Beam Loss Monitoring

Eva Barbara Holzer, CERN

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Beam Loss Monitoring – A Roadmap

- How to design the Beam Loss Monitoring System?
- Collection of requirements
- Monitor choices
  - Optical Fibers
  - Overview Sensitivity

Design of BLM System

Required for CDR December 2010: Functional specifications and cost estimate

For the cost estimate:

- Choice of technology
- Investigation of SIL
  - Possible need for redundant systems

Beam Loss in Standard Operation

1. Investigate particle loss locations in standard operation
    - Beam cleaning (collimation, absorbers), aperture limitations, beam dumps, …
    - Loss locations (spatial and moment distribution at impact)
    - Simulations (particle tracking) or
    - Rough determination by looking at apertures, lattice parameters and beam parameters

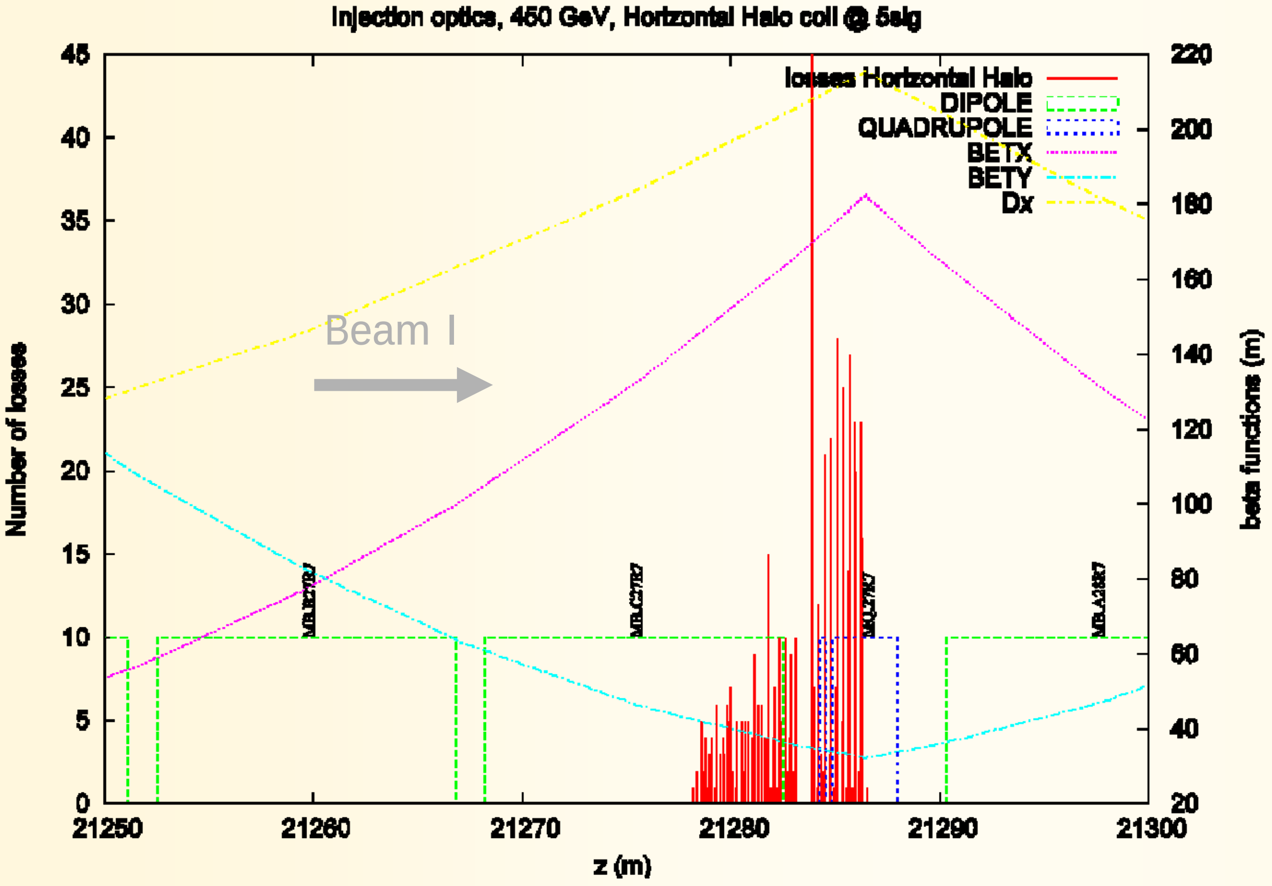
Watch the color code:

Complete list of tasks (somewhat frightening)

Reduced list of tasks (should be sufficient for CDR)

Example LHC: Topology of Loss (MQ27.R7)

Team R. Assmann



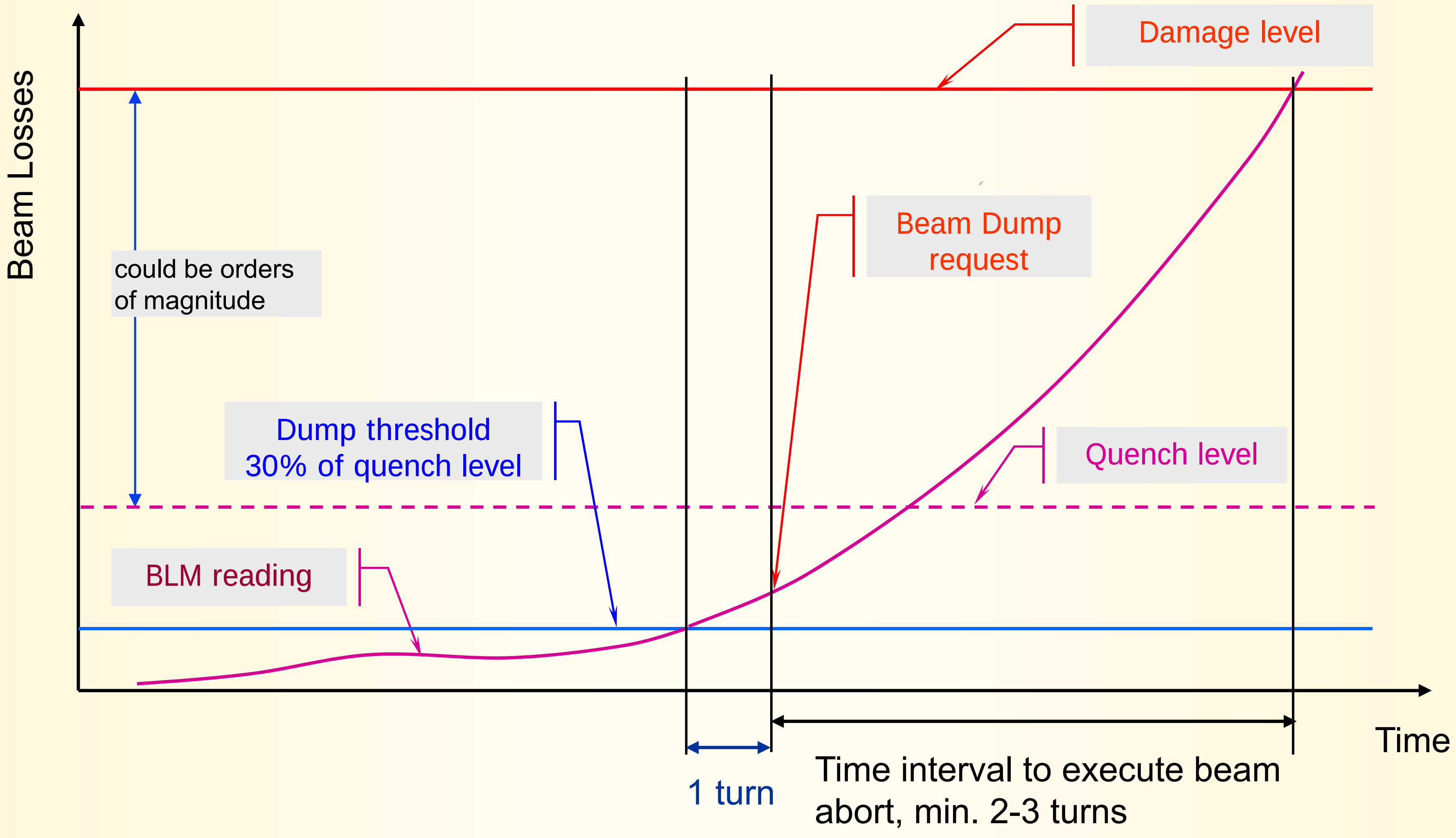
Maximum of dispersion and horizontal beta at centre of MQ: Losses start in the dipole and end in the middle of the quadrupole, highest peak at entry of MQ (aperture variations).

Failure Scenarios and Loss Locations

2. Investigate failure scenarios
   - Compile exhaustive list of failure scenarios: Magnet failures, collimator failures, kicker misfire, RF failure, power failure, mechanical problems (misalignment, obstacles, ground movement), temperature drift, vacuum problems, computer failures, operation failures, …
   - Identification of most critical failure scenarios
   - Loss locations (spatial and moment distribution at impact)
   - Time development of failure / beam loss:
     - Onset of the failure
     - Failure / loss reaches detectability (depends on technology of detection)
     - Loss reaches dangerous level
   - Extensive simulations and calculations
   - Start with the 2-3 most critical ones

Example: Beam Abort Sequence – Fast Beam Loss

Based on a graph by R. Schmidt



Loss Consequences – Limiting conditions I

3. Investigate limiting condition for each failure scenario and loss location

Quantities to consider:

- Single shot:
  - Energy (e.g. heat capacity)
  - Energy density (e.g. local damage)
- Continuous loss:
  - Power (e.g. global cooling power)
  - Poser density (e.g. local cooling power)

Loss Consequences – Limiting conditions II

3a) Limits for beam loss:

1) Mechanical damage to equipment at loss location
    - E.g. burning hole in vacuum pipe, …
2) Damage (operation impairment) to equipment further downstream or around – identify the most critical equipment
3) Impairment of operation
    - Heat load to equipment (operational range of RF cavity, superconducting wiggler magnets, …)
    - Radiation (electronics, …)

Loss Consequences – Limiting conditions III

3b) Additional limits for steady state beam loss:

- In general covered by separate dosimeter system(s)

1) Long term radiation damage (insulation material, electronics, …)
2) Activation issues (access for maintenance, equipment exchange, …)

- Extensive simulations (particle showers, heat flow, material damage) and measurements
- Simplified (geometry) model simulations (particle showers, heat flow) of the 2-3 most critical failure

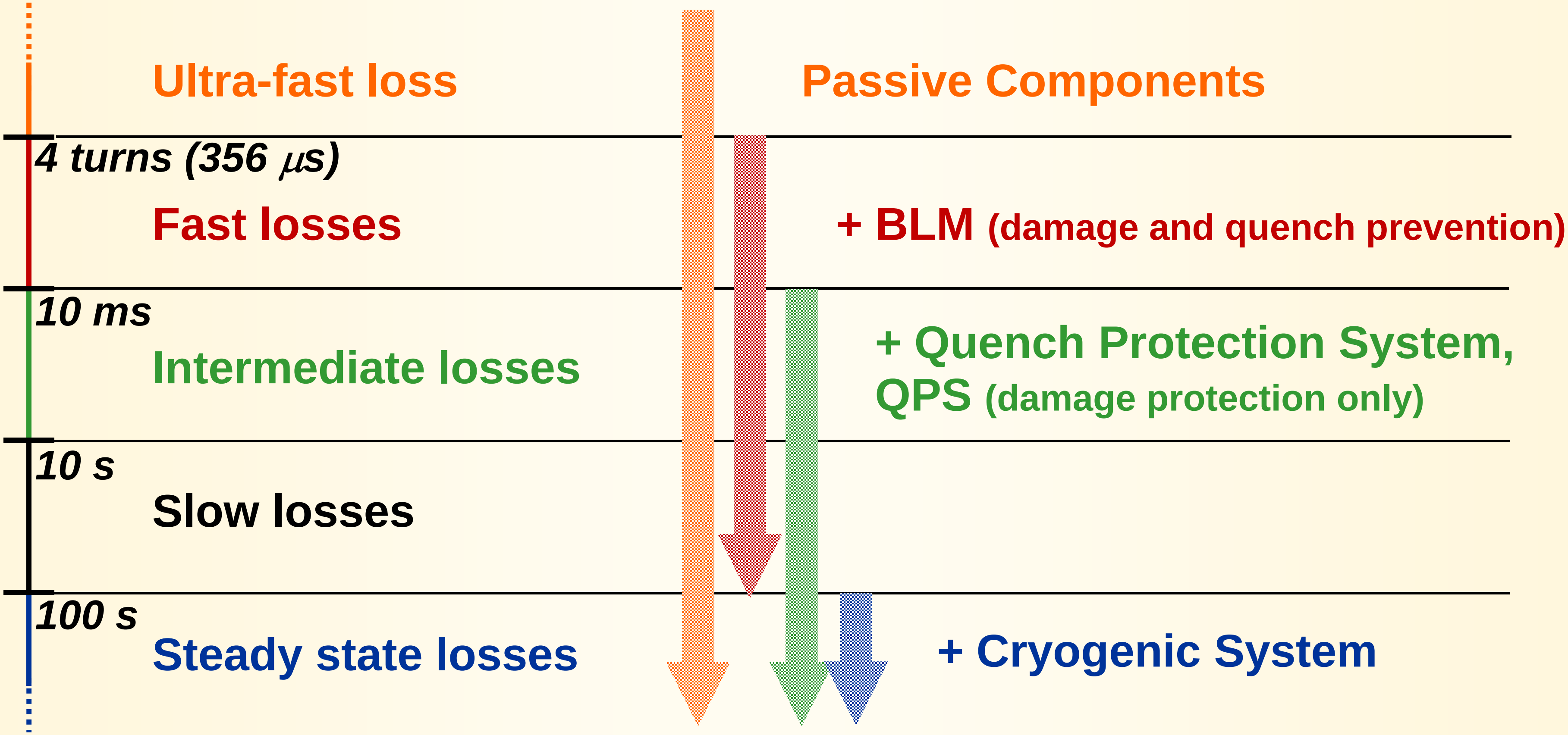
Protection Strategy - Choice of Technology

4. Choice of measurable to determine beam losses (or imminent beam losses)
   - BLM, fast (magnet) current change monitor, beam current transformer, BPM, transverse tail monitors, …
     - Resolution required vs achievable
     - Reaction time required vs achievable
     - Dynamic range required vs achievable
   - Investigate SIL (safety integrity level) required and achieved
     - Need redundant systems for reliability?
     - Availability still ensured?
   - Dependability analysis (reliability, availability, maintainability and safety) or
   - Establish required SIL levels and estimate (based on previous dependability analysis) the SIL levels of various protection system, determine redundant systems when needed.
   - LHC, 2 month downtime, 30 MCHF repair – >SIL3: E-7 to E-8 failure rate per hour

Protection Strategy – ad ‘system reaction time’

- Time constant of failure development (from onset to dangerous loss):
  - Passive protection (collimators, absorbers)
  - Active protection - dump of the pulse tail
    - Drive beam accelerator: beam dump within < 0.14 ms: might be feasible
    - Main beam: < 156 ns does not seem feasible
  - Post pulse analysis (allow following pulse)
    - 20 ms is comfortable for beam loss measurement

LHC: Beam loss durations classes



LOSS DURATION **PROTECTION SYSTEM**

Ultra-fast loss — **Passive Components**

4 turns (356 μs)

Fast losses — **+ BLM (damage and quench prevention)**

10 ms

Intermediate losses — **+ Quench Protection System, QPS (damage protection only)**

10 s

Slow losses

100 s

Steady state losses — **+ Cryogenic System**

- The BLM is the main active system to prevent magnet damage from all the possible multi-turn beam losses.
- Prevention of quench only by BLM system

Choice of Technology – ad ‘BLM system’ I

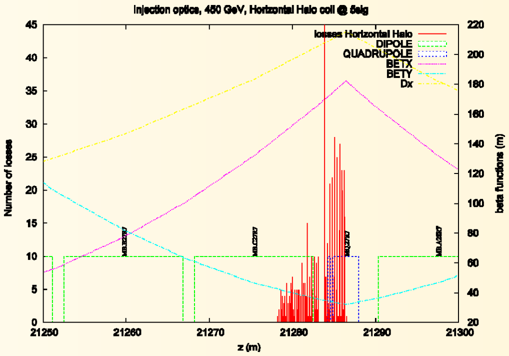
- Dynamic range? Given by the range from pilot beam to full intensity. Adjust, so that:
  - Pilot beam (or low intensity) and no losses observable → extrapolation to full intensity → safely below damage limit; or
  - Pilot → intermediate; intermediate → full intensity
  - Compare LHC: 10^8, two monitor types: 10^{13}

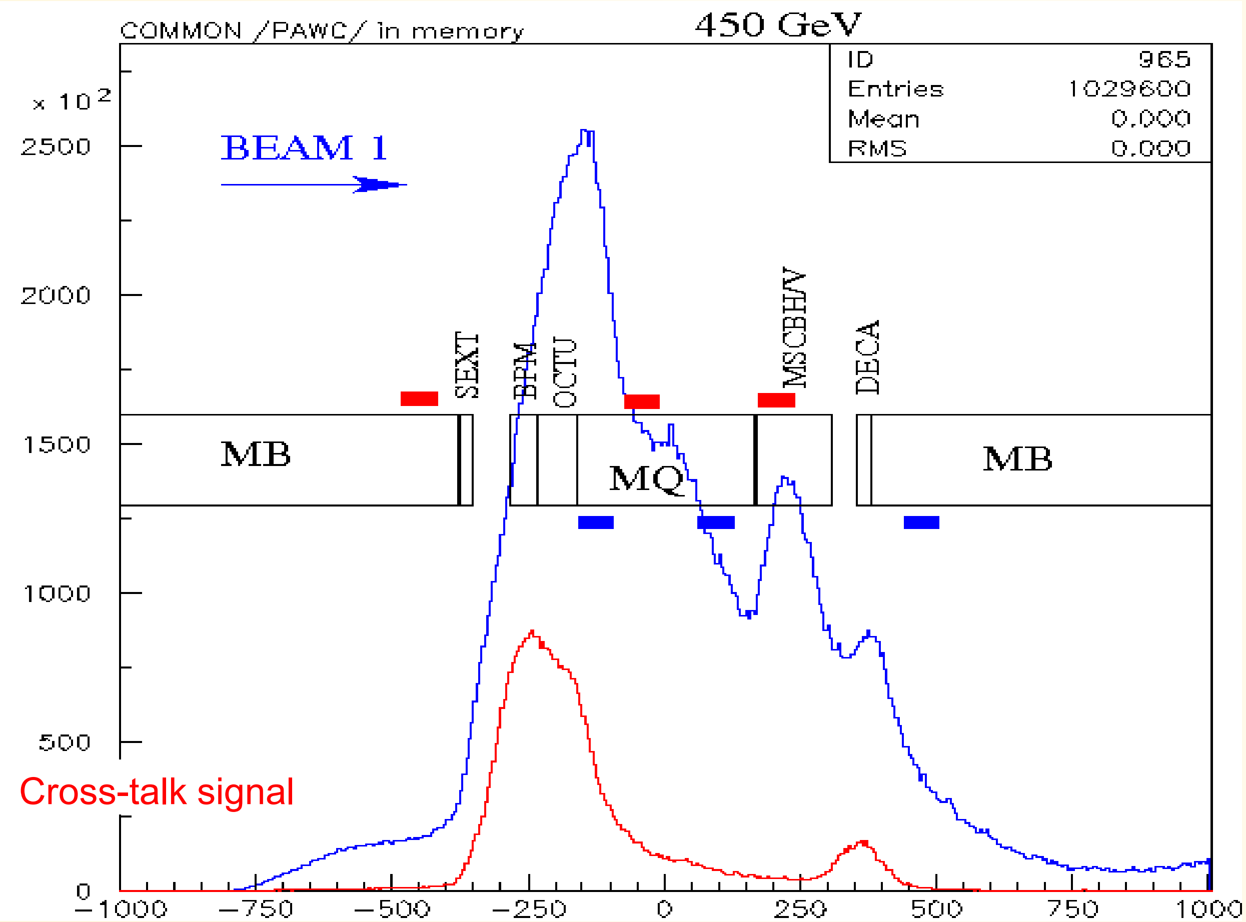
- Distinguish losses from:
  - Drive beam decelerator vs main beam in same tunnel vs beam transport lines, beam turns, beam dumps
  - Synchrotron light
  - Photons from RF cavities
  - Wigglers, undulators
  - EM noise
  - …

Example LHC MQ

L. Ponce

Distinguish losses from beam 1 and beam 2





Cross-talk signal

Choice of Technology – ad ‘BLM system’ II

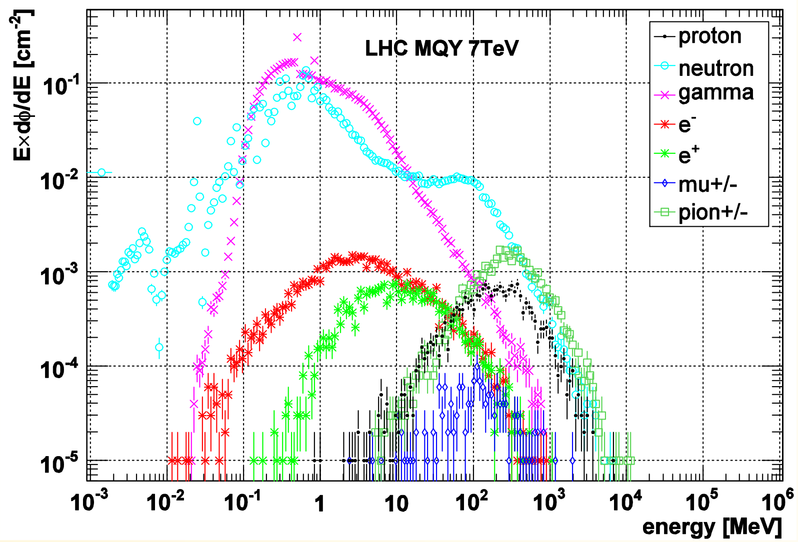
- Choice of monitor location
- Choice of monitor type (sensitive to selective type of radiation: particle species, energy range?)
- Can selective timing help to distinguish radiation source?
  - Thermal neutrons can significantly lengthen the signal (percentage of the signal?)
- Simulations to determine secondary particle fluence spectra and time distribution at possible monitor locations
- … for the most critical loss scenarios

- Simulations to determine monitor response or
- Simplified simulations or estimation of approximate monitor response

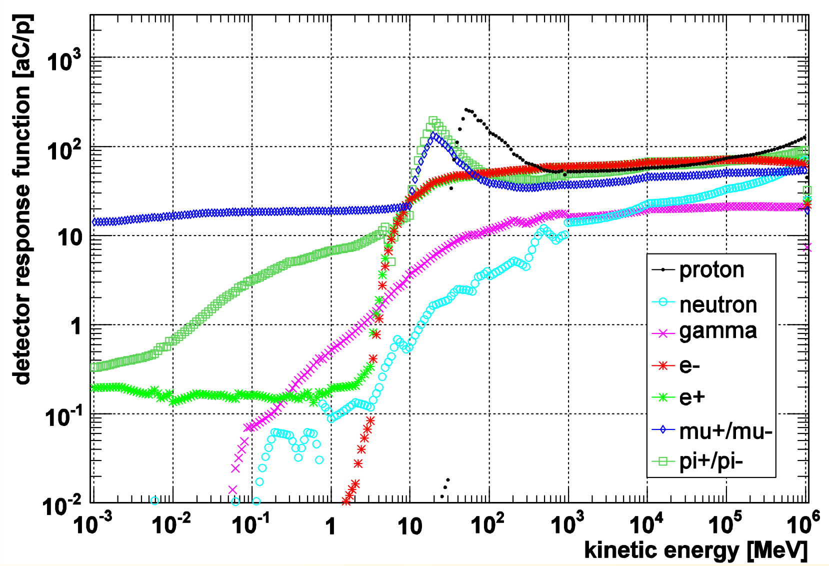
Example LHC Simulations I

M. Stockner

MQY LHC quadrupole magnet 7TeV



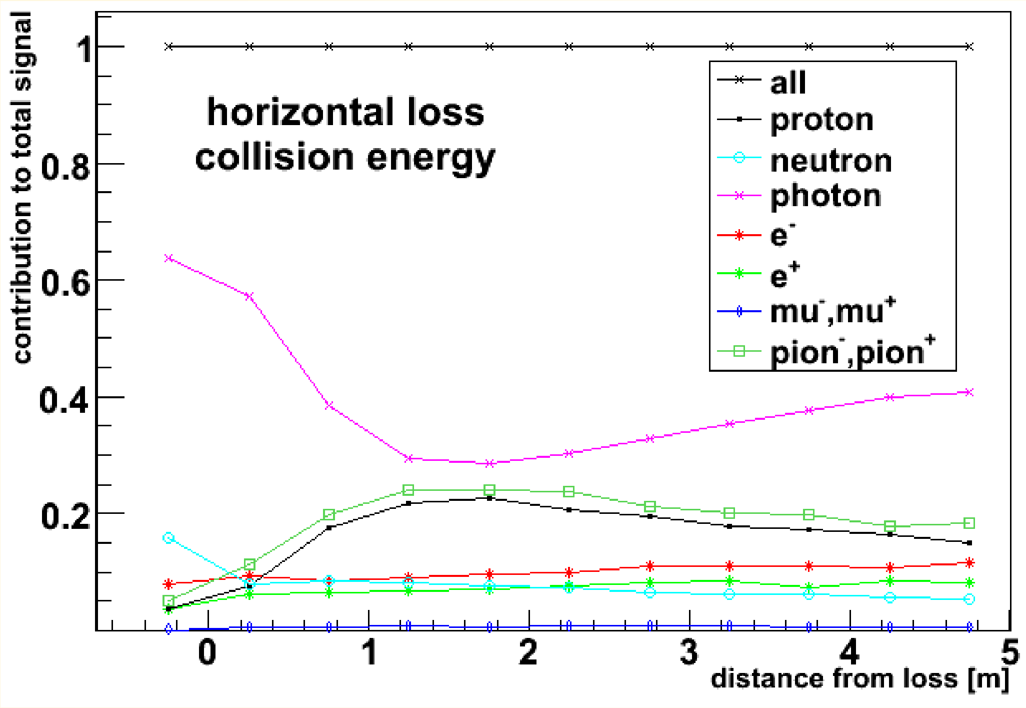
Secondary particle fluence spectrum on the outside recoded in a 3.4 m long stripe, lethargy representation.



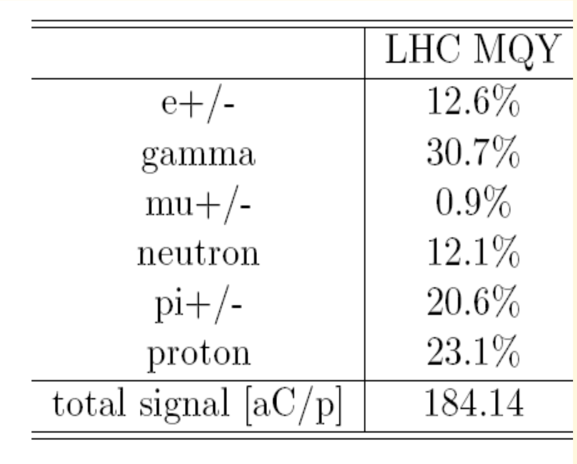
GEANT4 simulated LHC BLM detector response functions for particle impact direction of 60◦

Example LHC Simulations II

M. Stockner



Contribution from various particles: domination of photons, protons and pions



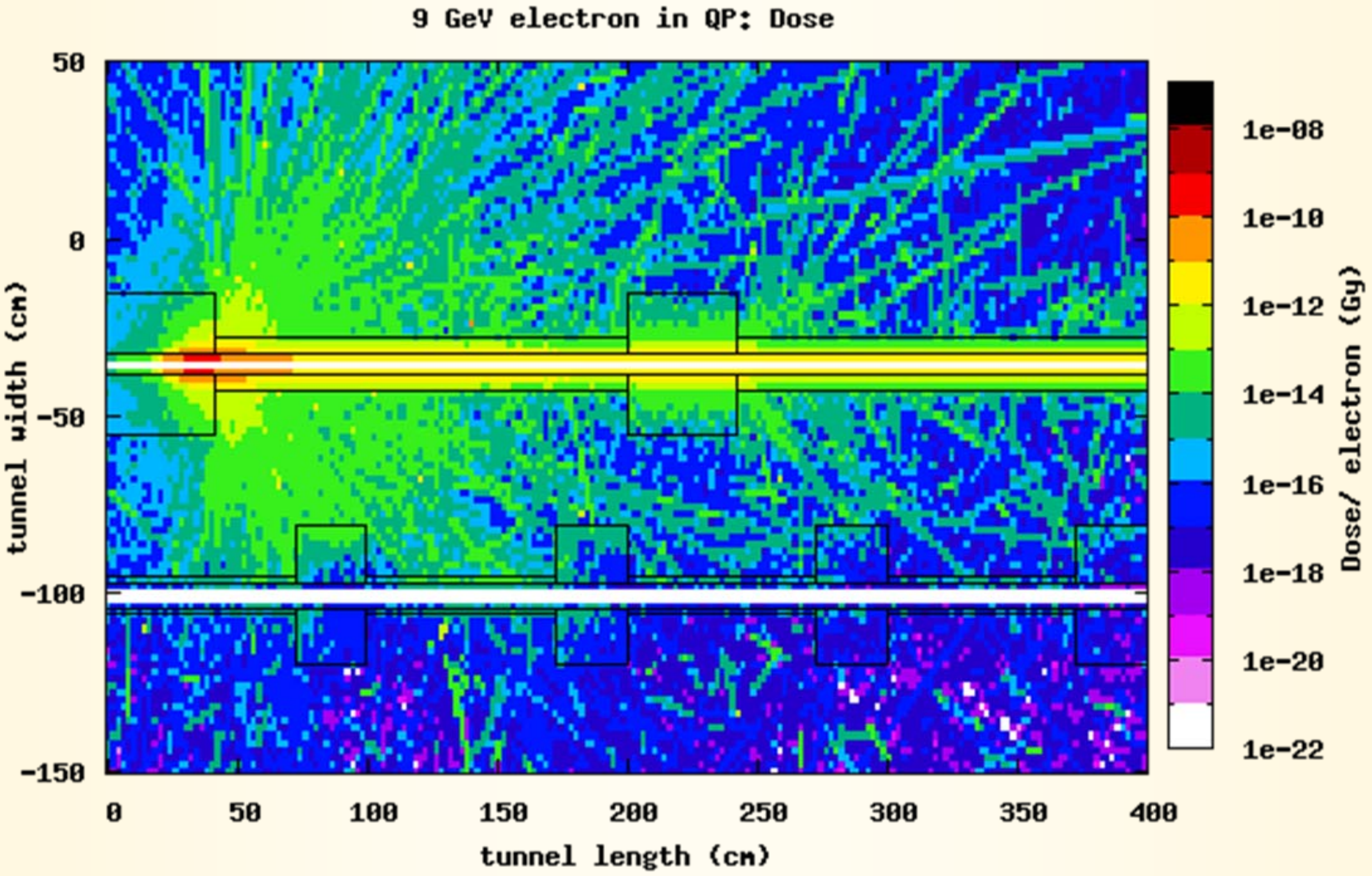
	LHC MQY
e+/-	12.6%
gamma	30.7%
mu+/-	0.9%
neutron	12.1%
pi+/-	20.6%
proton	23.1%
total signal [aC/p]	184.14

Contribution from the different particle types to the signal.

CLIC FLUKA Simulation

Th. Otto, CLIC Workshop 2008

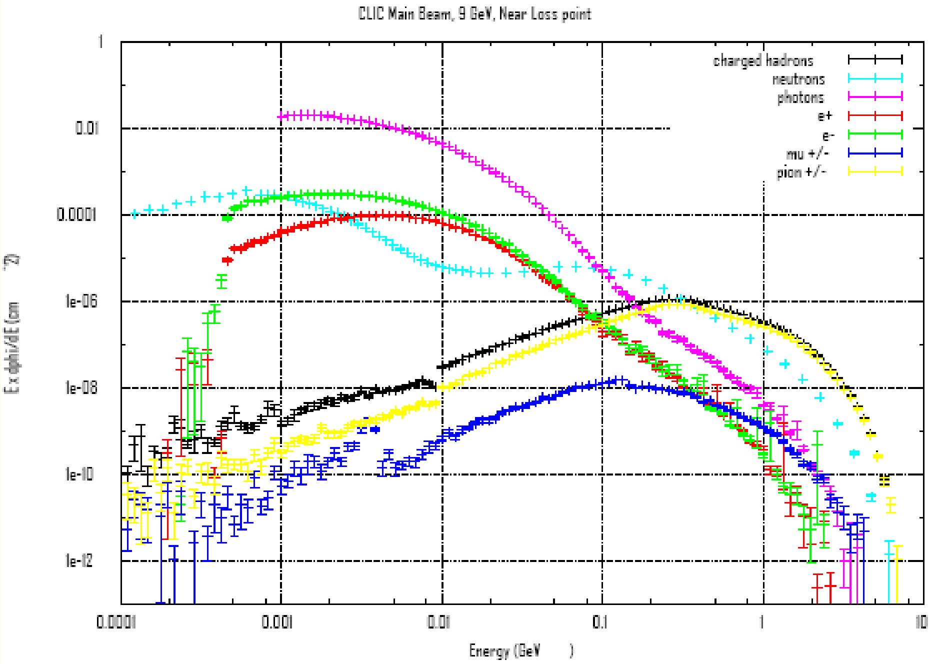
Simplified model of drive beam and main beam; Loss location: middle of quadrupole. To avoid long term radiation damage (drive beam 2.4 GeV, main beam 1.5 TeV), **limit for fractional beam loss : ~< 2 E -7**



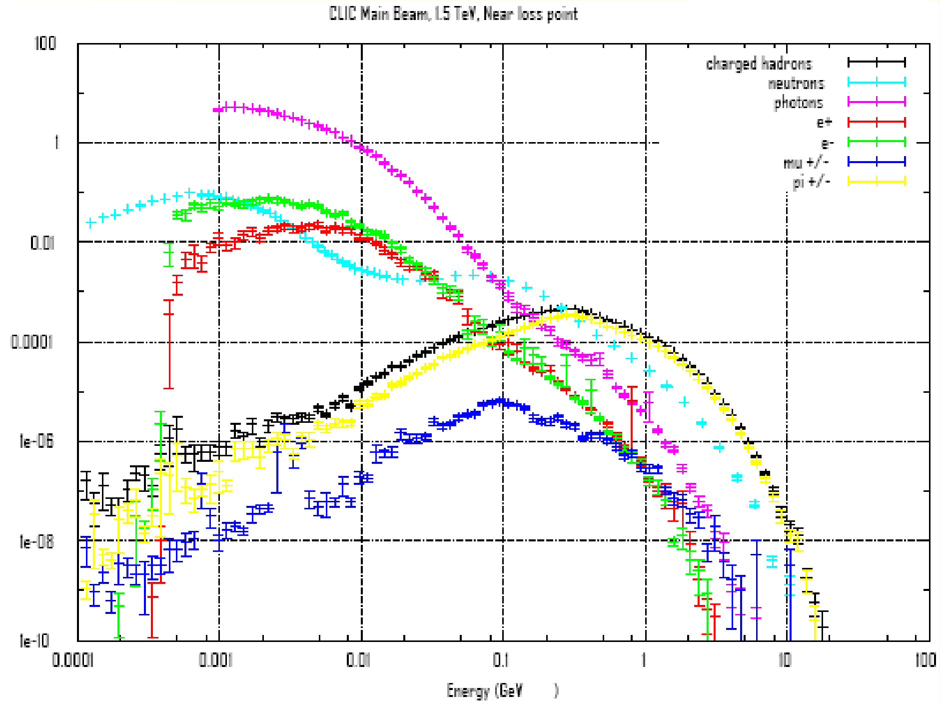
Main Beam - Preliminary

Sophie Mallows

9 GeV



1.5 TeV

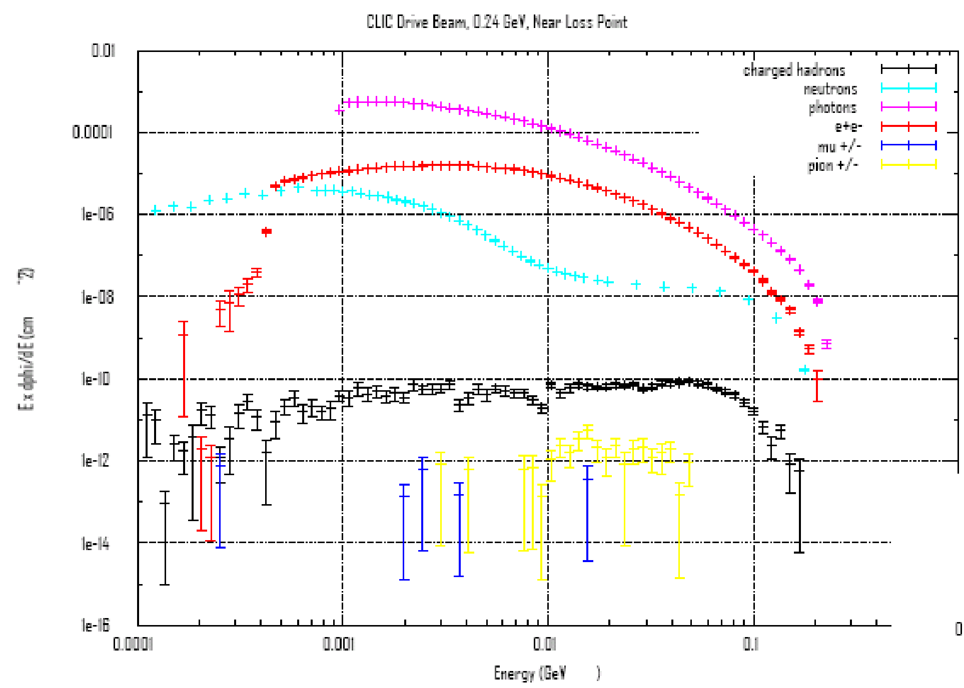


Same FLUKA simulation set-up.

Particle fluence spectra after quadrupoles.

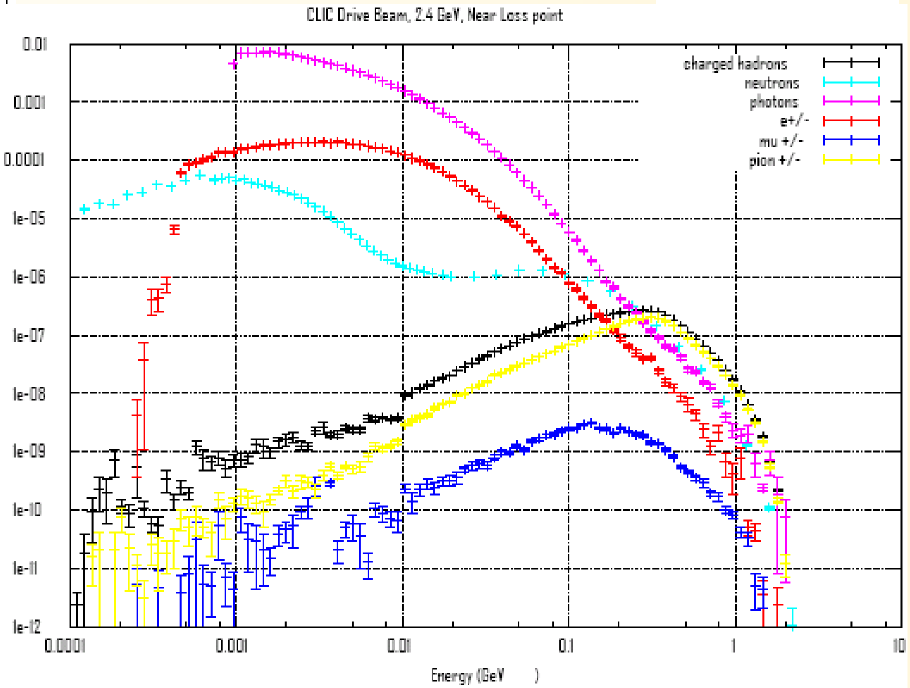
Drive Beam - Preliminary

Sophie Mallows



0.24 GeV

2.4 GeV



Same FLUKA simulation set-up.

Particle fluence spectra after quadrupoles.

Collection of Requirements

- Damping Ring: fast BLM to protect superconducting wigglers
  - Time from loss detection to beam abort : ~ 10 μs desired
  - Compare LHC: 356 μs (resolution: 40 μs)
- Main beam and drive beam:
  - Dosimetry fractional beam loss (long term magnet destruction, simplified FLUKA model, Th. Otto)

Main beam 1.5 TeV	1.5 E-7
Main beam 9 GeV	5 E-5
Drive beam 2.4 GeV	2.3 E-7
Drive beam 0.24 GeV	1.3 E-6

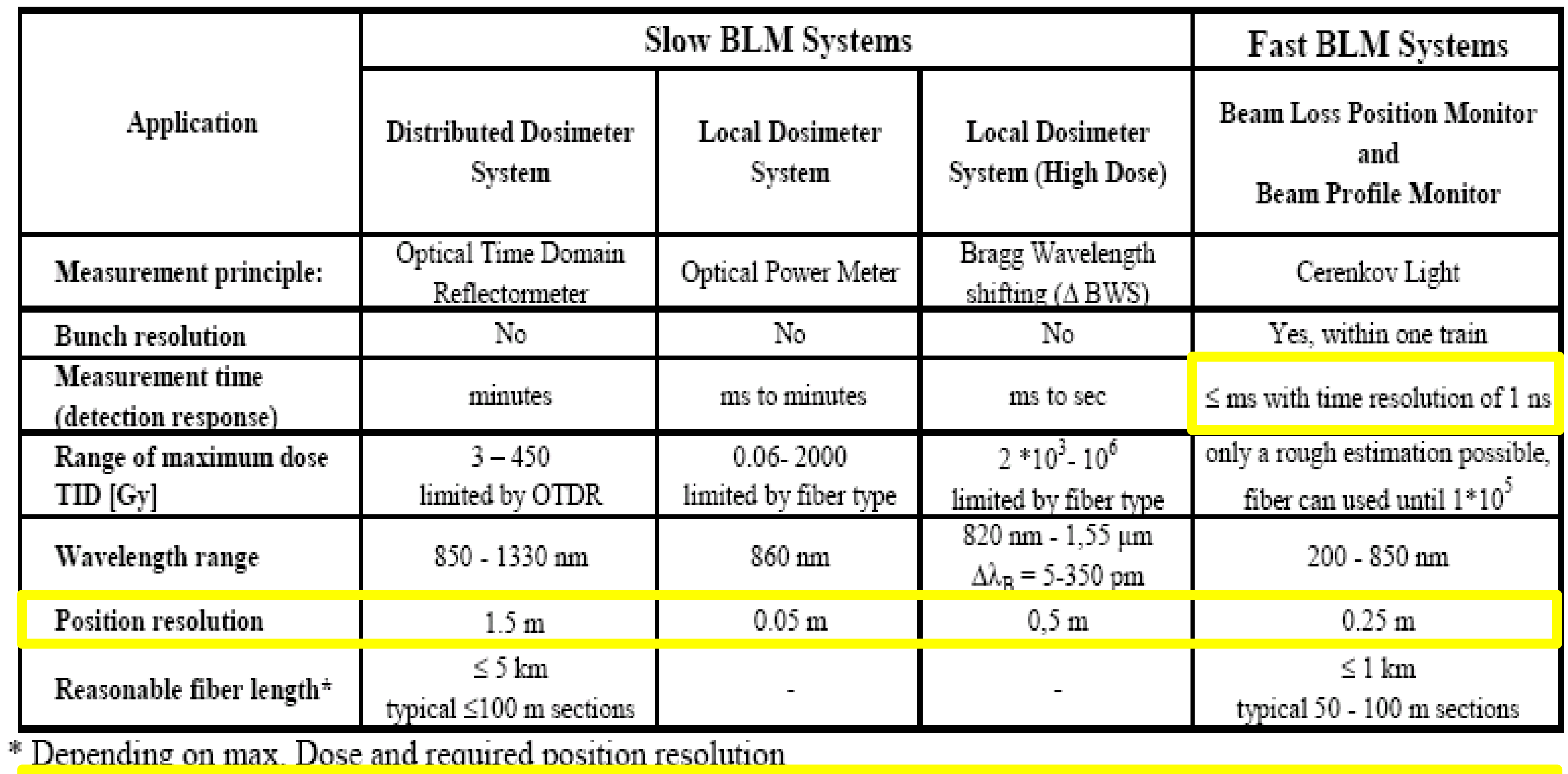
  - Fast fractional beam loss (very rough estimate on melting Cu, M. Jonker)

Main beam 1.5 TeV	~ 1 E-4
Main beam 2.8 GeV at damping ring	~0.5 E-4
Drive beam decellerator 2.4 GeV	~0.1

- Drive beam decelerator
  - Sensitivity: ~1% of one bunch lost: fractional loss of ~3 E-6 of one train

Recent Developments in Fiber Loss Monitors I

Beam Loss and Beam Profile Monitoring with Optical Fibers; F. Wulf, M. Körfer; DIPAC 2009.



	Slow BLM Systems			Fast BLM Systems
Application	Distributed Dosimeter System	Local Dosimeter System	Local Dosimeter System (High Dose)	Beam Loss Position Monitor and Beam Profile Monitor
Measurement principle:	Optical Time Domain Reflectormeter	Optical Power Meter	Bragg Wavelength shifting (Δ BWS)	Cerenkov Light
Bunch resolution	No	No	No	Yes, within one train
Measurement time (detection response)	minutes	ms to minutes	ms to sec	≤ ms with time resolution of 1 ns
Range of maximum dose TID [Gy]	3 – 450 limited by OTDR	0.06- 2000 limited by fiber type	$2 * 10^3 - 10^6$ limited by fiber type	only a rough estimation possible, fiber can used until $1*10^5$
Wavelength range	850 - 1330 nm	860 nm	820 nm - 1,55 µm $\Delta\lambda_B$ = 5-350 pm	200 - 850 nm
Position resolution	1.5 m	0.05 m	0,5 m	0.25 m
Reasonable fiber length*	≤ 5 km typical ≤100 m sections	-	-	≤ 1 km typical 50 - 100 m sections

* Depending on max. Dose and required position resolution

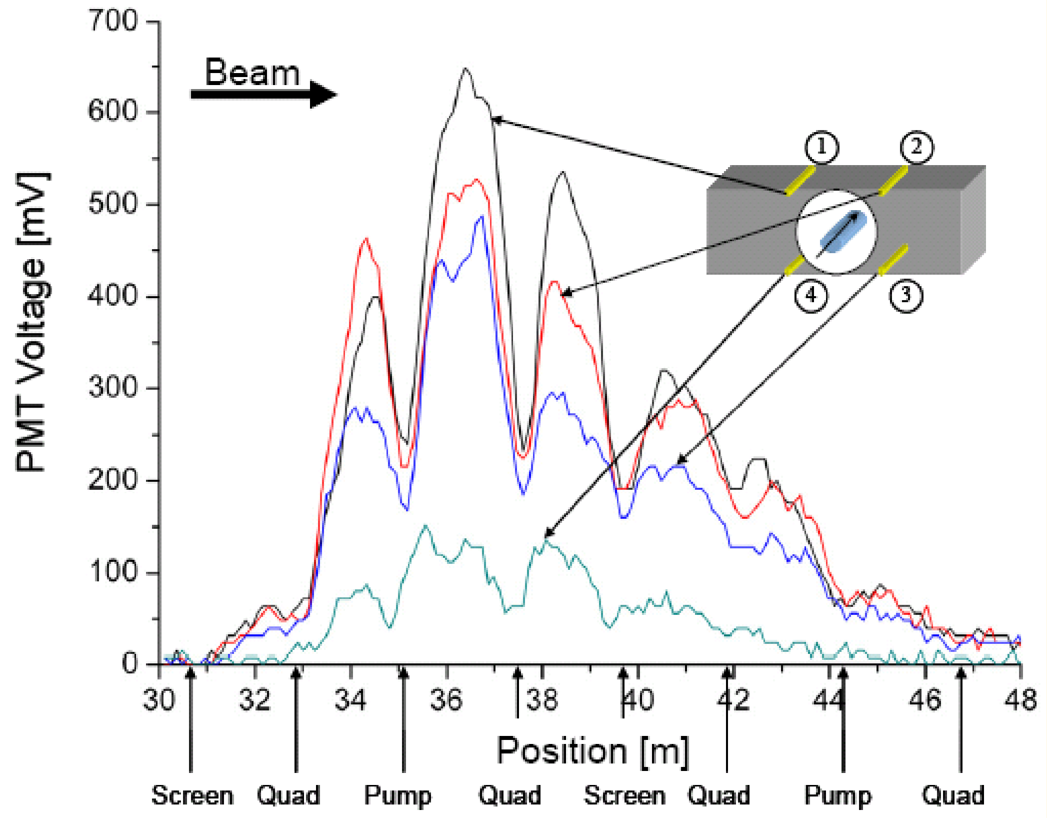
Dose resolution	**3 Gy**	**60 mGy**	**2 kGy**	**?**
Dynamic range	**~100**	**~30’000**	**~500**	**?**

Recent Developments in Fiber Loss Monitors II

Beam Loss and Beam Profile Monitoring with Optical Fibers; F. Wulf, M. Körfer; DIPAC 2009.

BLPM (beam loss position measurement); losses generated by inserting OTR screen.

Fibres can also be used as detector for wire scanner BPM; two sets of fibres to increase resolution of the beam tails (adapt PMT amplification).

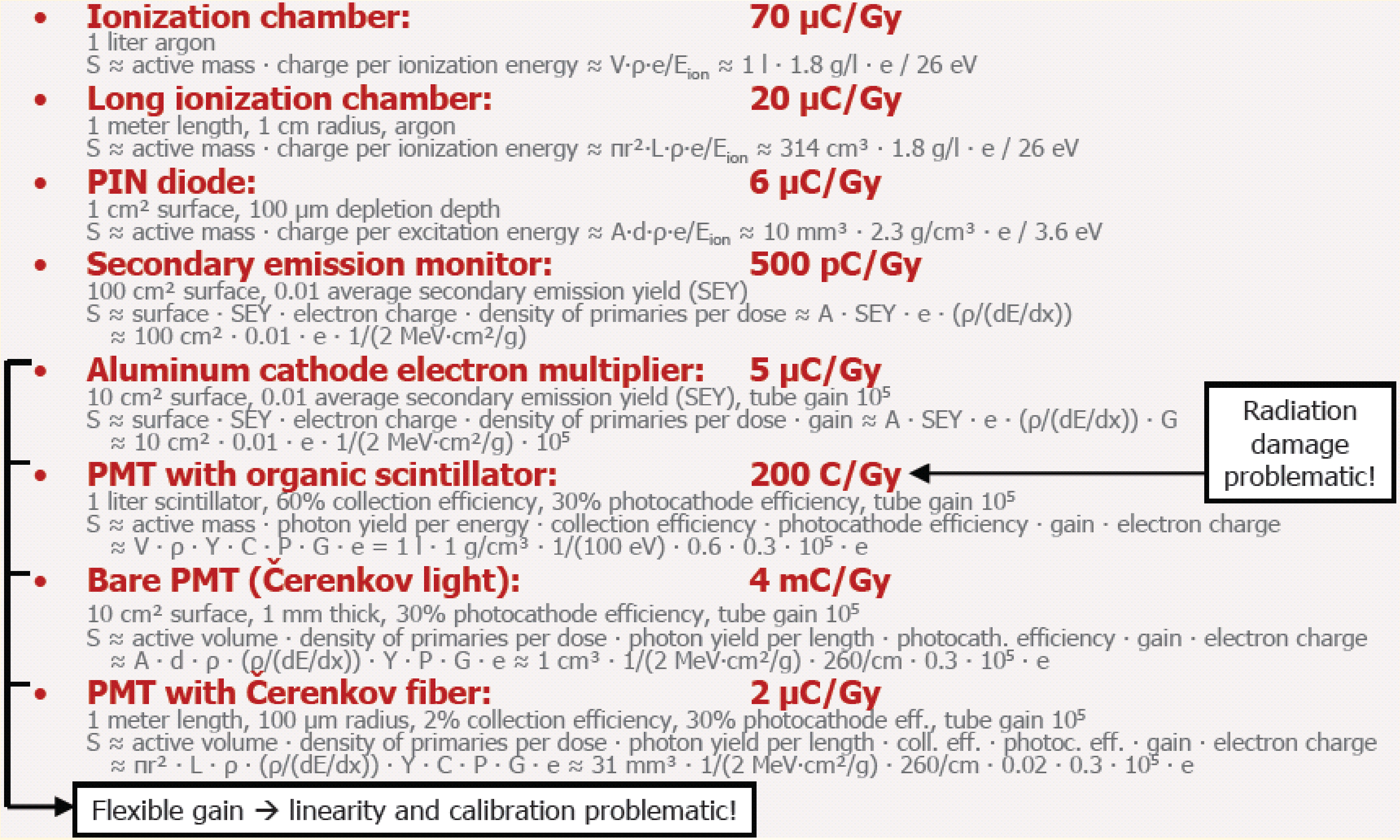


BLM Fibers

- Pros:
  - Cover complete length
  - Transverse position (and profile) also possible
  - Time resolution (up to 1 ns)
  - Minimal space requirement
  - Insensitive against E and B fields
  - Radiation hard (depending on type)
  - Combination fiber / readout can adapt to a wide dose range
  - Dose measurement
- Cons:
  - Resolution (3 Gy, 60 mGy, 2 kGy)
  - Dynamic range (literature: 100, 30’000, 500 - compare LHC: 10^8, 10^{13})

Monitor Choices – Estimated Sensitivities

Lars Fröhlich, DESY; ERL Instrumentation Workshop 2008.



- **Ionization chamber:** **70 µC/Gy**
  1 liter argon
  $S \approx$ active mass · charge per ionization energy $\approx V \cdot \rho \cdot e/E_{ion} \approx 1\ \mathrm{l} \cdot 1.8\ \mathrm{g/l} \cdot e\ /\ 26\ \mathrm{eV}$
- **Long ionization chamber:** **20 µC/Gy**
  1 meter length, 1 cm radius, argon
  $S \approx$ active mass · charge per ionization energy $\approx \pi r^2 \cdot L \cdot \rho \cdot e/E_{ion} \approx 314\ \mathrm{cm}^3 \cdot 1.8\ \mathrm{g/l} \cdot e\ /\ 26\ \mathrm{eV}$
- **PIN diode:** **6 µC/Gy**
  1 cm² surface, 100 µm depletion depth
  $S \approx$ active mass · charge per excitation energy $\approx A \cdot d \cdot \rho \cdot e/E_{ion} \approx 10\ \mathrm{mm}^3 \cdot 2.3\ \mathrm{g/cm}^3 \cdot e\ /\ 3.6\ \mathrm{eV}$
- **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 $\approx A \cdot \mathrm{SEY} \cdot e \cdot (\rho/(dE/dx))$
  $\approx 100\ \mathrm{cm}^2 \cdot 0.01 \cdot e \cdot 1/(2\ \mathrm{MeV \cdot cm^2/g})$
- **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 $\approx A \cdot \mathrm{SEY} \cdot e \cdot (\rho/(dE/dx)) \cdot G$
  $\approx 10\ \mathrm{cm}^2 \cdot 0.01 \cdot e \cdot 1/(2\ \mathrm{MeV \cdot cm^2/g}) \cdot 10^5$
- **PMT with organic scintillator:** **200 C/Gy**
  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
  $\approx V \cdot \rho \cdot Y \cdot C \cdot P \cdot G \cdot e = 1\ \mathrm{l} \cdot 1\ \mathrm{g/cm}^3 \cdot 1/(100\ \mathrm{eV}) \cdot 0.6 \cdot 0.3 \cdot 10^5 \cdot e$
- **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
  $\approx A \cdot d \cdot \rho \cdot (\rho/(dE/dx)) \cdot Y \cdot P \cdot G \cdot e \approx 1\ \mathrm{cm}^3 \cdot 1/(2\ \mathrm{MeV \cdot cm^2/g}) \cdot 260/\mathrm{cm} \cdot 0.3 \cdot 10^5 \cdot e$
- **PMT with Čerenkov 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
  $\approx \pi r^2 \cdot L \cdot \rho \cdot (\rho/(dE/dx)) \cdot Y \cdot C \cdot P \cdot G \cdot e \approx 31\ \mathrm{mm}^3 \cdot 1/(2\ \mathrm{MeV \cdot cm^2/g}) \cdot 260/\mathrm{cm} \cdot 0.02 \cdot 0.3 \cdot 10^5 \cdot e$

Radiation damage problematic!

Flexible gain → linearity and calibration problematic!

- **Diamond, Dosimeter fibers**

Summary - Roadmap

- Particle loss locations in standard operation
- Identification of most critical failure scenarios (loss locations and time development)
- Acceptable loss limits for most critical failure scenarios (particle showers, heat flow, material damage)

- Choice of measurables and technology:
  - Resolution
  - Reaction
  - Dynamic range
- Dependability analysis

- Secondary particle fluence spectra and time distribution at possible monitor locations
- Determine monitor response
- Distinguish radiation sources?

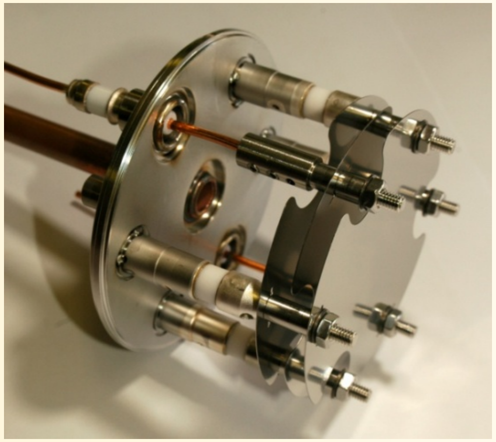
Some More Slides

LHC Monitor Types

- Design criteria: Signal speed and robustness
- Dynamic range (> 10^9) limited by leakage current through insulator ceramics (lower) and saturation due to space charge (upper limit).

Secondary Emission Monitor:

- Length 10 cm
- Components UHV compatible, steel vacuum fired
- Detector contains 170 cm2 of NEG St707 to keep the vacuum < 10-4 mbar during 20 years



Ionization chamber:

- N_2 gas filling at 100 mbar over-pressure
- Length 50 cm
- Sensitive volume 1.5 l
- Ion collection time 85 μs
- ~ 60000 times higher gain

Both monitors:

- Parallel electrodes (Al, SEM: Ti) separated by 0.5 cm
- Low pass filter at the HV input
- Voltage 1.5 kV

The LHC BLM System: Challenges

- Reliable (tolerable failure rate 10^{-7} per hour per channel)
  - Reliable components, radiation tolerant electronics
  - Redundancy, voting
  - Monitoring of availability and drift of channels
- Less than 2 false dumps per month (operation efficiency)
- High dynamic range (10^{8}, 10^{13} – two monitor types at the same location)
- Fast (1 turn, 89 μs) trigger generation for dump signal
- Quench level determination with an uncertainty of a factor 2 (calibration)