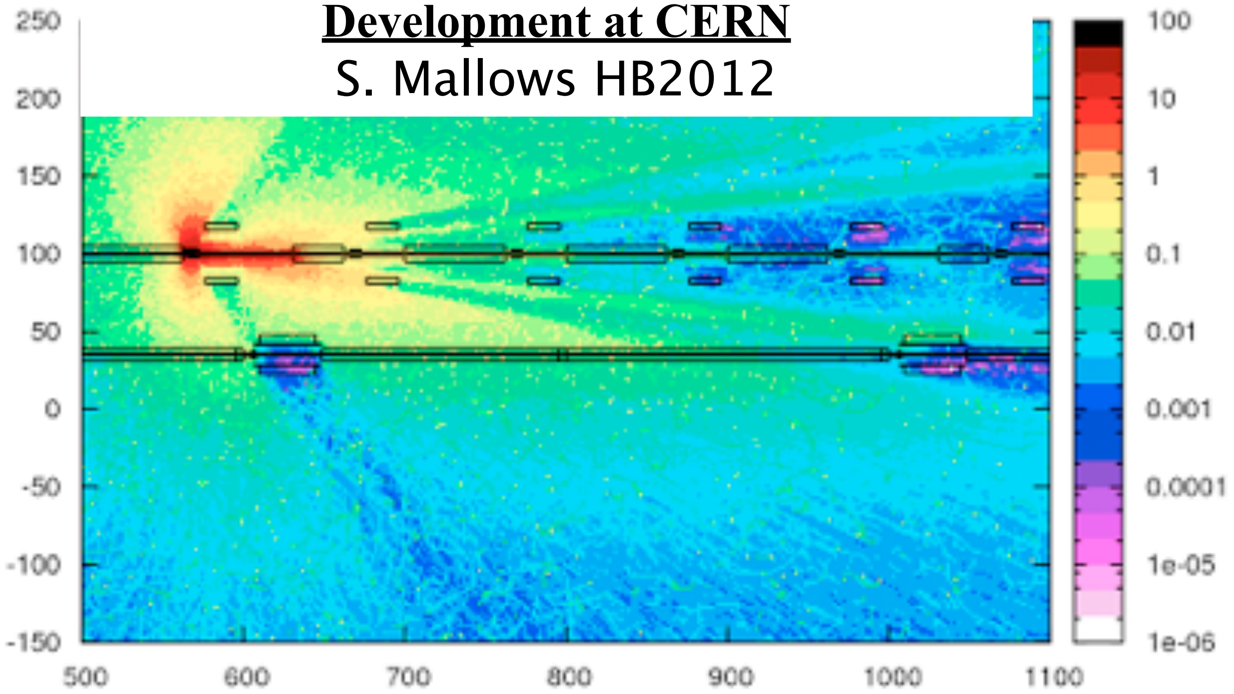
Advanced School on Accelerator Optimization
RHUL 08-07-2014

E. Nebot del Busto
CERN BE-BI-BL
University of Liverpool, Department of Physics

The BLM business

Definitions

- Beam Losses:
  - Particles deviating from the design orbit may eventually hit the aperture limit and be “lost” from the beam
  - The impact of particles in the vacuum chamber produce particle showers



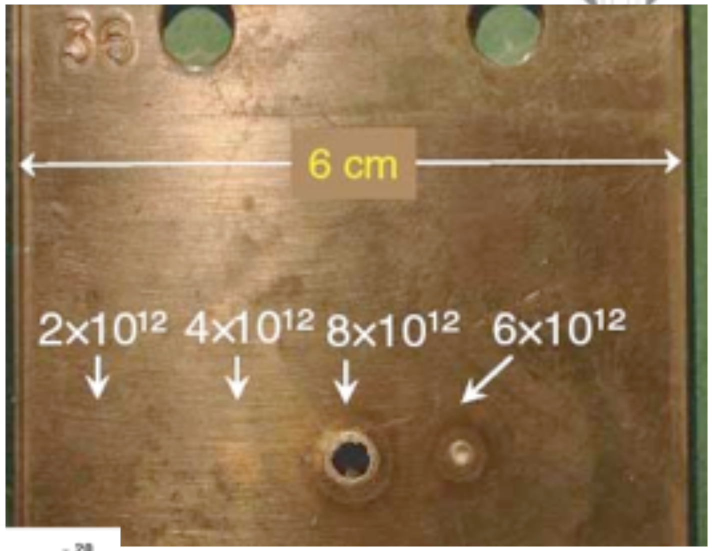
Fiber Based BLM System Research and Development at CERN

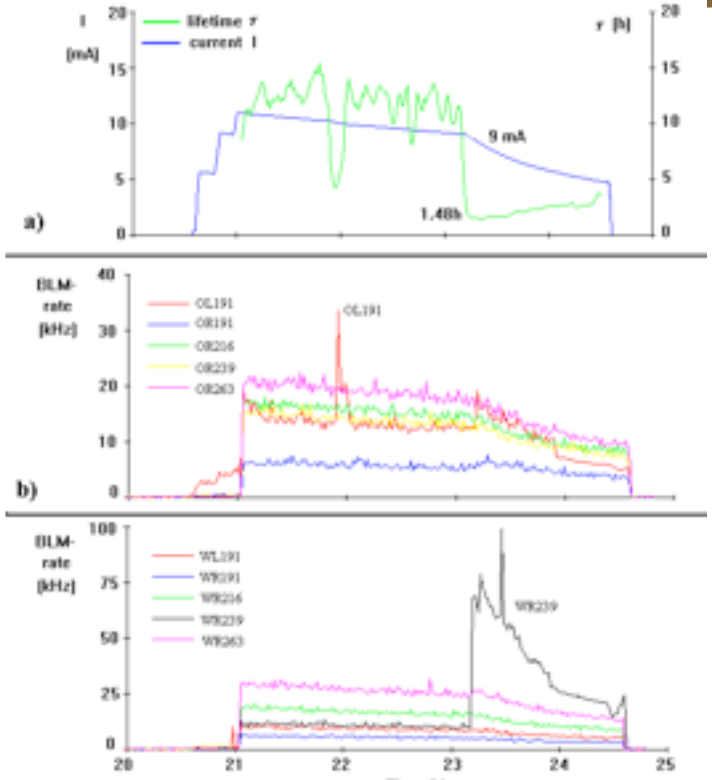
S. Mallows HB2012

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

Main goals

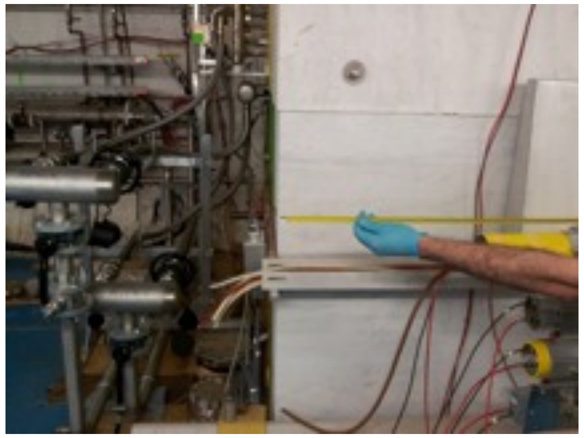
- Machine protection
  - The impact of a high power beam into a single location may have catastrophic consequences on equipment
  - “Stop” the beam if the beam is “not safe”





- Beam diagnostics
  - Beam tuning
  - Halo measurement

- Keep activation levels low
  - Production of “radioactive waste”
  - Protection against human hazard



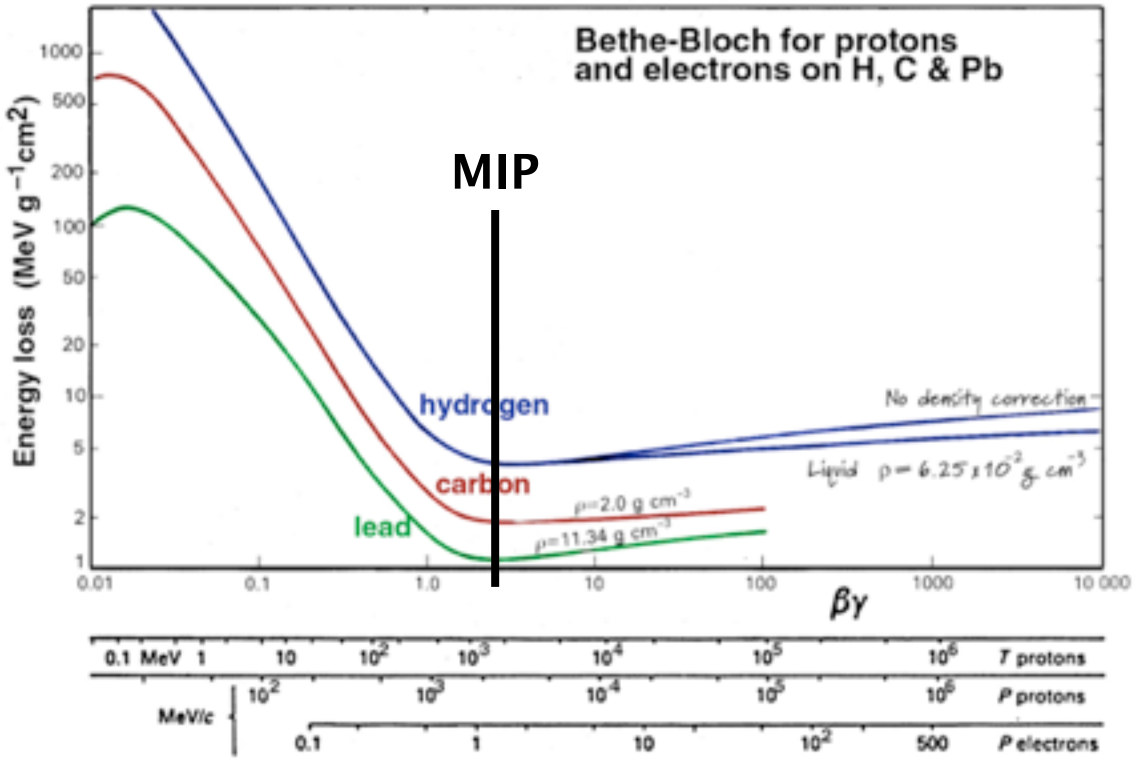
Type of losses

- Beam Loss categorization
  - Irregular beam losses
    - They are avoidable but sometimes tolerated
    - RF trips
    - vacuum leaks
    - Injection losses
    - Beam instabilities
    - 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)

Source of BLM signal

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

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

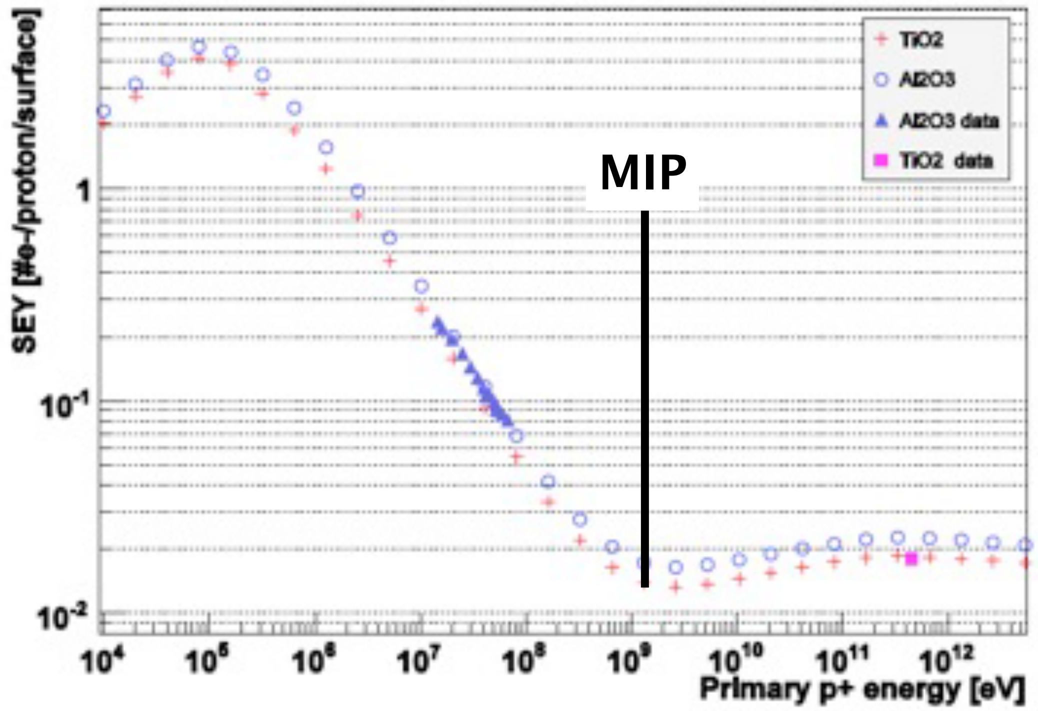


- Scintillation

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

- Secondary emission

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



- Cherenkov light

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

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

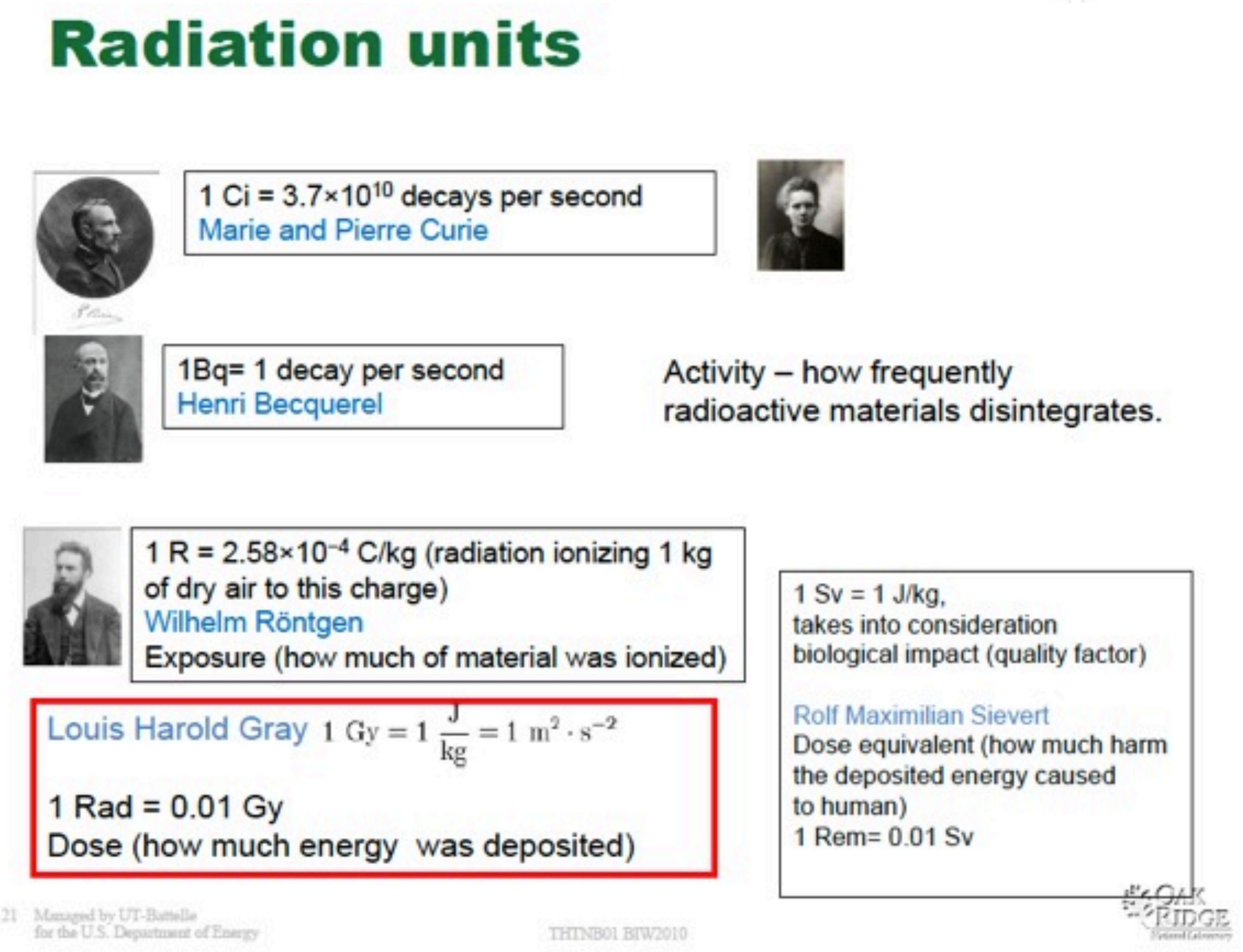
Radiation units and conversion factors

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

- With the assumption

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

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



Radiation units

$1\ \mathrm{Ci} = 3.7\times10^{10}$ decays per second
Marie and Pierre Curie

1Bq= 1 decay per second
Henri Becquerel

Activity – how frequently radioactive materials disintegrates.

$1\ \mathrm{R} = 2.58\times10^{-4}$ C/kg (radiation ionizing 1 kg of dry air to this charge)
Wilhelm Röntgen
Exposure (how much of material was ionized)

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

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

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

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

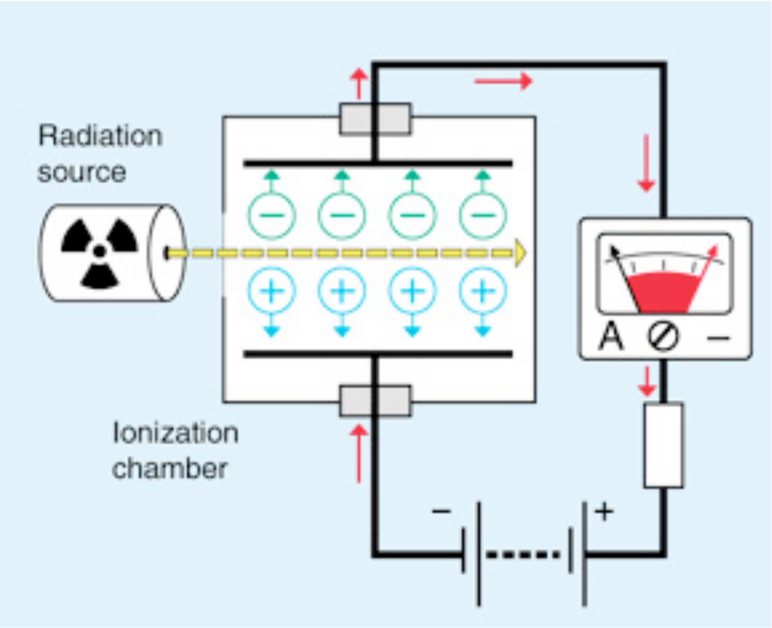
21 Managed by UT-Battelle for the U.S. Department of Energy

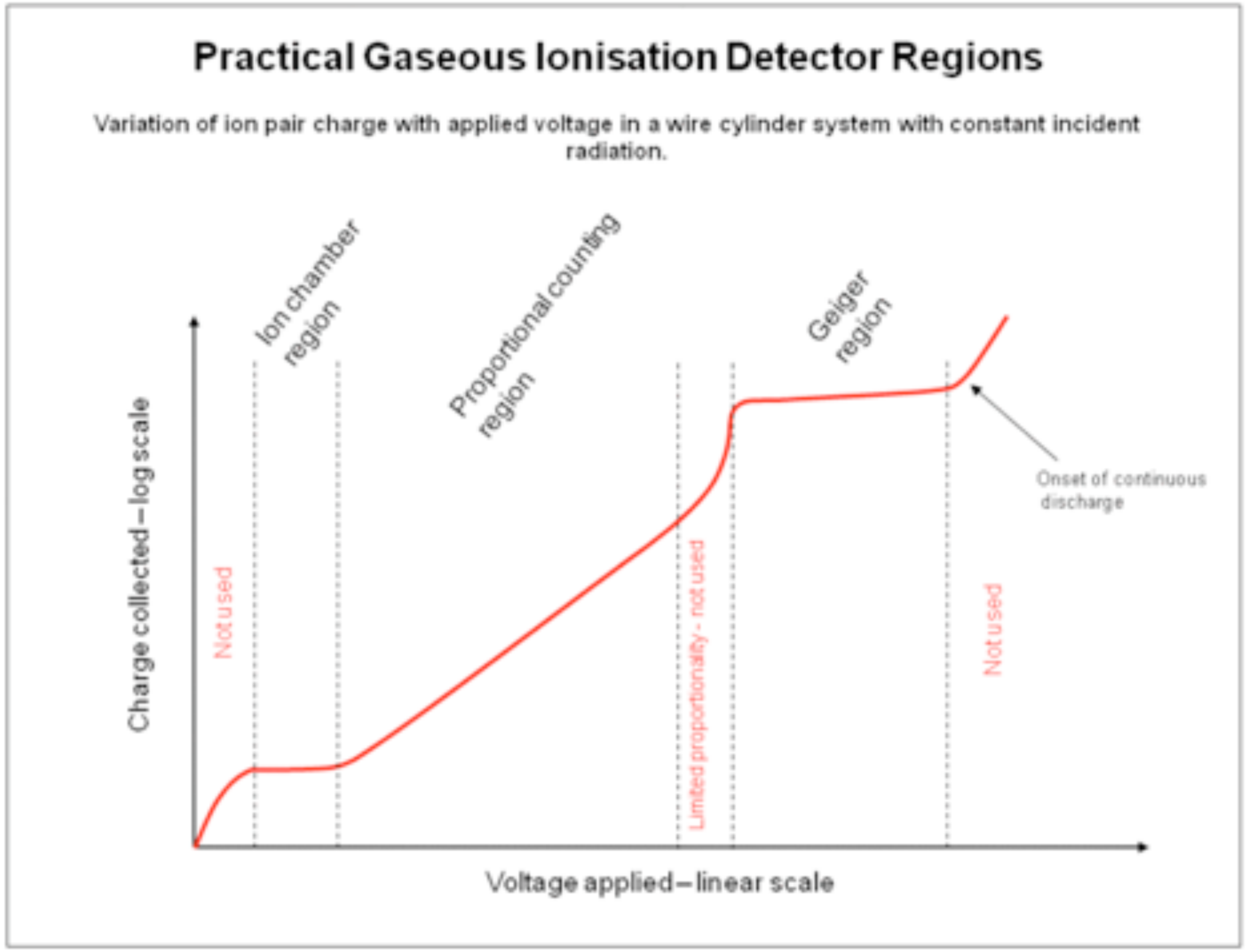
THTNB01 BIW2010

$$1\mathrm{Gy} = 1\frac{\mathrm{J}}{\mathrm{kg}} \cdot \frac{\mathrm{MIP}\cdot\mathrm{kg}}{3.2\cdot10^{-10}\cdot\mathrm{J\ cm}^2} = 3.1\cdot10^{9}\frac{\mathrm{MIP}}{\mathrm{cm}^2}$$

Ionization based BLMs

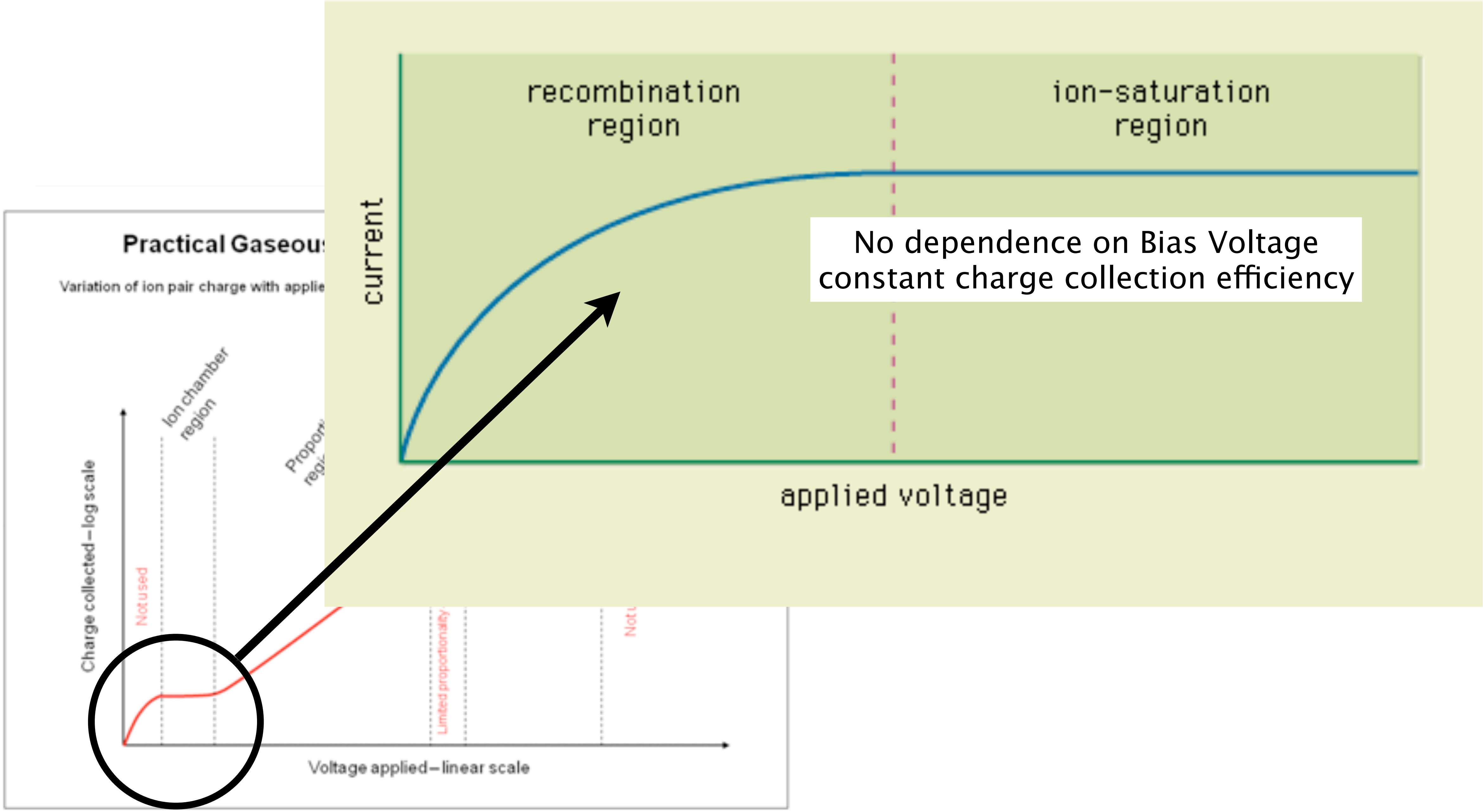
- Ionization Chamber
  - Gas detector: Incident particle ionizes the active gas producing electrons (fast, a few ~100ns) and ions (slow, a few 100us) as charge carriers
  - (25-100) eV/pair depending on active gas





Ionization based BLMs

- Ionization Chamber

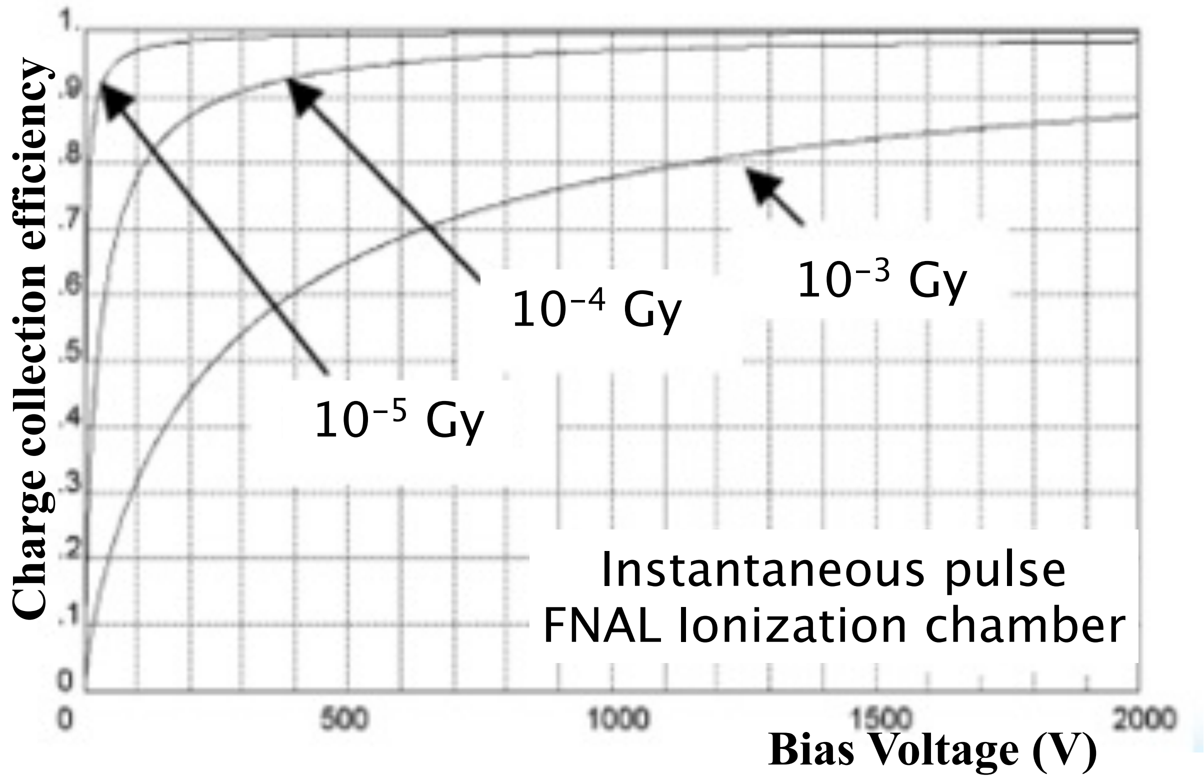


No dependence on Bias Voltage
constant charge collection efficiency

Ionization based BLMs

• Ionization Chamber: Saturation

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

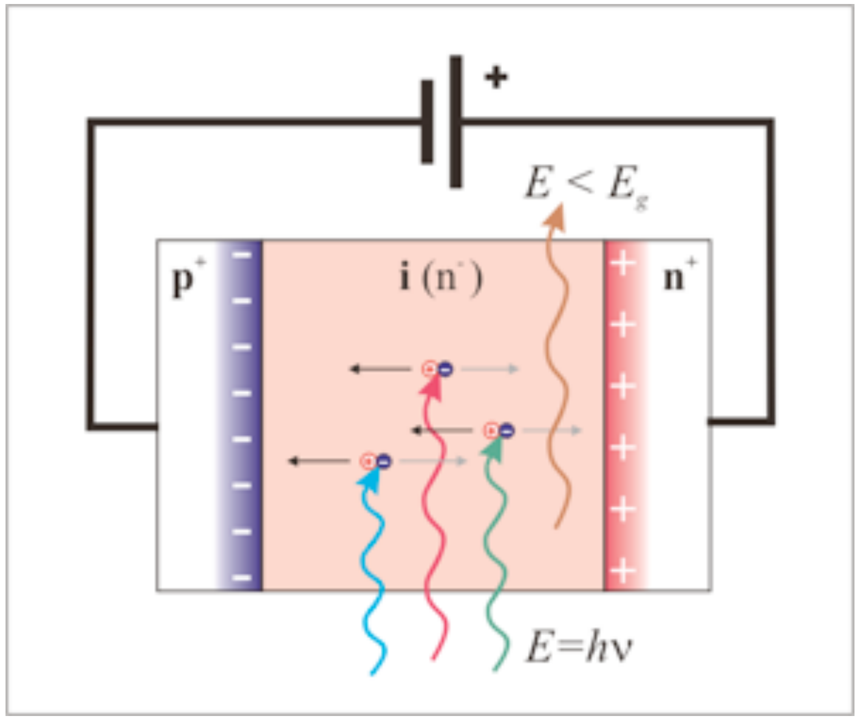


PRO/CONs:

- 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

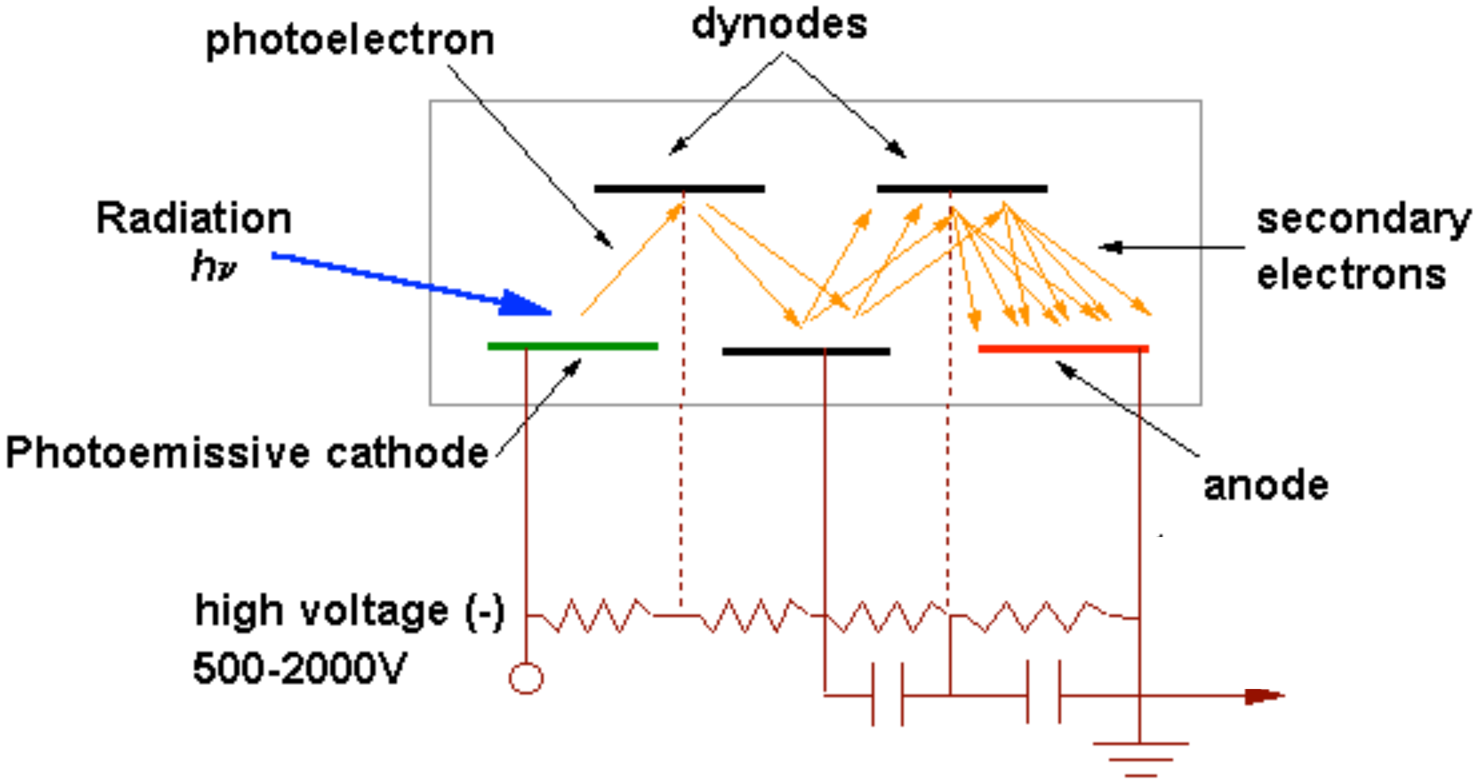
- Semiconductor (PIN, diamond, Si,....). Solid state ionization chambers
  - Incident particles produce electron/holes as charge carriers (3-10eV/pair)
  - $t_{hole} \gtrsim t_{electron} \sim$ 5-10 ns
  - smaller size



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

Scintillation based BLMs

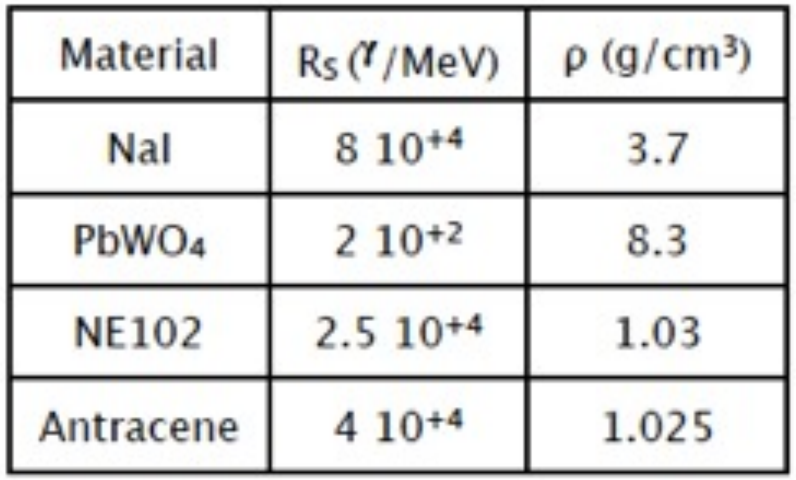
- Light produced by de-excitation of atomic/molecular levels
- Several types of scintillators
  - Inorganic crystals: NaI, CsI, ...
  - Organic (plastic): NE102, Antracene,...
  - Liquid



- 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



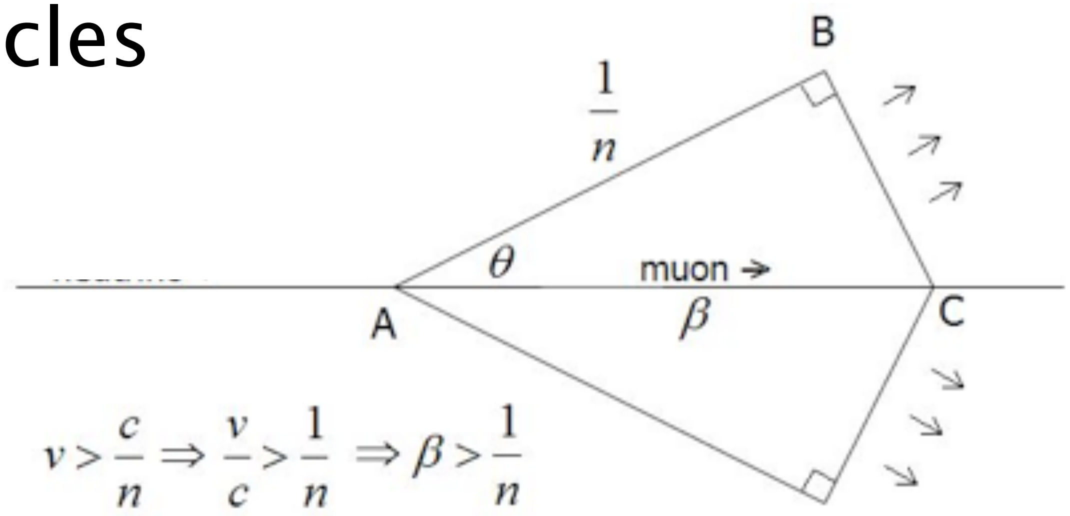
Material	Rs (γ/MeV)	ρ (g/cm³)
NaI	$8\ 10^{+4}$	3.7
$PbWO_4$	$2\ 10^{+2}$	8.3
NE102	$2.5\ 10^{+4}$	1.03
Antracene	$4\ 10^{+4}$	1.025

PRO/CONs:

- 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



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

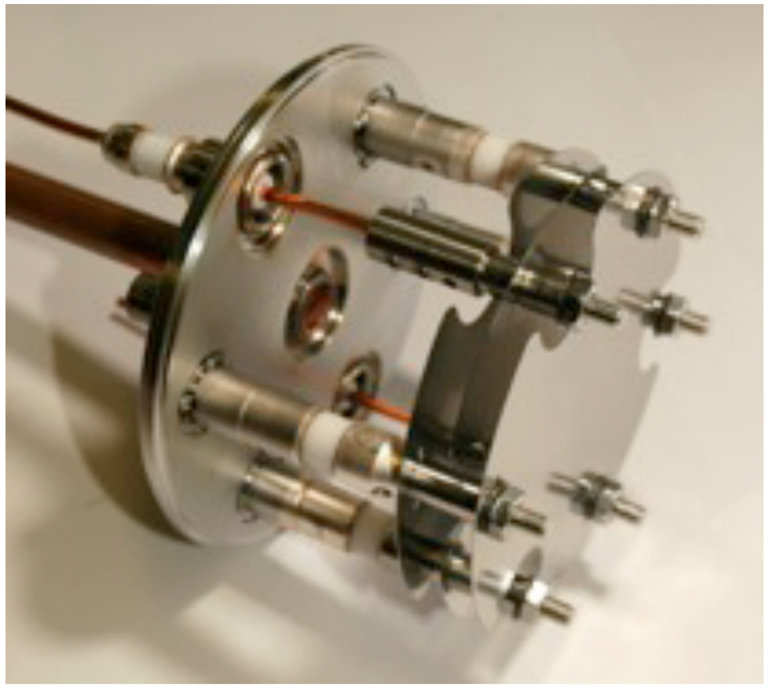
$$\cos\theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$$

- As for scintillators we need to consider collection efficiency and quantum efficiency of photosensor

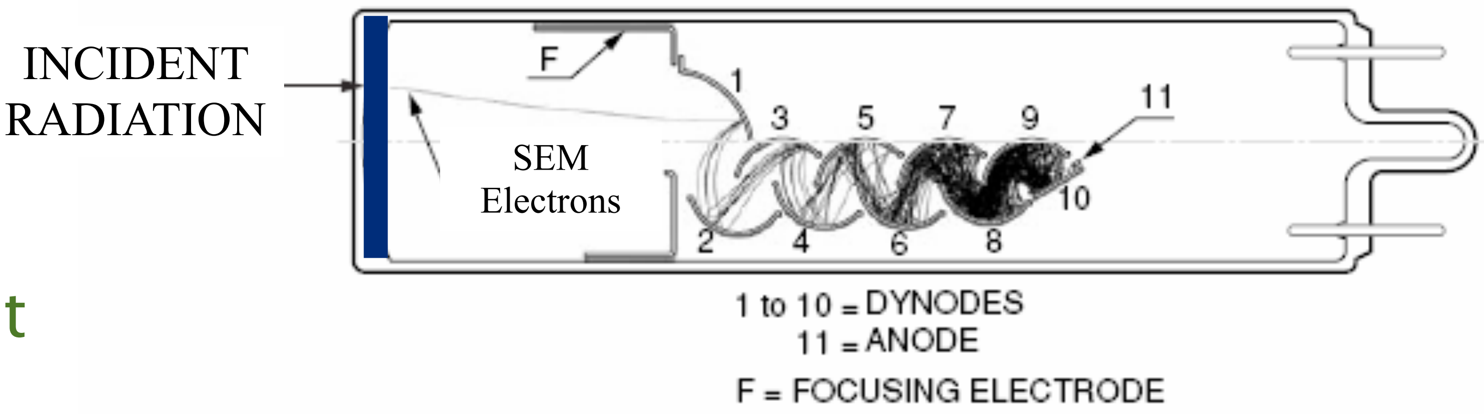
PRO/CONs:
- Insensitive to neutral radiation
- Fast (defined by your PMT or photosensor)
- Low sensitivity
- Limited radiation hardness (10-100MGy)

Secondary emission based BLM

- 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)

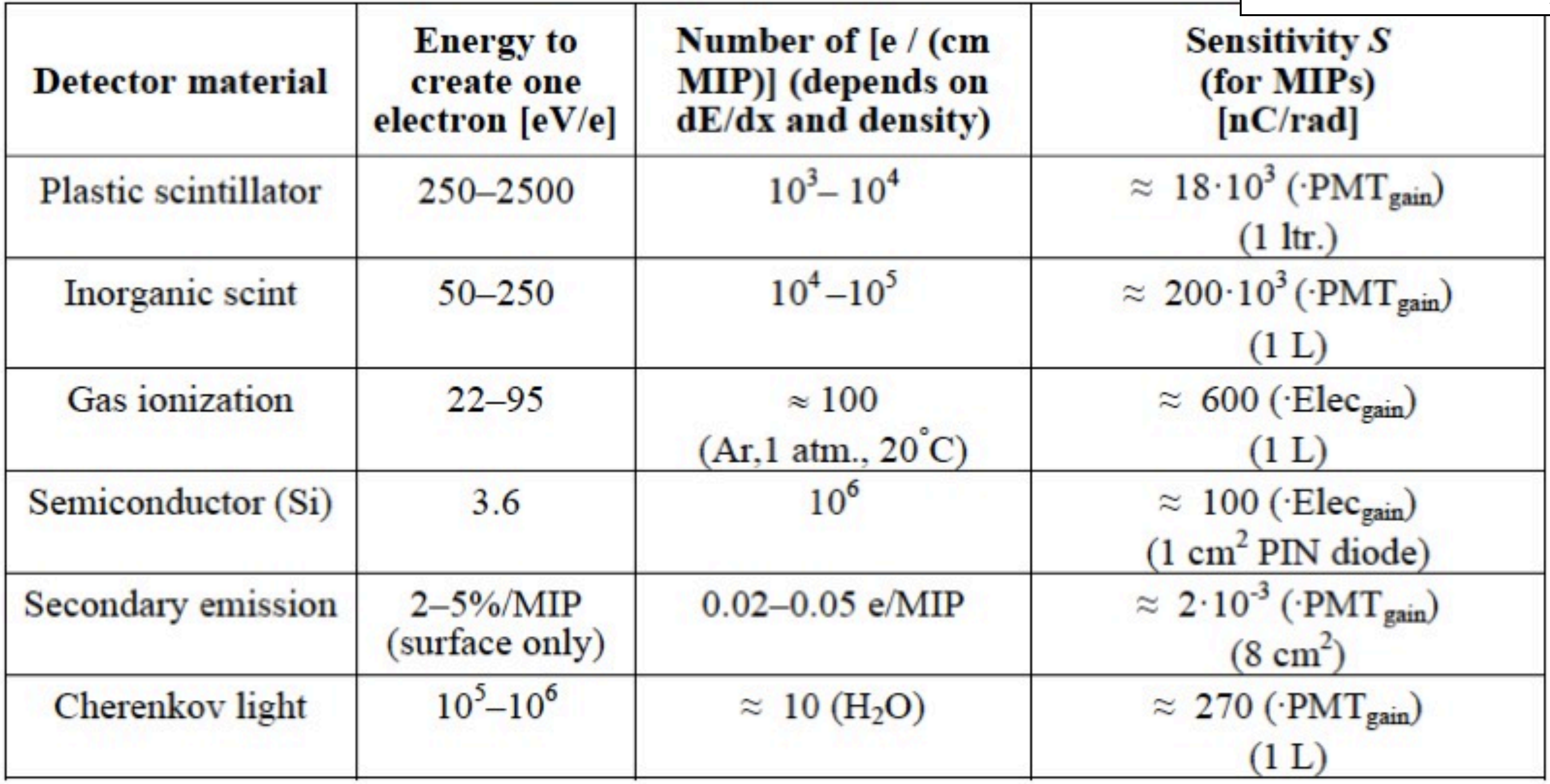


PRO/CONs:

- Fast (<10ns). Electron transit
- Very linear
- Radiation hard (without PMT). Ideal for high radiation environments
- Very low sensitivity (without PMT)
- Insensitive to neutral particles

Sensitivity summary

K. Wittenburg



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	≈ $18\cdot10^3$ (·PMT_{gain}) (1 ltr.)
Inorganic scint	50–250	10^4–10^5	≈ $200\cdot10^3$ (·PMT_{gain}) (1 L)
Gas ionization	22–95	≈ 100 (Ar,1 atm., 20°C)	≈ 600 (·Elec_{gain}) (1 L)
Semiconductor (Si)	3.6	10^6	≈ 100 (·Elec_{gain}) (1 cm^2 PIN diode)
Secondary emission	2–5%/MIP (surface only)	0.02–0.05 e/MIP	≈ $2\cdot10^{-3}$ (·PMT_{gain}) (8 cm^2)
Cherenkov light	10^5–10^6	≈ 10 (H_2O)	≈ 270 (·PMT_{gain}) (1 L)

↕ 9 o. o. m

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!!!!

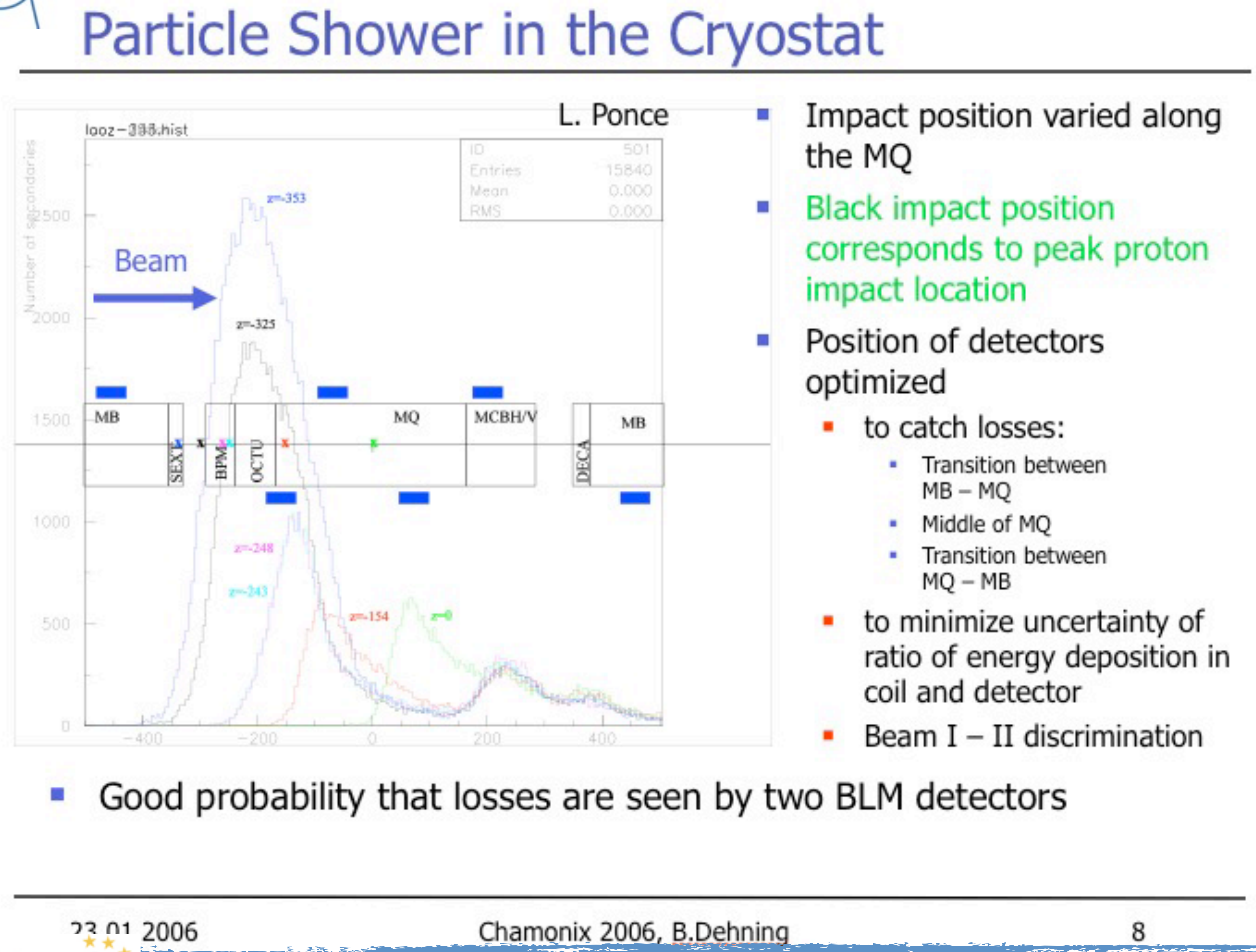
- What's the best "realistic" location of a BLM?

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

Location of BLMs



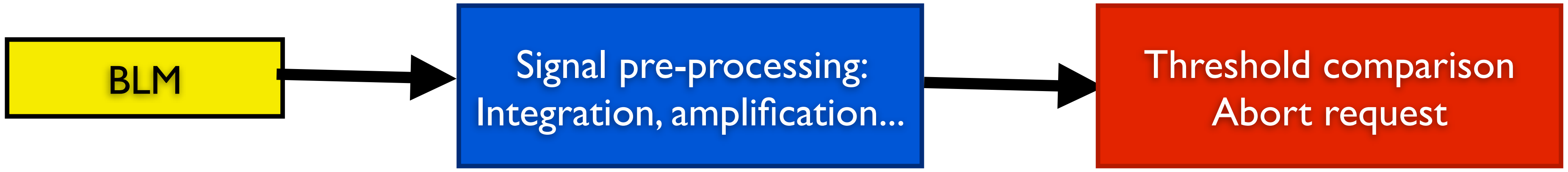
Particle Shower in the Cryostat

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

23.01.2006 Chamonix 2006, B.Dehning 8

Machine Protection


BLM

Signal pre-processing: Integration, amplification...

Threshold comparison Abort request

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

Machine Protection: Abort thresholds

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

Energy deposited in BLM

Energy deposited in magnetic coil

Quench margin

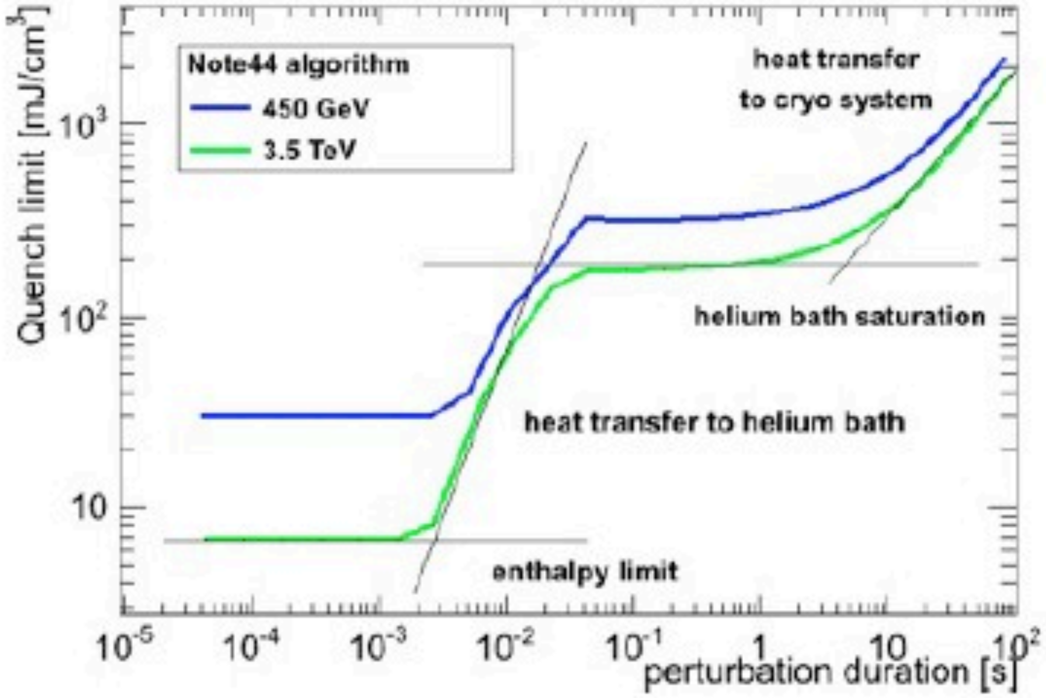
$$T(t,E) = \left(E_{BLM}(E)\ /E_{COIL}(t, E) \times Q_L(t, E)\right) + \text{Corrections}$$

Monte Carlo (Geant4/FLUKA) dedicated measurements

Monte Carlo (Geant4/FLUKA)

Note 44/QP3 (models)

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

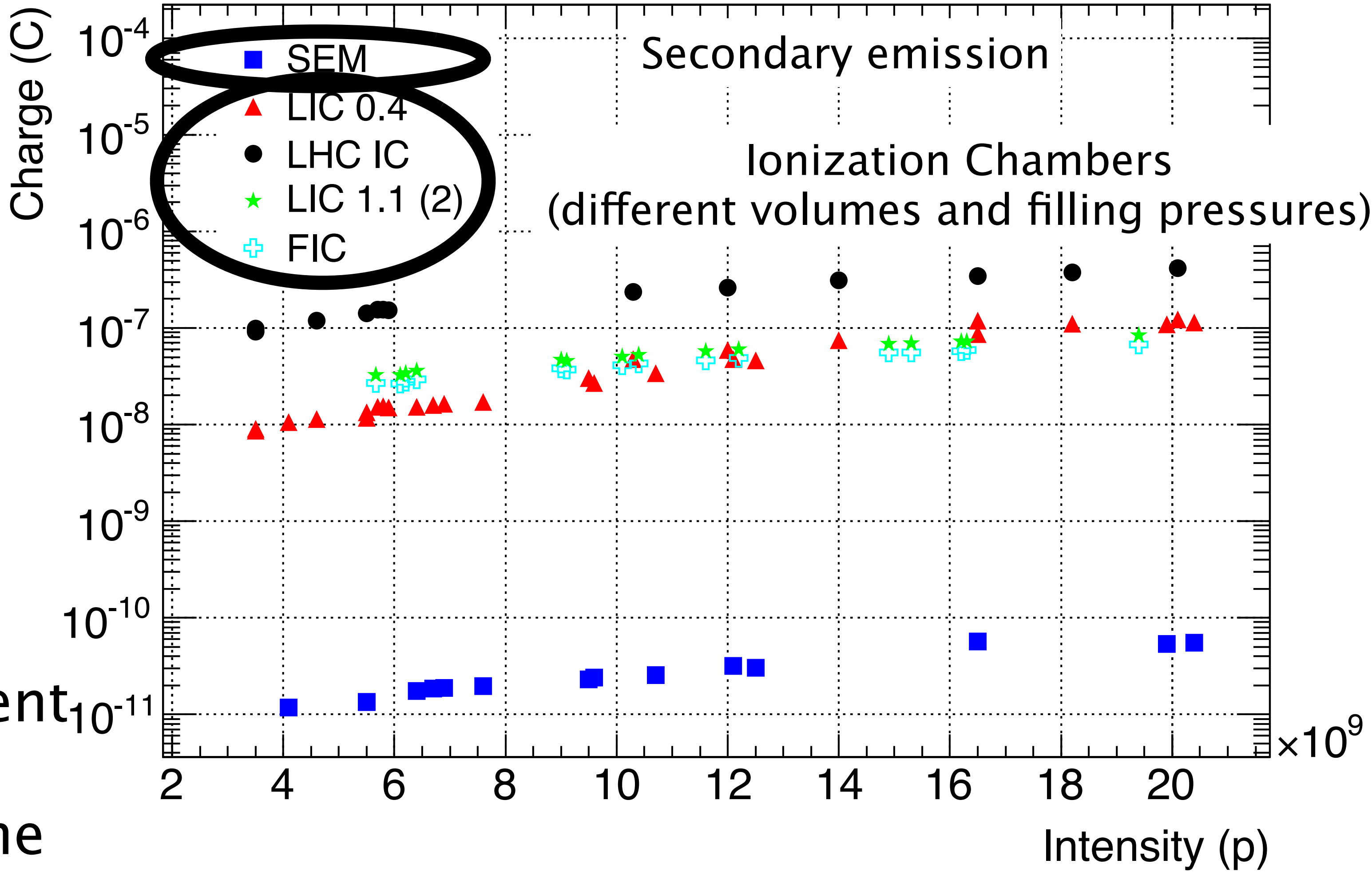
Challenges

Dynamic range

- New machines require ≳ 10^{+6}:
  - detector technologies
  - electronics:
    - RF amp: linear 10^{+4}, log 10^{+5}
    - ADC: $4 \times 10^{+3}$ (12 bit), $6 \times 10^{+4}$(16 bit), $2 \times 10^{+7}$ (24 bit)

- Solution 1: Various detector technologies with same electronics

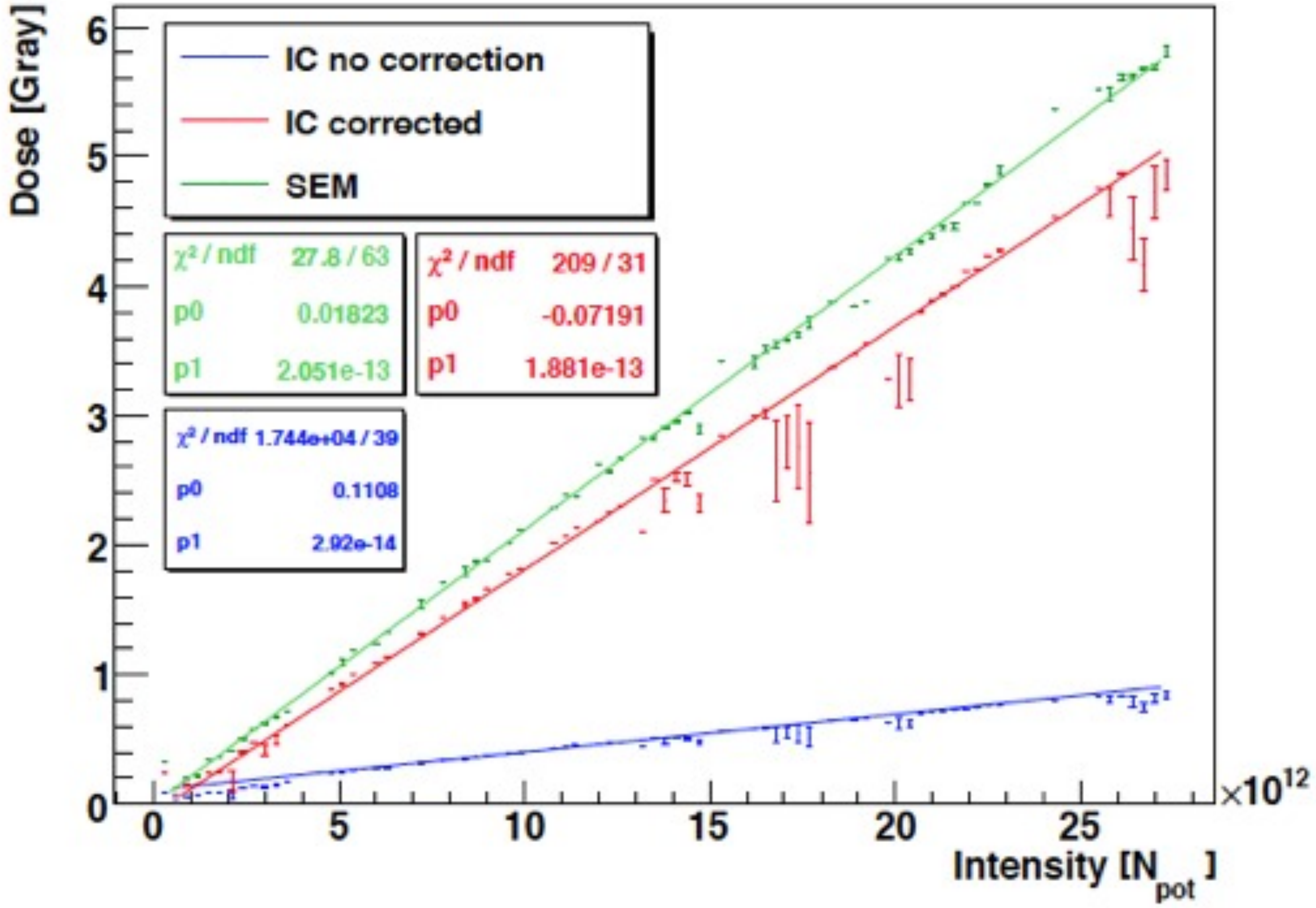
- Solution 2: Two independent BLM systems:
  - Machine protection: measurement of total loss
  - diagnostics: Position and/or time resolution, bunch by bunch capabilities...

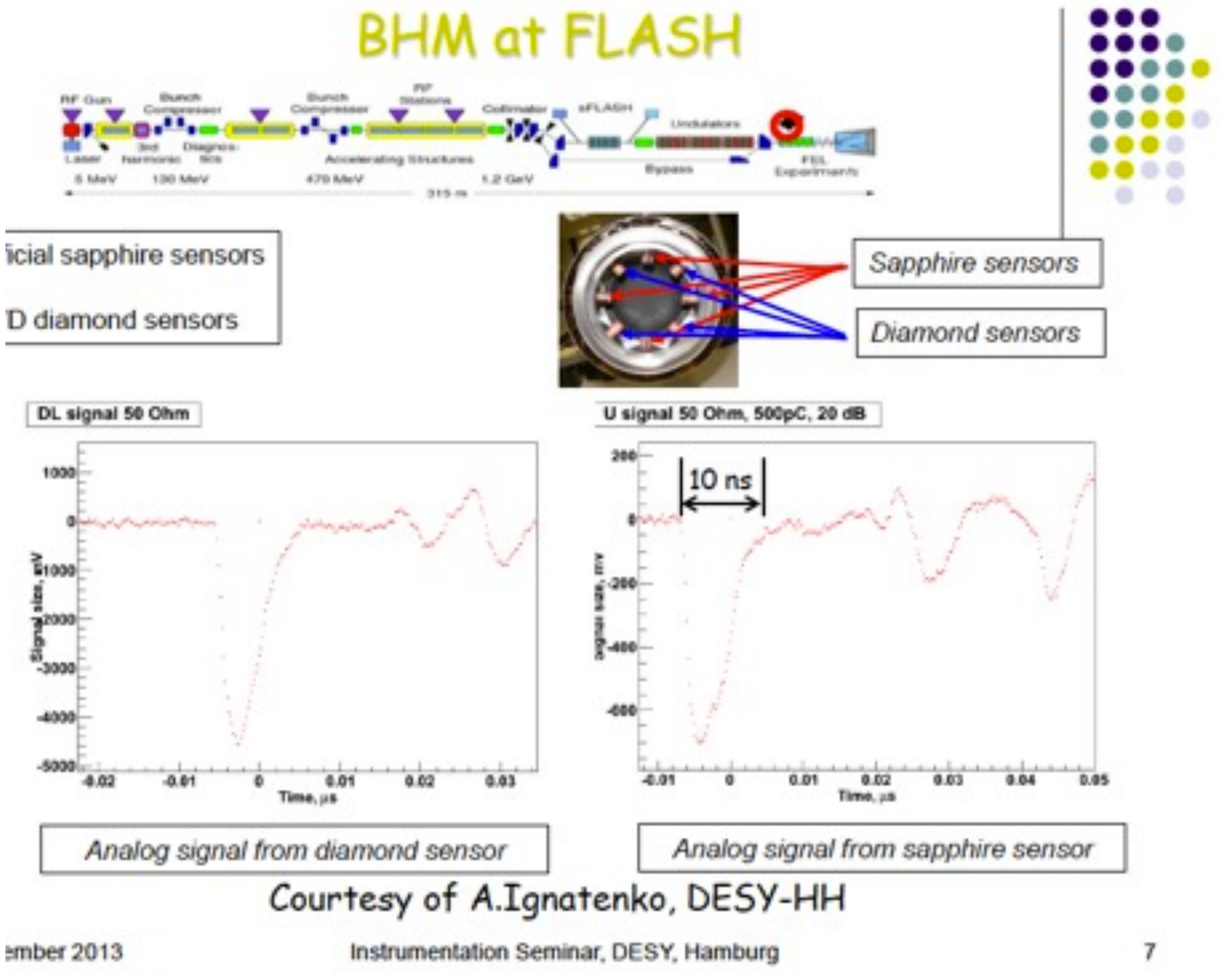


High radiation environments

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

Design and implementation of a detector for a high flux mixed radiation field.
D. Kramer Thesis




BHM at FLASH

icial sapphire sensors

D diamond sensors

Sapphire sensors

Diamond sensors

DL signal 50 Ohm

U signal 50 Ohm, 500pC, 20 dB

10 ns

Analog signal from diamond sensor

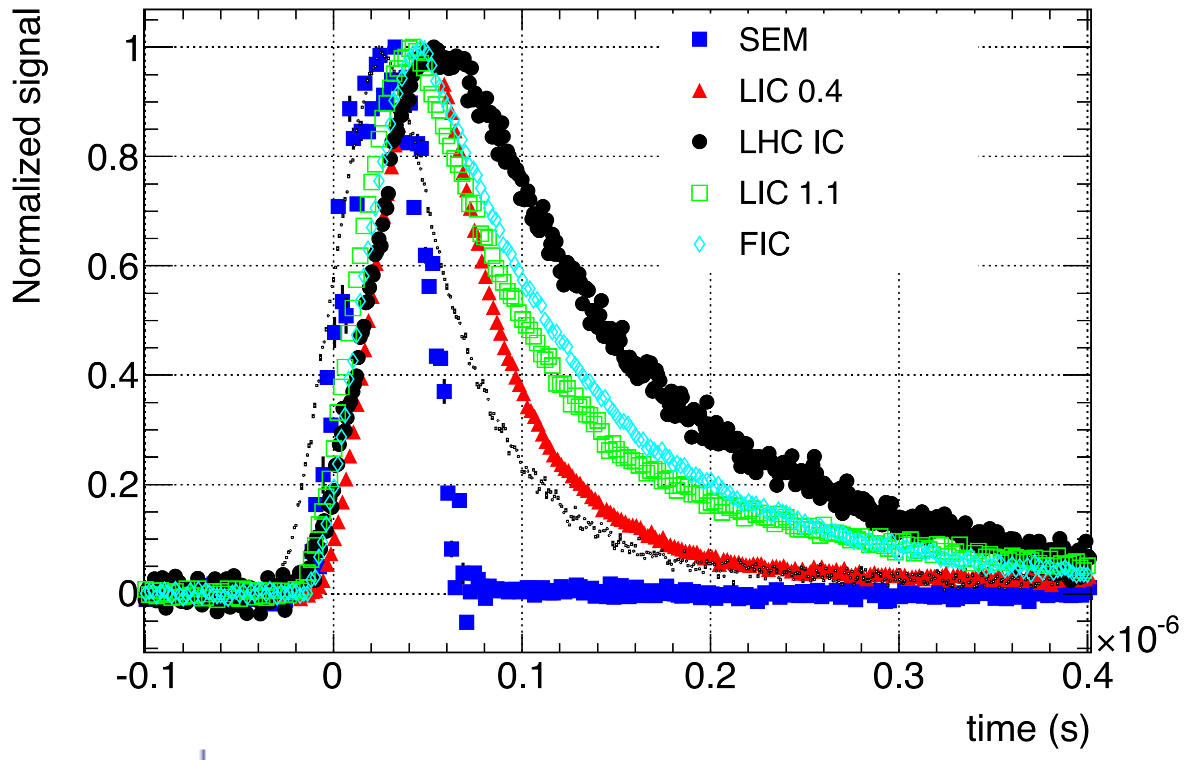
Analog signal from sapphire sensor

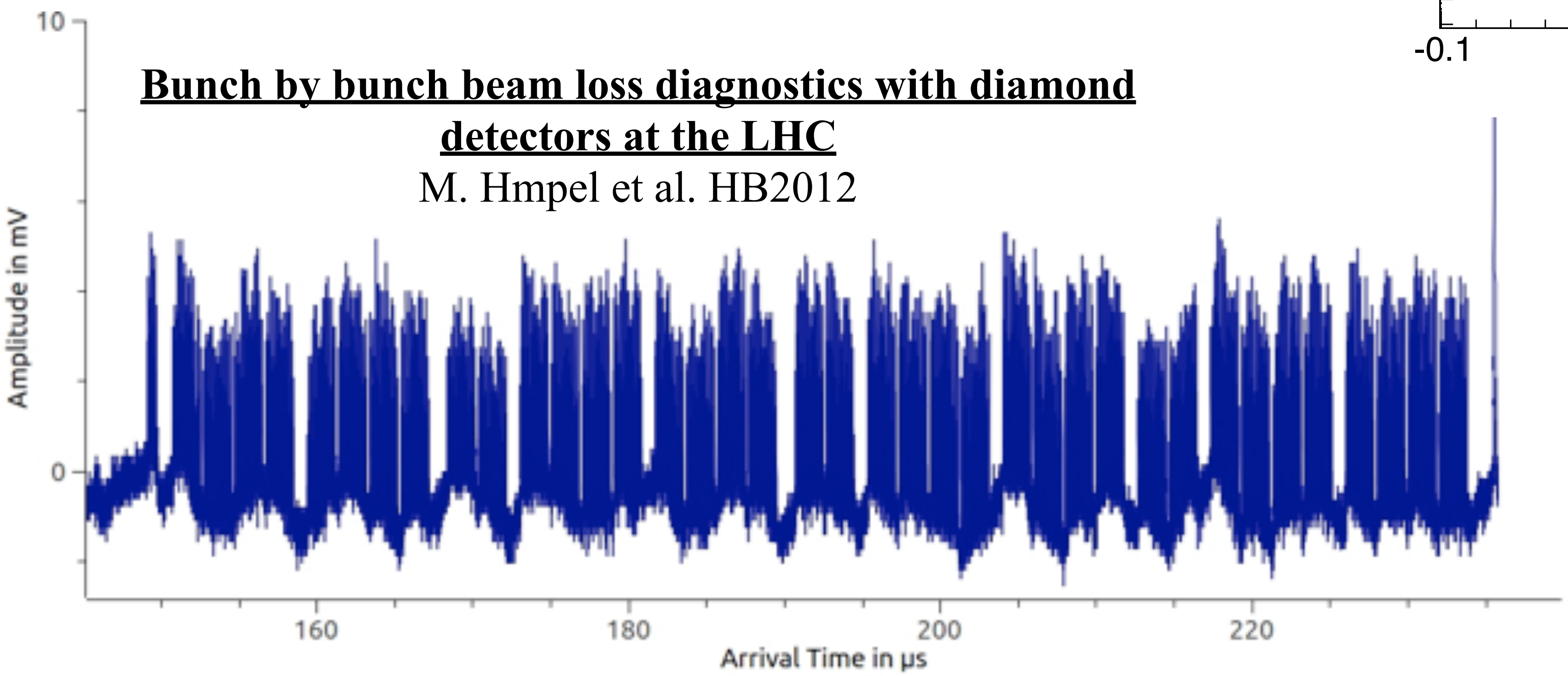
Courtesy of A.Ignatenko, DESY-HH

ember 2013 Instrumentation Seminar, DESY, Hamburg 7

Time resolution

- Determined by the need of measuring bunch by bunch “everything” (that includes beam losses)
  - ICs are typical BLMs (radiation hard, reliable, ...) but can’t resolve single bunches
  - SEM (without PMT) are faster but very insensitive. (Broadband amplifiers for < 10ns resolution)





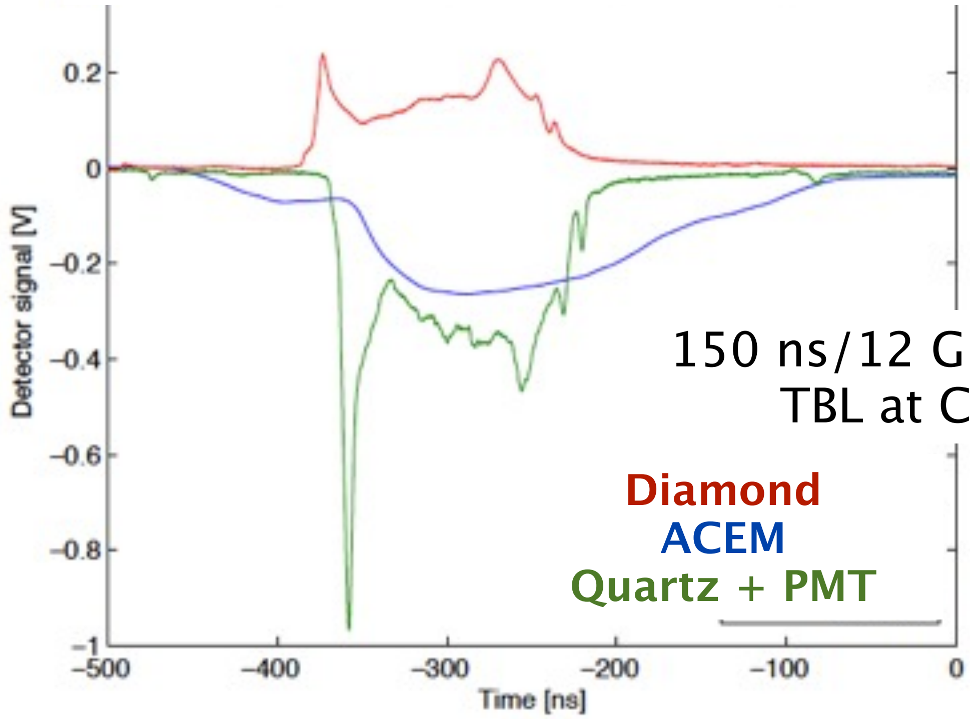
Bunch by bunch beam loss diagnostics with diamond detectors at the LHC
M. Hmpel et al. HB2012

- 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

Development of a Beam Loss Monitoring system for CTF3 TBL
E. Branger, Master thesis



150 ns/12 GHz pulse
TBL at CTF3

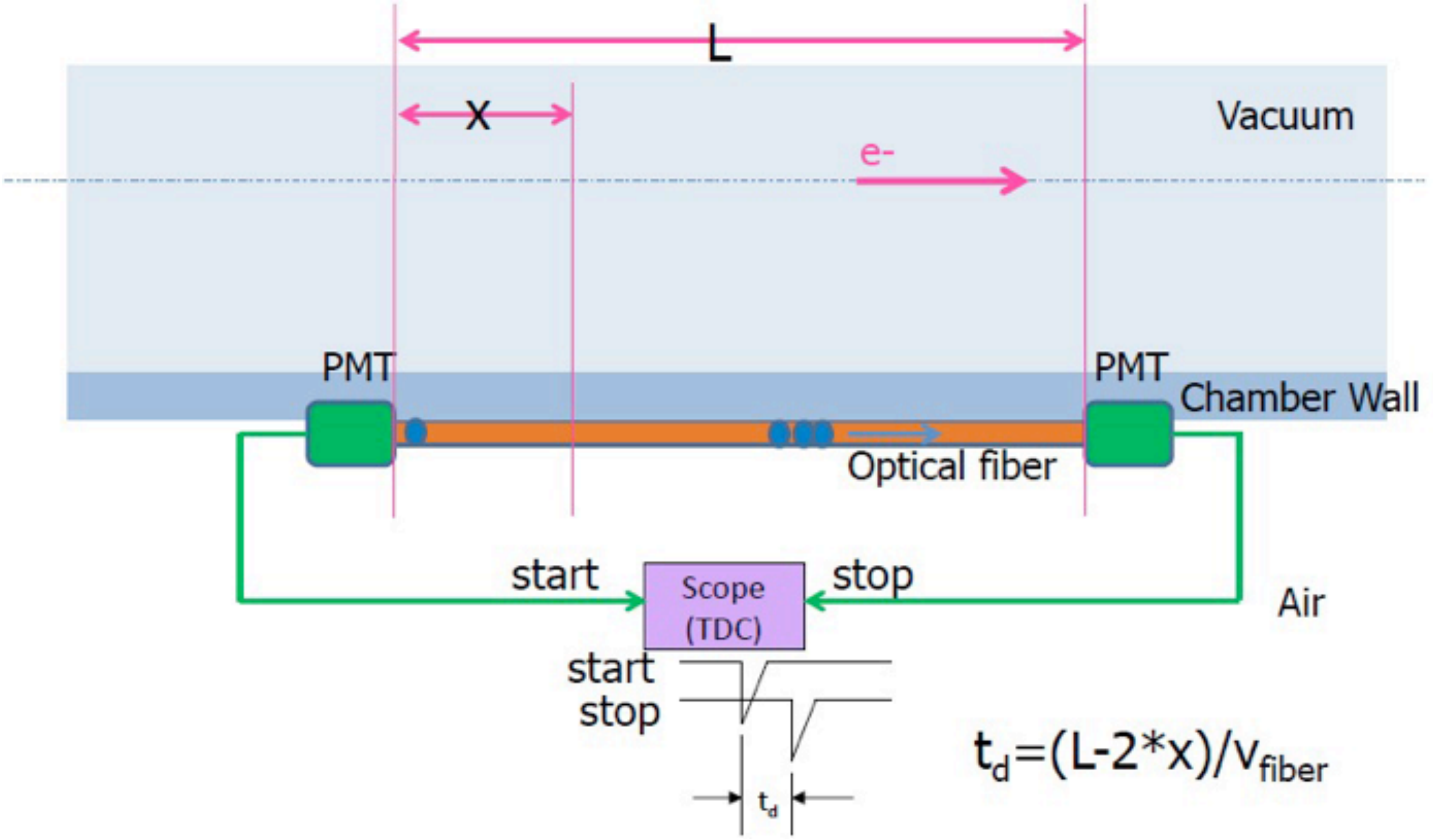
- Cherenkov light (as prompt radiation) is currently the best candidate for fast BLMs
  - Ultra fast photo sensor have been demonstrated to disentangle 12GHz bunch spacing

Application of Metal-Semiconductor-Metal (MSM) Photodetectors for Transverse and Longitudinal Intra-Bunch Beam Diagnostics
R. Steinhagen et al. IBIC13

Position resolution

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

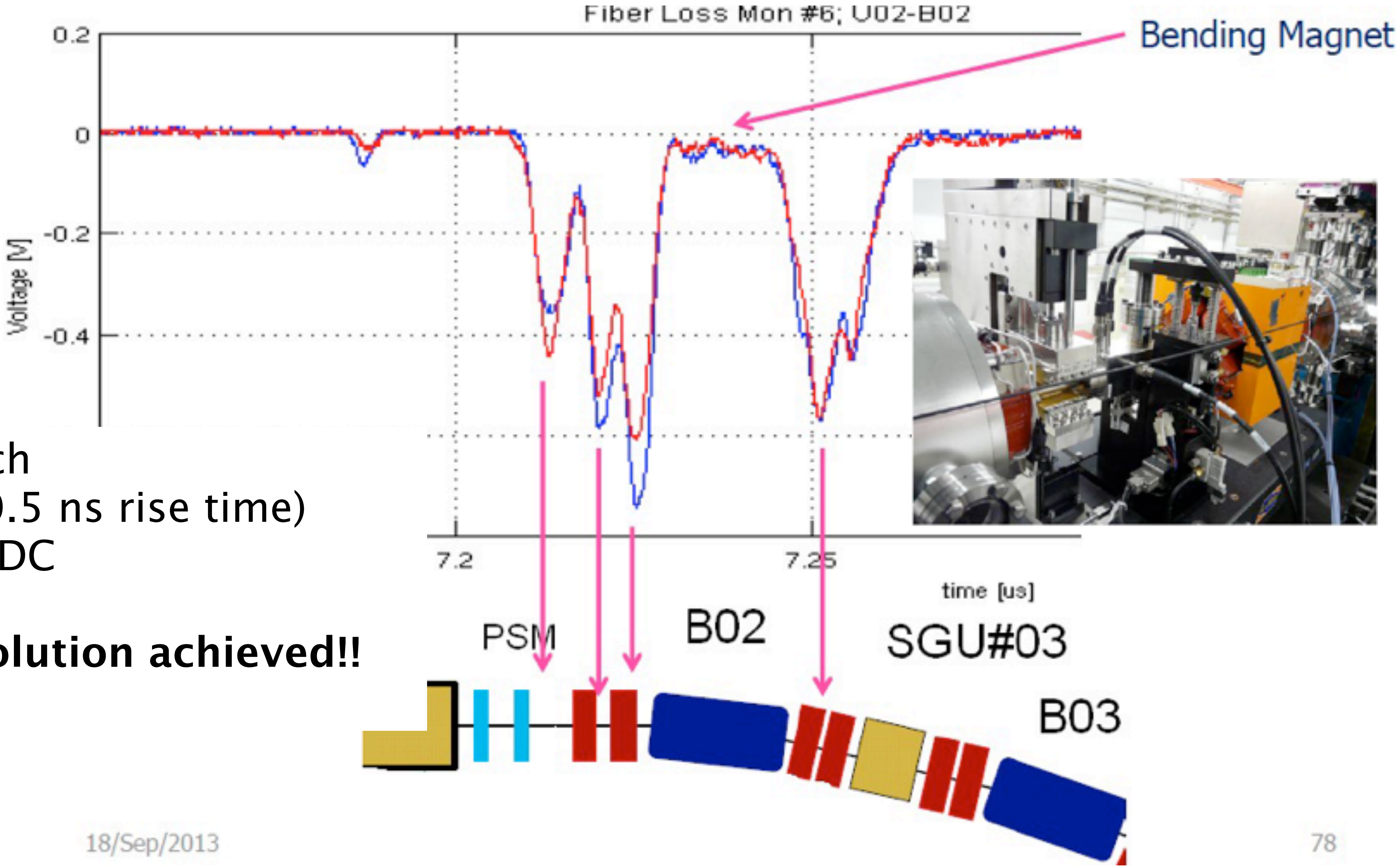
- Optical fibers provide position resolution by measuring signal delay



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

Position resolution

- KEK-PF
- 2.5 GeV electrons
- single bunch

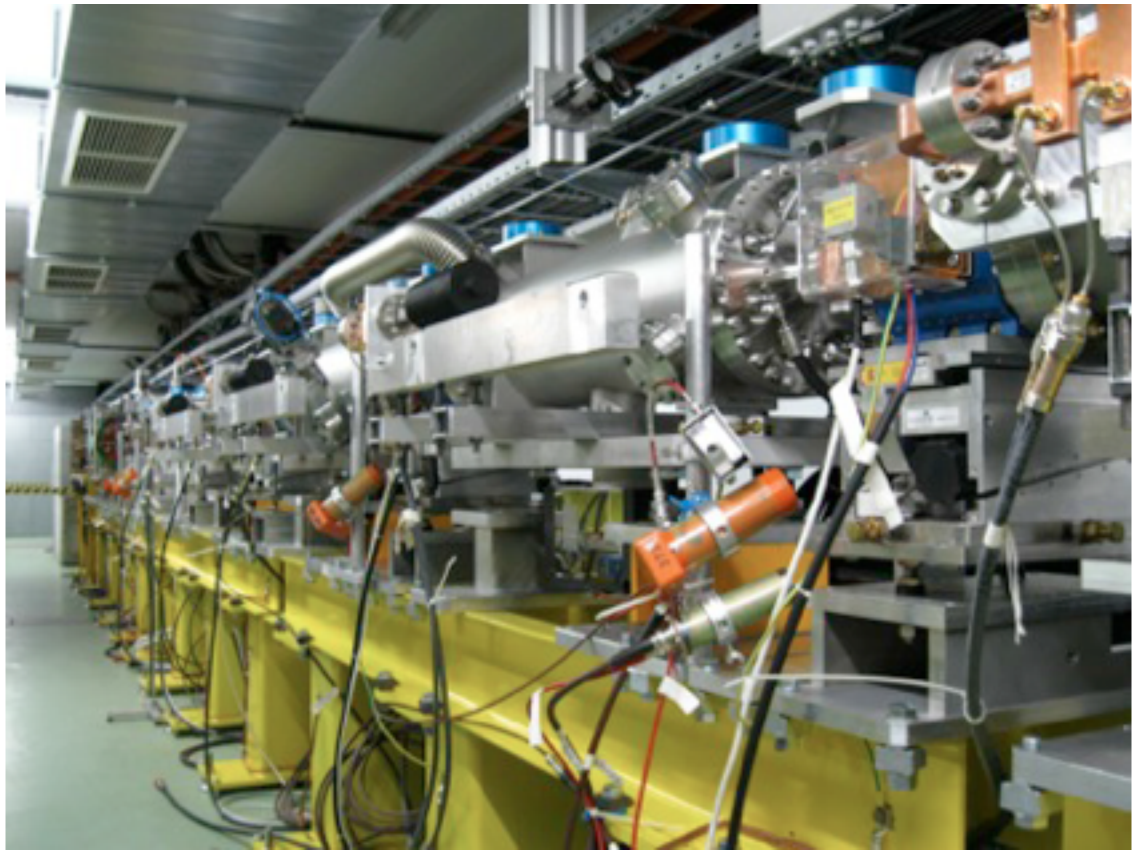


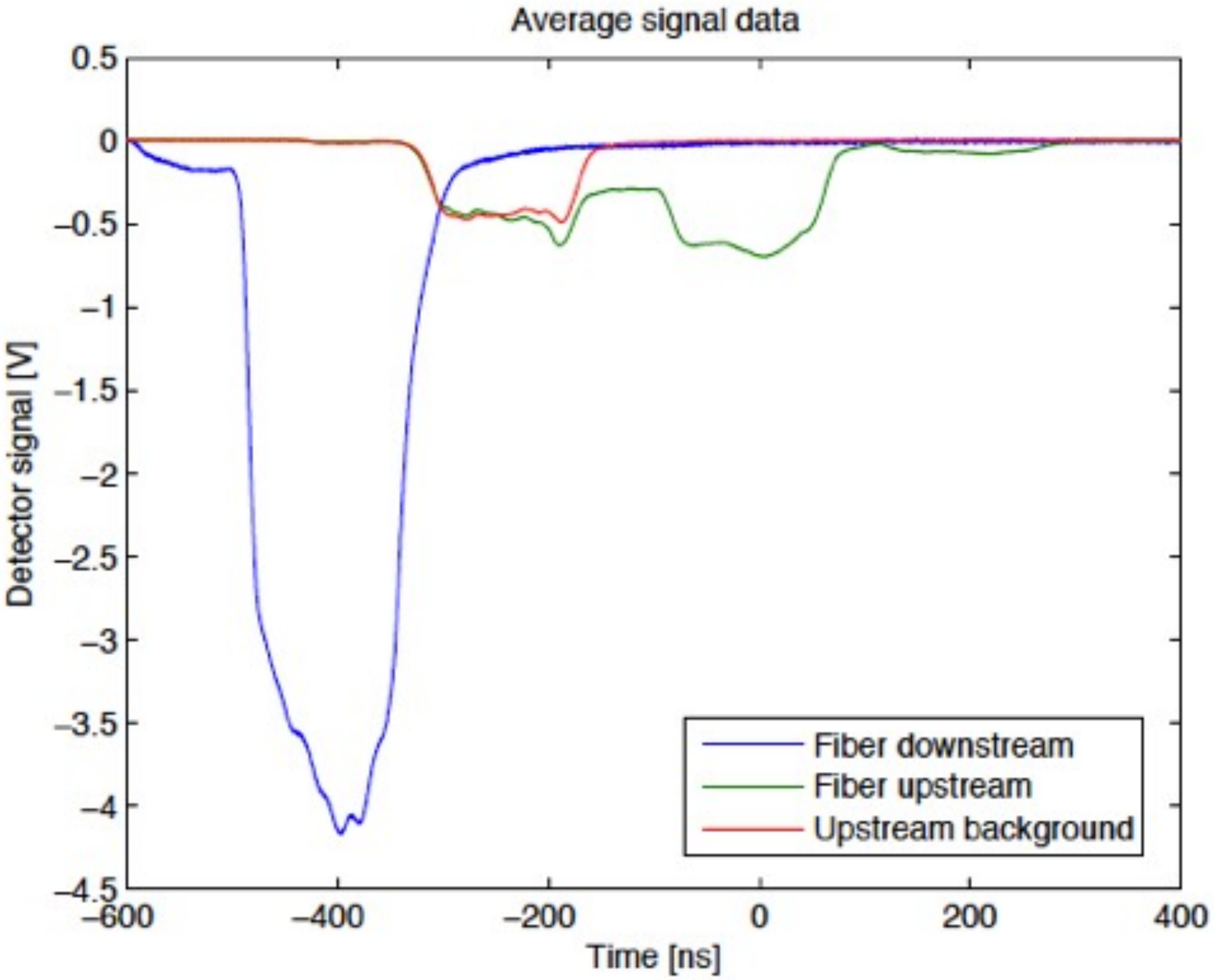
Single bunch
Fast PMT (0.5 ns rise time)
500 MHz ADC

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)





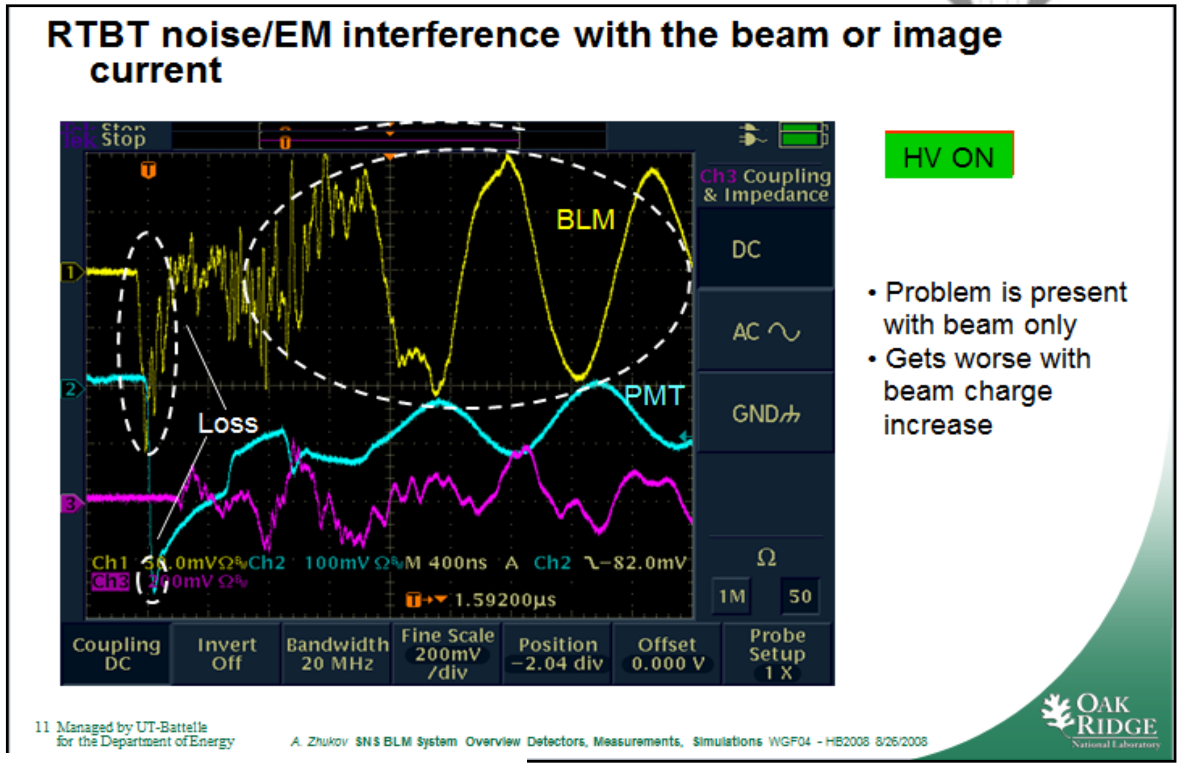
High background environments

- 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

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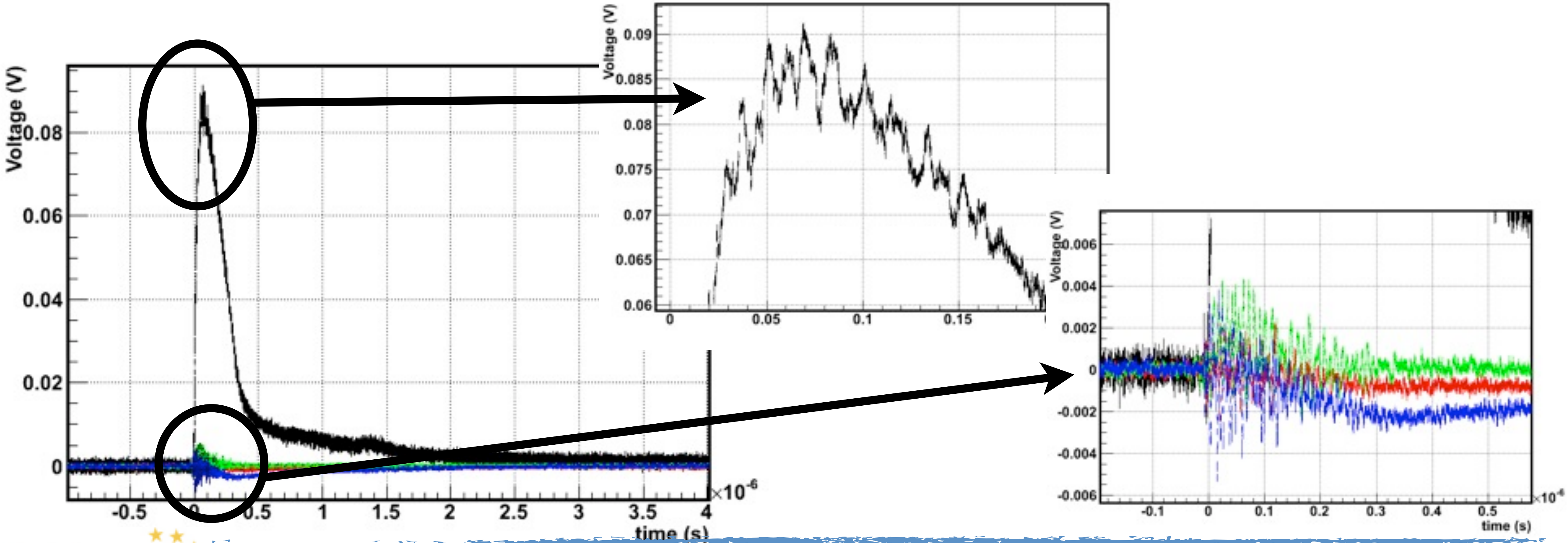
A. Zhukov SNS BLM System Overview Detectors, Measurements, Simulations WGF04 - HB2008 8/26/2008



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

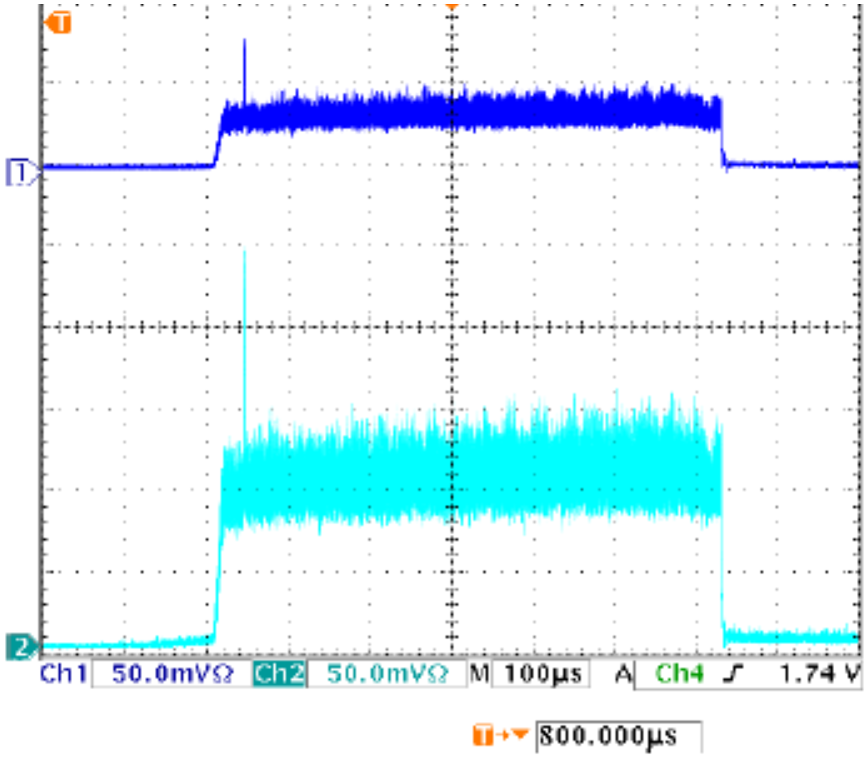


Figure 4: BLM signals from a single bunch and dark current at FLASH (April 2012): BLM with SQ1 synthetic fused silica (top, HV=700 V) and BLM with a scintillator (HV=550 V).

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

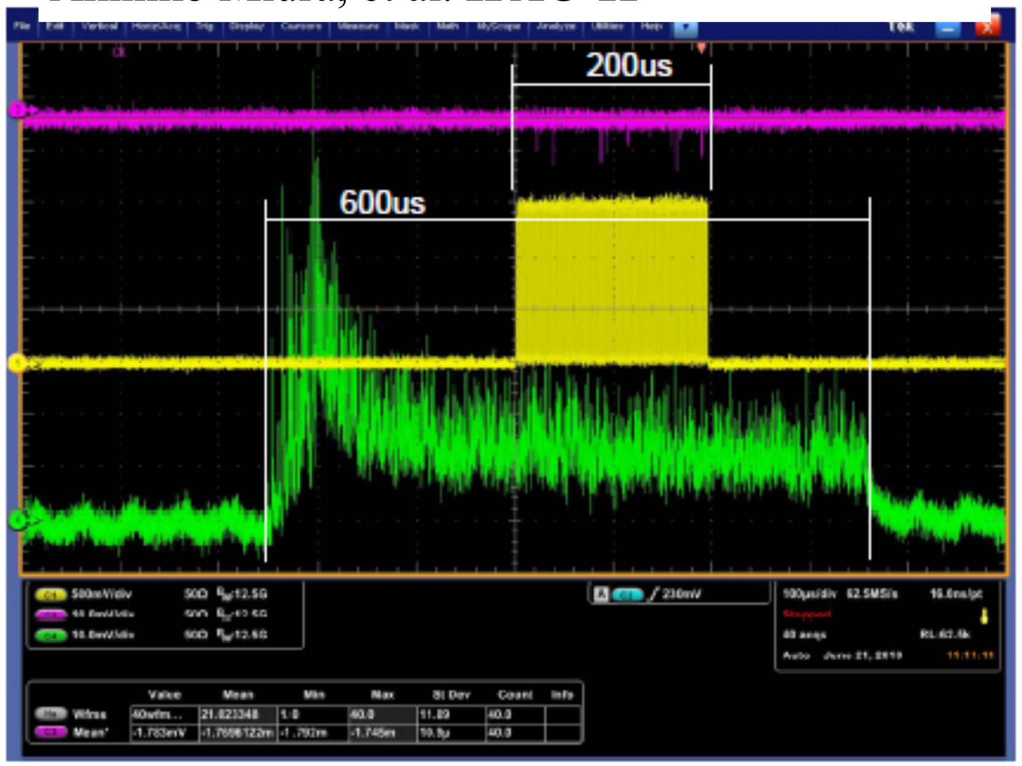


Figure 5: Signals from a gas proportional monitor (green) and plastic scintillation monitor (magenta) at SDTL13 section, during beam operation with chopped beam. The beam current signal with a current transformer is also shown (yellow).

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

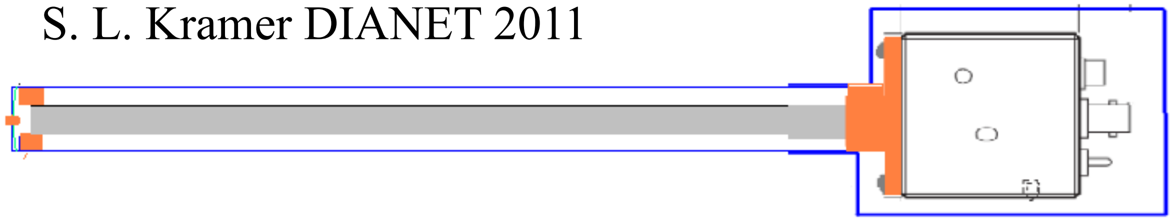
High background environments

- Synchrotron radiation
  - X rays

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

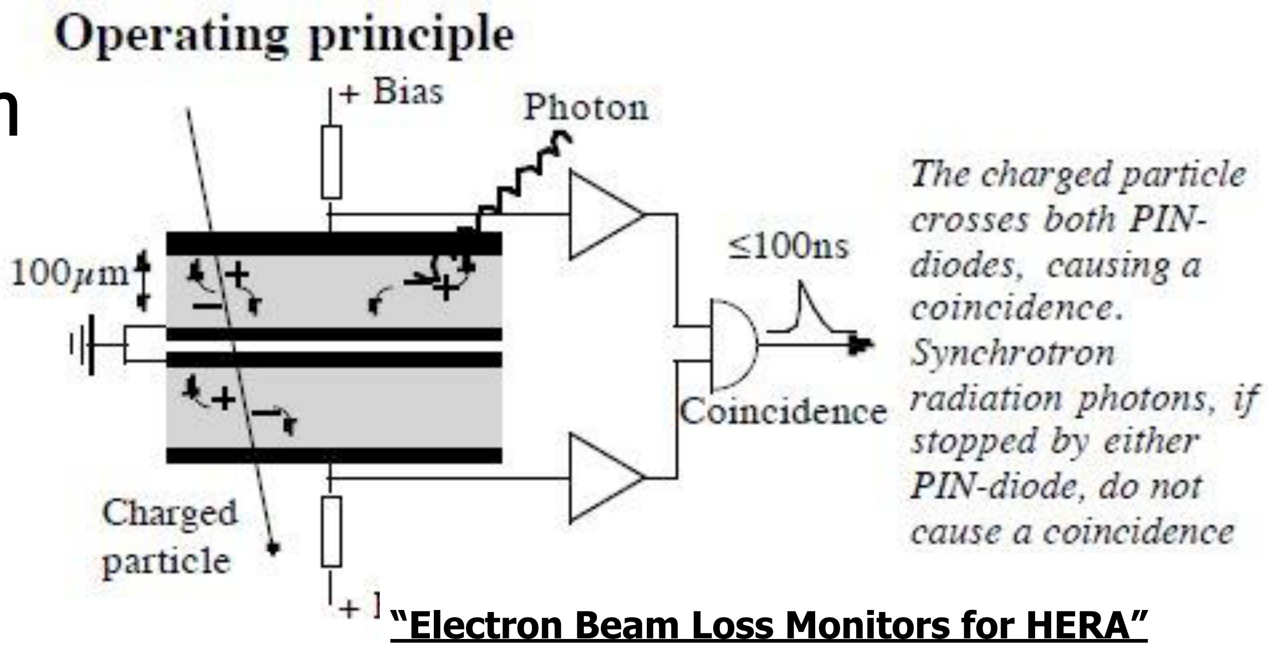
- Quartz rods and fibers (as Cherenkov light radiators) are insensitive to neutral radiation

- PIN diode “sandwiches” in coincidence



NSLS-II Beam Loss Monitor System

S. L. Kramer DIANET 2011



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”

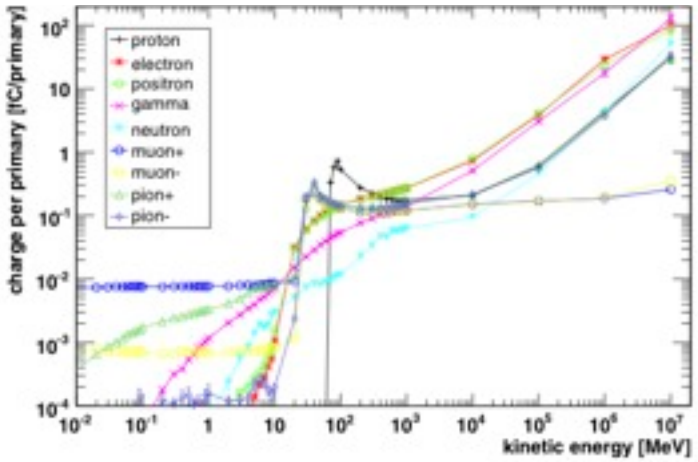
W. Bialowons et al.

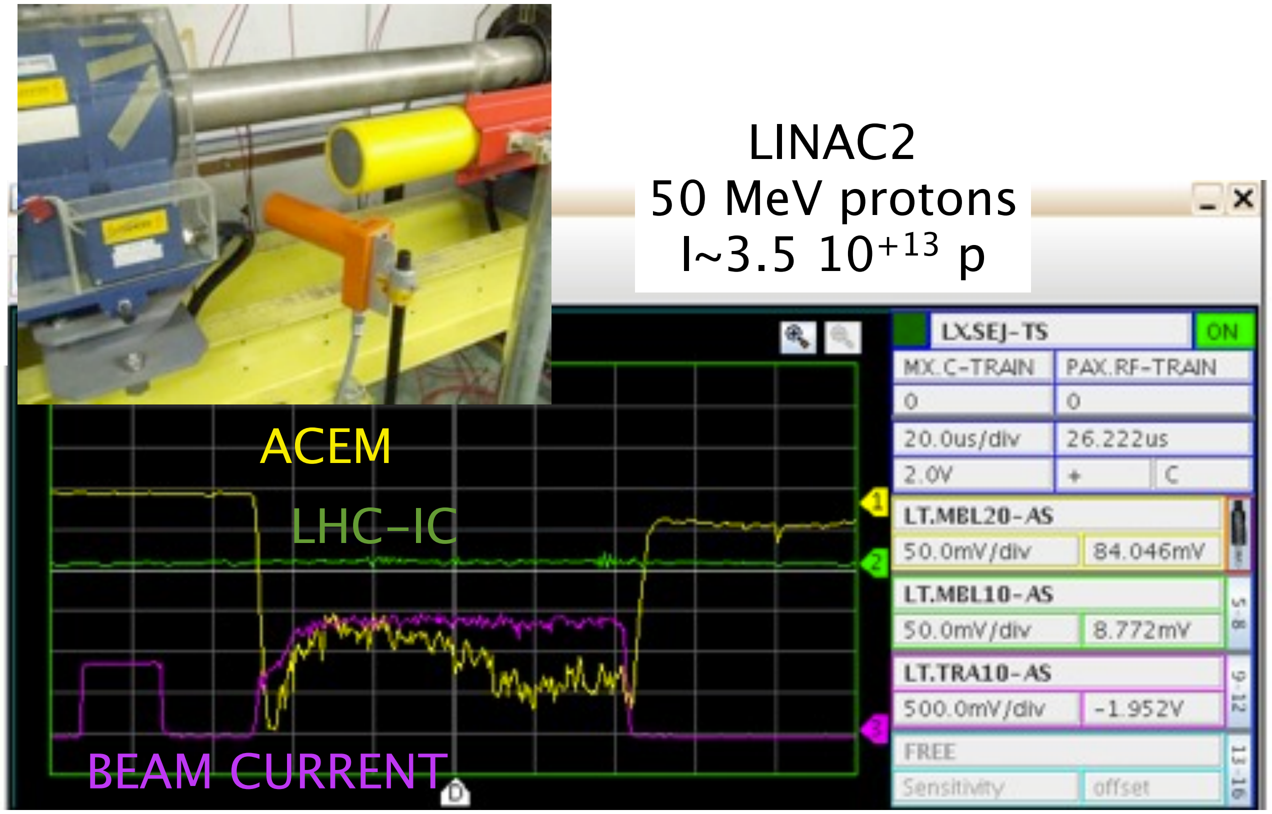
Beam Losses at low energy

- 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

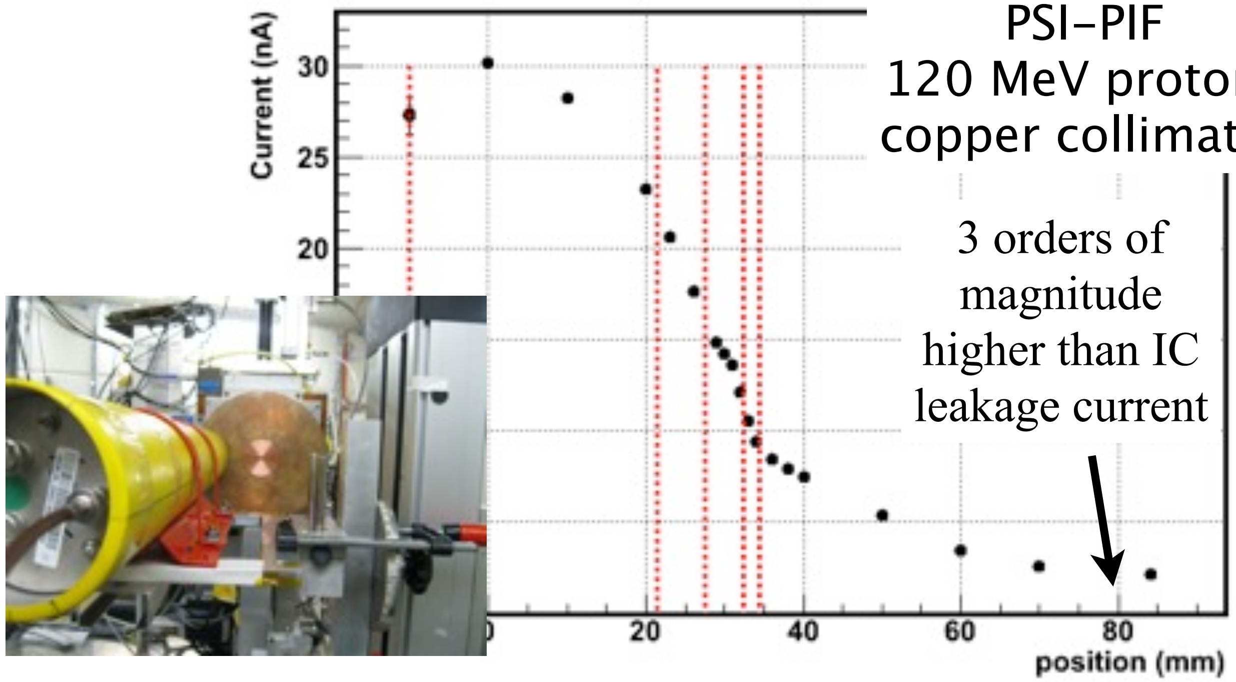




LINAC2
50 MeV protons
I~3.5 10^{+13} p

LX.SEJ-TS ON
MX.C-TRAIN 0
PAX.RF-TRAIN 0
20.0us/div 26.222us
2.0V + C
LT.MBL20-AS 50.0mV/div 84.046mV
LT.MBL10-AS 50.0mV/div 8.772mV
LT.TRA10-AS 500.0mV/div -1.952V
FREE Sensitivity offset

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



PSI–PIF
120 MeV protons
copper collimator

3 orders of magnitude higher than IC leakage current

Summary

- 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)

- Many challenges to overcome
  - Currently only solutions (ways around them) for a few of them
  - Need your ideas

Thank you for your attention

Extra Slides

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
- “Sapphire detectros”. S. Schuwalow. U. of Hamburg/DESY. Instrumentation seminar

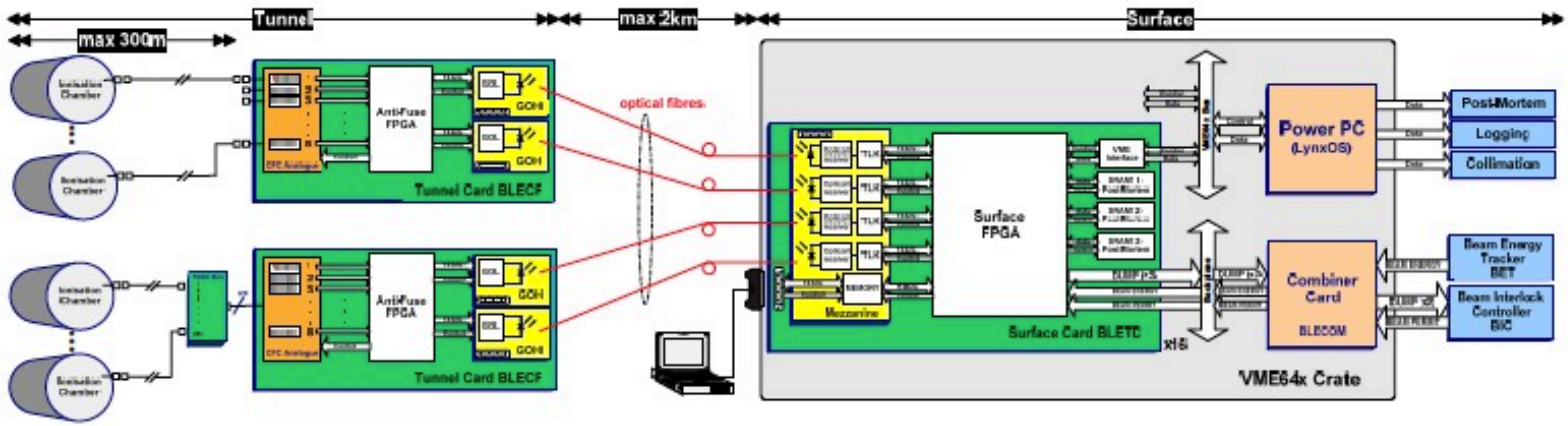
- “Beam instrumentation and diagnostics. P. Strehl

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

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

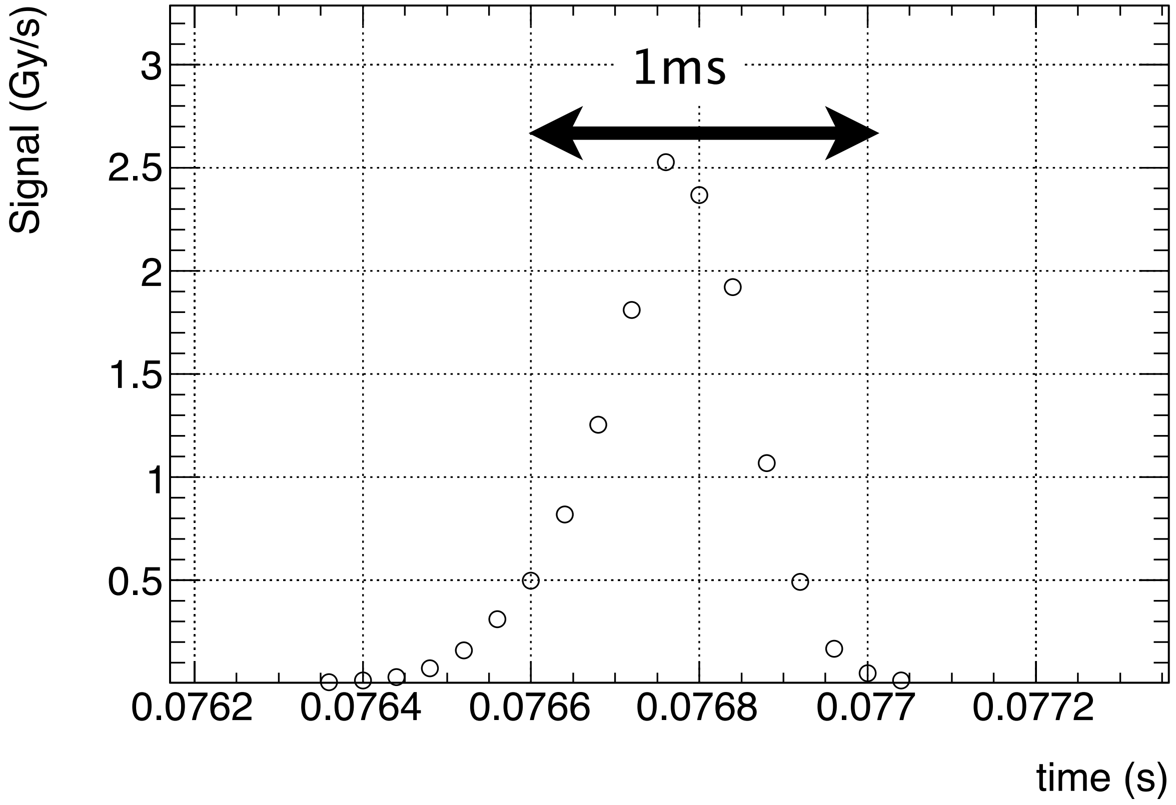
Machine Protection: the LHC case

- **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

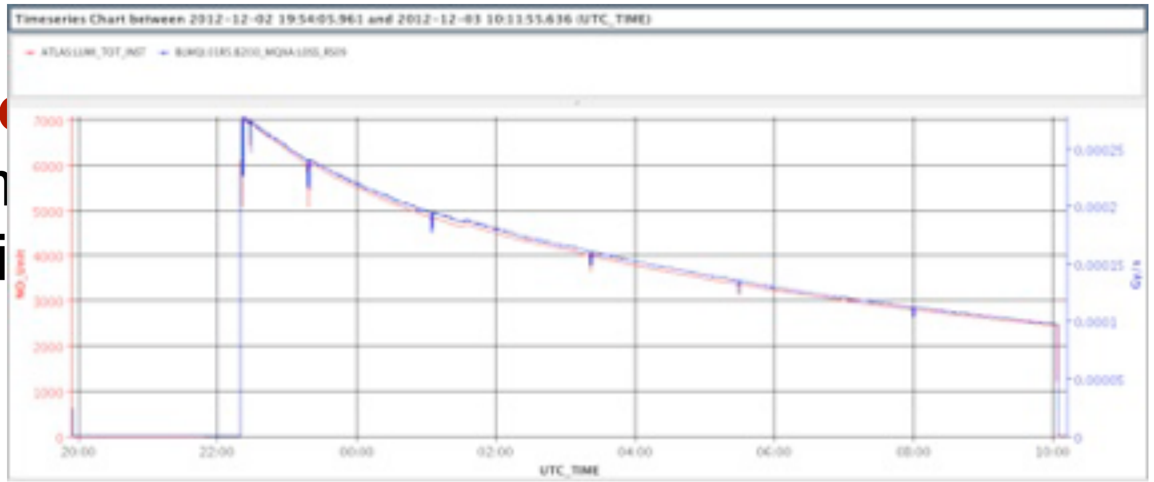


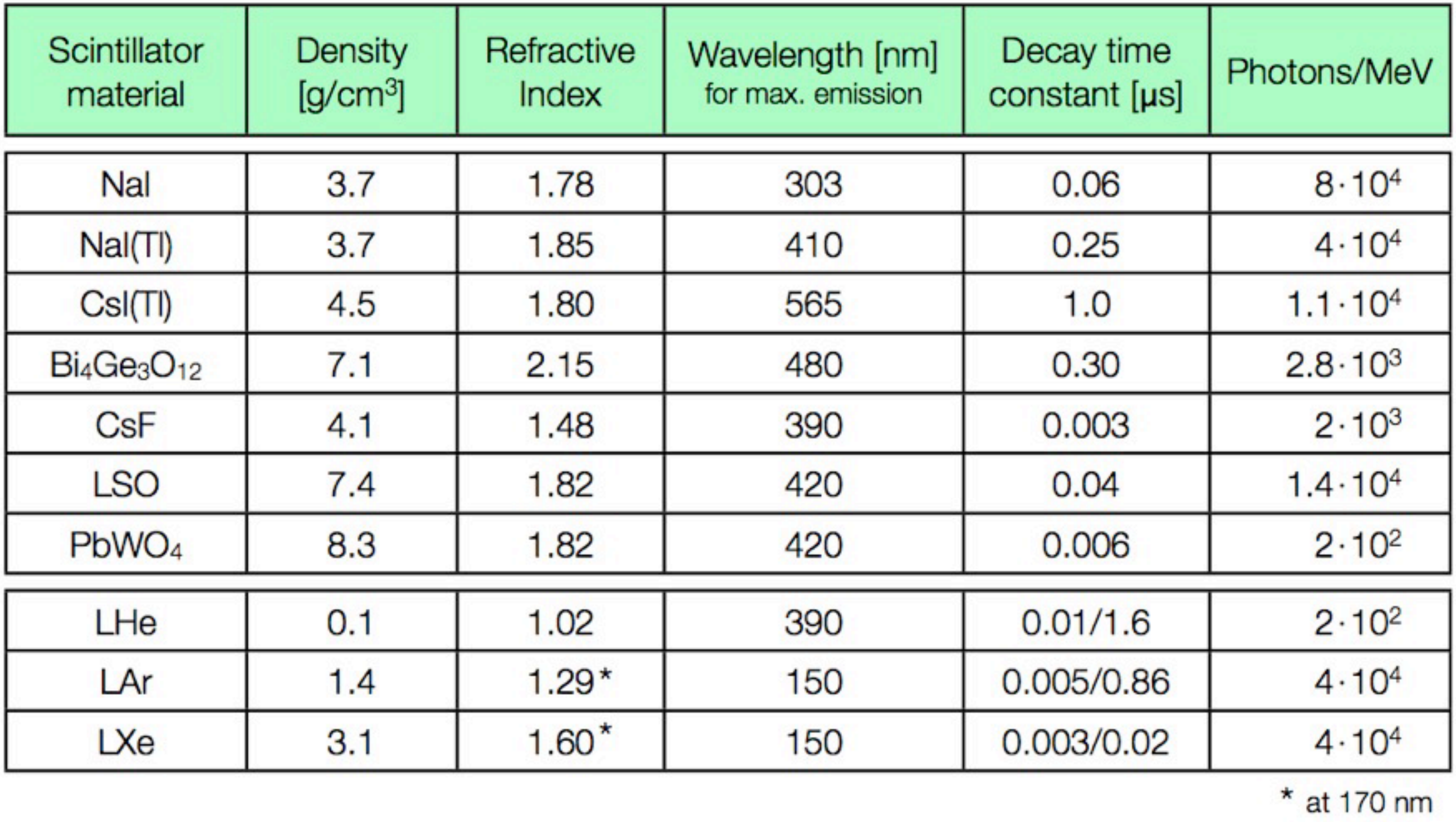
Type of losses

- Beam Loss categorization
  - Irregular beam losses
    - They are avoidable but sometime
    - RF trips
    - vacuum leaks
    - Injection losses
    - **Obstacles in the beam**



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





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

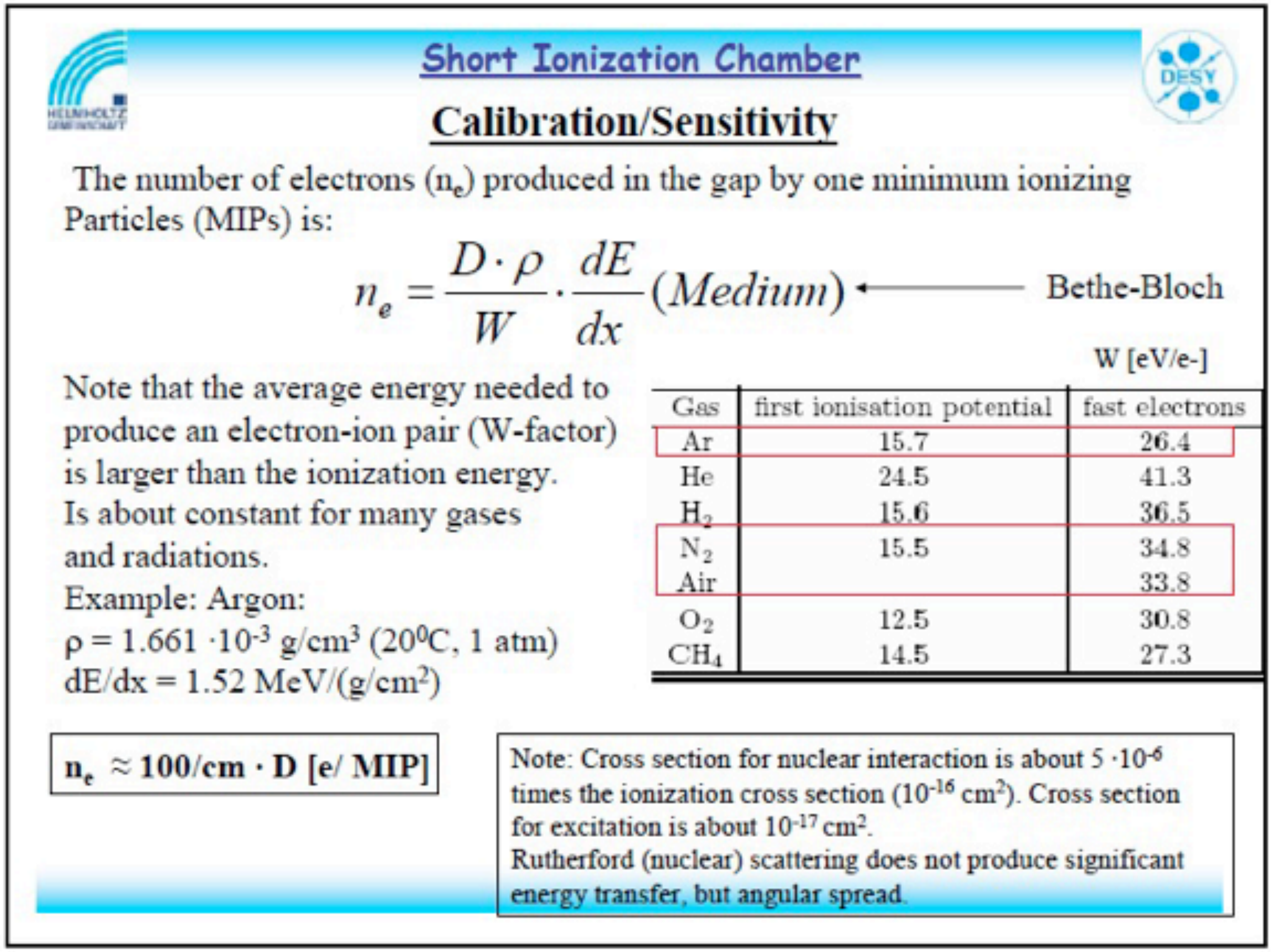
Scintillator material	Density [g/cm^3]	Refractive Index	Wavelength [nm] for max. emission	Decay time constant [ns]	Photons/MeV
Naphtalene	1.15	1.58	348	11	$4\cdot10^3$
Antracene	1.25	1.59	448	30	$4\cdot10^4$
p-Terphenyl	1.23	1.65	391	6-12	$1.2\cdot10^4$
NE102*	1.03	1.58	425	2.5	$2.5\cdot10^4$
NE104*	1.03	1.58	405	1.8	$2.4\cdot10^4$
NE110*	1.03	1.58	437	3.3	$2.4\cdot10^4$
NE111*	1.03	1.58	370	1.7	$2.3\cdot10^4$
BC400**	1.03	1.58	423	2.4	$2.5\cdot10^2$
BC428**	1.03	1.58	480	12.5	$2.2\cdot10^4$
BC443**	1.05	1.58	425	2.2	$2.4\cdot10^4$

Sensitivity calculation

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/cm^3 (20^{0}C, 1 atm)

$$S_{Ion} = \underbrace{100\frac{erg}{\cancel{g}}}_{\text{1 rad}} \cdot \underbrace{\frac{1eV}{1.6\cdot 10^{-12}\,erg}}_{\text{eV---> erg}} \cdot \underbrace{\frac{1e^-}{26\,eV}}_{\text{W}} \cdot \underbrace{\frac{1.66\cdot 10^{-3}\,\cancel{g}}{cm^3}}_{\rho} \cdot \underbrace{1000\,cm^3}_{\text{1 ltr.}} \cdot \underbrace{\frac{1.6\cdot 10^{-19}\,C}{e^-}}_{\text{e}^-\text{ charge}} = \boxed{638\frac{nC}{rad}}$$



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/cm^3 (20^{0}C, 1 atm)
dE/dx = 1.52 MeV/(g/cm^2)

	W [eV/e-]	
Gas	first ionisation potential	fast electrons
Ar	15.7	26.4
He	24.5	41.3
H_2	15.6	36.5
N_2	15.5	34.8
Air		33.8
O_2	12.5	30.8
CH_4	14.5	27.3

$n_e \approx$ 100/cm · D [e/ MIP]

Note: Cross section for nuclear interaction is about 5 ·10^{-6} times the ionization cross section (10^{-16} cm^2). Cross section for excitation is about 10^{-17} cm^2.
Rutherford (nuclear) scattering does not produce significant energy transfer, but angular spread.