Beam Loss Monitoring for Demanding Environments

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Melbourne

Special thanks for their input to Sanja Damjanovic and Eduardo Nebot
Contributions from: Bernhard Auchmann, Marcin Bartosik, Mark Boland, Bernd Dehning, Maria Kastriotou, Anton Lechner, Sophie Mallows, Giuseppe Venturini, Arden Warner, Kay Wittenburg, Manuel Zingl

Overview

- Considerations for the Design of a BLM System
  - Machine Protection
  - Short vs. Distributed Detectors
  - Machine Size and Radiation
- Background Sources
  - Synchrotron Radiation
  - Distant Losses
  - Accelerating Structures
- Summary

plus examples

Design Considerations

Beam Loss Monitors Roles

Beam diagnostics —
operation and commissioning

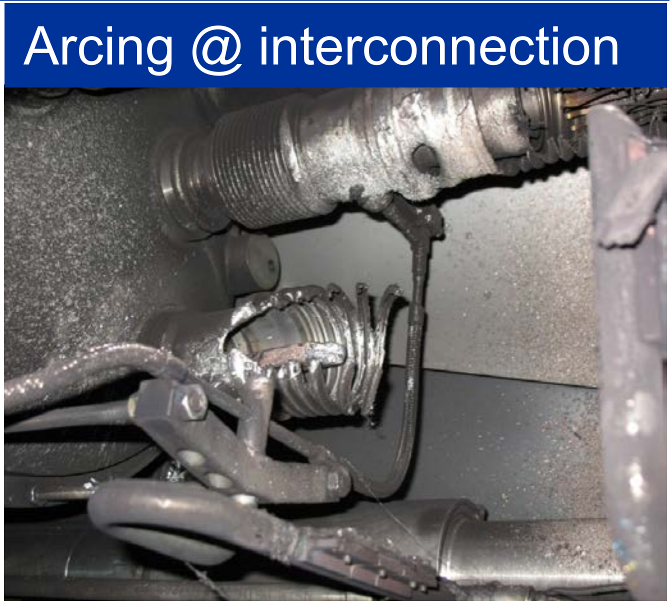
Quench / damage protection

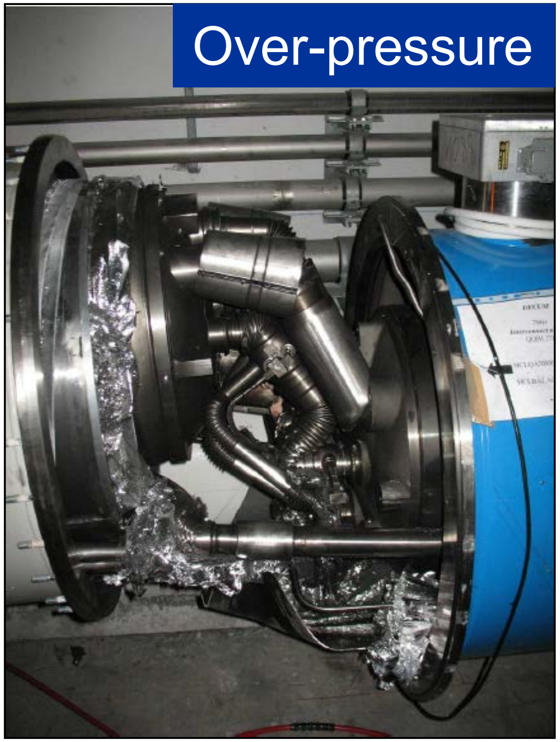
Activation / aging / human exposure

Machine Protection

Energy stored in the Magnets — Release of 600 MJ

- LHC 2008 incident **without beam**
  - Electrical arc provoked a He pressure wave damaging ≈600 m of LHC
- LHC magnets at 7 TeV: 10 GJ



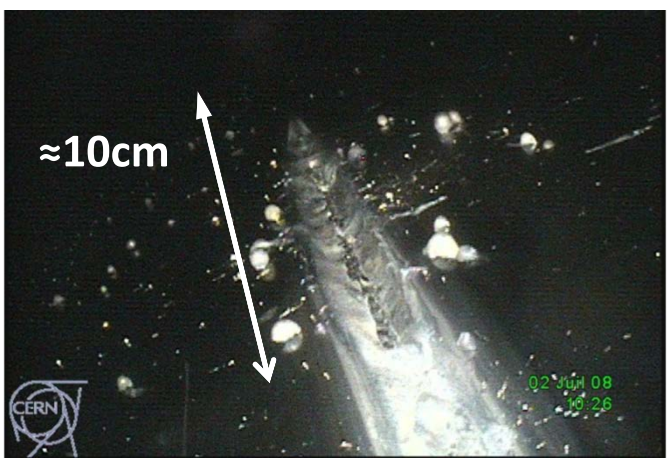


Energy stored in the Beams — Uncontrolled Losses

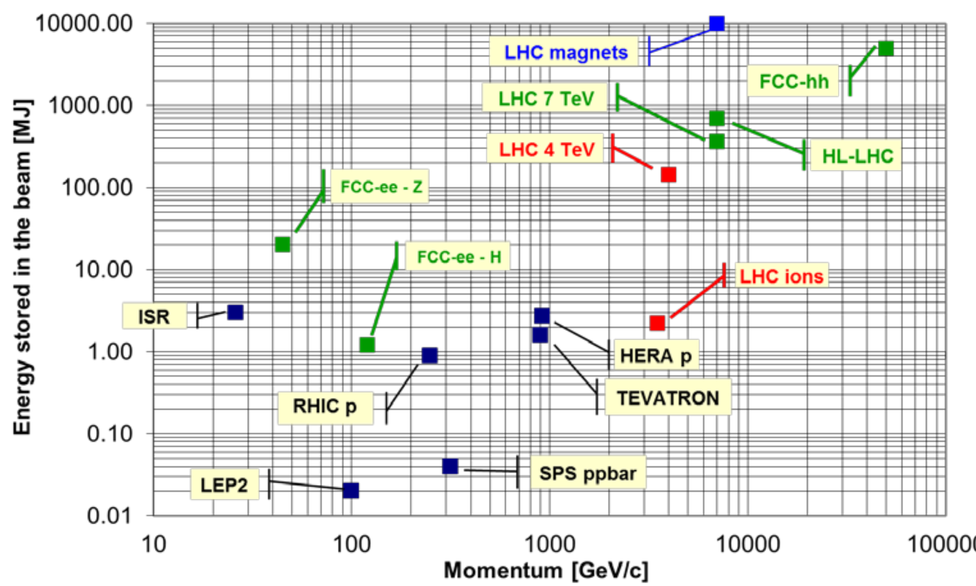
- LHC at 7 TeV 360 MJ:
  - Pilot bunch of 5×10^9 close to damage level
  - Loss of 3×10^{-7} of nominal beam over 10 ms can create a quench

1MJ can heat and melt 1.5 kg of copper

- SPS incident in June 2008, 400 GeV beam with **2 MJ** (*J. Wenninger, CERN-BE-2009-003-OP*)



World record: LHC 140 MJ @ 4 TeV



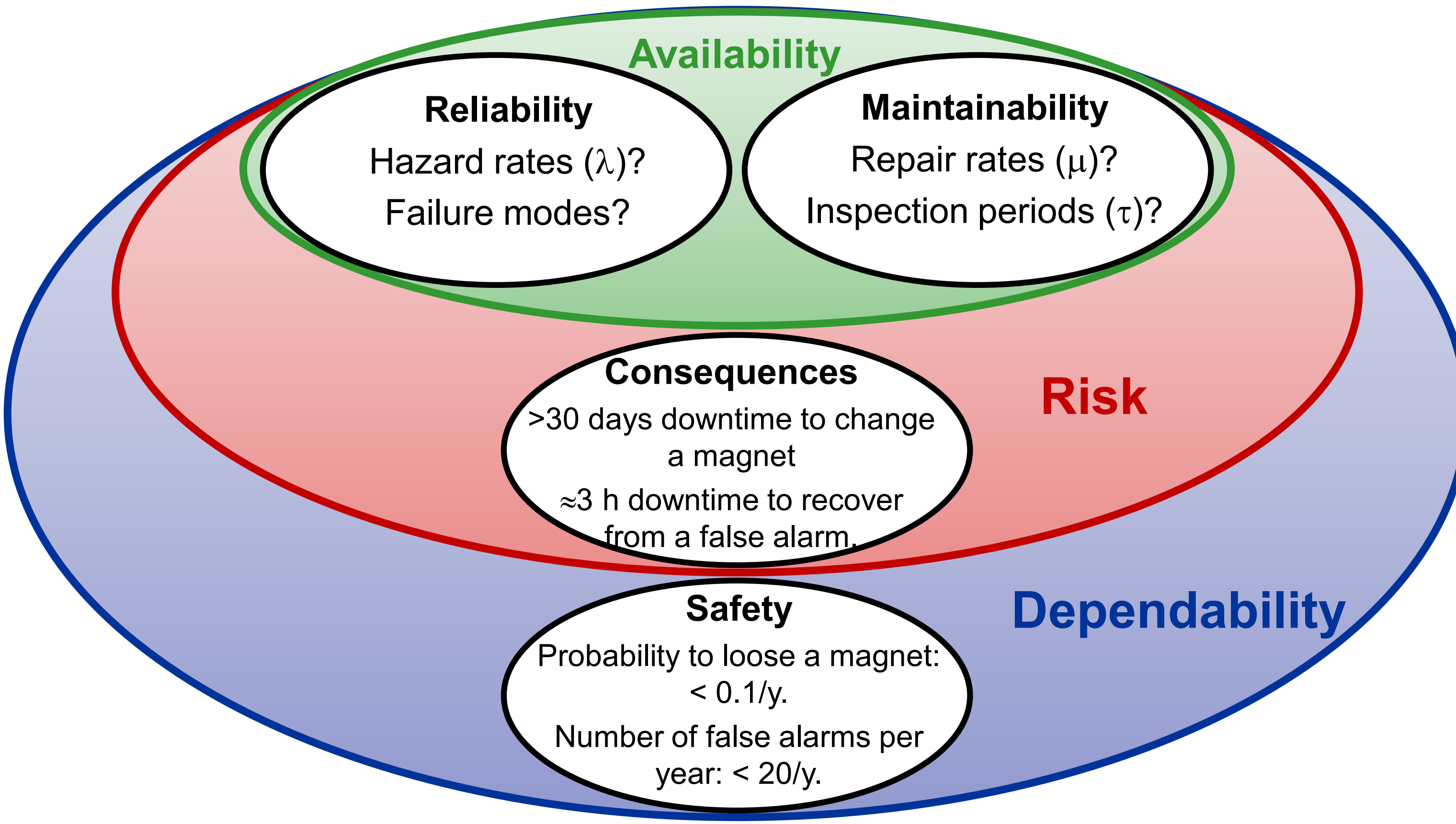
Machine Protection by BLM

- LHC
  - Safely extract beam when loss exceeds threshold (on any of ≈3600 detectors)
  - ≈1.5 million thresholds depend on
    - Detector location
    - Beam energy
    - Integration time (40μs–84s)

- CLIC
  - **Prevent subsequent injection** when potentially dangerous beam losses are detected ("next cycle permit")
  - Damage to beam-line components determined by power density (not by beam power) of the beams

Dependability (colloquially: reliability) **analysis**

- Machine protection system must be integrated in the machine design
- Dependability (reliability, availability, maintainability and safety) analysis → allowances for
  - Probability of component damage due to malfunctioning
  - Downtime due to false alarms
  - Downtime due to maintenance



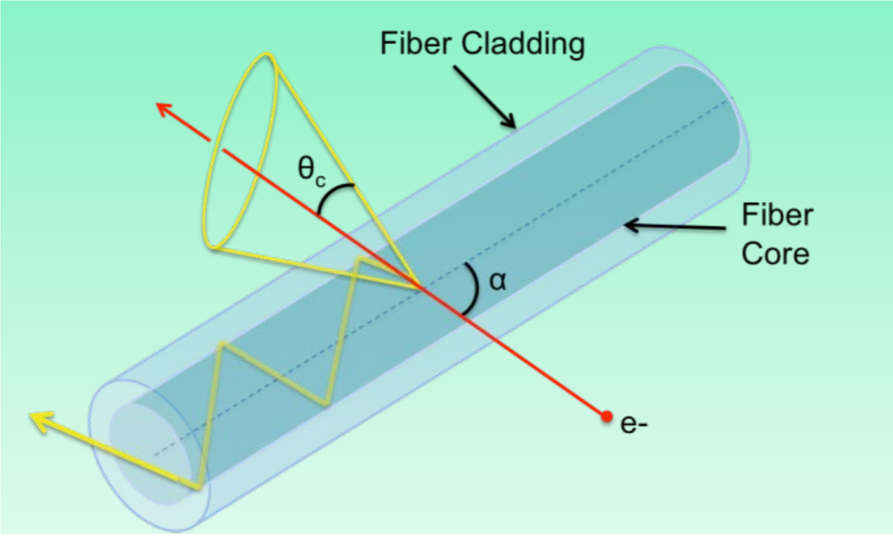
Short vs. Distributed Detectors

Short localised detectors vs. Long distributed detectors

Short localised detectors	Long distributed detectors
Time resolution	Coverage
Coverage	Cost
Position resolution	
Position ↔ Magnitude	**Short beams**
Loss magnitude	Position resolution
	Time resolution
	Loss magnitude (calibration including attenuation)
Machine protection	
	Long trains
	Position ↔ Time ↔ Magnitude
	R&D needed for machine protection

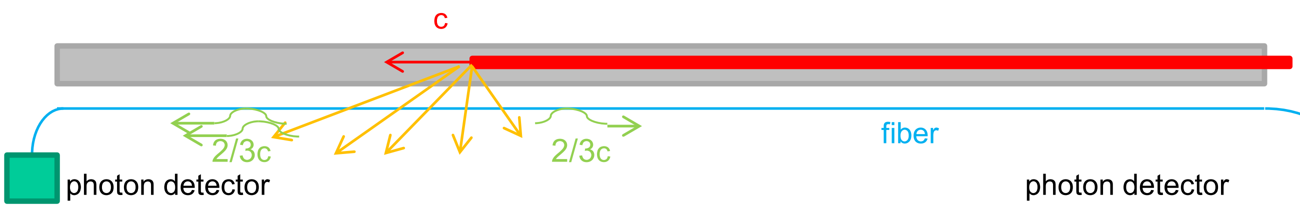
Cherenkov Fibers BLMs — Detection Principle

- When a charged particle with *v>c* enters the fiber, photons are produced along Cherenkov cone



$$\cos\theta_{\text{Cherenkov}} = \frac{1}{n_{\text{core}}\beta}$$

- Optical fibers for loss measurement are increasingly popular
- Overview: *T. Obina ,Y. Yano, IBIC 2013*; *L. Fröhlich et al., DIPAC 2011*; *F. Wulf, M. Körfer, DIPAC 2009*; …



Cherenkov Fiber BLMs — Pros and Cons

- Insensitive to photons
- Insensitive to *E* and *B* fields
- Small and fast
- Relatively radiation hard (depending on type)
- Combination fiber / readout can adapt to a wide dose range
- Time resolution 1 ns
- Position resolution 0.5 – 1 m
- (Radiation induced) attenuation and dispersion (multi mode fibers)
- Position ↔ time ↔ magnitude
  - Ideas:
    - Couple with localised high time resolution measurement
    - Match pattern to a catalogue of known loss scenarios (experience, simulation)

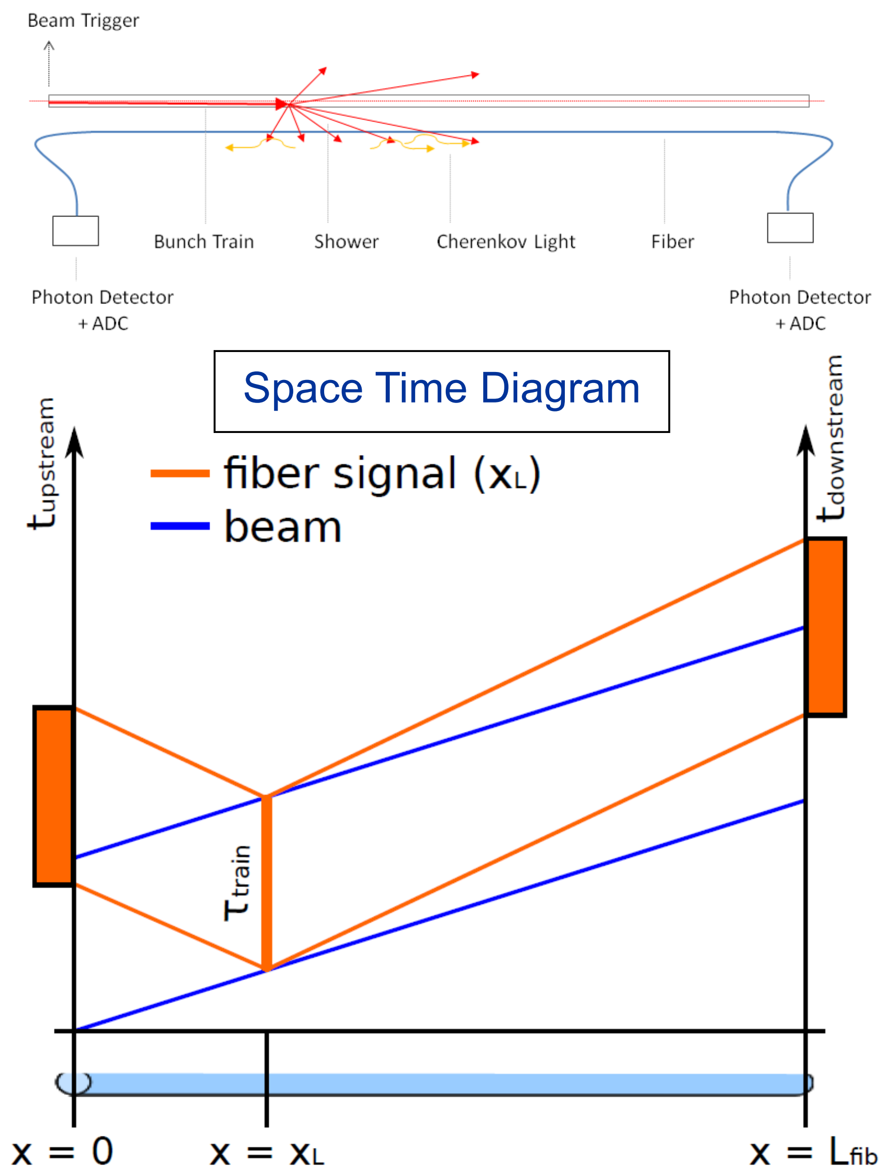
Position Resolution for Long Bunches

- Case: single loss location — constant for all bunches

- Simulations:
  - Starting point of the losses can be determined from the signal's rising edge, with:
    - < 1m longitudinal resolution
    - ≈ 1ns time resolution

- First results from installation at the Australian Synchrotron and at CTF3 (CLIC Test Facility):

E. Nebot: "Position Resolution of Optical Fibre-Based Beam Loss Monitors Using Long Electron Pulses"



UFO Losses

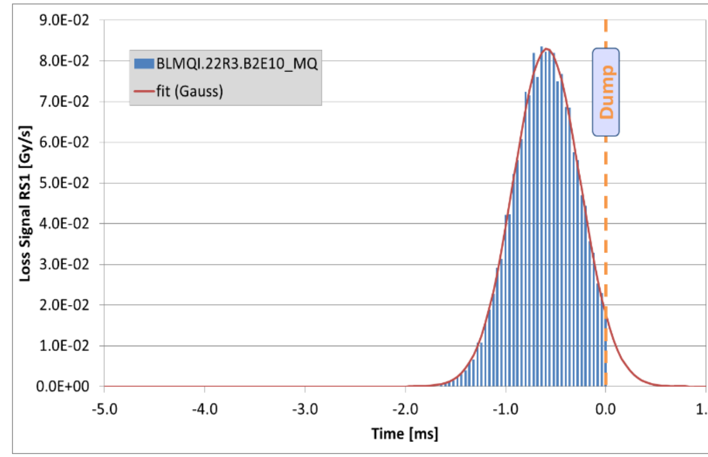
Position ↔ magnitude

Determine position and magnitude with simulations

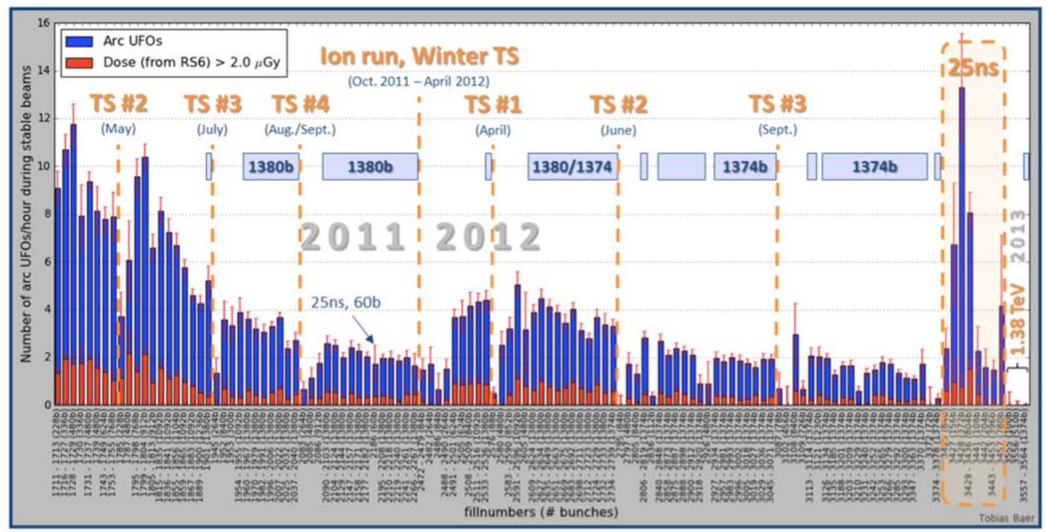
Improve longitudinal coverage

UFOs — Causing Quenches at 6.5 TeV

- Fast and localised losses all around the ring believed to be caused by macro particles interacting with the beam
- "UFO": Unidentified Falling Objects



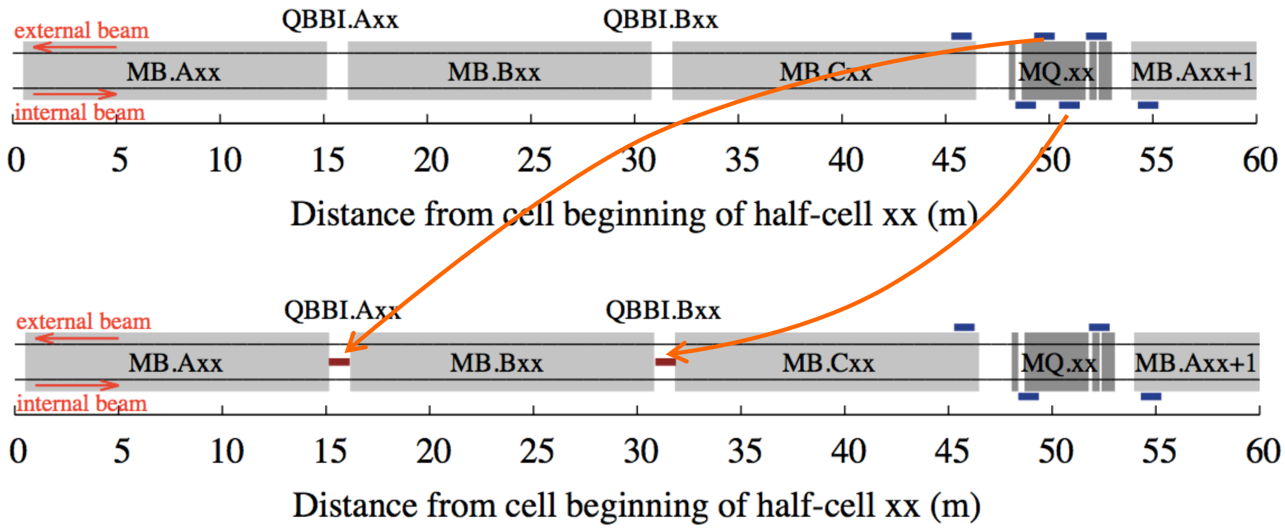
- No quenches at 4 TeV
  - Less heat deposited
  - Lower magnetic field
  - Conservative BLM thresholds



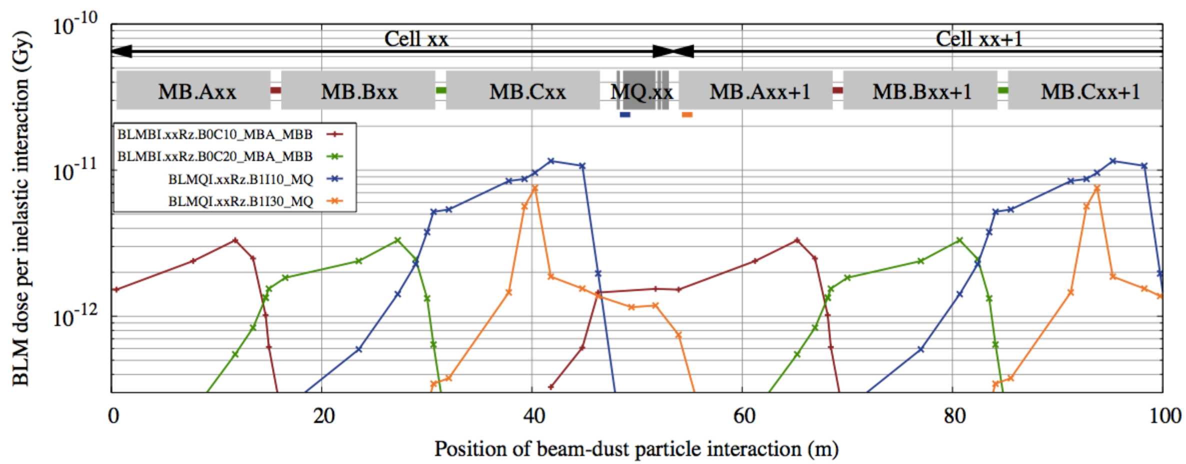
- 6.5 TeV: thresholds set to quench limit
  → quenches occurred

Tobias Baer

Relocation of 1/3 of Arc Detectors (Long Shutdown 1)



- Coverage post-LS1: increases sensitivity by a factor 30 → 100% coverage can be achieved

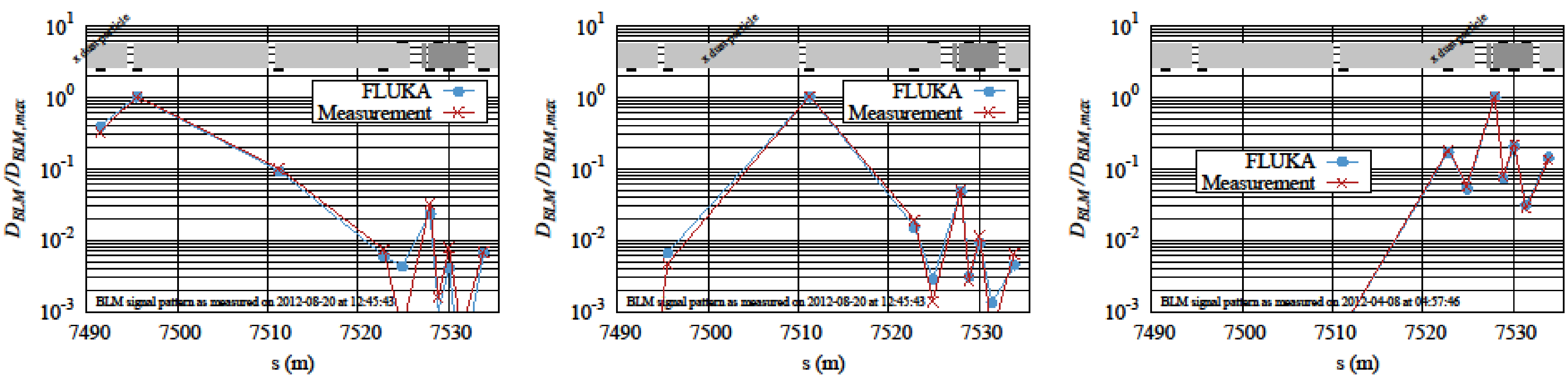


A. Lechner, Workshop on Beam-Induced Quenches, CERN, 2014

UFO Losses: Comparison Simulation — Measurement

Anton Lechner

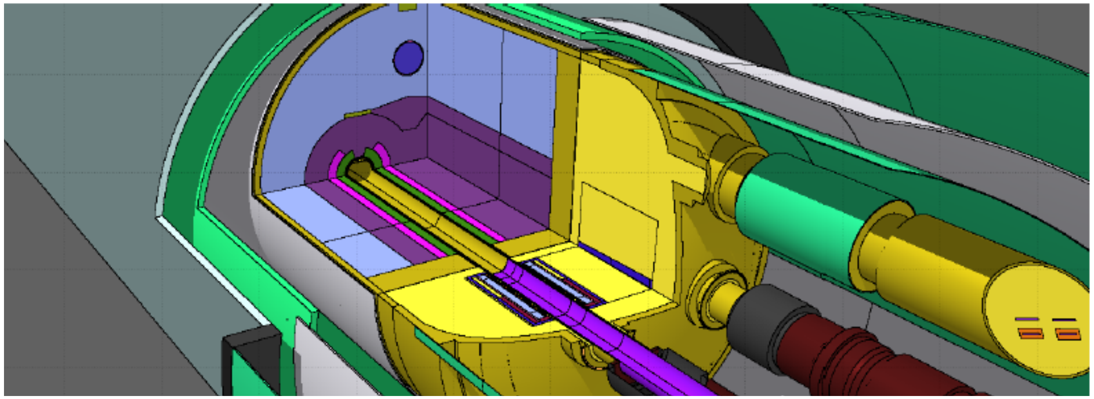
- If several detectors record the loss: Determine the loss position and magnitude with the help of simulations
  - Loss position: +/- 1 m
  - Number of inelastic proton-dust particle interactions: factor 2

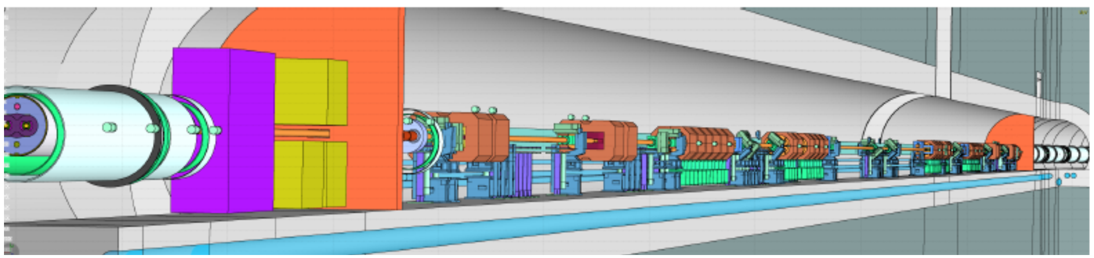


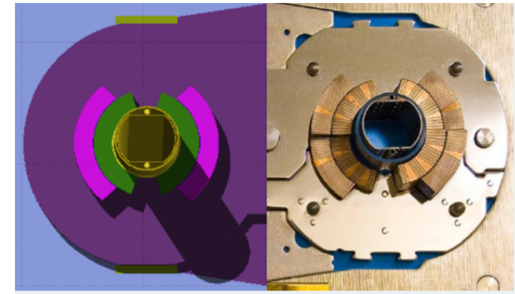
- 1–4 × 10^6 inelastic proton-dust particle interactions in this cell
- Other cells 10–100 times higher

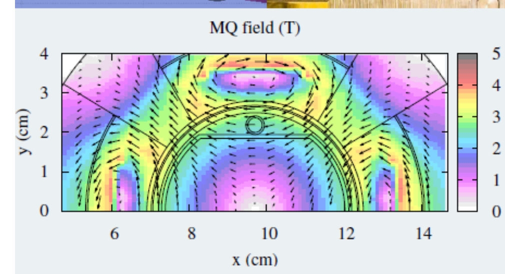
A. Lechner, Workshop on Beam-Induced Quenches, CERN, 2014

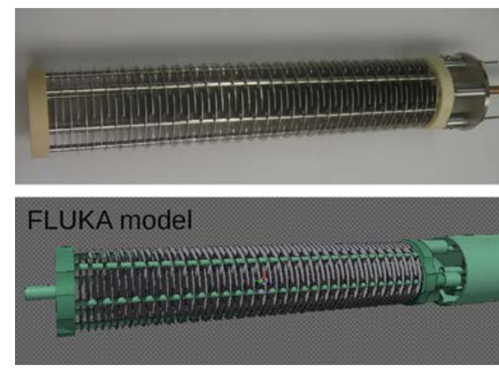
Require Very Accurate Models

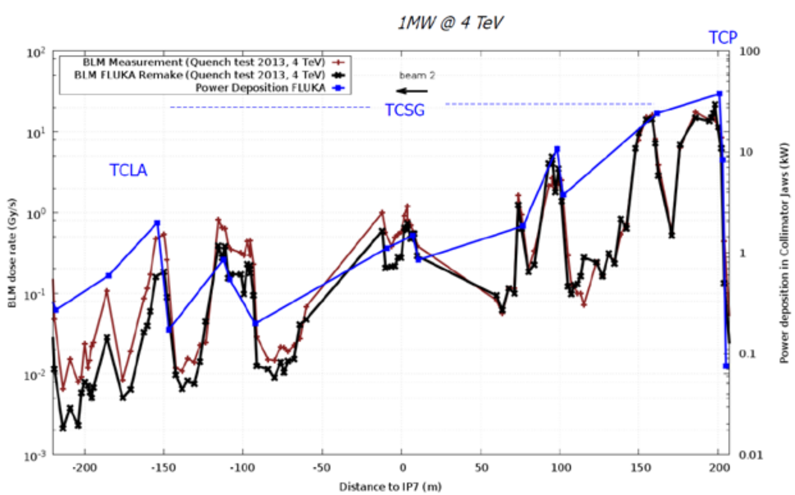












Francesco Cerutti, Anton Lechner, Eleftherios Skordis (FLUKA team)

High Time Resolution

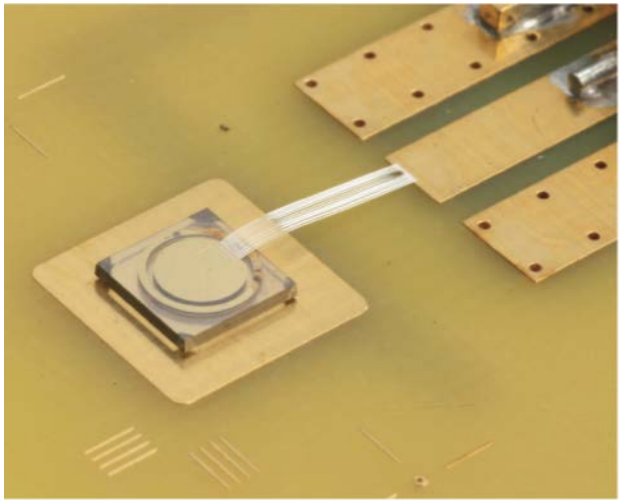
Require very small detector

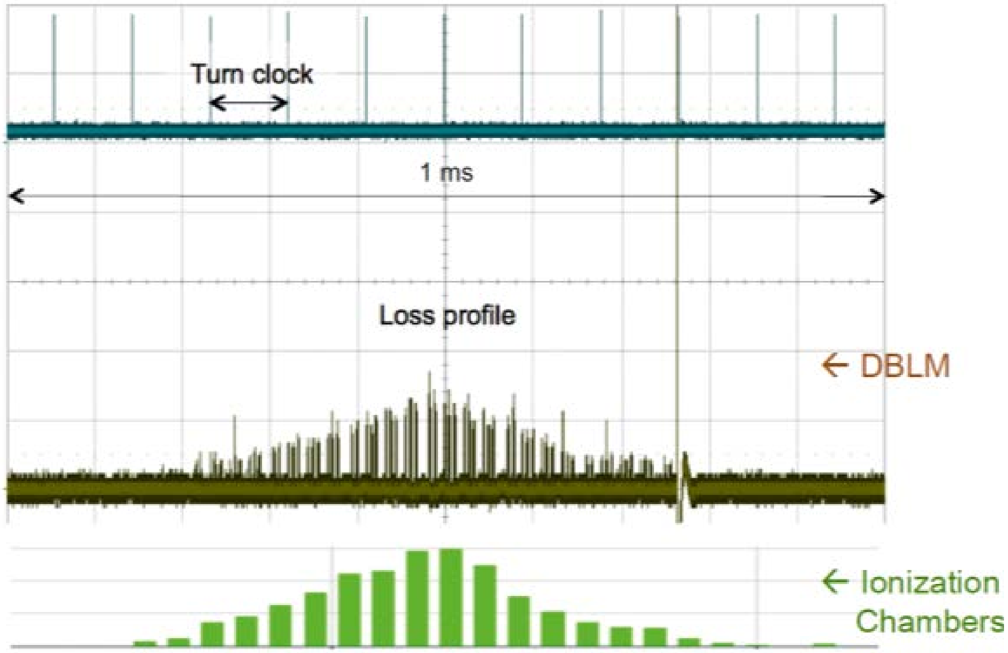
→ Diamond detector LHC
(few ns)

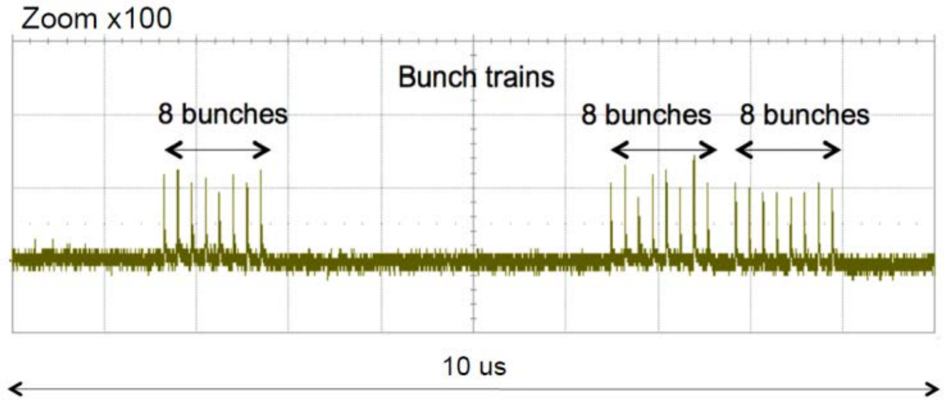
→ Small Cherenkov + ultrafast readout:
Could they reach ≈100ps?

LHC Diamond Detectors

- Fast and sensitive
- Small and radiation hard
- Used in LHC to distinguish bunch-by-bunch losses
- Dynamic range of monitor: 10^9
- Temporal resolution: few ns

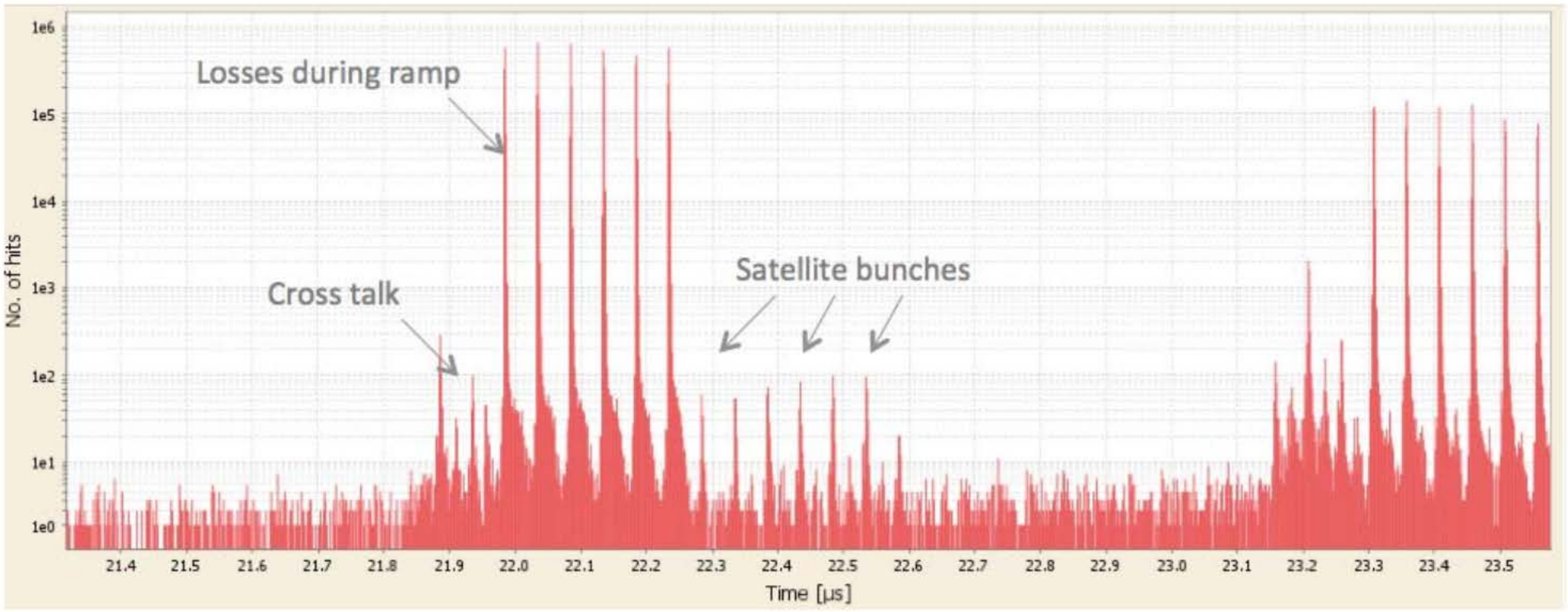






Diamond: Arrival Time Histogram During Ramp

- 50 ns bunch spacing
- Loss signal at 25 ns is from opposite beam ("cross talk")
  → sub 25 ns resolution required to resolve



B. Dehning

Machine Size and Radiation

Machine Size Implications

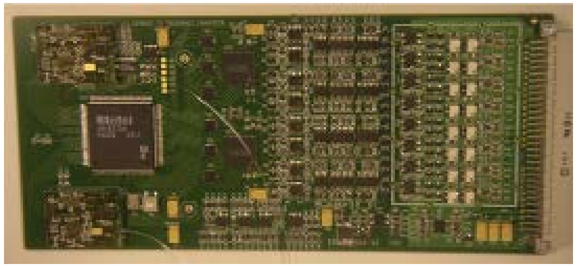
Short detectors: cost, dependability per channel, data treatment

Front-end electronics in the tunnel → radiation tolerant

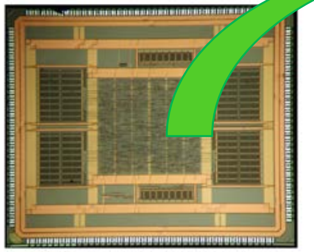
Low noise, low loss signal transmission: optical techniques

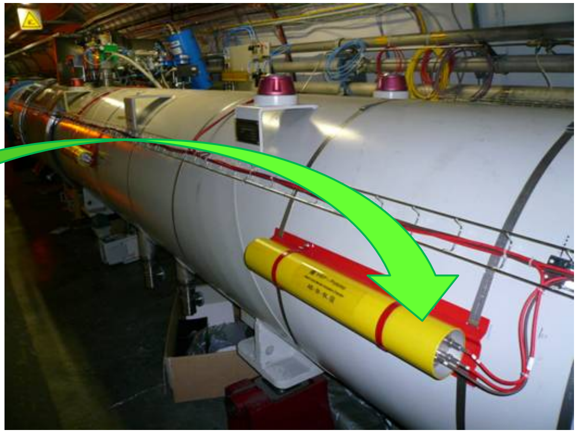
Radiation Tolerant Readout

- LHC BLM front-end: charge-to-frequency converter
  - 500 Gy certified — ok for arcs
  - Insertion regions:
    up to 300–800 m long cables



- New development: radiation hard Application Specific Integrated Circuit (ASIC)
  - Dynamic range 10^6
  - Bipolar input current
  - Certified up to 100 kGy





G. Venturini

Background

Background Implications

Limit sensitivity to primary beam losses

Can compromise machine protection

Synchrotron Radiation

Synchrotron Radiation Background

- FLUKA simulation study for CLIC damping ring (DR) arc
- Aim: worst case estimate using a simplified geometry
- Impacting on vacuum chamber: wall thickness 1.5 mm
- Detectors: 10 cm and 40 cm from beam pipe

- Many CLIC DR parameters similar to third generation light sources (but: very small longitudinal normalised emittance of 6 keV m)

	Elettra	ALBA	DLS	ESRF	APS	Spring-8	ASLS	CLIC DR
Energy [GeV]	2	3	3	6	7	8	3	2.86
Circumf. [m]	259	269	562	845	1104	1436	216	427.5
Lattice type	DBA	DBA	DBA	DBA	DBA	DBA	DBA	TME (arc) / FODO (LSS)
Current [mA]	300	400	300	200	100	100	200	200

(table based on: *A. Wolski, Synchrotron Light Machines, CAS 2012*)







CLIC DR and Australian Synchrotron Comparison

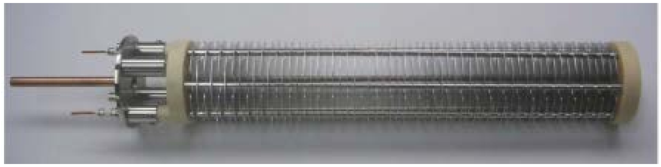
	E [GeV]	Intensity [electrons]	bunches	Pulse length [ns]	Circumf. [m]	F_{rev} [MHz]	Bunch spacing [ns]	$\gamma\varepsilon_x$ [nm rad]	$\gamma\varepsilon_y$ [nm rad]
CLIC DR	2.86	1.28×10^{12}	312	156	427.5	0.73	0.5	472	4.8
ASLS	3.0	0.9×10^{12}	300	600	216	1.38	2	58708	< 5

	Dipole					**Wiggler**	
	B [T]	E_{crit} [keV]	ρ [m]	L [m]	$\Delta\theta$ [mrad]	B [T]	E_{crit} [keV]
CLIC DR	1	5.4	9.5	0.6	60	2.5	14
ASLS	1.3	7.8	7.7	1.7	220	1.9	12

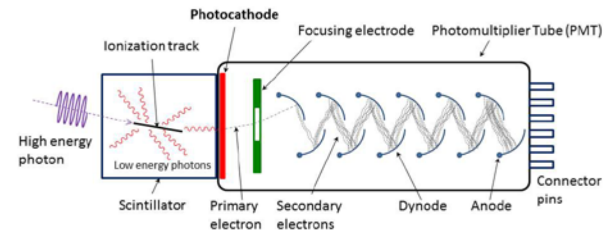
Simulated Detectors

Sanja Damjanovic

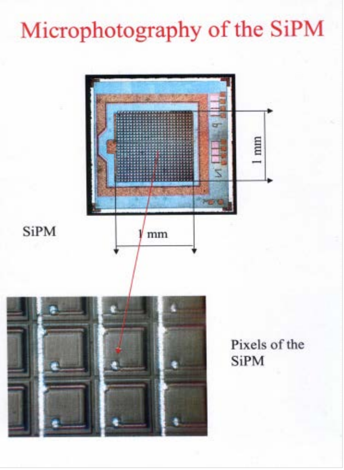
- LHC type ionization chambers (IC)
  - N_2 at 1.1 bar
  - 1.5 liter, 50 cm long



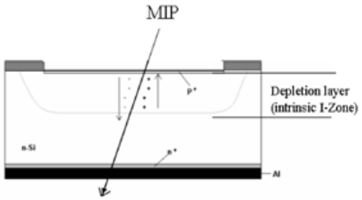
- Plastic NE102 scintillators, 0.8 liter ($25 \times 16 \times 2$ cm^3) + photomultiplier (gain 10^4)



File by Qwerty123uiop / CC BY-SA 3.0



- Small quartz Cherenkov crystals, 1 cm^3 + photomultiplier (gain 10^4) OR + SiPM (gain 10^5)



(*K. Wittenburg, CAS*)

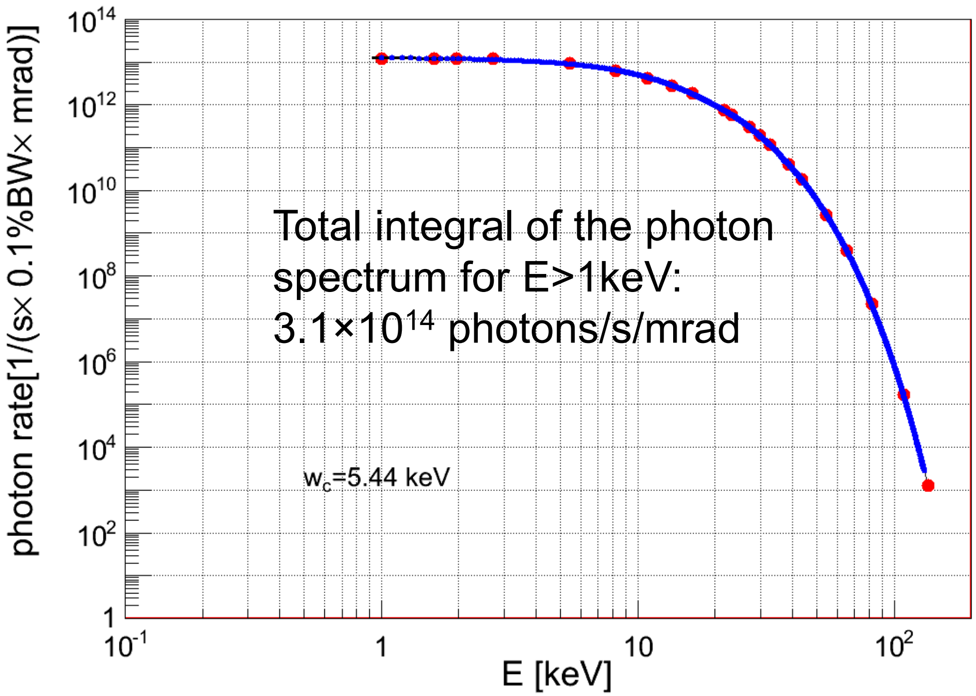
- Silicon PIN diodes in **current mode**, 1 cm^2, depletion layer 100 µm

Synchrotron Radiation Spectrum

Sanja Damjanovic

- Spectrum is not hard enough to produce electrons above the Cherenkov threshold in quartz (≈190 keV)

➔ Cherenkov detectors are insensitive to the synchrotron radiation induced charged particle showers

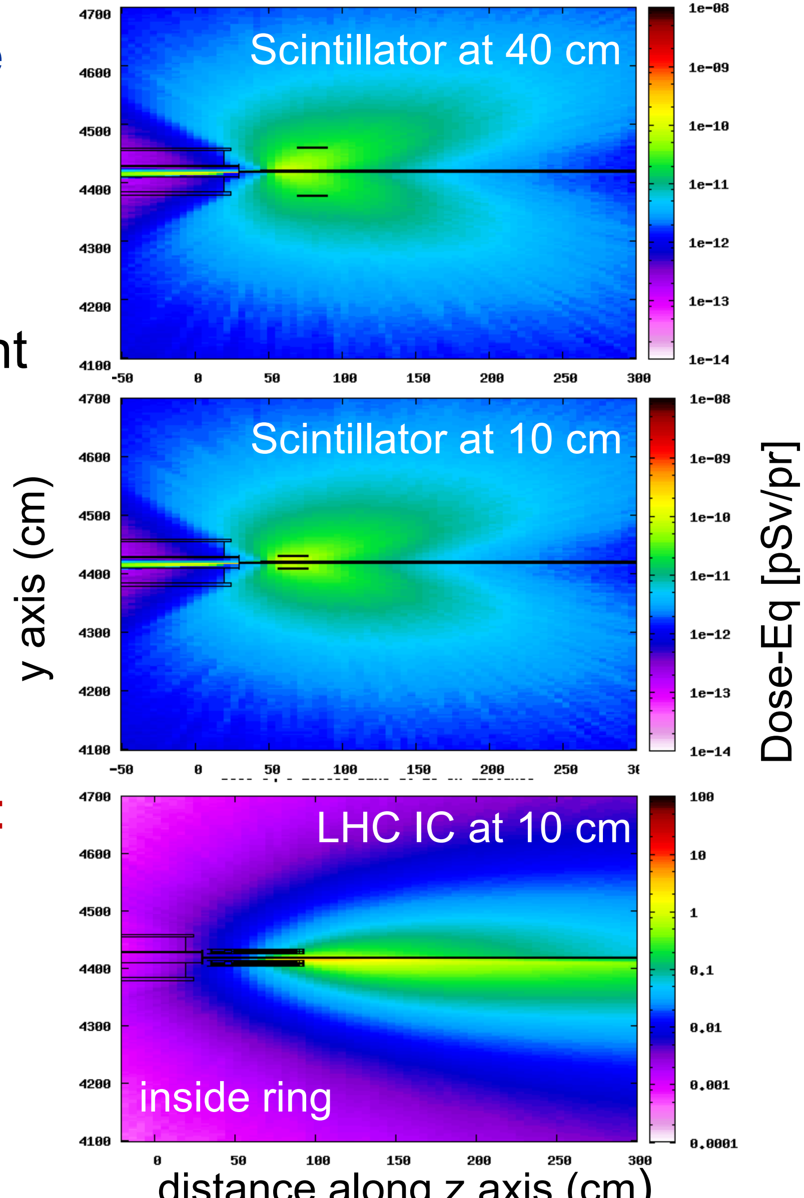


$$N(\lambda) = 2.457 \times 10^{13} E[GeV] I[A] G_1 \left[\frac{photons}{s \cdot 0.1\% BW \cdot mrad\theta}\right]$$

FLUKA Results

Sanja Damjanovic

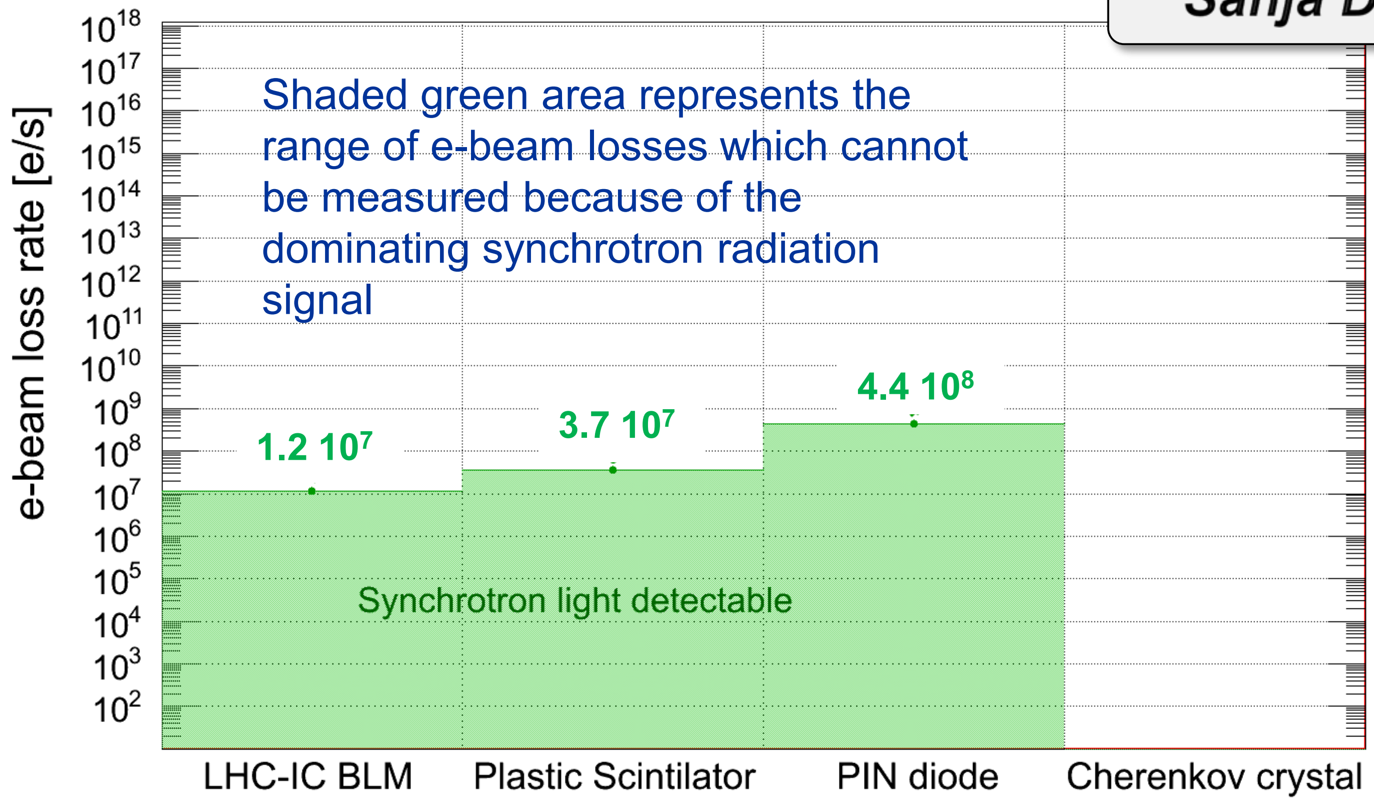
- Synchrotron radiation at 10 cm, outside of the ring, maximizing the signal:
  - IC 80 pA
  - Scintillator 64 A
  - PIN 300 pA < typ. dark current
  - Quartz insensitive



- Electron loss at same detector location:
  - IC 1.5×10^{-6} GeV/e
  - Scintillator 1.0×10^{-13} Gy/e
  - PIN 1.4×10^{-13} Gy/e
  - Quartz 9.3×10^{-14} Gy/e

Sensitivity Limits to Beam Loss due to Synchrotron Rad.

Sanja Damjanovic



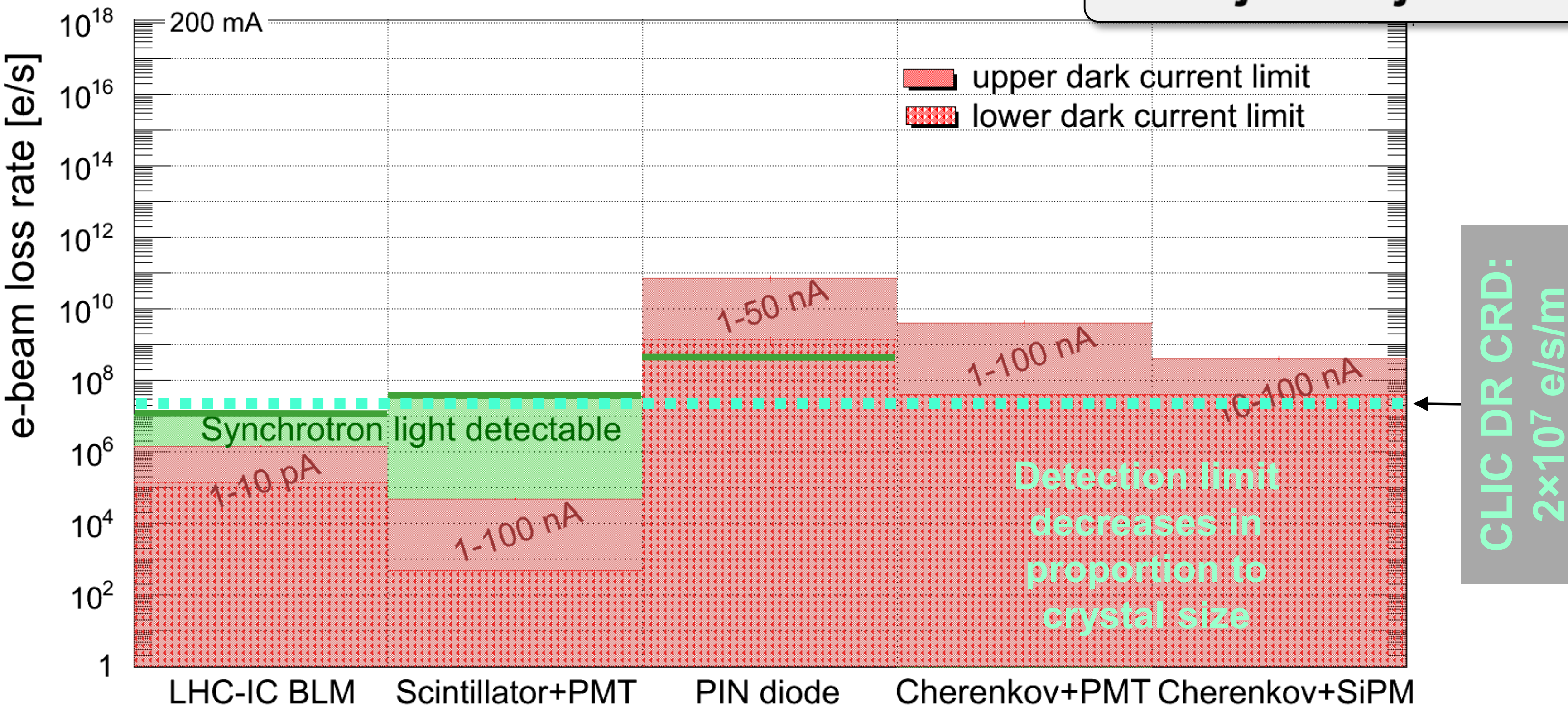
Worst case estimate

- e-beam loss rates generating detector currents equal to the currents produced by synchrotron light:

LHC-IC	1.2×10^7 e/s
Plastic scintillator	3.7×10^7 e/s
PIN diode	4.4×10^8 e/s

Sensitivity Limits due to Detector Dark Current

Sanja Damjanovic

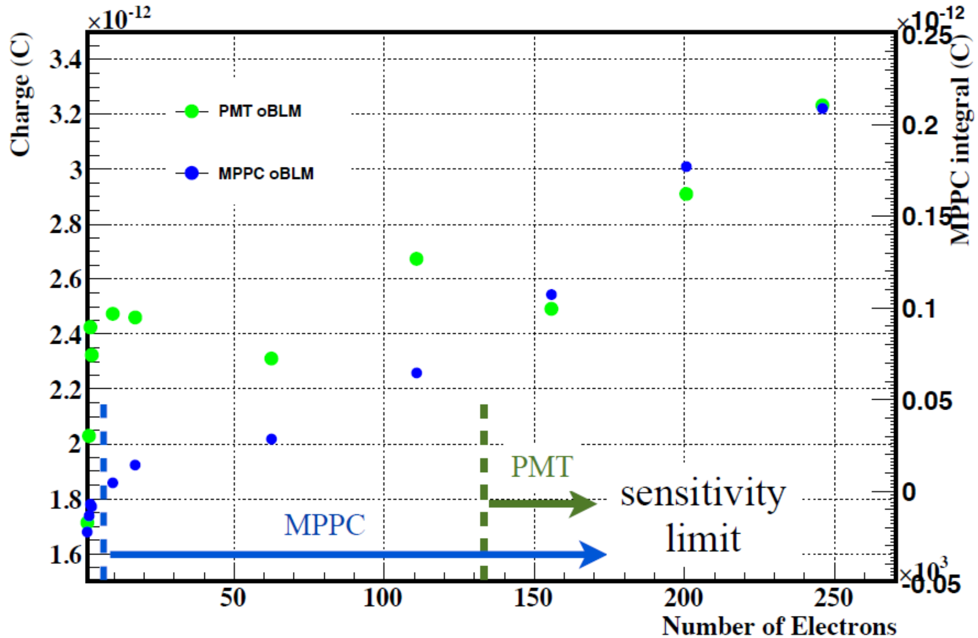


- Primary e-beam losses would be detectable for beam loss rates larger than:

LHC-IC	≥ 1.5×10^5 e/s
Plastic scintillator	≥ 5 $\times10^2$ e/s
PIN diode	≥ 1.5×10^9 e/s
Cherenkov crystal	≥ 4 $\times10^7$ e/s

Optical Fiber Loss Measurements, Australian Synchrotron

Eduardo Nebot et al.



CLIC DR CRD:
2×10^{7} e/s/m

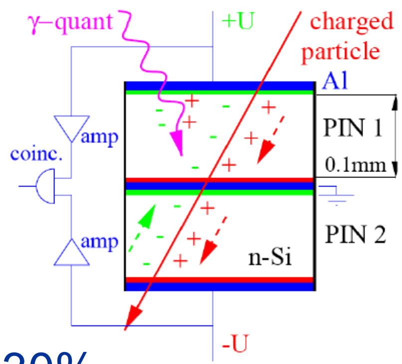
- Sensitive to $\approx1\times10^{4}$ electrons lost in single location with MPPC (Multi-Pixel Photon Counter)
- Linear response up to 1×10^{9} electrons with PMT
- Combination of photon-sensors → dynamic range $\approx10^{5}$

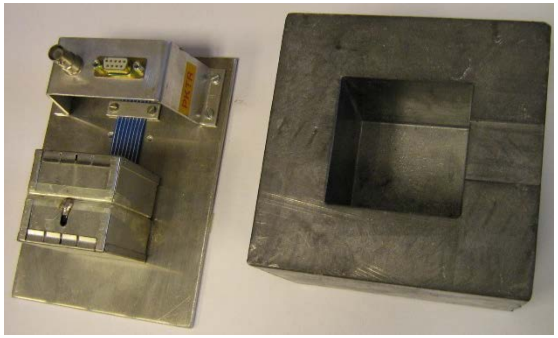
E. Nebot et al., "Measurement of Beam Losses at the Australian Synchrotron", IBIC 2014

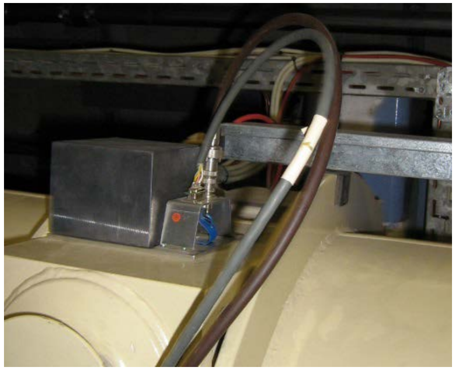
PIN Diodes HERA Proton Ring

Kay Wittenburg

- Quench protection
- Superconducting 6.3 km p-ring (920 GeV/c)
- e-ring (30 GeV/c)
- Synchrotron radiation:
  - E_{crit} = 88 keV
  - Dose rate ≈10^4 Gy/year
- Two silicon PIN diodes in coincidence counting mode + shielding box
  - Efficiency charge particle >30%
  - Efficiency photon 3.5×10^{-5}
- 10.4 MHz count rate (96 ns bunch spacing)
- Integration time: 5.2 ms — speed limited by low count rate
- Dynamic range of up to 10^9
- Good calibration: measured lifetime by current decay and losses agree within factor 2



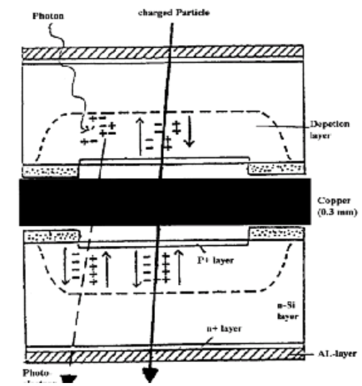




PIN Diodes HERA Electron Ring

Kay Wittenburg

- Photon coincidence counting:
  - Statistically
  - Electron created (photoelectric absorption, Compton effect) reaches second diode energy
  - → add thin metal layer between the diodes



- Electrons which lose energy are lost at dispersive aperture restrictions (close to horizontal quadrupoles)

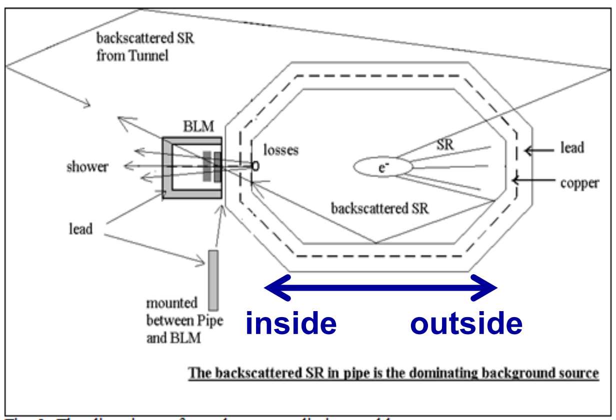
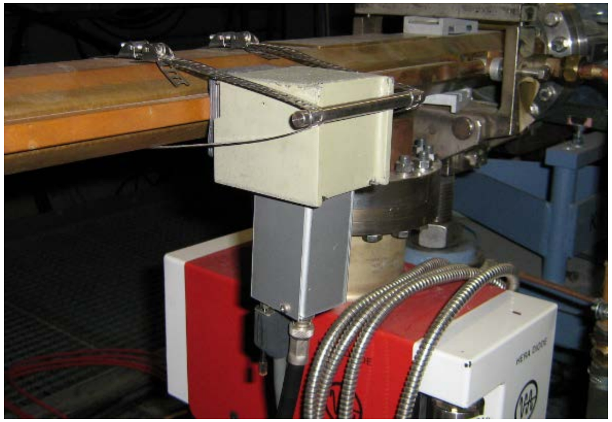
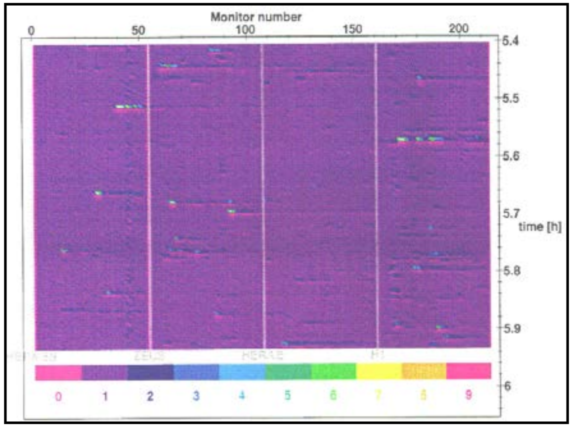


Fig. 2: The directions of synchrotron radiation and losses





Distant Losses

Distant Losses

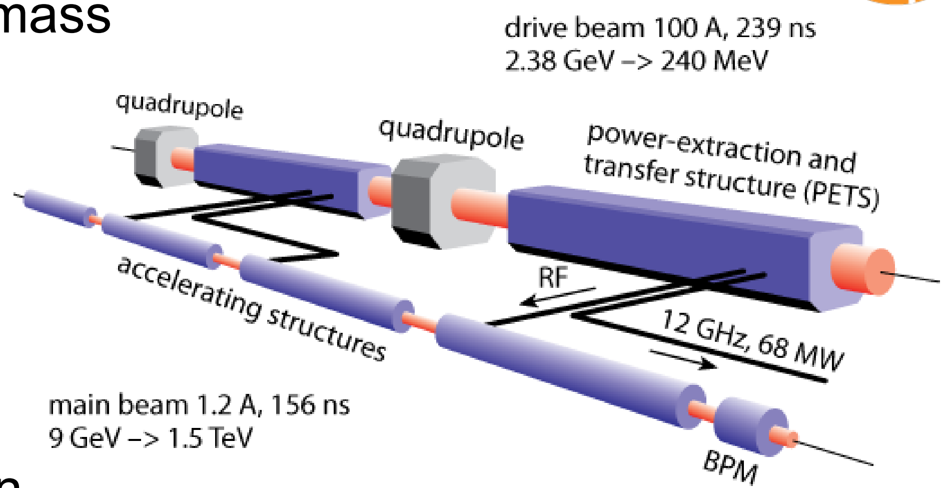
Collimation regions

Injection and extraction

Around interaction points

The CLIC (Compact Linear Collider) Two-Beam-Module

- Future e^+/e^- collider, centre of mass energy of 3 TeV
- High accelerating gradients (100 MV/m) → novel two beam acceleration method
- High intensity Drive Beam decelerated in Power-Extraction and Transfer Structures (PETS)
- RF power at 12 GHz is transferred to the Main Beam



	Energy range [GeV]	Pulse length	Electrons per train
Drive Beam	2.4 → 0.24	244 ns ≈ 80 m	1.53×10^{14}
Main Beam	9 → 1500	156 ns ≈ 50 m	1.16×10^{12}

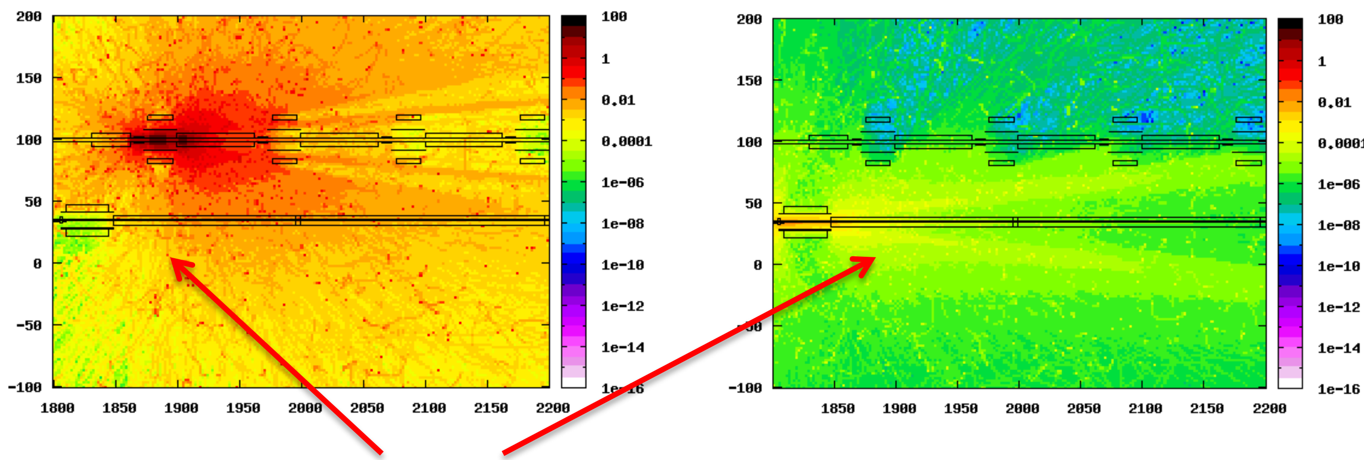
Distinguish Losses CLIC Two-Beam Module – "crosstalk"

Sophie Mallows

- Dose (Gy) from FLUKA simulations:

Destructive Drive Beam loss
1.0% of bunch train hits single aperture restriction

Destructive Main Beam loss
0.01% of bunch train hits single aperture restriction



- At the very beginning of the Main Beam: Destructive Drive Beam loss provokes similar signal as destructive Main Beam loss in the region close to Main Beam quadrupole
- **Not** a machine protection issue — **dangerous loss would never go unnoticed**

	Energy
Drive Beam	2.4 GeV
Main Beam	9 GeV

First Measurements CTF3 Two-Beam Module – "crosstalk"

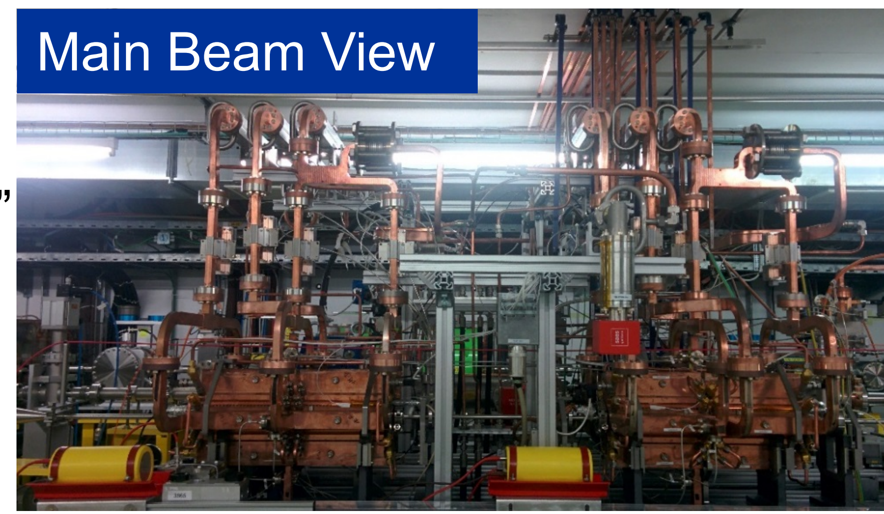
Maria Kastriotou


Drive Beam View

- 10^{-3} losses of either beam → unacceptable luminosity losses due to beam loading variations
- FLUKA simulations show: $BLM_{DriveBeam}$ up to $100 \times BLM_{MainBeam}$
- How to measure Main Beam losses in the presence of Drive Beam losses?

- Little ionization chambers
- Optical fibers
- Drive / Main Beam: 120 / 200 MeV
- First results show 1–5% "crosstalk" on the other beam

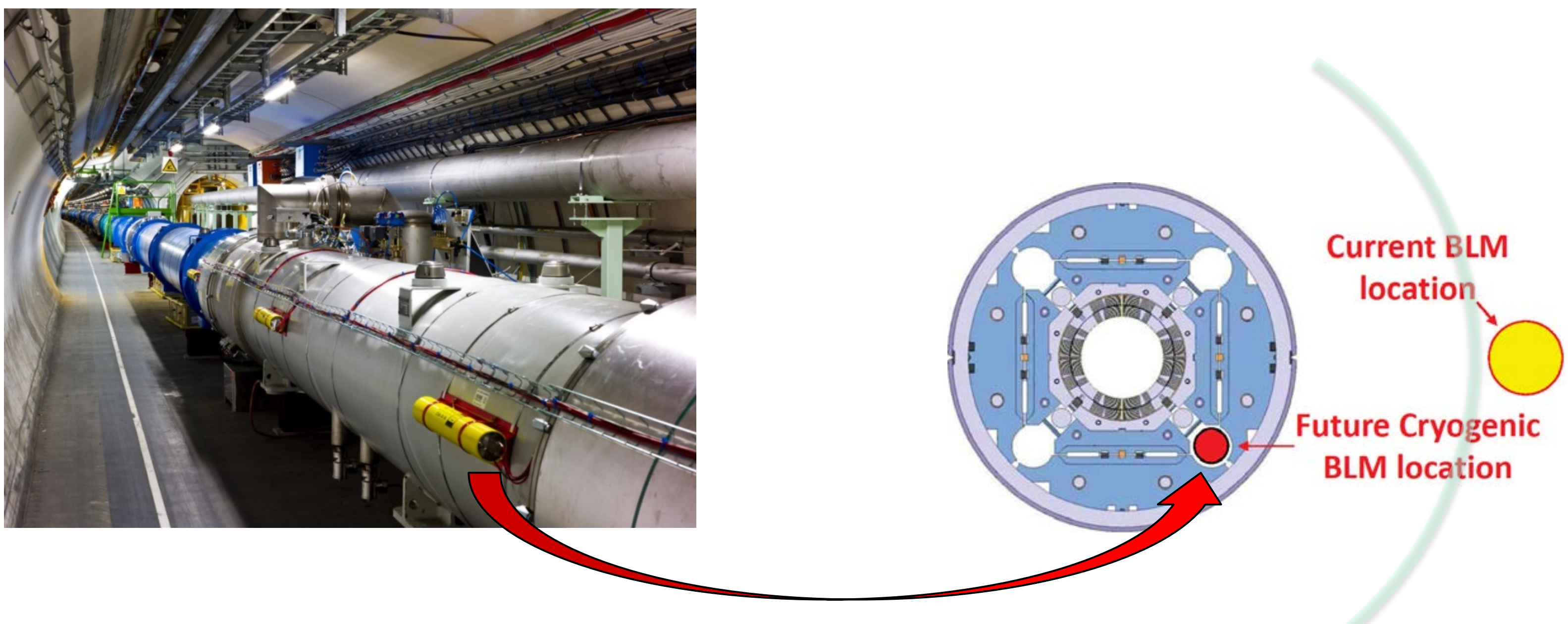
M. Kastriotou et al., "BLM Crosstalk Studies at the CLIC Two-Beam Module", MOPB045


Main Beam View

Cryogenic BLM at LHC

Christoph Kurfuerst, Bernd Dehning

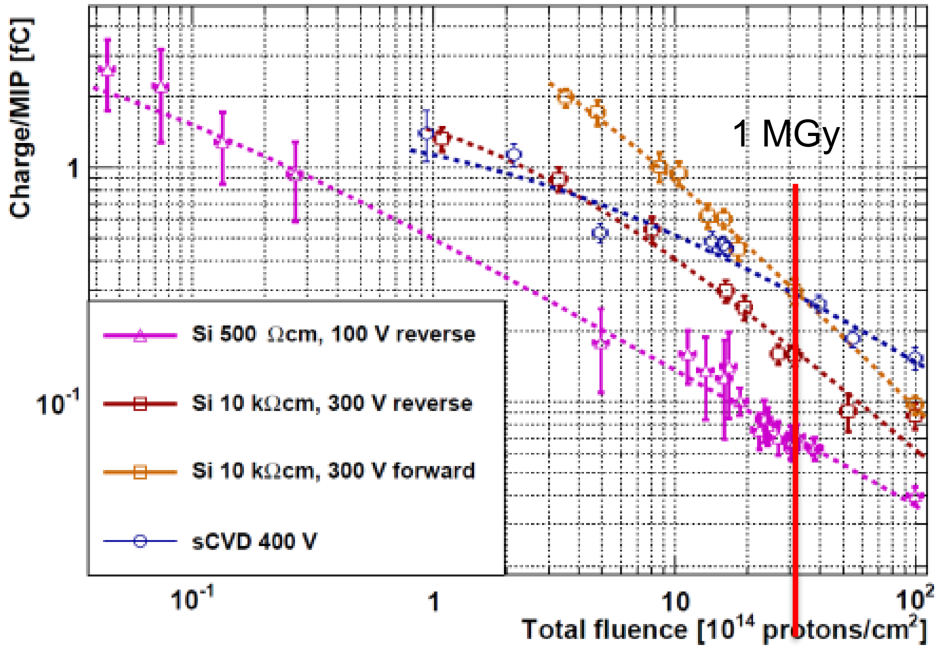
- Loss monitor closer to loss location → avoid that the signal is dominated by other radiation sources (e.g. physics debris at the insertion region triplet magnets)
- HL-LHC triplets: move detector inside the cryostat
  - Operate in liquid helium at 1.9 K and at 2 T
  - Dose of 2 MGy in 20 years, without access
  - Fast pressure rise (1.1 to 20 bar) in case of quench



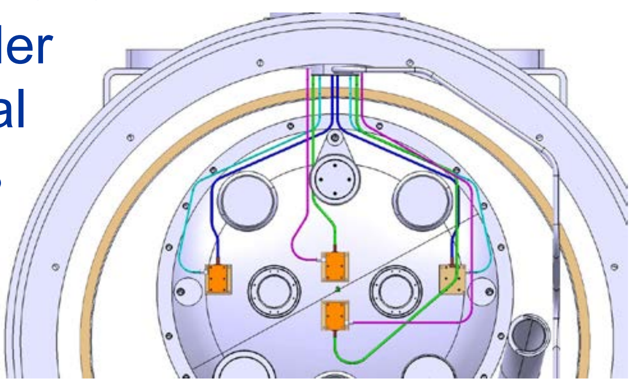
Cryogenic BLM Tests

Marcin Bartosik, C. Kurfuerst, B. Dehning

- Since 2011 extensive classification program of the detector parameters in cryogenic temperature under radiation
- Single crystal chemical vapour deposition (scCVD) diamond
- p^+-n-n^+ silicon
- Both materials can operate up to 2 MGy:
  - Diamond/silicon sensitivity reduction 14% / 25%
- Leakage current of Si irradiated at cold much less than at room temperature



Now testing both detectors in LHC cryostat at ≈20 K under operational conditions



M. Bartosik, "Cryogenic Beam Loss Monitors for the Superconducting Magnets of the LHC", MOPB042

Accelerating Structures

RF Structures

Dark current (field emission) and voltage breakdown (electric arcs) → electrons and X-rays

Limits the sensitivity to primary beam losses

Can be monitored with BLM

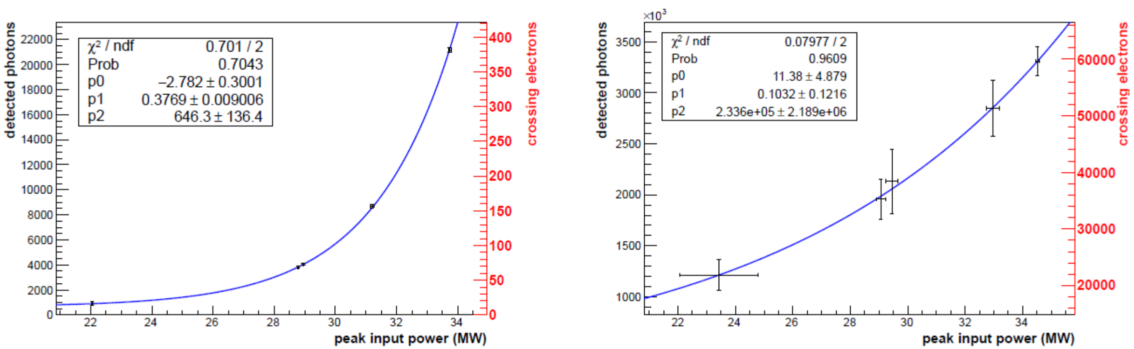
CLIC Main Linac Cavity

- Test at CTF3 of unloaded cavity
- Optical fiber 900 µm at 2.5 cm distance (30 cm exposure)
- 200ns RF pulses: Measured dark current and breakdown as function of cavity input power
- Extrapolated to 40 MW (unloaded) and 60 MW (loaded) structure

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

- Detected photons: $2{\times}10^5$ (dark current), $6{\times}10^6$ (breakdown) at 40 MW
- → very high electron background

M. Kastriotou et al., "RF cavity induced sensitivity limitations on Beam Loss Monitors", LA3NET 2015, Physics Procedia, to be published



(a) Electron field emission

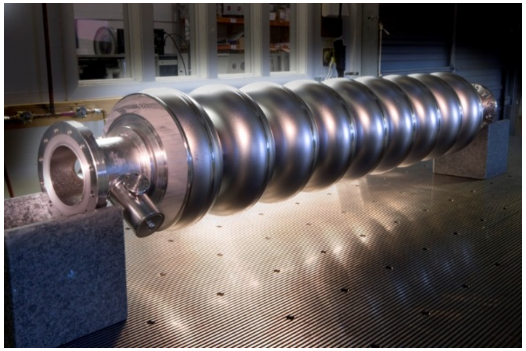
(b) RF breakdown

Fig. 5. Detected photons and estimation of the number of electrons with $\beta = 1$ that will give the respective signal when crossing the BLM

Cryogenic Loss Monitors (CLM) at Fermilab

Arden Warner

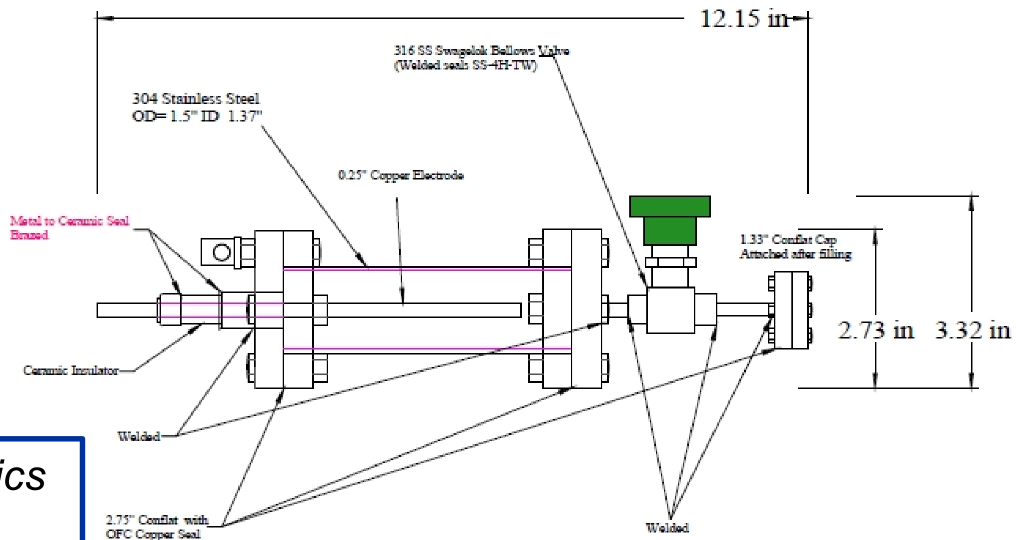
- Superconducting RF (SRF) cavities measure primary beam losses and dark current losses at Fermilab's Advanced Superconducting Test Accelerator (ASTA)
- 5 K (inside SRF cryo-module) to 350 K



- Stainless steel vessel, coaxial design, 120 cm^3, He-gas 1.0–1.5 bar
- Sensitivity: 1.9 pA/(rad/h), max. dose rate: 30 krad/h
- Readout via current-to-frequency converter and FPGA-TDC
- Housing at -95 V

Fill port

A. Warner and J. Wu, Physics Procedia 37 (2012) 2031.



First Measurements

Arden Warner

- Dark current measurements at the A0-photo-injector test accelerator and the Horizontal Test Stand (HTS)

Loss due to Dark current background at A0-photo-injector; measured to be ≈400 nA downstream of bend magnet

40 µs RF gate (dark current only no photo-electrons injected)

Test cavity

HTS installation

A. Warner and J. Wu, "Cryogenic loss monitors with FPGA TDC signal processing", Physics Procedia 37 (2012) 2031.

Summary

- Pro — contra of localized vs. distributed systems
  - Position resolution
  - Time resolution
  - Absolute measurement

- Challenges for machine protection, large machines and radiation environment

- Background sources limiting sensitivity to primary beam losses
  - Synchrotron radiation
  - Distant beam losses and physics collision debris
  - RF accelerating structures

Thank you for your Attention

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