CLIC Beam Loss Measurements

Tasks for 2010

Eva Barbara Holzer, CERN

CLIC09 Workshop
CERN, October 15, 2009

- Protection Strategy
- Collection of Requirements
- Design of BLM System – CDR
  - Required input
  - Choice of technology
- Collaborations
- Roadmap and Schedule of Tasks for 2010

Watch the color code of this talk:

List of tasks for end of 2010

Protection Strategy – Failure Time Scale

- Slow failures > 20ms: **main task of BLM**
  - 18 ms for post pulse analysis and decision taking (comfortable)

- Fast failures < 20ms
  - Mostly rely on passive protection (collimators, absorbers)
  - Some active protection possible
    - Beam dump from the rings
      - Combiner rings
      - Damping rings
    - Beam dump at turn-around and/or of the pulse tail
      - Drive beam: beam dump within < 0.14 ms: might be feasible
      - Main beam: < 156 ns does not seem feasible

Protection Strategy - Example

- Add masks (aperture limitations) at regular distances to main and drive beam.
- Place BLM right after to measure losses at mask
  - Concentrate losses to be able to distinguish between beams
  - Earlier detection of abnormal performance
  - Inhibit the next pulse when losses are above ‘normal’

Collection of Requirements

- Collection of requirements for BLM system from sub-systems and components
- Examples:
  - 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)
  - Long term magnet destruction :
    - Fractional beam loss per QP (S.Mallows, T.Otto, see following slides)
    - Same BLM system or different system?

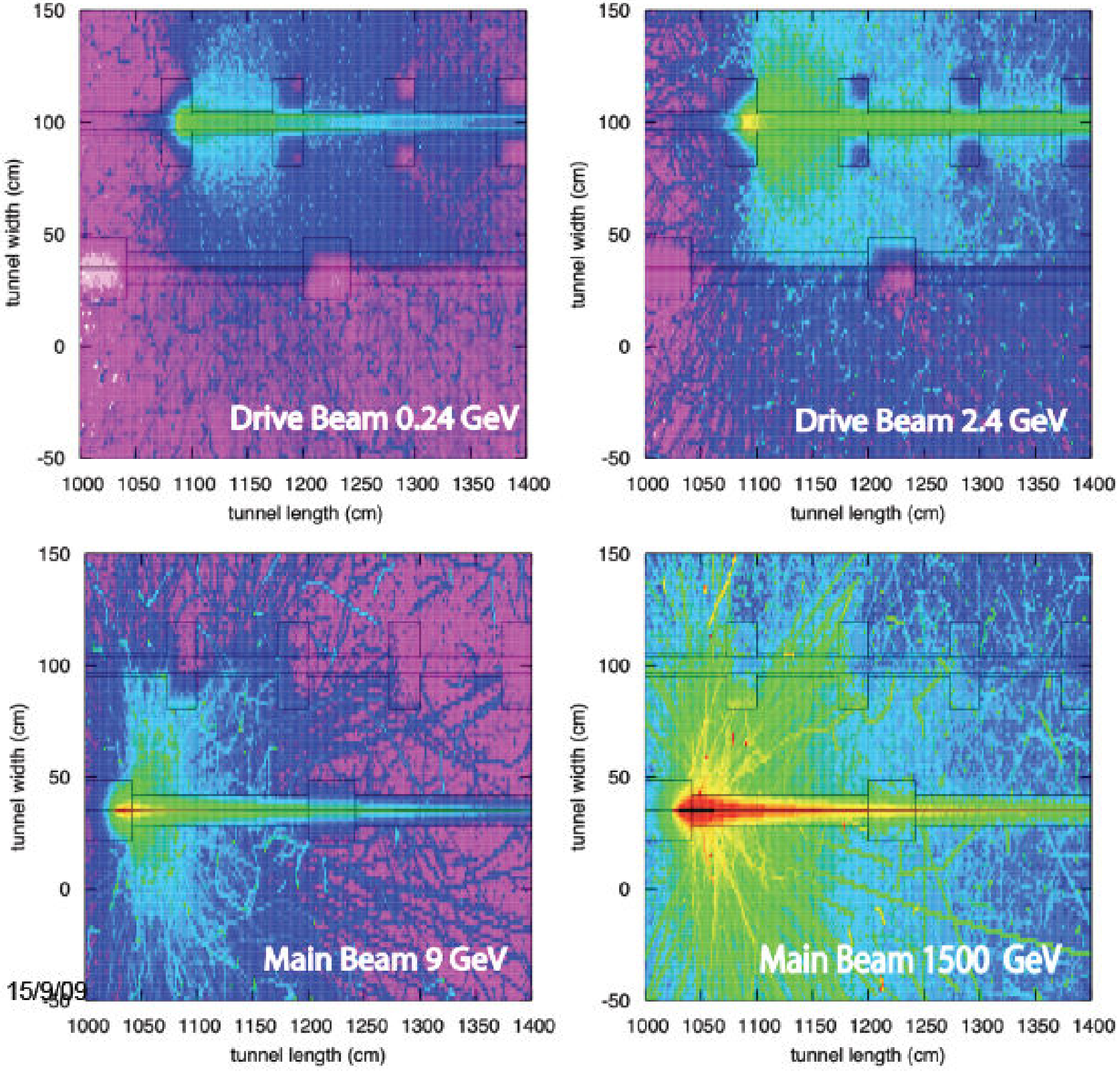
Main beam 1.5 TeV	7.3 E -8
Main beam 9 GeV	1.7 E -6
Drive beam 2.4 GeV	1 E -7
Drive beam 0.24 GeV	4.7 E -7

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

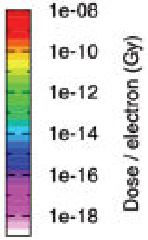
Main beam 1.5 TeV	~ 1 E-4
Main beam 2.8 GeV at damping ring	~0.5 E-4
Drive beam decellerator 2.4 GeV	~0.1

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

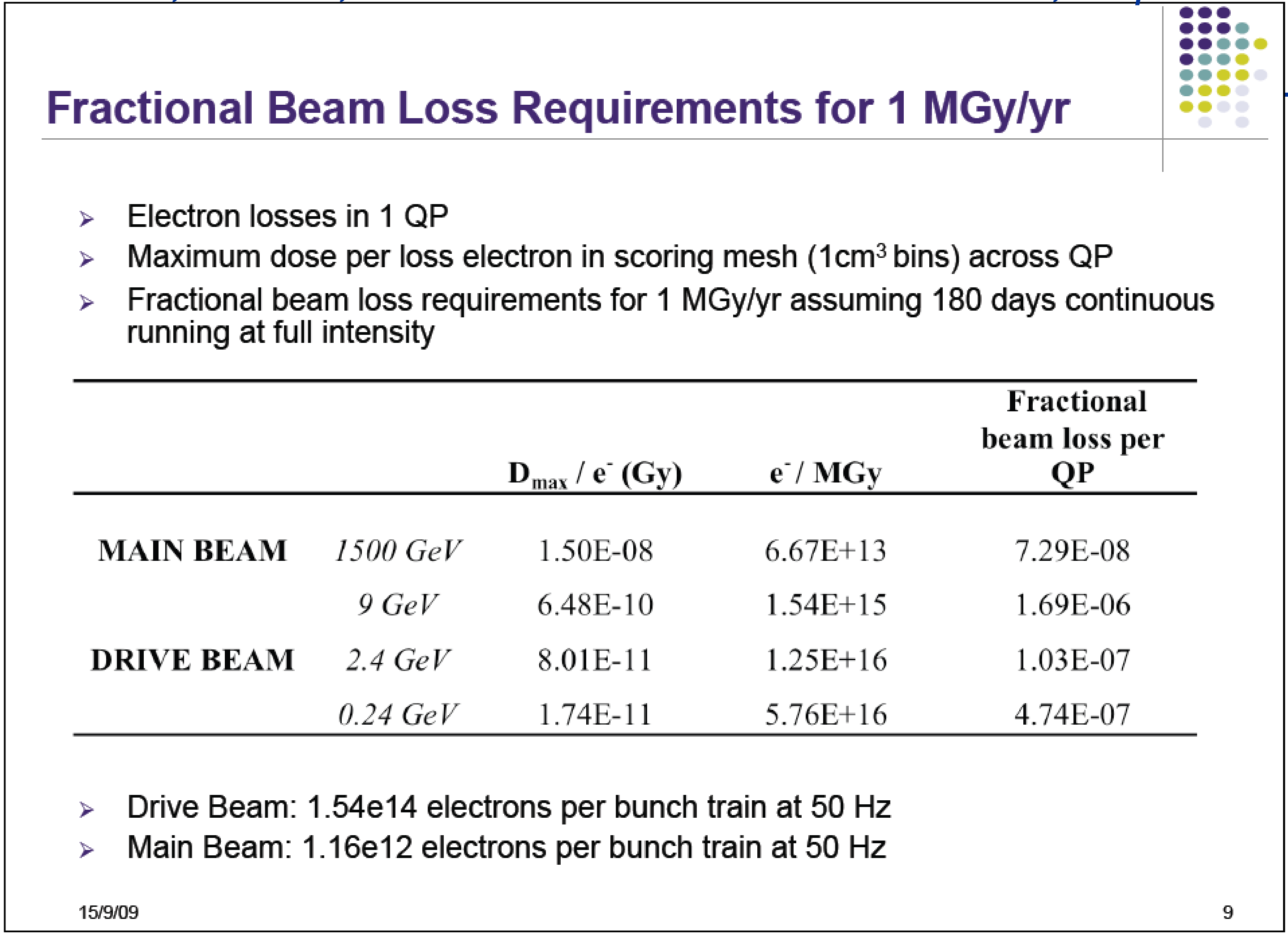
Calculation – Dose (QPs)



- **Spatial Distributions of Dose, for 4 Beam Loss Energies**
- Normalization : 1 electron
- Losses in 1 QP



S. Mallows, T. Otto, CLIC Two-Beam Module Review, September 2009



Fractional Beam Loss Requirements for 1 MGy/yr

- Electron losses in 1 QP
- Maximum dose per loss electron in scoring mesh (1cm^3 bins) across QP
- Fractional beam loss requirements for 1 MGy/yr assuming 180 days continuous running at full intensity

		D_{max} / e$^-$ (Gy)	e$^-$ / MGy	Fractional beam loss per QP
MAIN BEAM	*1500 GeV*	1.50E-08	6.67E+13	7.29E-08
	9 GeV	6.48E-10	1.54E+15	1.69E-06
DRIVE BEAM	*2.4 GeV*	8.01E-11	1.25E+16	1.03E-07
	0.24 GeV	1.74E-11	5.76E+16	4.74E-07

- Drive Beam: 1.54e14 electrons per bunch train at 50 Hz
- Main Beam: 1.16e12 electrons per bunch train at 50 Hz

15/9/09

9

Fractional beam loss per QP

5E-7

1.25E-6

Compare to assumption: Equally (per quadrupole) distributed fractional beam loss of

- 10E-3 over the 2000 main beam quadrupoles and -> 5E-7
- 10E-3 over the 800 drive beam quadrupoles (of one sector) -> 1.25E-6

Collection of Requirements

- Required resolutions for main beam and drive beam
  - Identify loss location (~ 1m)
  - Distinguish beam head from tail?
- Distinguish between beam losses in the same tunnel from:
  - Drive beam decelerator
  - Main beam
  - Transport lines
  - Beam turns
  - Beam dumps
- Simulations – ‘crosstalk’ (see following 4 slides)
- Distinguish beam losses from other sources of radiation:
  - Synchrotron light
  - Photons from RF cavities
  - Wigglers, undulators
  - EM noise, etc.
- Investigate and document the radiation sources in tunnel (other than beam loss)

Crosstalk: main beam – drive beam I

- About to be published*: S.Mallows, T.Otto: Radiation Levels in the CLIC Tunnel*

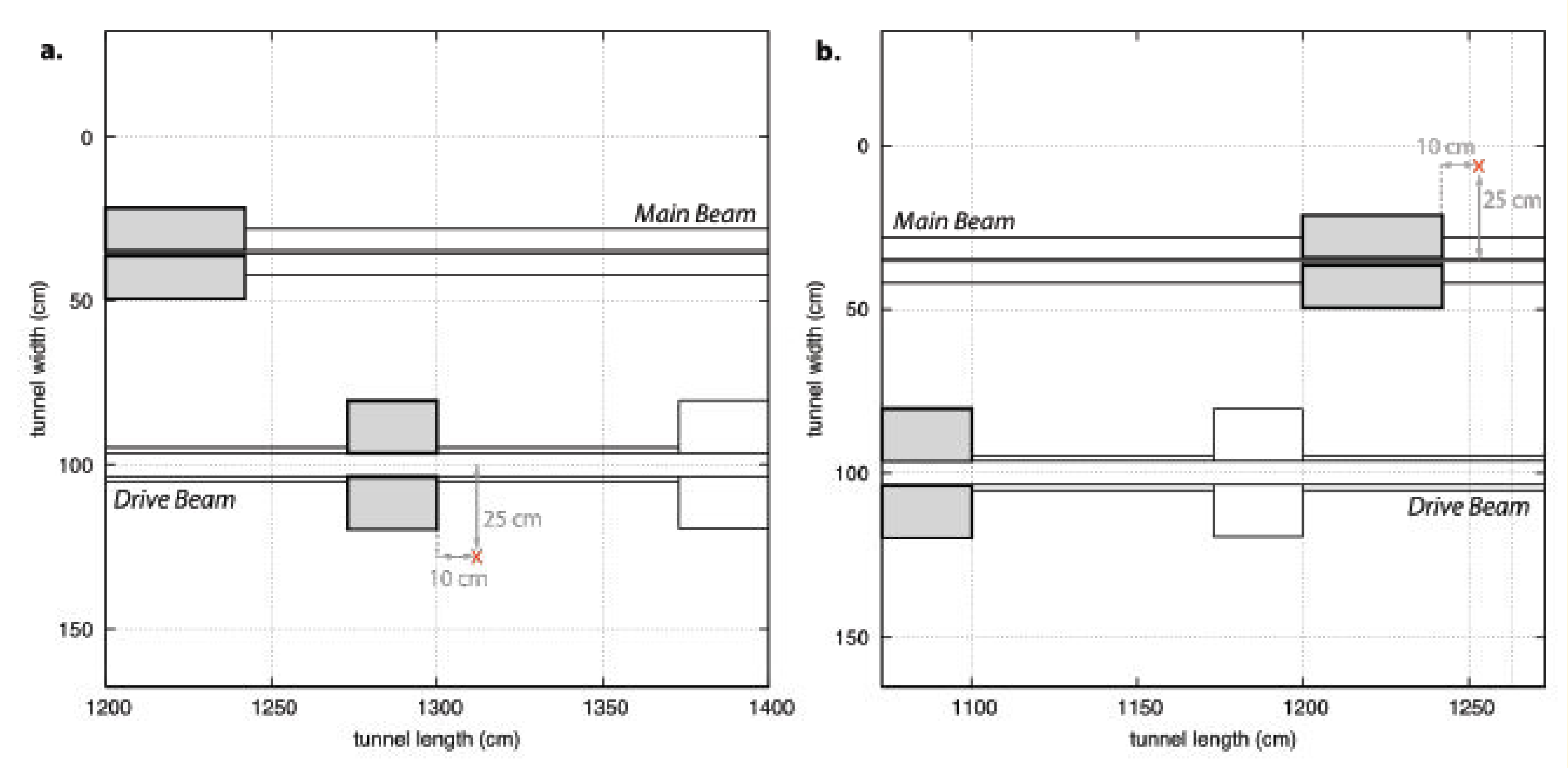


Figure 4 Location of volume for scoring doses **a.** near the drive beam line **b** near the main beam line. (The geometry is viewed looking towards the tunnel floor).

Crosstalk: main beam – drive beam II

S. Mallows, T. Otto

- Signal to crosstalk ratios for **equal fractional beam loss** on one quadrupole of the main beam and drive beam (statistical uncertainty ~ 10%)
- Higher loss on drive beam: main beam losses are shadowed!
- Can spectral sensitivity help?

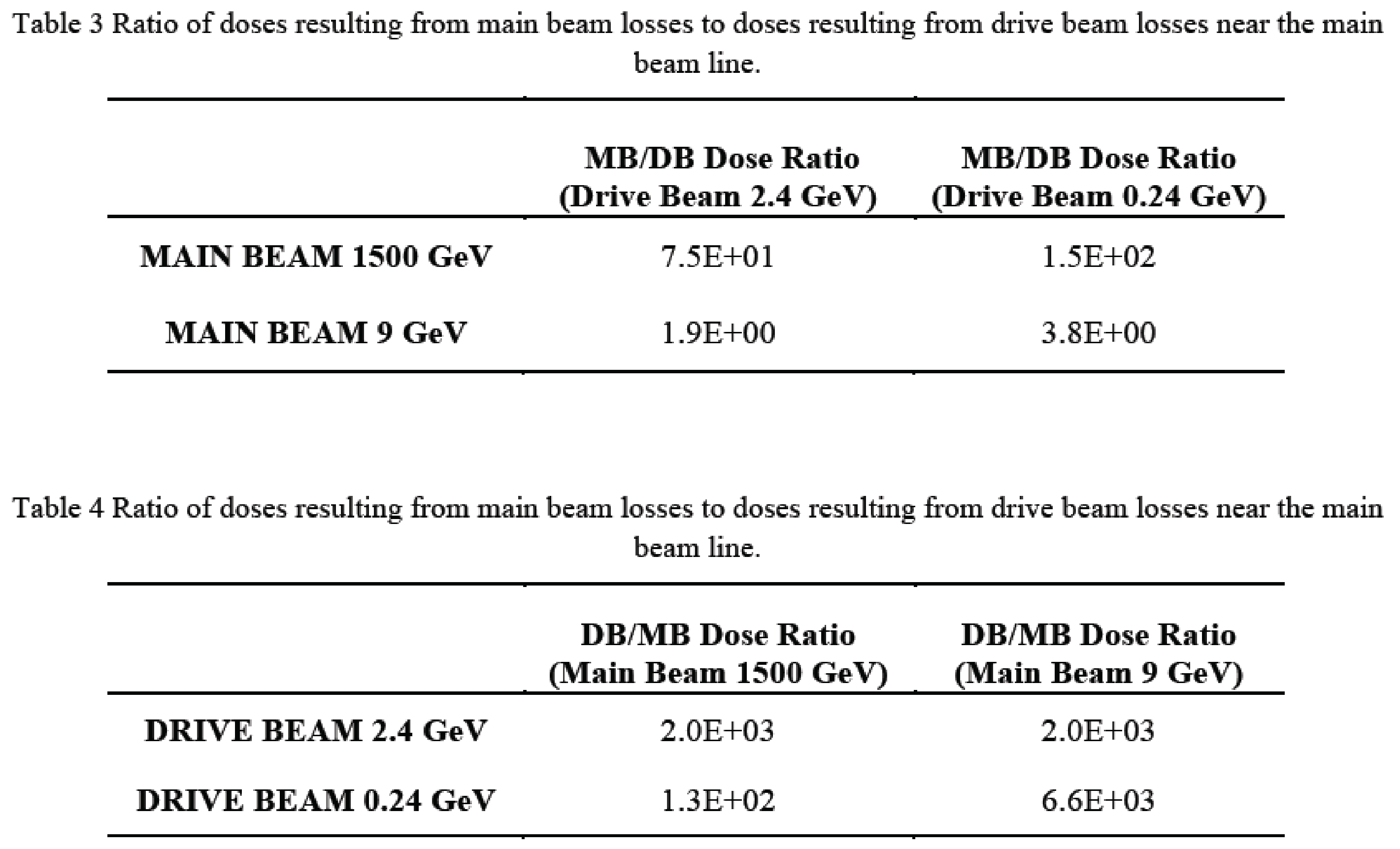


Table 3 Ratio of doses resulting from main beam losses to doses resulting from drive beam losses near the main beam line.

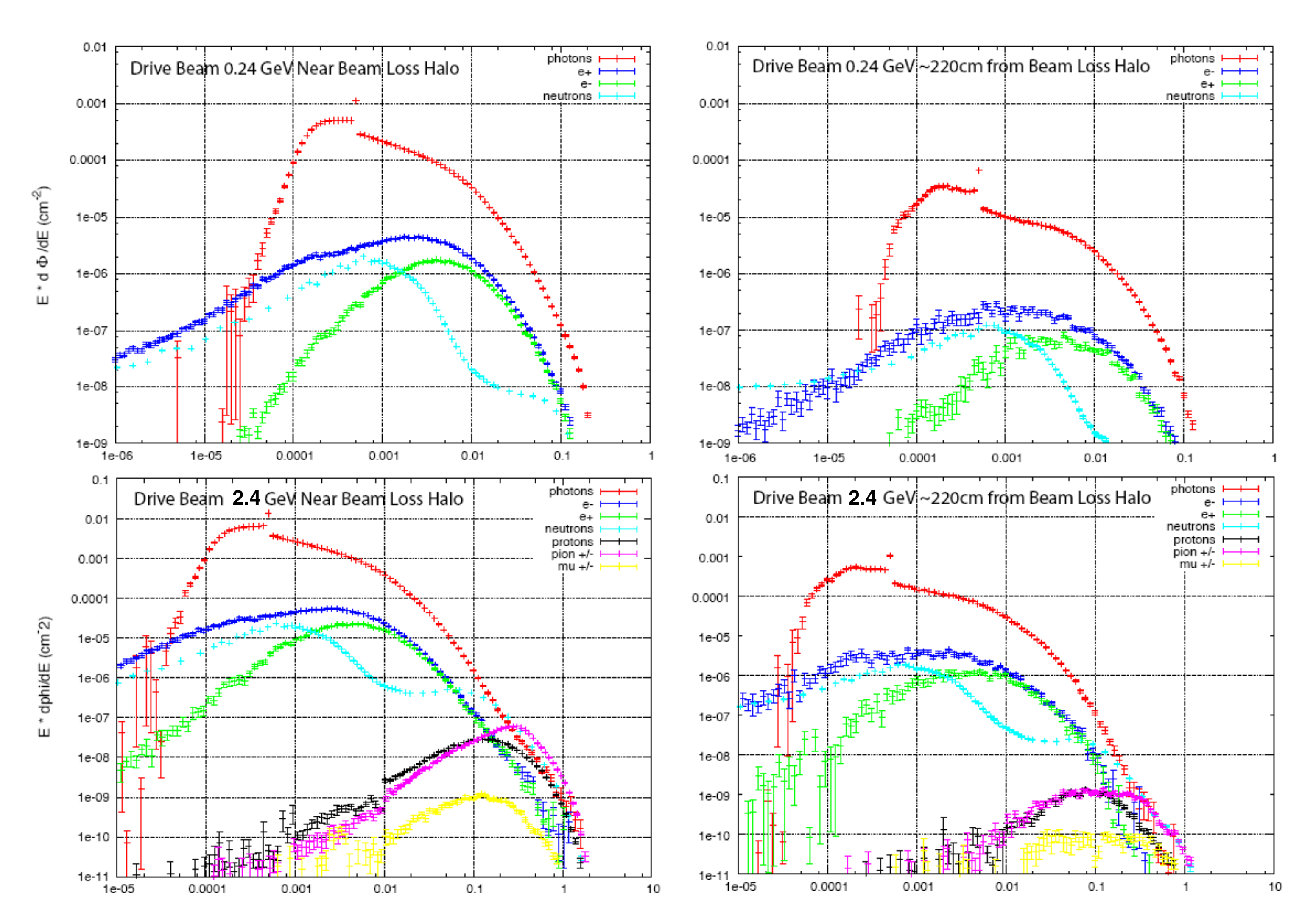
	MB/DB Dose Ratio (Drive Beam 2.4 GeV)	**MB/DB Dose Ratio (Drive Beam 0.24 GeV)**
MAIN BEAM 1500 GeV	7.5E+01	1.5E+02
MAIN BEAM 9 GeV	1.9E+00	3.8E+00

Table 4 Ratio of doses resulting from main beam losses to doses resulting from drive beam losses near the main beam line.

	DB/MB Dose Ratio (Main Beam 1500 GeV)	**DB/MB Dose Ratio (Main Beam 9 GeV)**
DRIVE BEAM 2.4 GeV	2.0E+03	2.0E+03
DRIVE BEAM 0.24 GeV	1.3E+02	6.6E+03

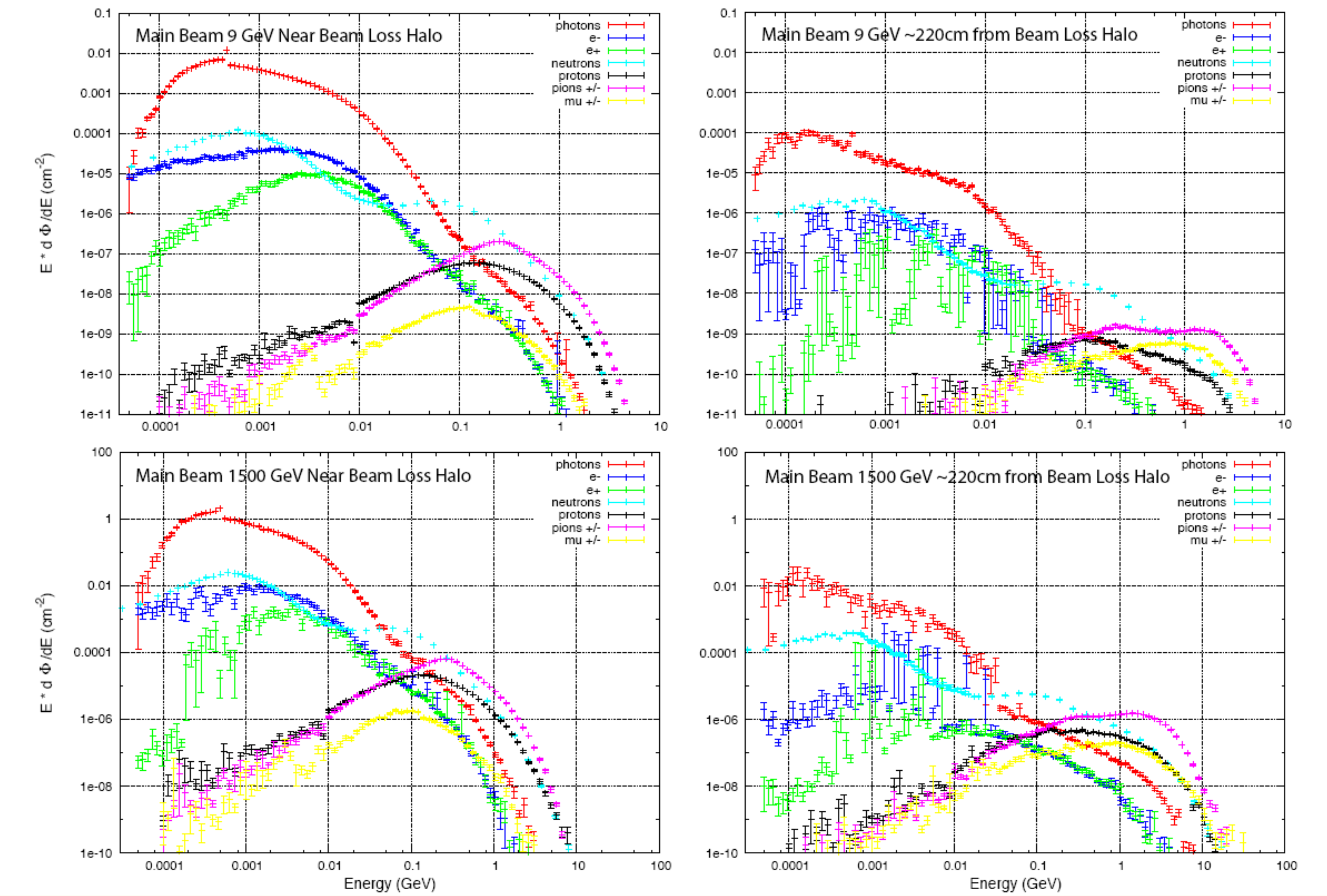
Drive Beam: particle fluence spectra after quadrupoles

S.Mallows, T.Otto: Radiation Levels in the CLIC Tunnel



Main Beam: particle fluence spectra after quadrupoles

S.Mallows, T.Otto: Radiation Levels in the CLIC Tunnel



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

- Investigate existing solutions for the CLIC sub-systems (see next 5 slides); document cost and number of monitors
- Identify the costly and/or technologically difficult parts

Several steps for the CDR

1- Collect the beam instrumentation requirements for each CLIC sub-systems and identify Critical Items and the need for new R&D

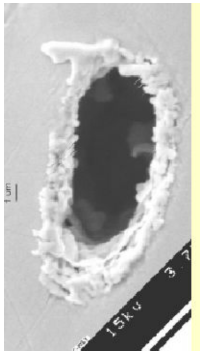
2- Evaluate the performance of already-existing technologies

- **CLIC specific instruments**
    - Luminosity monitors
    - 20-50fs timing synchronization
- **CTF3 beam diagnostics – importable to CLIC**
- **ILC instruments with similar requirements as for CLIC**
    - Laser Wire Scanner or Cavity BPM
    - Beam Delivery System instrumentation
      Ex: Polarization monitor, Beam Energy measurements
    - Damping ring instrumentation developed at ATF2
- **3rd and 4th generation light sources**
    - Damping ring instrumentation
    - Bunch Compressor instrumentation very similar to XFEL projects

Thibaut Lefevre, CLIC Beam Instrumentation Workshop June 2009

CLIC vs CTF3

	CTF3	CLIC
Beam Energy (GeV)	0.15	2.4
RF Frequency (GHz)	3	1
Multiplication Factor	8	24
Initial Beam Current (A)	3.75	4.2
Final Beam Current (A)	30	100
Initial Pulse length (us)	**1.2**	**140**
Final Pulse Length (ns)	140	240
Total Beam Energy (kJ)	**0.7**	**1400**
Repetition Rate (Hz)	5	50
Average Beam Power (MW)	**0.0034**	**70**
Charge density (nC/cm^2)	**0.4 10^6**	**2.3 10^{10}**



The thermal limit for ‘best’ material (C, Be, SiC) is 10^6 nC/cm^2

▲ Still considerable extrapolation to CLIC parameters

- Especially total beam power (loss management, machine protection)
- Development of non-destructive instruments
- Stability and reliability

Thibaut Lefevre, CLIC Beam Instrumentation Workshop June 2009

CLIC vs ILC

Thibaut Lefevre, CLIC Beam Instrumentation Workshop June 2009

	CLIC 3TeV	CLIC 500GeV	ILC
Center of mass energy (GeV)	3000	500	500
Main Linac RF Frequency (GHz)	12	12	1.3
Luminosity (10^{34} cm^{-2} s^{-1})	5.9	2.3	2
Linac repetition rate (Hz)	50	50	5
Accelerating gradient (MV/m)	100	[illegible]	33.5
Proposed site length (km)	[illegible]	13	31
Total power consumption (MW)	415	129.4	216
Wall plug to main beam [illegible] (%)	6.8	7.5	9.4

Requirements for CLIC are always tighter

Critical Beam Parameter

	CLIC 3TeV	CLIC 500GeV	ILC
Bunch Length in the Linac (fs)	150	230	900
Typical Beam Size in the Linac (μm)	**1**	**1**	**5**
Beam Emittance H/V (nm.rad)	**660/20**	**2400/25**	**10^4/40**
Beam size at IP : σ_x / σ_y (nm)	40/1	202/2.3	640/5.7

http://clic-study.web.cern.ch/CLIC-Study/

http://www.linearcollider.org/cms/

CLIC vs Light Sources

Thibaut Lefevre, CLIC Beam Instrumentation Workshop June 2009

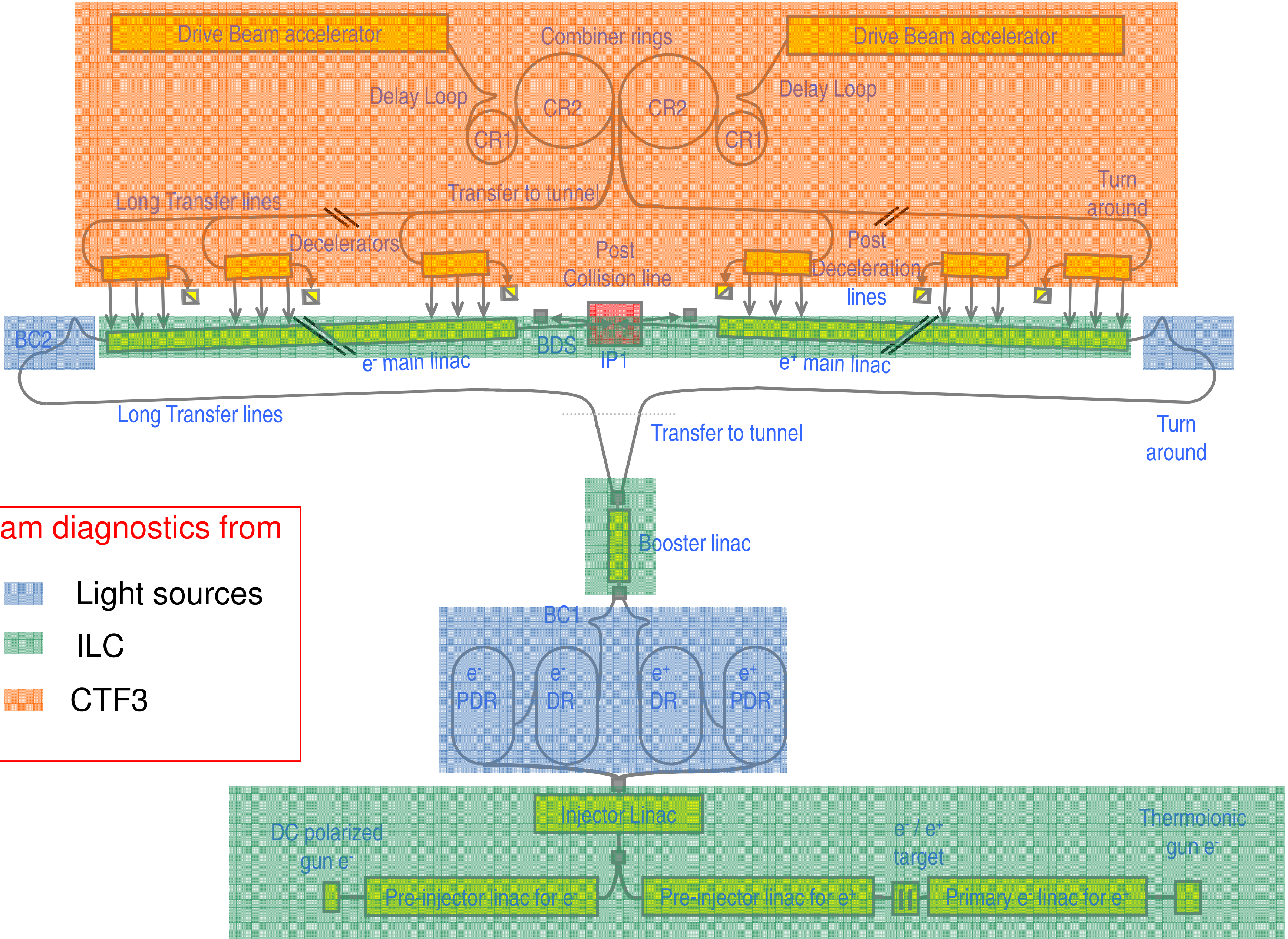
	CLIC DR	SLS	Diamond	Soleil
Beam Energy (GeV)	2.86	2.4	3	2.75
Ring Circonfrence (m)	493	288	561.6	354
Bunch charge (nC)	0.6	1	1	0.5
Energy Spread (%)	0.134	0.09	0.1	0.1
Damping times (x,y,E) (ms)	2,2,1	9,9,4.5	-	6.5,6.5,3.3
Orbit stability (um)	1	1	1	1

	CLIC linac	XFEL	LCLS
Beam Energy (GeV)	3000	[illegible]	15
Linac RF Frequency (GHz)	12	[illegible]	2.856
Bunch charge (nC)	[illegible]	1	1
Bunch Length (fs)	150	80	73

Development of BLM for long linac

CLIC Instrumentation

Thibaut Lefevre



Beam diagnostics from

- 🟦 Light sources
- 🟩 ILC
- 🟧 CTF3

Required Input

1. Beam loss in standard operation
    - Spatial-, momentum- and time distribution
2. Identification of most critical failure scenarios (loss locations and time development)
    - Loss locations (spatial and momentum 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

- Prepare list of the required information

Required Input – cont.

3. Acceptable loss limits (particle showers, heat flow, material damage, impairment of operation, long term radiation damage, etc.)

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

Choice of Technology

- Choice of measurable to determine beam losses (or imminent beam losses)
  - BLM, beam current transformer, BPM, transverse tail monitors, etc.
  - Required versus achievable
    - Resolution
    - Reaction time
    - Sensitivity
    - Dynamic range
- Investigate existing technologies (see following slides)
  - Example: Intensity measurement existing technology
    - Relative precision of ~ 0.1%
    - Absolute precision of ~ 1%
    - Compare to requirements in next two slides
      - Intensity measurement can reduce the requirements on BLM

Specifications of sector instruments

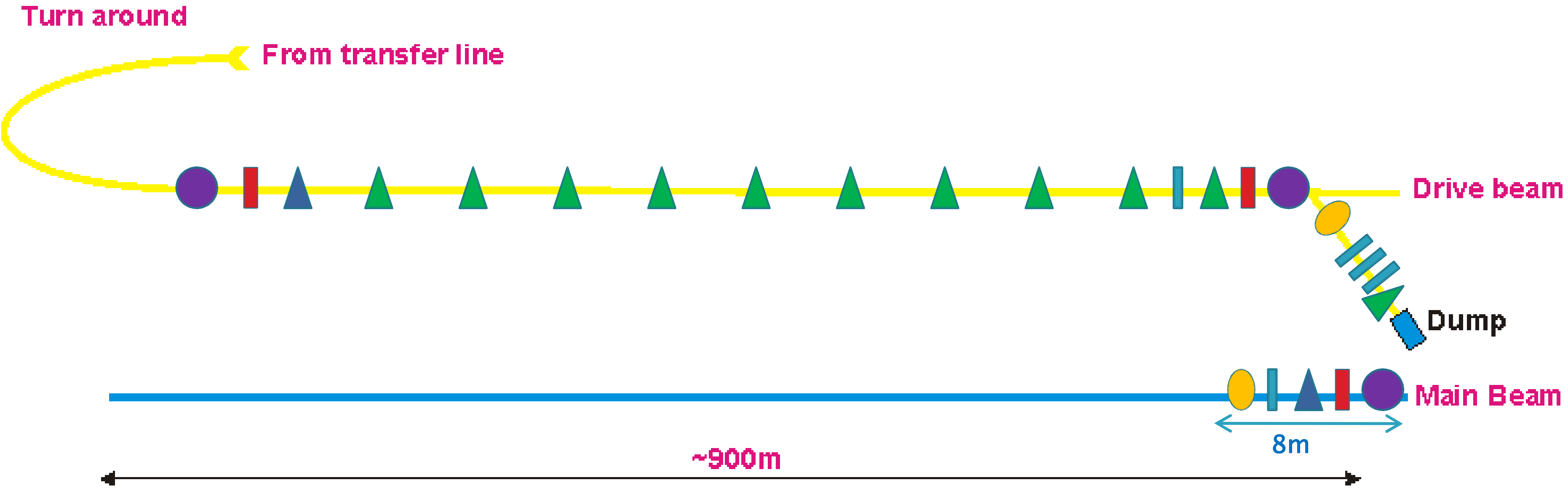
Main beam

	Accuracy	*Resolution*	*Bandwidth*	*Beam tube aperture*	*Stability*	*Non-intercepting device?*	*How many?*	*Used in RT Feedback?*	*Machine protection Item ?*	*Comments*	*Ref*
Intensity	0.1%						48	No	Yes		
Beam Size / Emittance	10%	2%				yes	48	No	No		
Energy	0.10%					yes	48	Yes			
Energy Spread								?			
Bunch Length							48			single shot	
Beam Phase		0.1°					48	Yes	No		

Drive beam

	Accuracy	*Resolution*	*Range*	*Bandwidth*	*Beam tube aperture*	*Stability*	*Non-intercepting device?*	*How many?*	*Used in RT Feedback?*	*Machine protection Item ?*	*Comments*	*Ref*
Intensity	0.1%			20MHz	23mm		Yes	48	No	Yes		
Intensity	1%			20MHZ	23mm		Yes	~864	No	Yes	Still Valid?	
Beam Size / Emittance	50um				23mm		No	288	No	No		
Energy	10um		10mm	12GHz	?			48	No	No		
Energy Spread					?							
Bunch Length	1%				23mm			24	No	No	single shot	
Beam Phase					23mm			96				

Sector instrumentation



▮ Transverse profile monitors, L~300mm

⬮ Fast (12GHz) BPM, L~100mm, Energy

🟥 Form factor, Fast bunch shape measurement,L~500mm

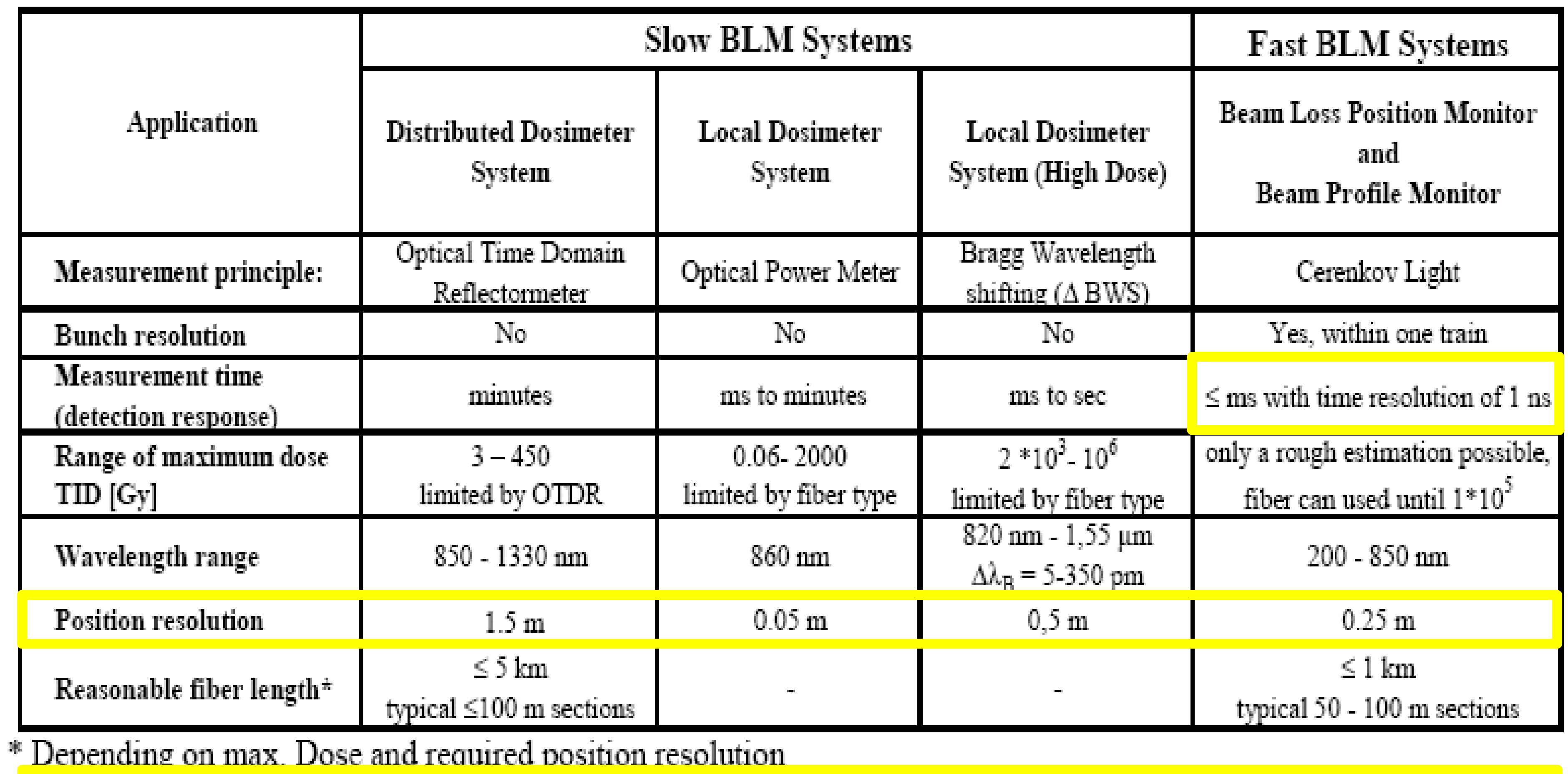
▲ Slow current measurement, L~150mm, 1%

▲ Slow current measurement, L~150mm, 0.1%

● Beam Phase 🟦 Segmented dump, Energy

Recent Developments in Fiber Loss Monitors I

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



Application	Slow BLM Systems			Fast BLM Systems
	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 $\Delta\lambda_B = 5\text{-}350$ 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

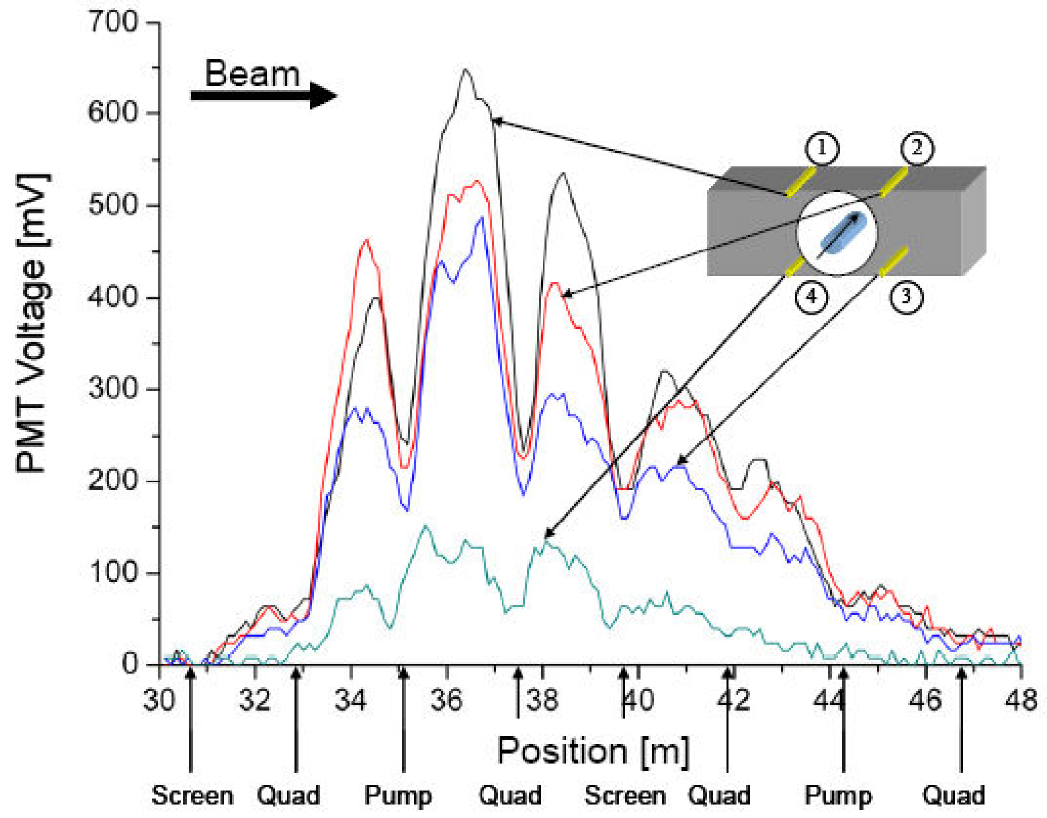
Dose resolution	**3 Gy**	**60 mGy**	**2 kGy**	**?**
Dynamic range	**~100**	**~30’000**	**~500**	**?**

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).

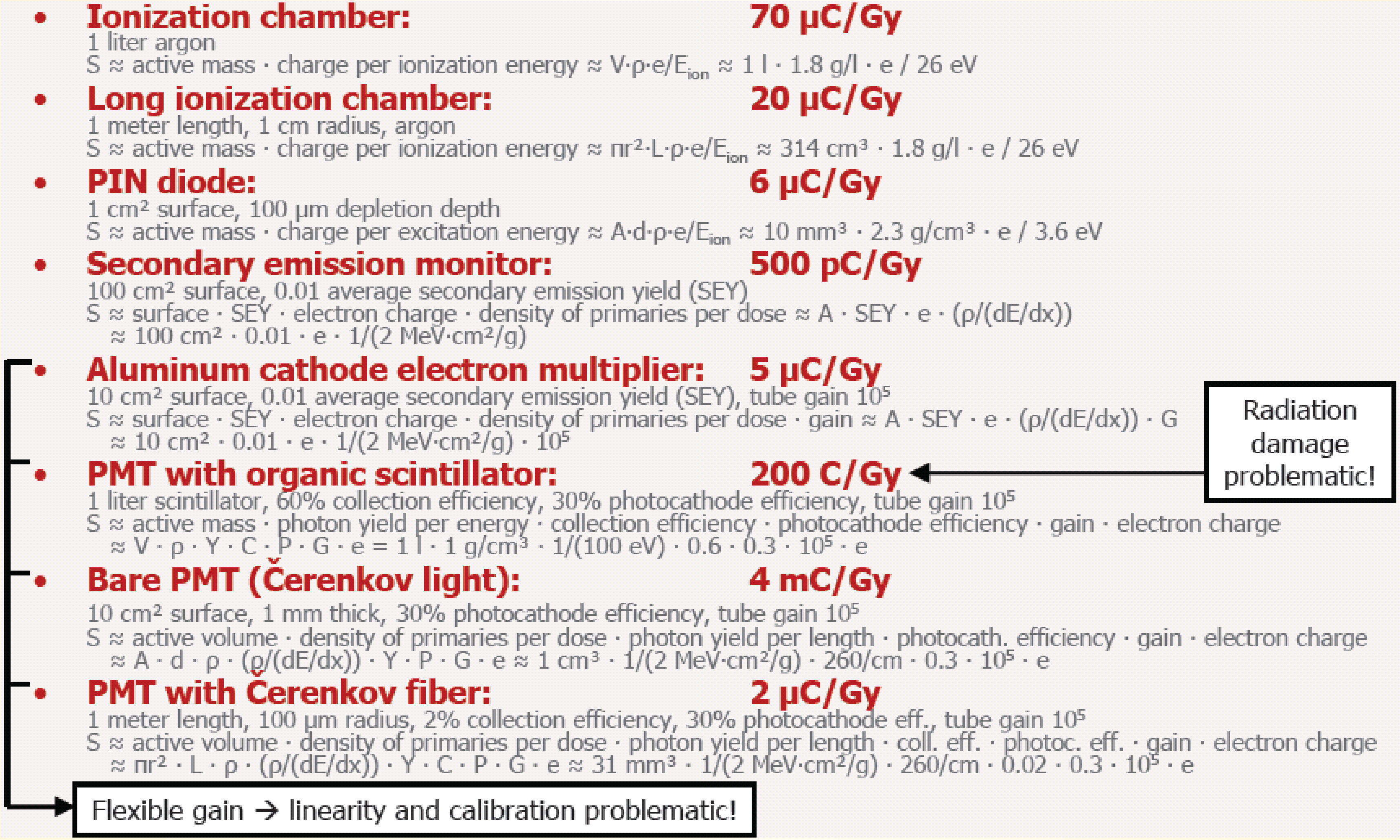


BLM Fibers

- 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 ≈ active mass · charge per ionization energy ≈ $V\cdot\rho\cdot e/E_{ion}$ ≈ 1 l · 1.8 g/l · e / 26 eV
- **Long ionization chamber:** **20 μC/Gy**
  1 meter length, 1 cm radius, argon
  S ≈ active mass · charge per ionization energy ≈ $\pi r^2\cdot L\cdot\rho\cdot e/E_{ion}$ ≈ 314 cm³ · 1.8 g/l · e / 26 eV
- **PIN diode:** **6 μC/Gy**
  1 cm² surface, 100 μm depletion depth
  S ≈ active mass · charge per excitation energy ≈ $A\cdot d\cdot\rho\cdot e/E_{ion}$ ≈ 10 mm³ · 2.3 g/cm³ · e / 3.6 eV
- **Secondary emission monitor:** **500 pC/Gy**
  100 cm² surface, 0.01 average secondary emission yield (SEY)
  S ≈ surface · SEY · electron charge · density of primaries per dose ≈ A · SEY · e · (ρ/(dE/dx))
  ≈ 100 cm² · 0.01 · e · 1/(2 MeV·cm²/g)
- **Aluminum cathode electron multiplier:** **5 μC/Gy**
  10 cm² surface, 0.01 average secondary emission yield (SEY), tube gain 10^5
  S ≈ surface · SEY · electron charge · density of primaries per dose · gain ≈ A · SEY · e · (ρ/(dE/dx)) · G
  ≈ 10 cm² · 0.01 · e · 1/(2 MeV·cm²/g) · 10^5
- **PMT with organic scintillator:** **200 C/Gy**
  1 liter scintillator, 60% collection efficiency, 30% photocathode efficiency, tube gain 10^5
  S ≈ active mass · photon yield per energy · collection efficiency · photocathode efficiency · gain · electron charge
  ≈ V · ρ · Y · C · P · G · e = 1 l · 1 g/cm³ · 1/(100 eV) · 0.6 · 0.3 · 10^5 · e
- **Bare PMT (Čerenkov light):** **4 mC/Gy**
  10 cm² surface, 1 mm thick, 30% photocathode efficiency, tube gain 10^5
  S ≈ active volume · density of primaries per dose · photon yield per length · photocath. efficiency · gain · electron charge
  ≈ A · d · ρ · (ρ/(dE/dx)) · Y · P · G · e ≈ 1 cm³ · 1/(2 MeV·cm²/g) · 260/cm · 0.3 · 10^5 · 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 ≈ active volume · density of primaries per dose · photon yield per length · coll. eff. · photoc. eff. · gain · electron charge
  ≈ πr^2 · L · ρ · (ρ/(dE/dx)) · Y · C · P · G · e ≈ 31 mm³ · 1/(2 MeV·cm²/g) · 260/cm · 0.02 · 0.3 · 10^5 · e

Radiation damage problematic!

Flexible gain → linearity and calibration problematic!

- **Diamond, Dosimeter fibers**

Choice of Technology

- 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.

- 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
  - Different beams

Choice of Technology

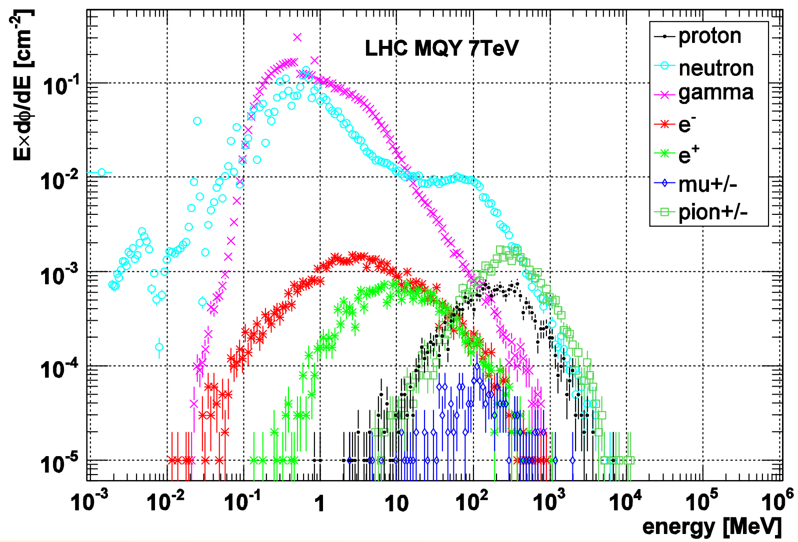
- Choice of monitor location
- Choice of monitor type (sensitive to selective type of radiation: particle species, energy range?)
- Can selective timing help to distinguish radiation source?
  - Thermal neutrons can significantly lengthen the signal (percentage of the signal?)
- Simulations to determine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

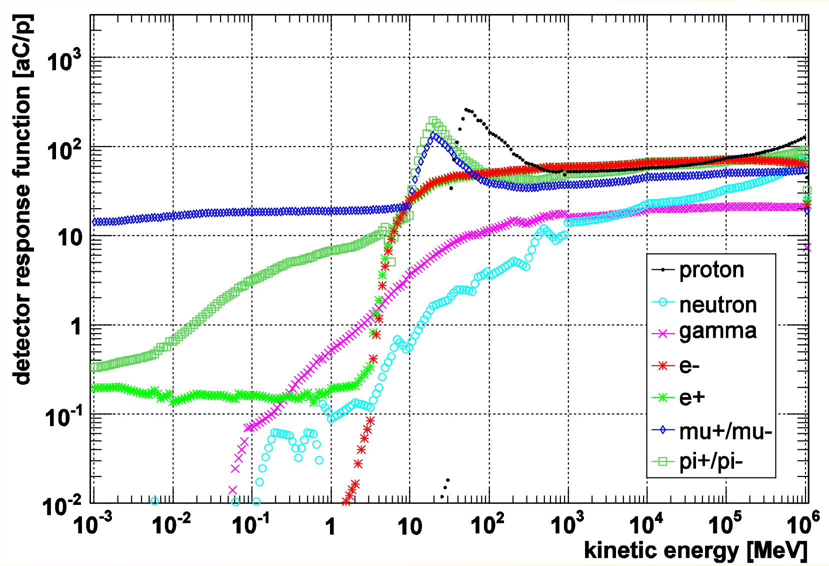
- Simulations to determine monitor response or
- Simplified simulations or estimation of approximate monitor response

Example LHC Simulations I

M. Stockner

MQY LHC quadrupole magnet 7TeV



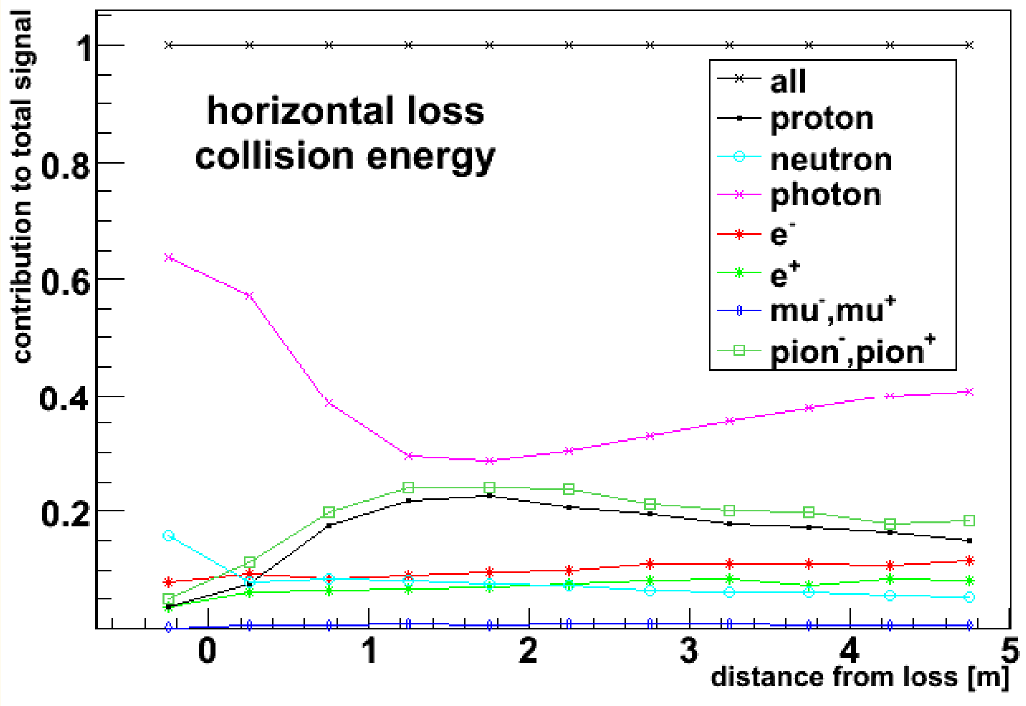


Secondary particle fluence spectrum on the outside recoded in a 3.4 m long stripe, lethargy representation.

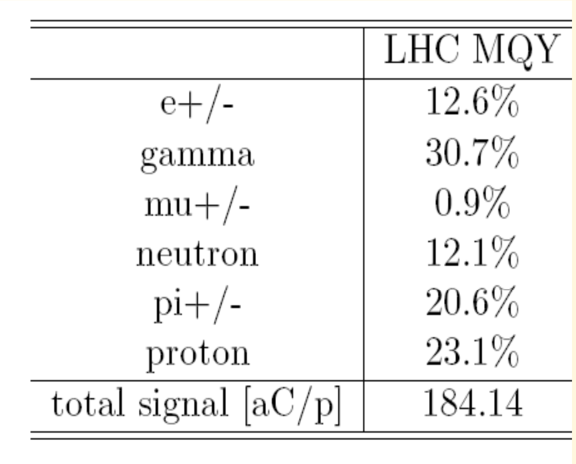
GEANT4 simulated LHC BLM detector response functions for particle impact direction of 60◦

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.

Collaborations

- University of Liverpool, Cockcroft Institute, QUASAR Group (Carsten Welsch, Angela Intermite, …)
- *Novel Beam Loss Monitoring Techniques based on Optical Fibres for Beam Loss Detection on the CLIC Main and Drive Beam LINACs*
    - Demonstration of the working principle on the CTF3 Test beam lines and on the Two-Beam Test Stand.
    - – Conceptual design and cost estimate of such a system for the CLIC Main and Drive Beam LINACs to be delivered by the end of 2010.

- Hope for further collaborations – on any of the “green” tasks
- CERN resources for CLIC BLM 2010: 2 person: 100% + 10%

Summary - Roadmap

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

- Choice of measurable and technology:
  1. Resolution
  2. Reaction time
  3. Dynamic range, etc.

Dependability analysis (damage protection and availability)

Secondary particle fluence spectra and time distribution at possible monitor locations

Determine monitor response

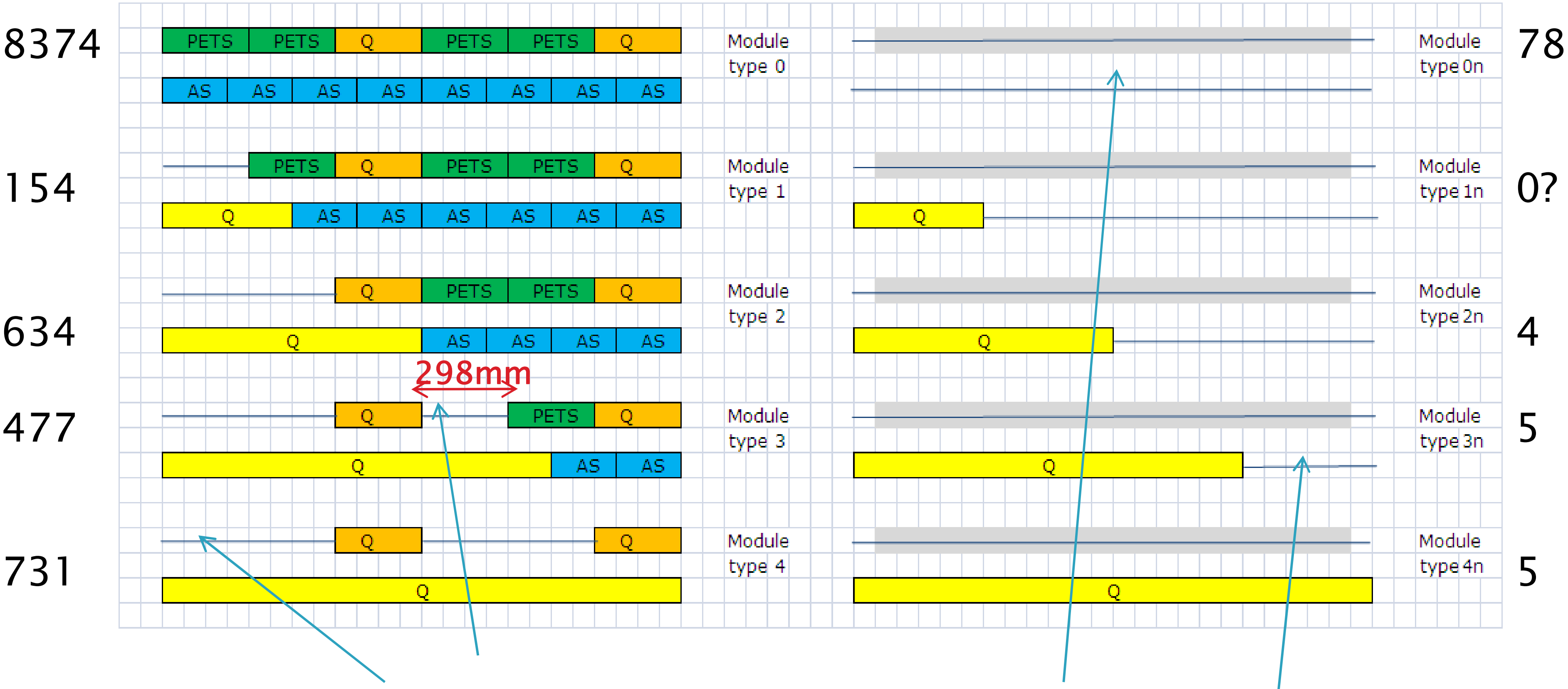
Distinguish radiation sources?

Schedule BLM tasks

Loss locations in standard operation: prepare list of required information	Q4 ‘09
List of failure scenarios and identification of most critical ones: prepare list of required information	Q4 ‘09
BLM system specs for fiber studies (Liverpool collaboration)	Q4 ‘09
Investigate and document the radiation sources in tunnel (other than beam loss)	Q4 ‘09
Investigate and document limiting equipment for loss (standard and failure)	Q4 ‘09
Investigate existing solutions for the CLIC components; document cost and number of monitors; identify costly and tech. difficult parts	Q1’10
Investigate existing technologies for a) BLM and b) for non-BL measurable	Q1 ‘10
Collection and documentation of requirements for BLM system for the CLIC sub-systems and their components (including steady state)	Q1 ‘10
Choice of measurable (BLM, current ,BPM, etc); establish required SIL (damage protection and availability) levels, estimate SIL levels of various protection systems, determine redundant systems when needed.	Q1 ‘10
Choice of BLM system. Simplified (geometry) model simulations for the most critical loss scenarios. Estimation a) limiting equipment and condition, and b) monitor response (accuracy ~ factor 10)	Q3 ‘10
Functional specs	Q4 ‘10
Cost estimate	Q4 ‘10

Some More Slides

Module types



Use "empty" space for "**sector**" beam instrumentation

Module length: 2.010 m

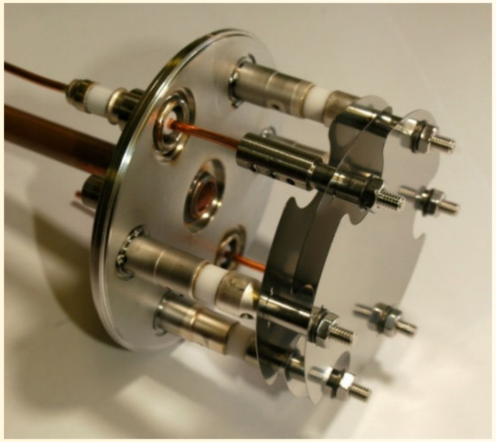
~4 type "xn" per sector at extraction

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

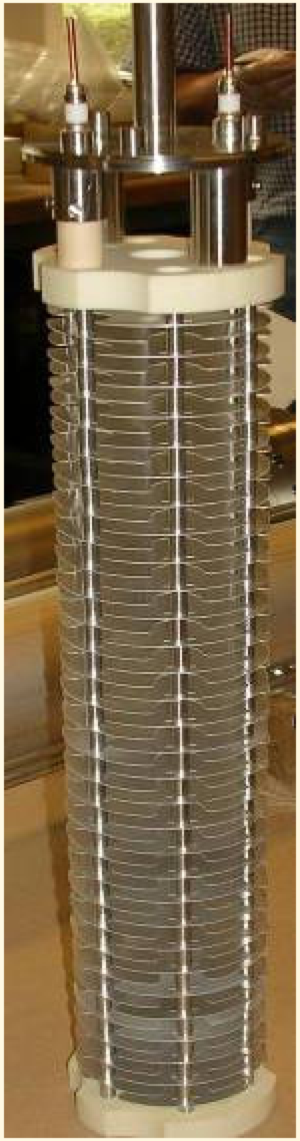


Ionization chamber:

- 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)

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, …)