The LHC BLM System: Overview and Experience

Eva Barbara Holzer
CERN, Geneva, Switzerland

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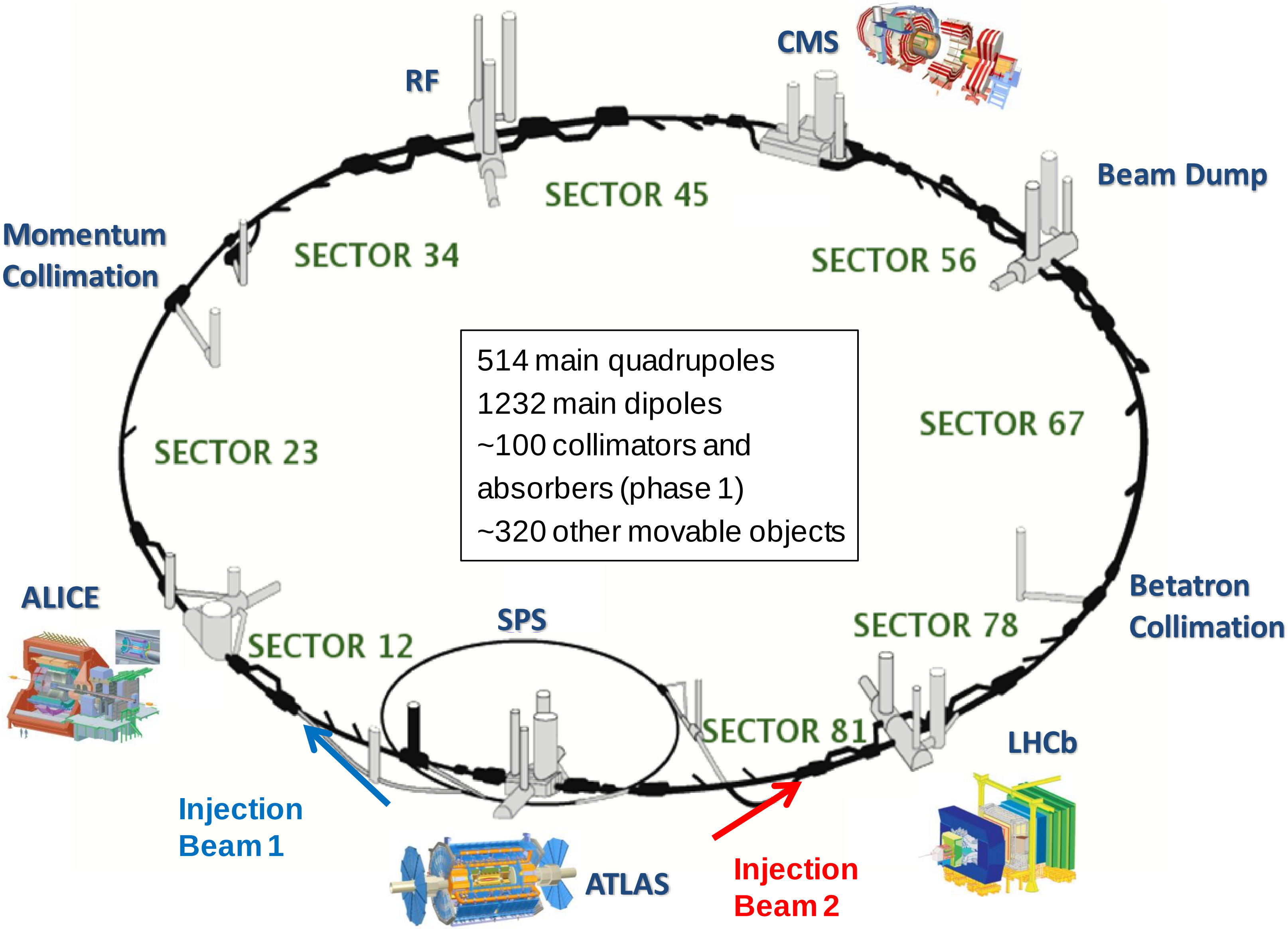
DESY, Hamburg

Content

- LHC Machine Protection
- BLM System Installation:
  - Monitors
  - Electronics
  - Location
- Determination of Thresholds
  - BLM Thresholds and Magnet Quench Levels
- Data published for
  - Logging display
  - Online and offline analysis
- Operational Experience
- Fast (ms-time-scale) losses, UFO: Unidentified Falling Object
- BLMs for Collimation

LHC Machine Protection

LHC: pp, PbPb and possibly pPb collisions



Stored Energy Challenge

Stored Energy	
Beam 7 TeV	2 x 362 MJ
2011 Beam 3.5 TeV	above 2 x 100 MJ
Magnets 7 TeV	10 GJ

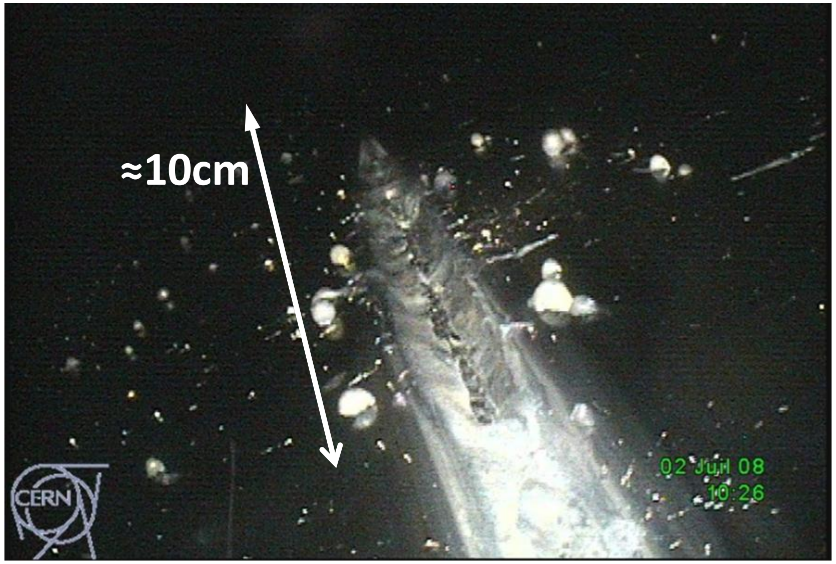
Quench and Damage at 7 TeV	
Quench level	≈ 1mJ/cm^3
Damage level	≈ 1 J/cm^3

- Failure in protection → loss of complete LHC is possible
- Magnet quench → hours of downtime
- Magnet damage → months of downtime, $ 1 million

SPS incident in June 2008

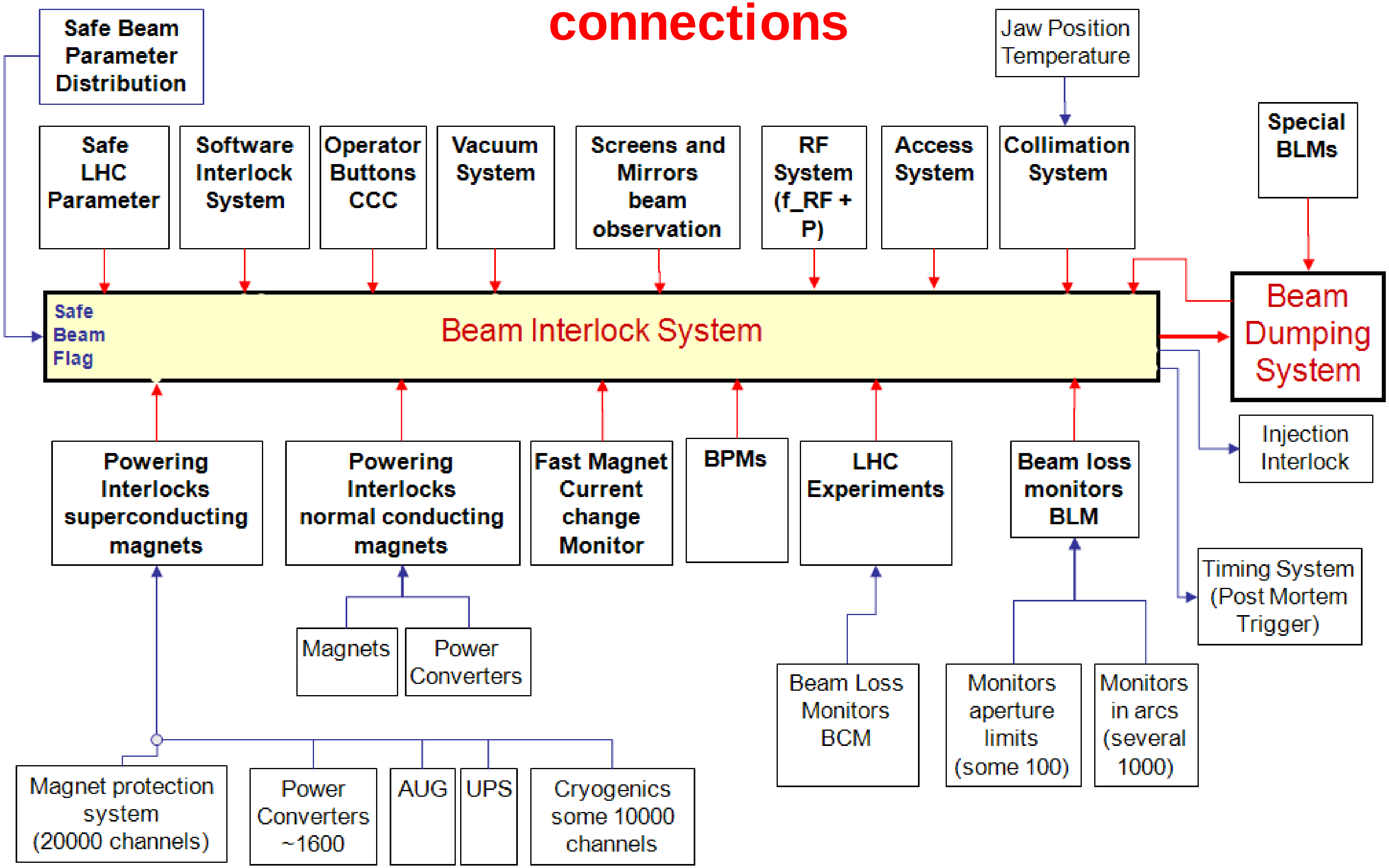
400 GeV beam with **2 MJ**

(J. Wenninger, CERN-BE-2009-003-OP)

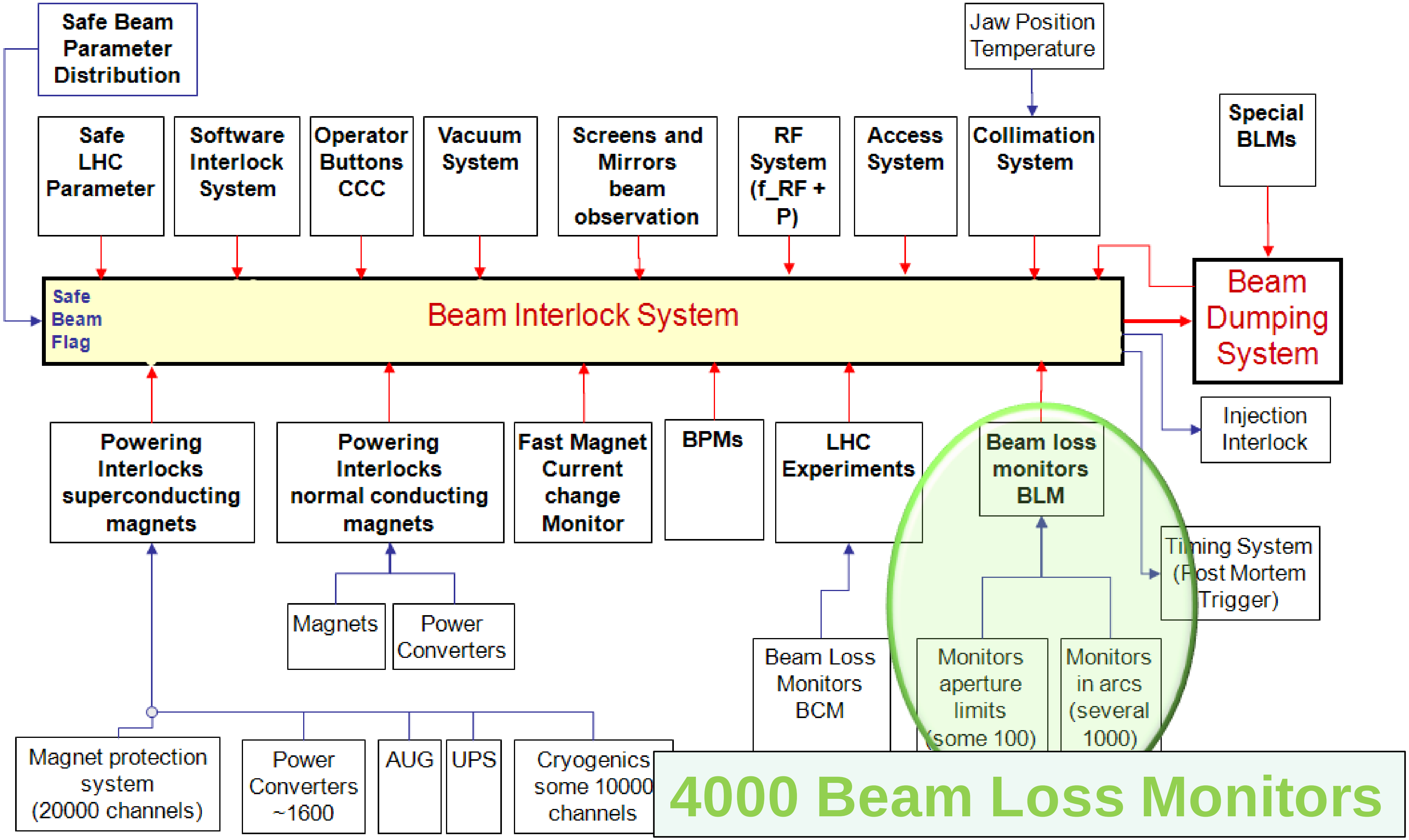


Machine Protection System

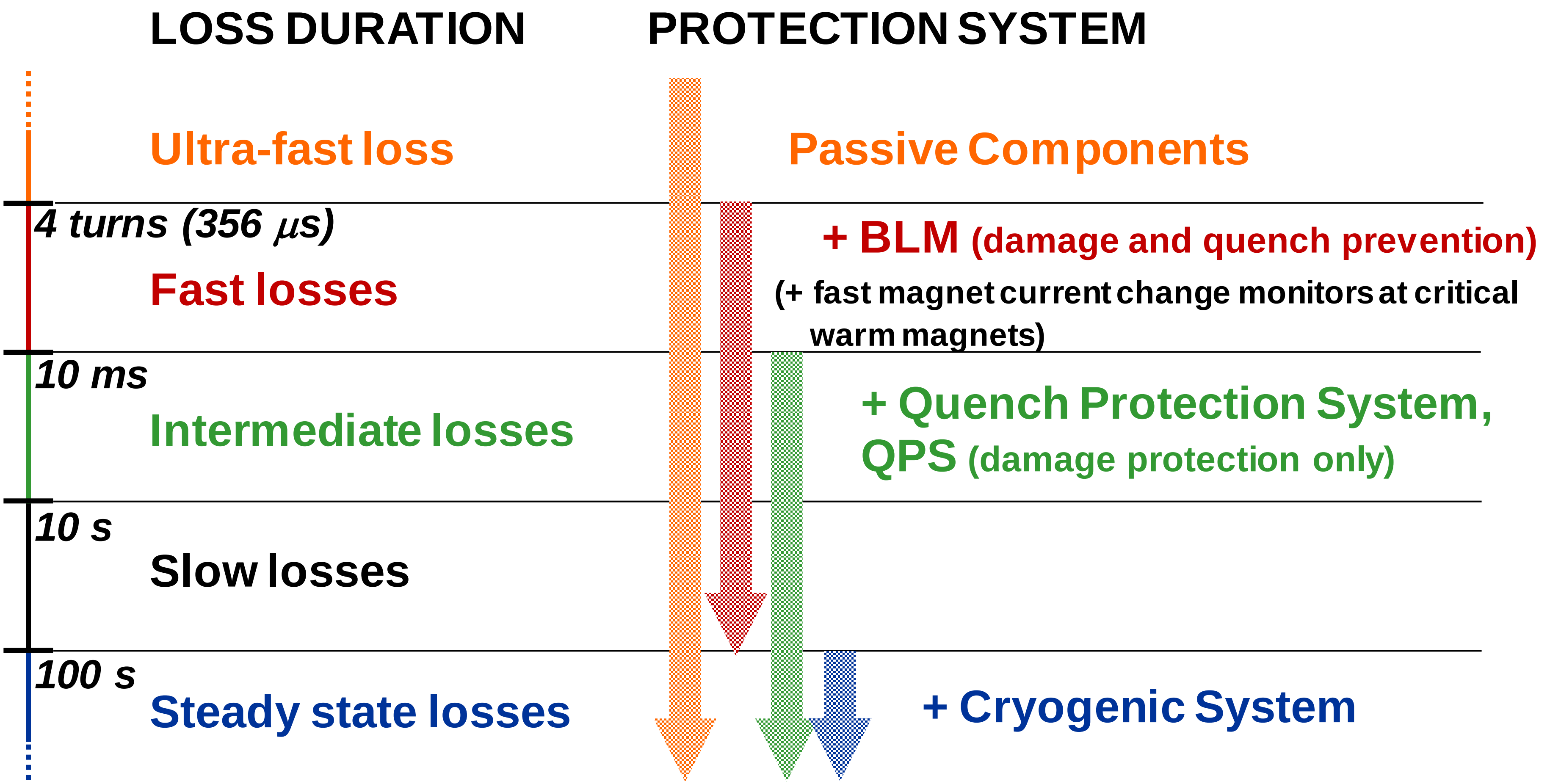
Several 10.000 channels from ≈ 250 user input connections



Machine Protection System



Beam Loss Durations Classes



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

BLM System Challenges: Design Specifications

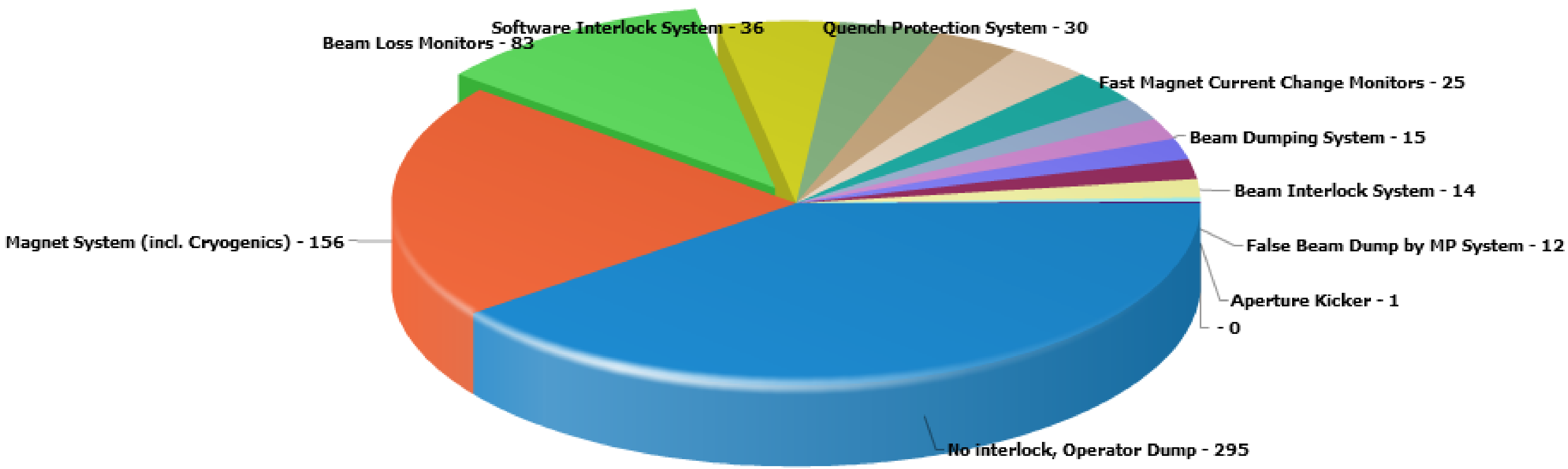
- Reliable (tolerable failure rate 10^{-7} per hour per channel) $\rightarrow$ 10^{-3} magnets lost per year (assuming 100 dangerous losses per year)
  - Reliable components, radiation tolerant electronics
  - Redundancy, voting
  - Monitoring of availability and drift of channels
- Less than 2 false 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 - protect against losses of 4 turns or more
- Quench level determination with an ultimate uncertainty of a factor 2
  - Extensive simulations and measurements
  - Threshold values are a function of loss duration and beam energy

For a complete description of the BLM system see: *Beam Loss Monitoring System for the LHC,* E.B. Holzer et al., Nuclear Science Symposium Conference Record, 2005 IEEE, Volume 2:1052 – 1056.

2010 and 2011 beam aborts above injection energy

Which system saved us / dumped the beam

BLMs: 18% of the protection dumps



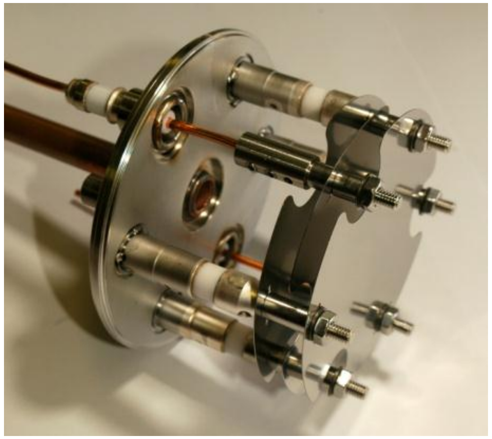
BLM System Installation

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 (SEM):

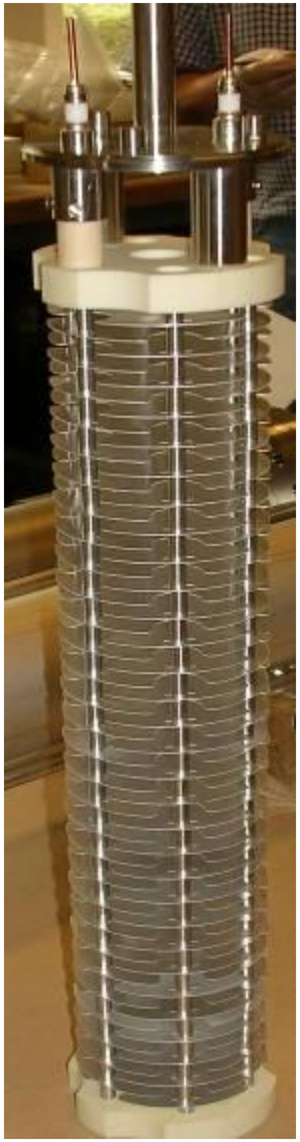
- Length 10 cm
- P < 10^{-7} bar
- ~ 70000 times smaller gain



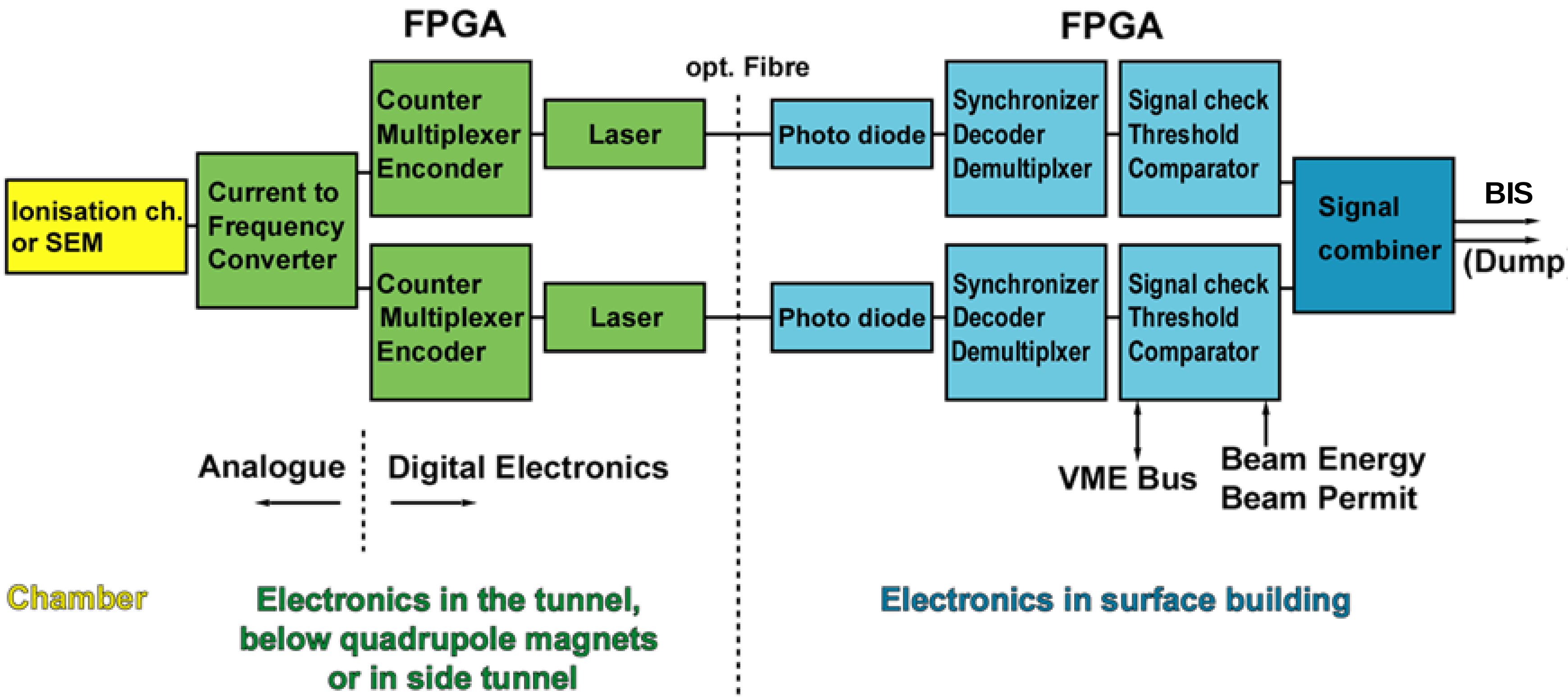
Ionization chamber (IC):

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

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



System Layout



Threshold Comparator: Losses integrated and compared to threshold table (12 time intervals and 32 energy ranges).

Beam Loss Measurement System Layout

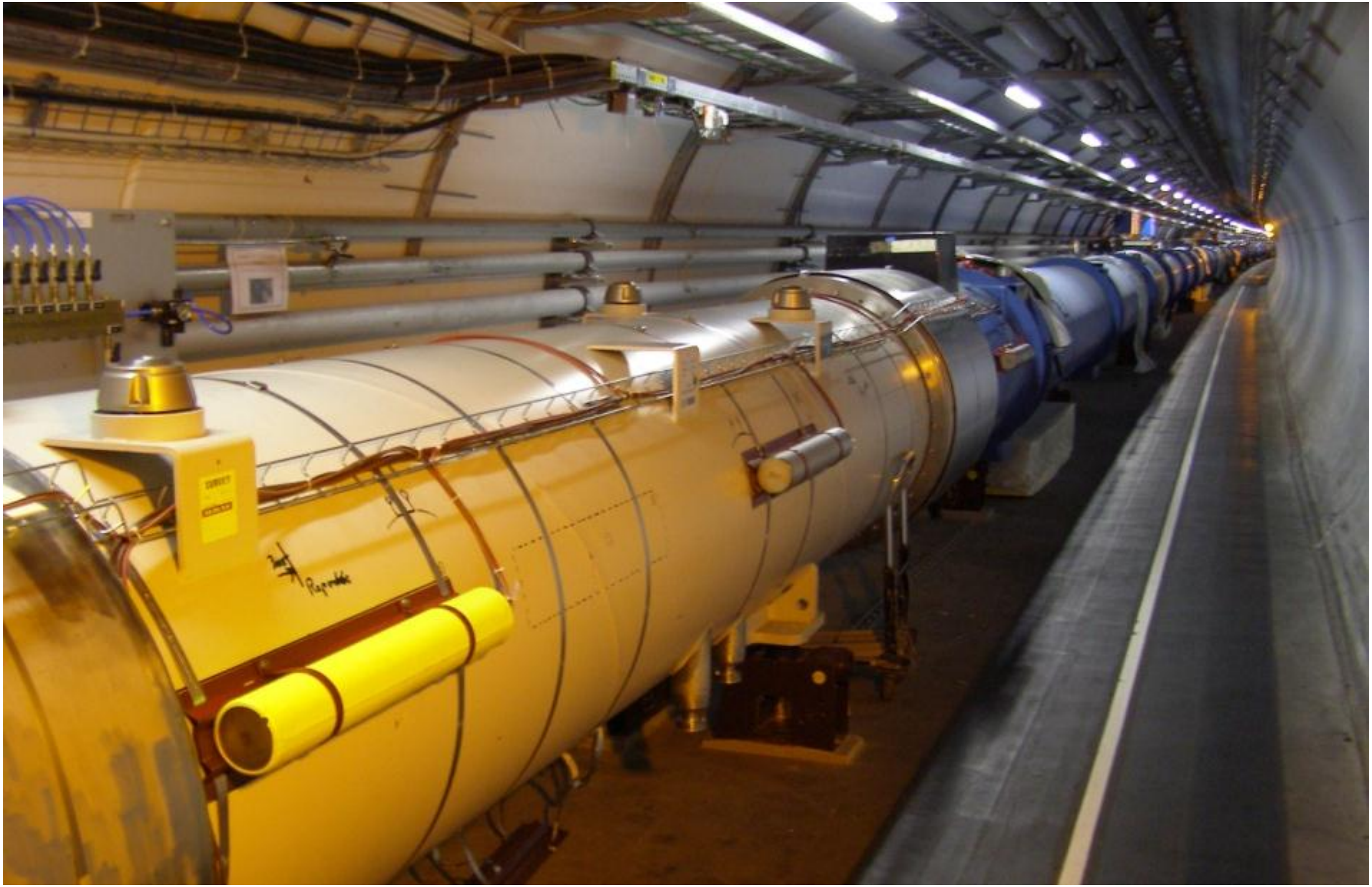
- Main purpose of the BLM system: prevent damage and quench
- In addition:
  - Setup of the collimators
  - Localization of beam losses and identification of loss mechanism
  - Machine setup and studies

→ placement of monitors:

  - At critical and at likely loss location:
    - 6 ICs around each quadrupole
    - IC + SEM after each collimator/absorber
    - Injection and extraction elements, movable elements, …

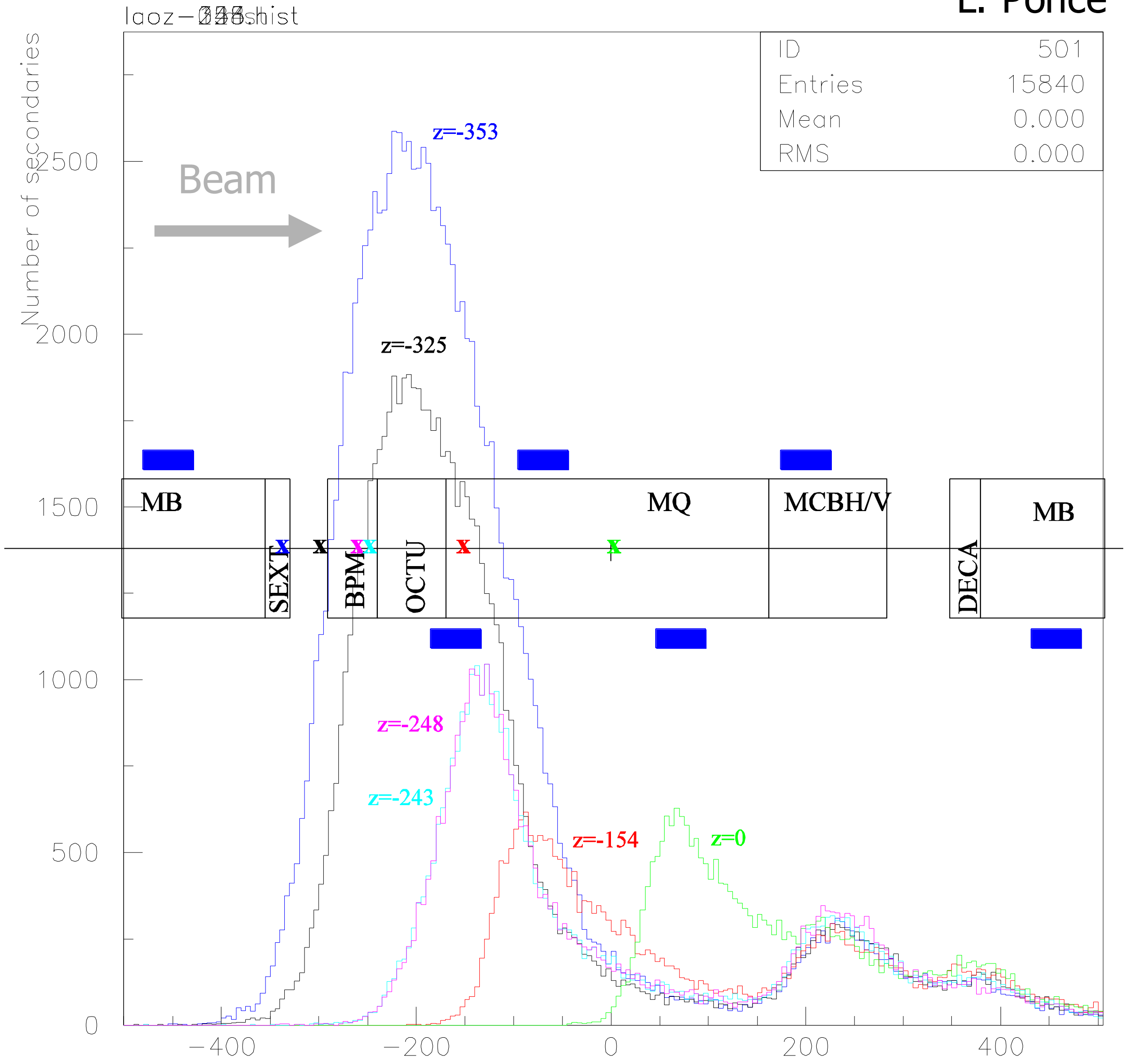
- 3600 Ionization chambers (IC) interlock (97%) and observation
- 300 Secondary emission monitors (SEM) for observation

Installation of 6 ICs around Arc Quadrupole



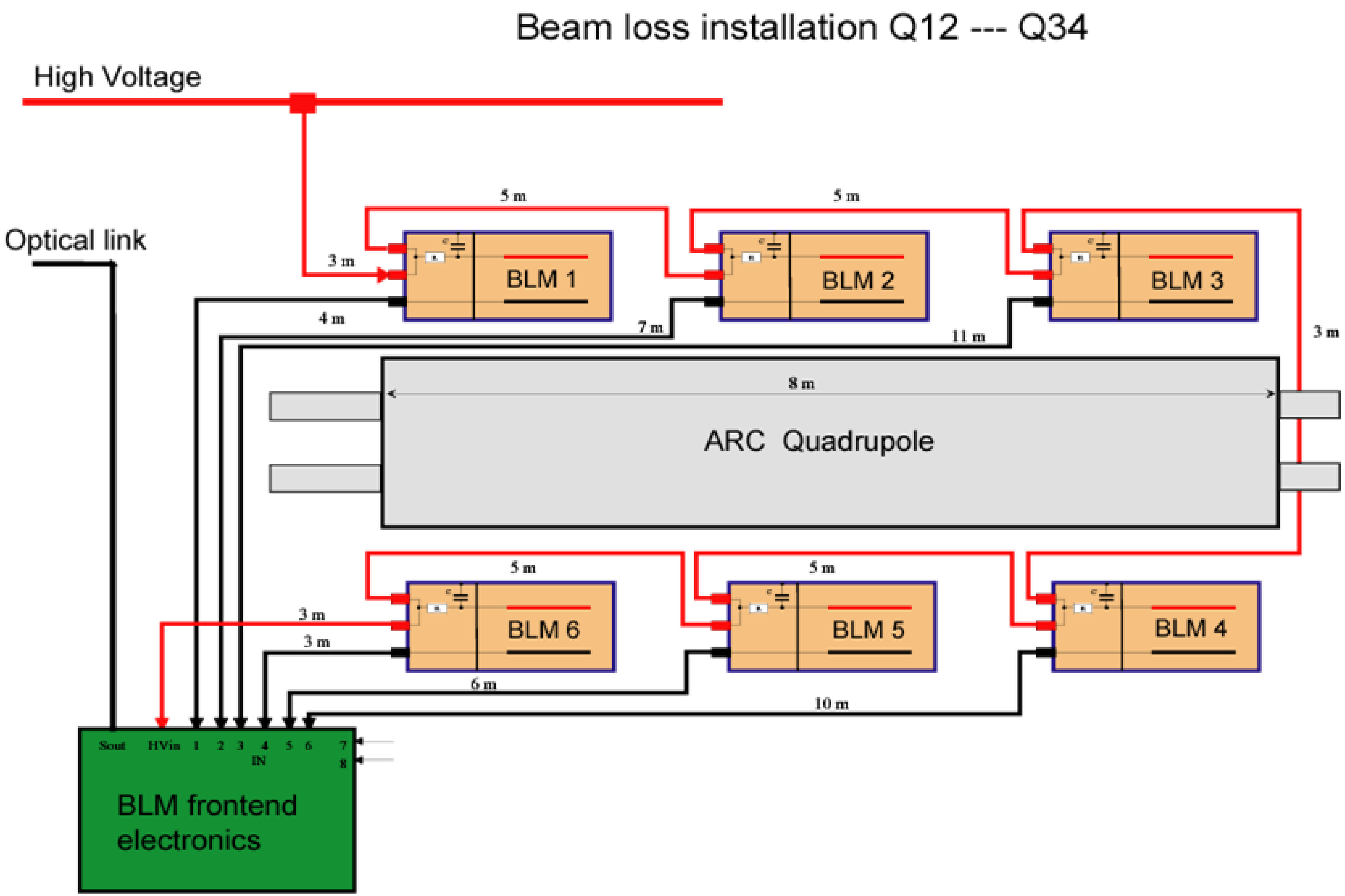
Shower Development in the Cryostat

L. Ponce



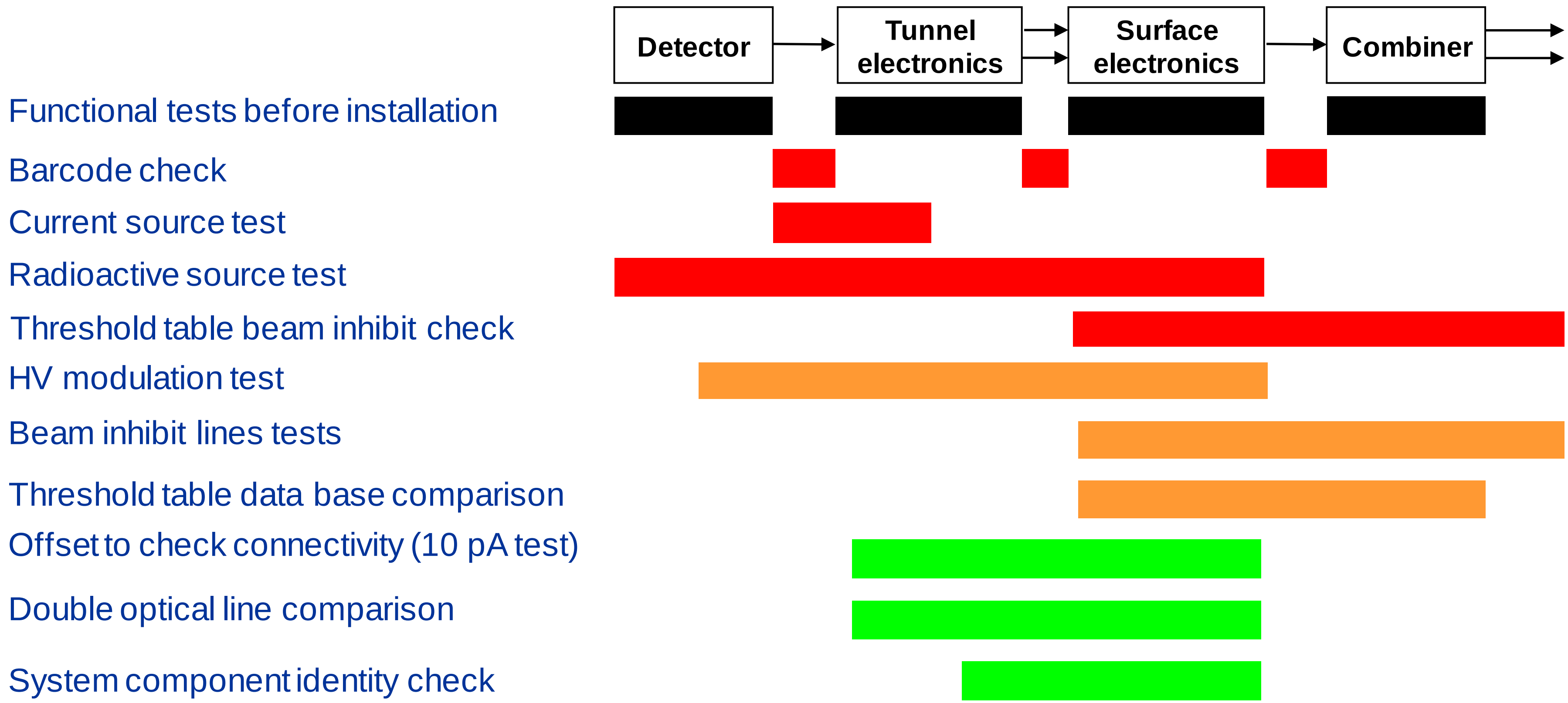
- Impact position varied along the MQ
- Highest signal from loss at the beginning of the MQ
- Position of detectors optimized
  - to catch losses:
    - Transition between MB – MQ
    - Middle of MQ
    - Transition between MQ – MB
  - to minimize uncertainty of ratio of energy deposition in coil and detector
  - Beam I – II discrimination

Arc Installation



Regular Validation Tests

PhD thesis Gianluca Guaglio

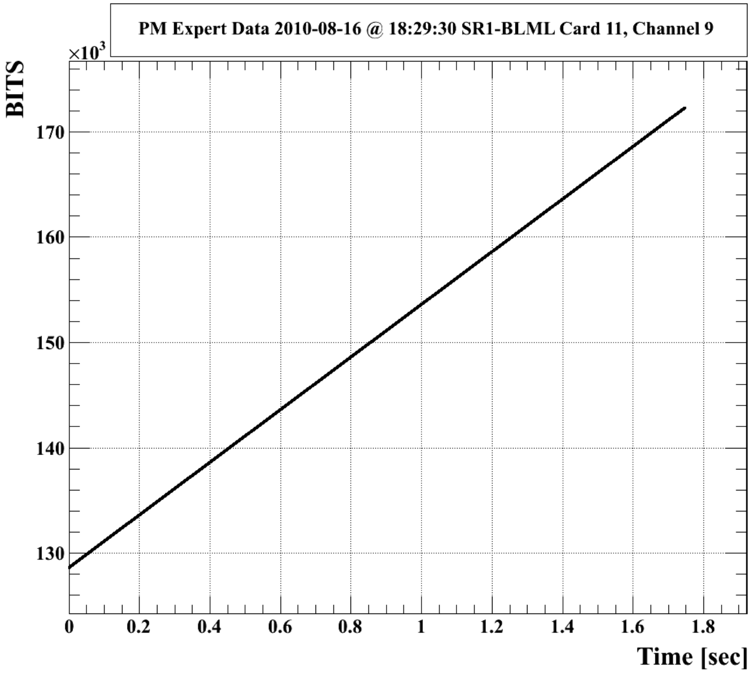


Inspection frequency:

Reception | Installation and yearly maintenance | Before (each) fill | Parallel with beam

System Validation Tests — Examples

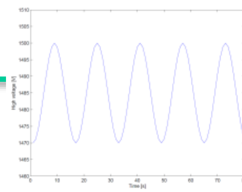
- Extensive firmware test before new release: all operational functionalities including all issues of previous versions
- `Vertical slice test'
  - Test system installed at LHC point – real environment
  - Complete chain: IC to beam interlock output
  - among others: front end emulator
    - Exhaustive threshold triggering
    - Optical link reception and status tests
    - Response to predefined input patterns (linearity etc.)



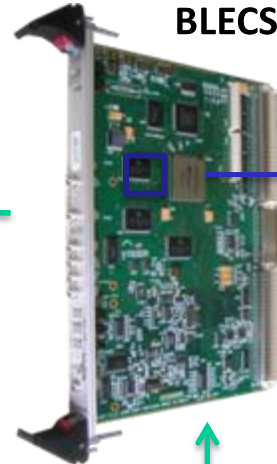
Regular Tests – HV Modulation Test

Monitors in tunnel

Modulate High Voltage

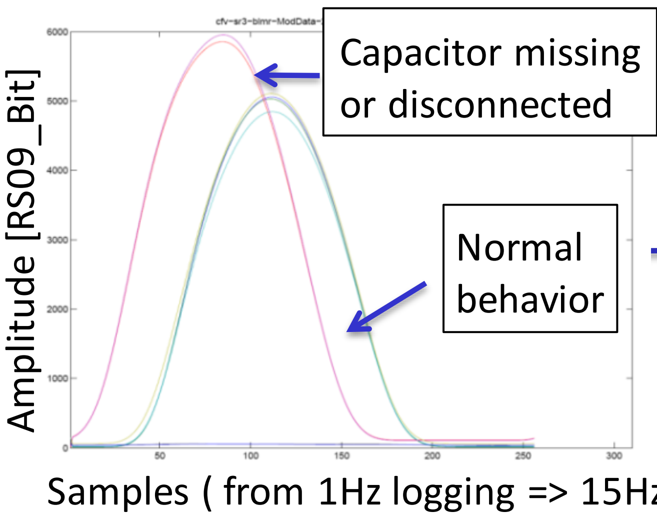


BLECS



BLM acquisition chain

BLM Diagnostic application



Digital signal processing and decision inside the FPGA

- Decision of pass or fail in surface electronics FPGA (combiner)
- Duration: 7 minutes

Tests:

- **Connectivity check (modulation of chamber HV voltage supply) amplitude and phase limit checks**
- **Comparison between data base and backend electronics (MCS)**
- **Internal beam permit line test (VME crate)**

Abort Threshold Determination

Master threshold and Applied threshold

- 12 integration intervals: 40µs (≈1/2 turn) to 84s (32 energy intervals)
  → 1.5 Million threshold values
- Give OP team certain tuning freedom on thresholds
  - Master thresholds:
    - Maximum thresholds which can be applied
    - Safety requirement:

Master thresholds < 10 * 'damage level' for integration times ≤ 100ms
(integration times > 100ms: also covered by QPS + cryogenic system)

  - Applied thresholds = Master thresholds * monitor factor (MF)
    - MF ≤ 1 (enforced in LHC setting database)
  - MF set individually for **each monitor**

Typically: thresholds set in conservative way at the start-up of LHC

Families and Protection Strategy

- **Family**: monitors with the same master thresholds
  - Similar/same:
    - Elements
    - Monitor location
    - Loss scenario
  - Between 1 and 360 monitors in one family

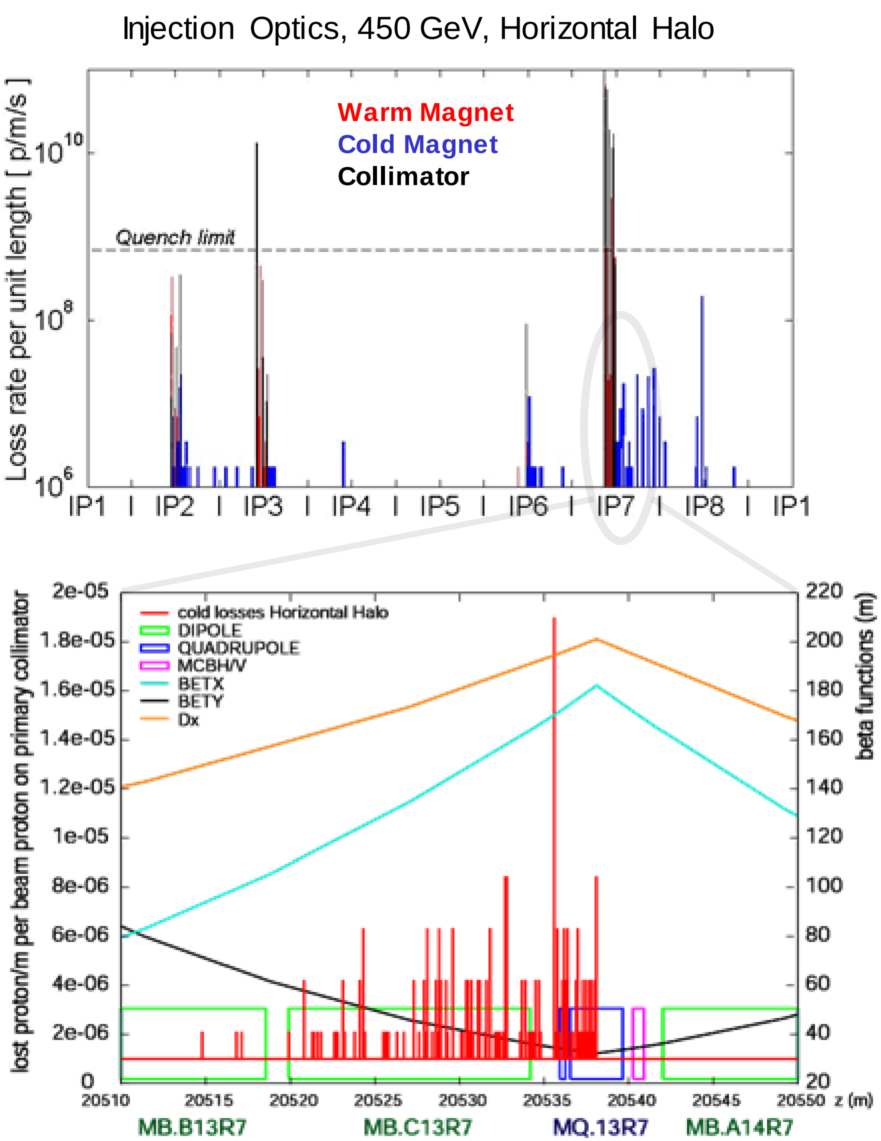
- **Each monitor** (connected to interlock system BIS) aborts beam:
  - One of 12 integration intervals over threshold
  - Internal test failed

- **Mostly: Local protection strategy**

Threshold Determination

- Typically: Applied threshold set to 30% of the magnet quench level
- Calibration of Thresholds:
  - Based on simulations
  - Cross-checked by measurements (before start-up) when possible
  - Beam tests (‘parasitical’ and dedicated test)
- Aim of calibration ⇒ relate the BLM signal to the:
  - Number of locally lost beam particles
  - Deposited energy in the machine component
  - Quench and damage levels

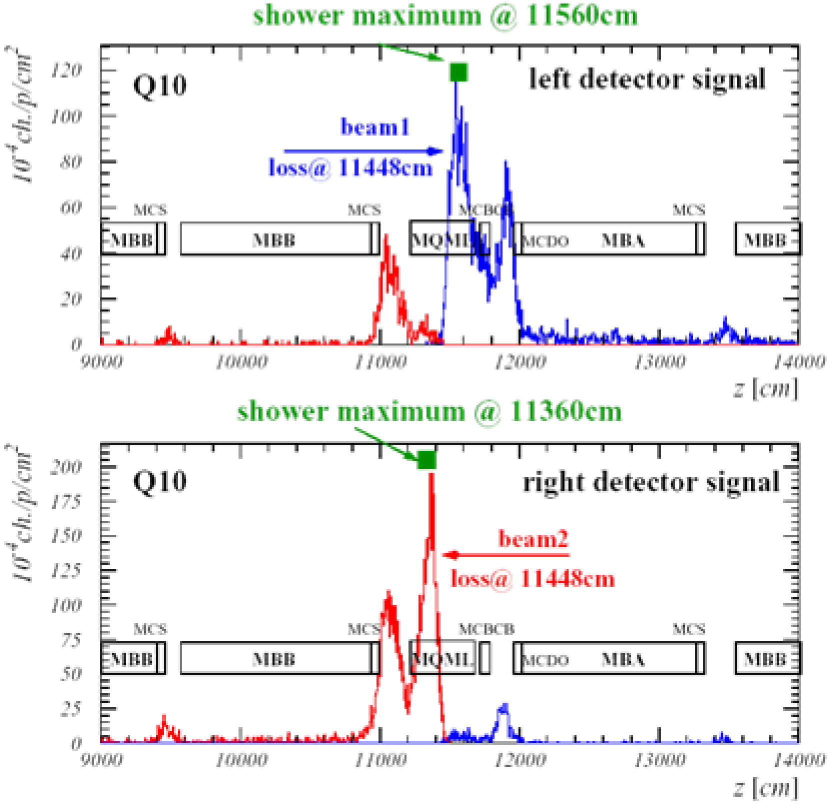
Threshold Determination



- Proton loss locations *(MAD-X, SIXTRACK, BeamLossPattern, measurements: LHC beam)*
- Hadronic showers through magnets *(GEANT, measurements: HERA/DESY, LHC beam)*
- Magnet quench levels as function of proton energy and loss duration *(SPQR, measurements: Laboratory, LHC beam)*
- Chamber response to the mixed radiation field in the tail of the hadronic shower *(GEANT, GARFIELD, measurements: booster, SPS, H6, HERA/DESY)*

(S. Redaelli, L. Ponce)

Threshold Determination



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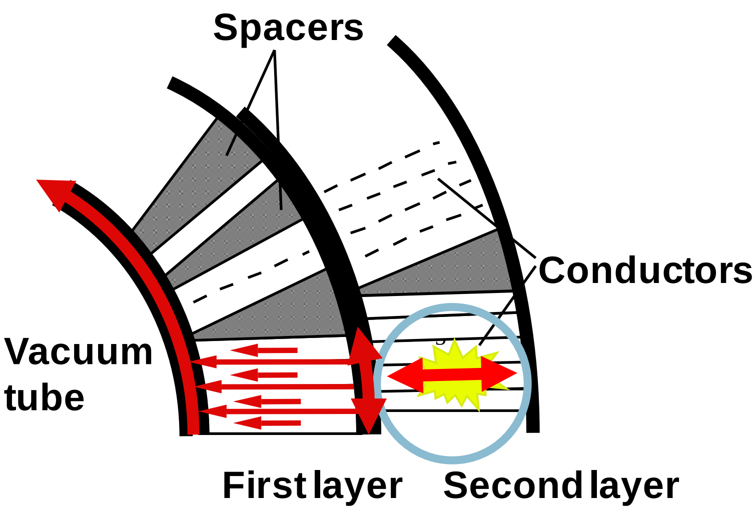
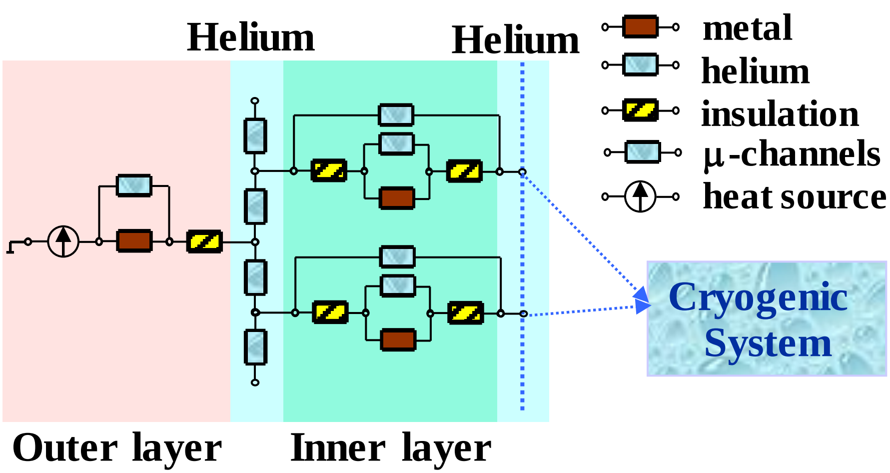
(E. Gschwendtner)

Threshold Determination





(D. Bocian)

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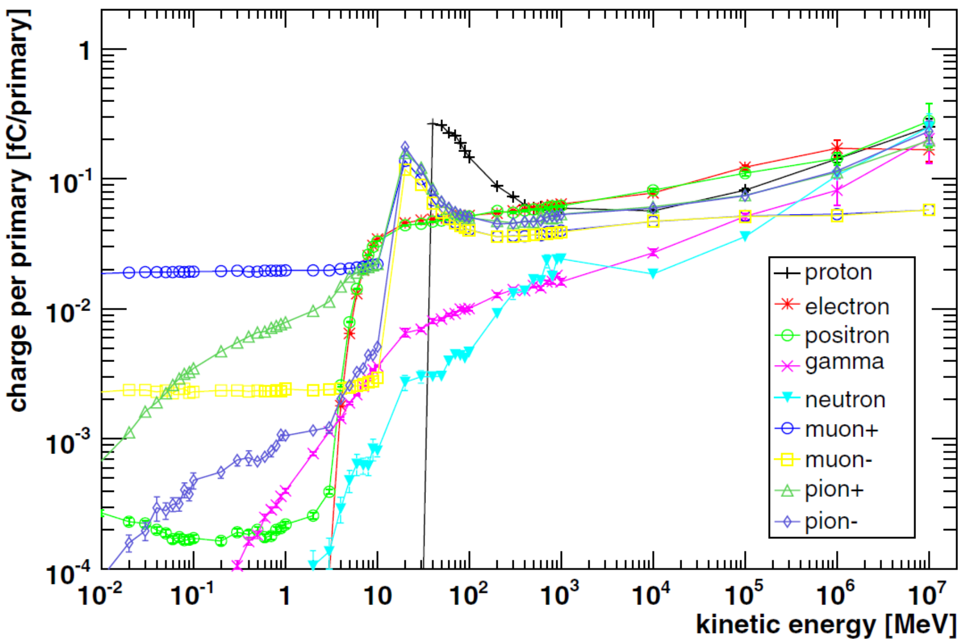
Threshold Determination



(M. Stockner)

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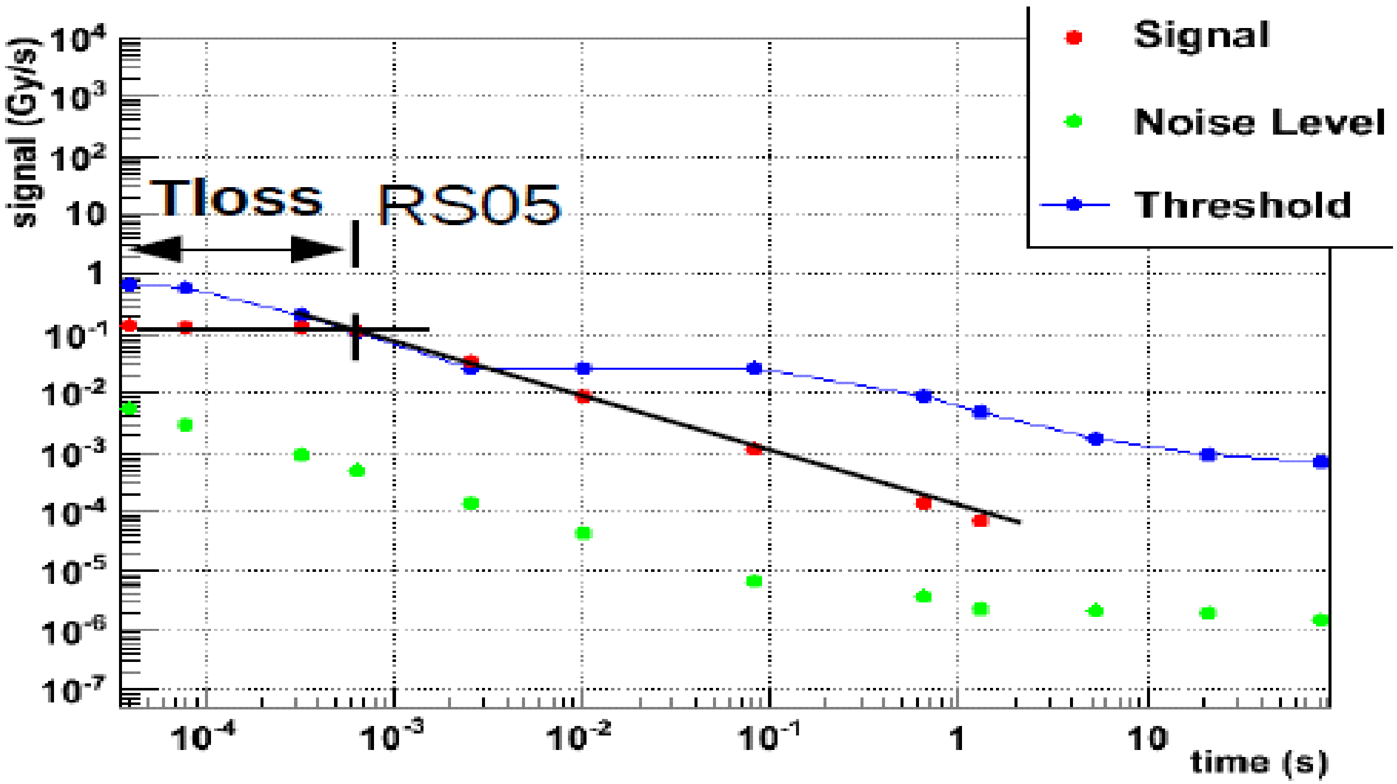
Data Published by BLM System

BLM Published Data – Logging Data

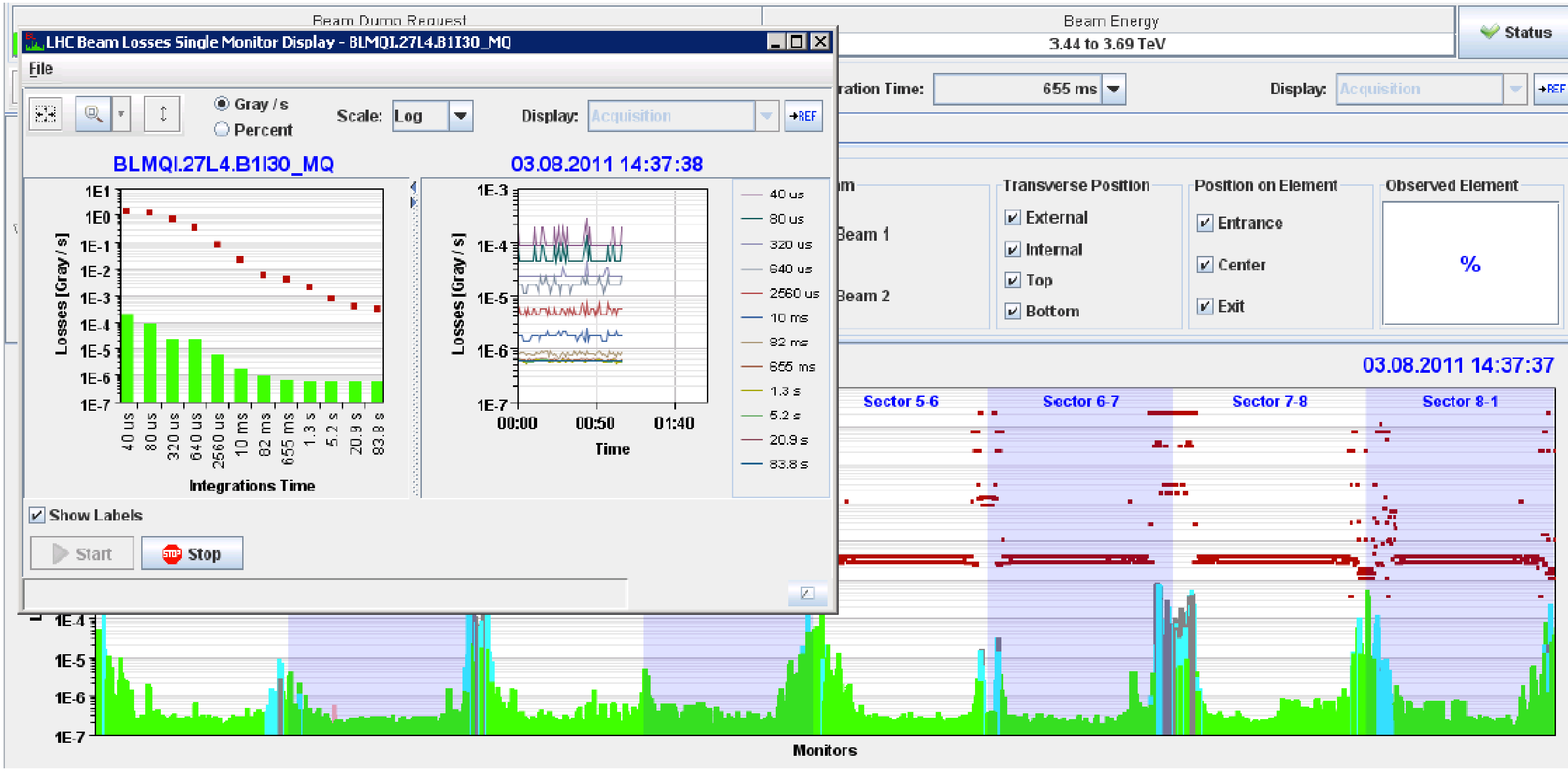
- Extensively used for operation verification and machine tuning
- Logging once per second (all 12 integration intervals)
  - Integration times < 1s: maximum during the last second is published

    → short losses are recorded and loss duration can be reconstructed (≈20% accuracy for UFOs)



BLM Published Data – Logging Data

- Logging Data also used for Online Display



BLM Published Data – Event triggered Data Buffers

- Event triggered BLM Data (40μs, 80μs or 2.6ms):

BLM Buffer (IC & SEM)		Integration Time	Buffer Length
Post Mortem		40μs	80ms online 1.72s offline
Collimation Buffer		2.6ms	80ms
Extraction Validation Buffer		40μs	80ms
Capture Data (2 modes)	Injection Quality Check (IQC) – 8 crates only	40μs	20ms
	Study (event triggered: for example UFO study)	80μs	Dynamical, currently up to 350ms

- CVD Diamond high resolution loss data (2ns):

Event triggered	Sampling Rate	Integration Time	Buffer Length
Post Mortem	0.2 ns	≈ 2ns	1ms

Operational Experience

Commissioning with Beam

- Machine protection functionalities **phased in**:
  - Provide required protection level for each commissioning stage depending on damage potential of the beam
  - Not compromise the availability
- Activation (‘unmasking’) of individual monitors in stages

  (‘masked’: abort request ignored, if ‘set-up beam’ flag true)
- System validation tests switched on in stages

System Modifications since January 2010

1) Increase upper end of **dynamic range**
   - Very high losses (>23 Gy/s) on IC saturate electronics while SEM mostly below noise

   →IC (measurement only) – RC readout delay filter (factor 180)

   → New less sensitive IC

2) Non-local losses - showers from upstream losses:

   Thresholds defined according to operational scenario - Deviate from local protection scheme on a few monitors

   a. Collimation regions
   b. Injection regions (injection energy thresholds)

3) Cold magnet thresholds changed (start-up 2011) according to quench tests and experience with measured losses

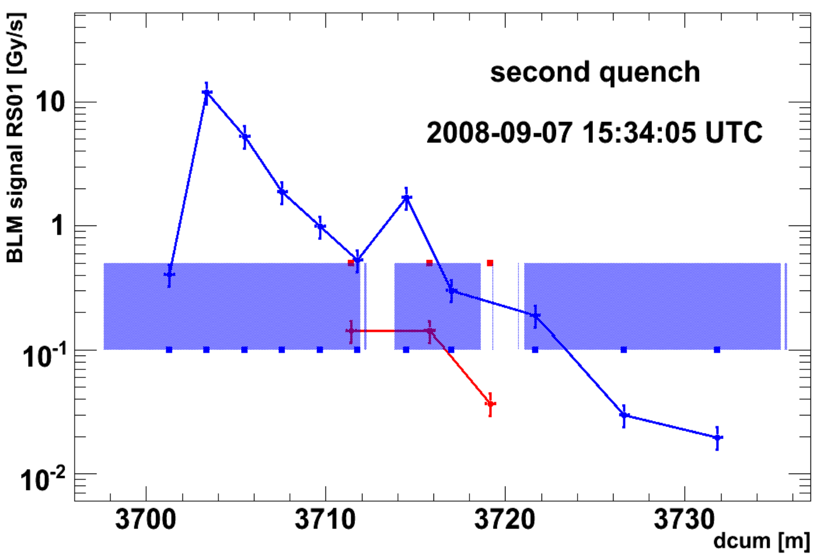
Accuracy of Thresholds

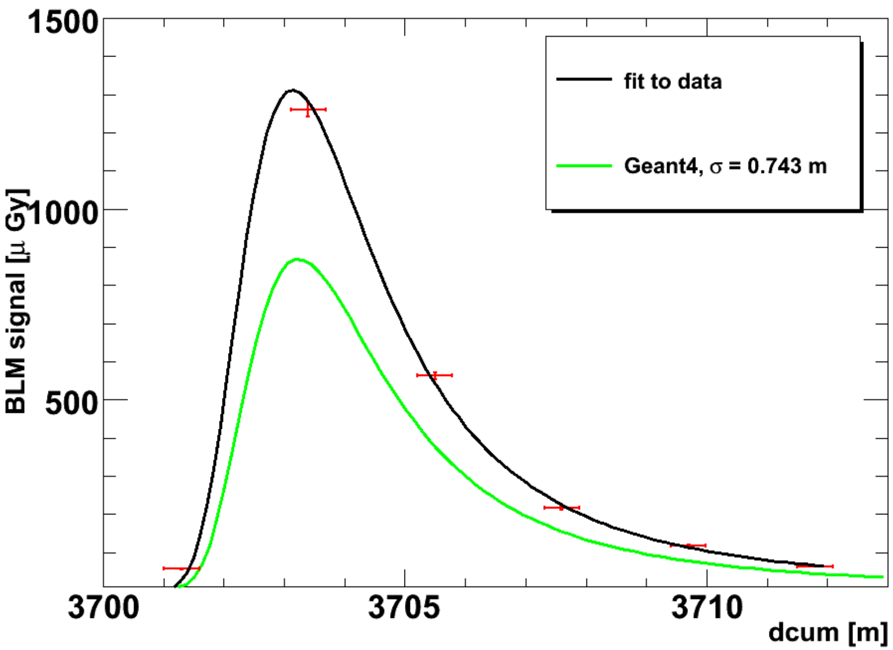
- All beam induced quenches so far on with injected beam.
- 2 dipole quenches in 2008: signals in BLMs could be reproduced by GEANT4 simulations to a factor of 1.5

→ thresholds raised by ≈ 50% in 2009

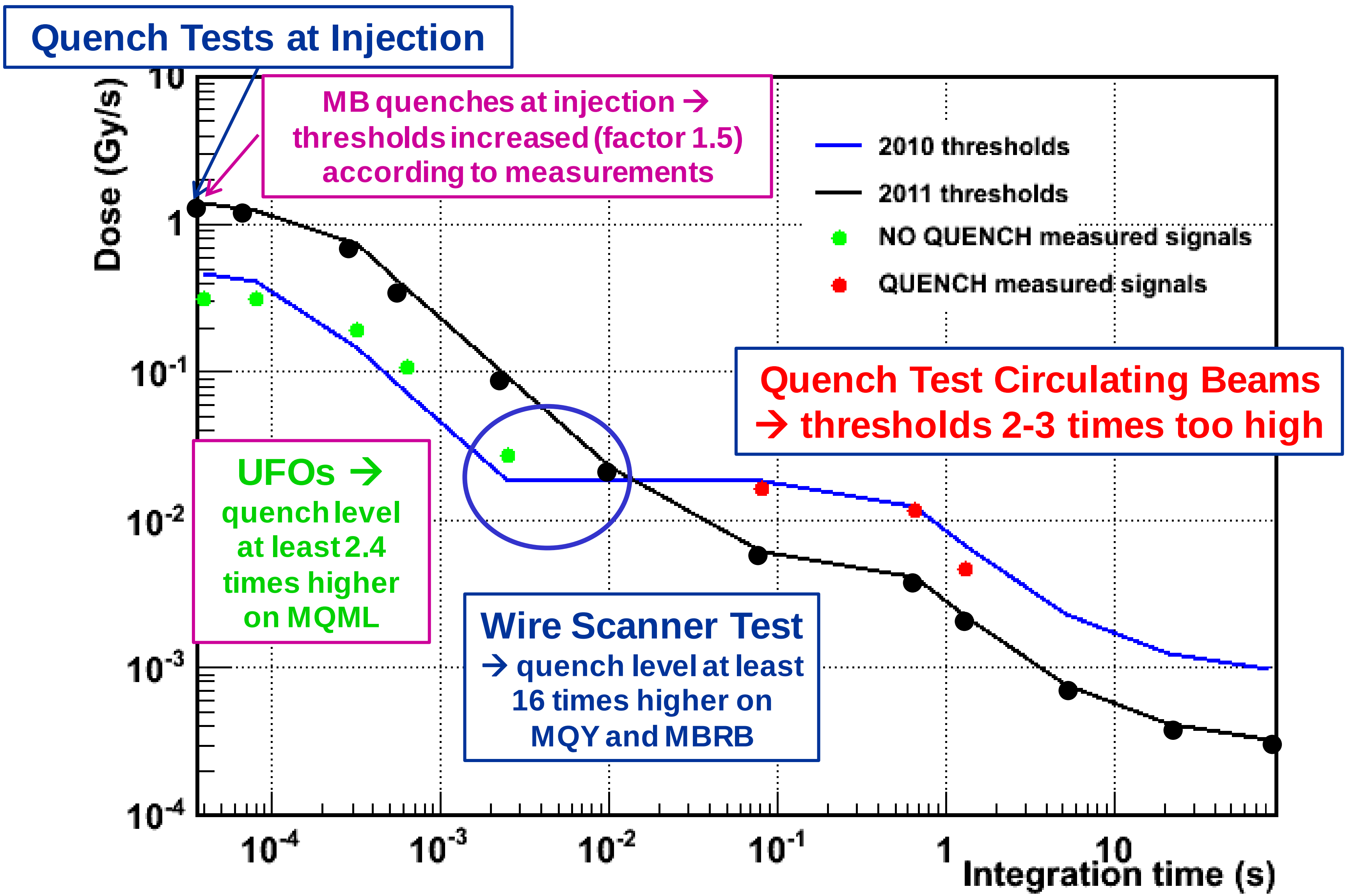
Analysis of second quench

LHC Project Note 422



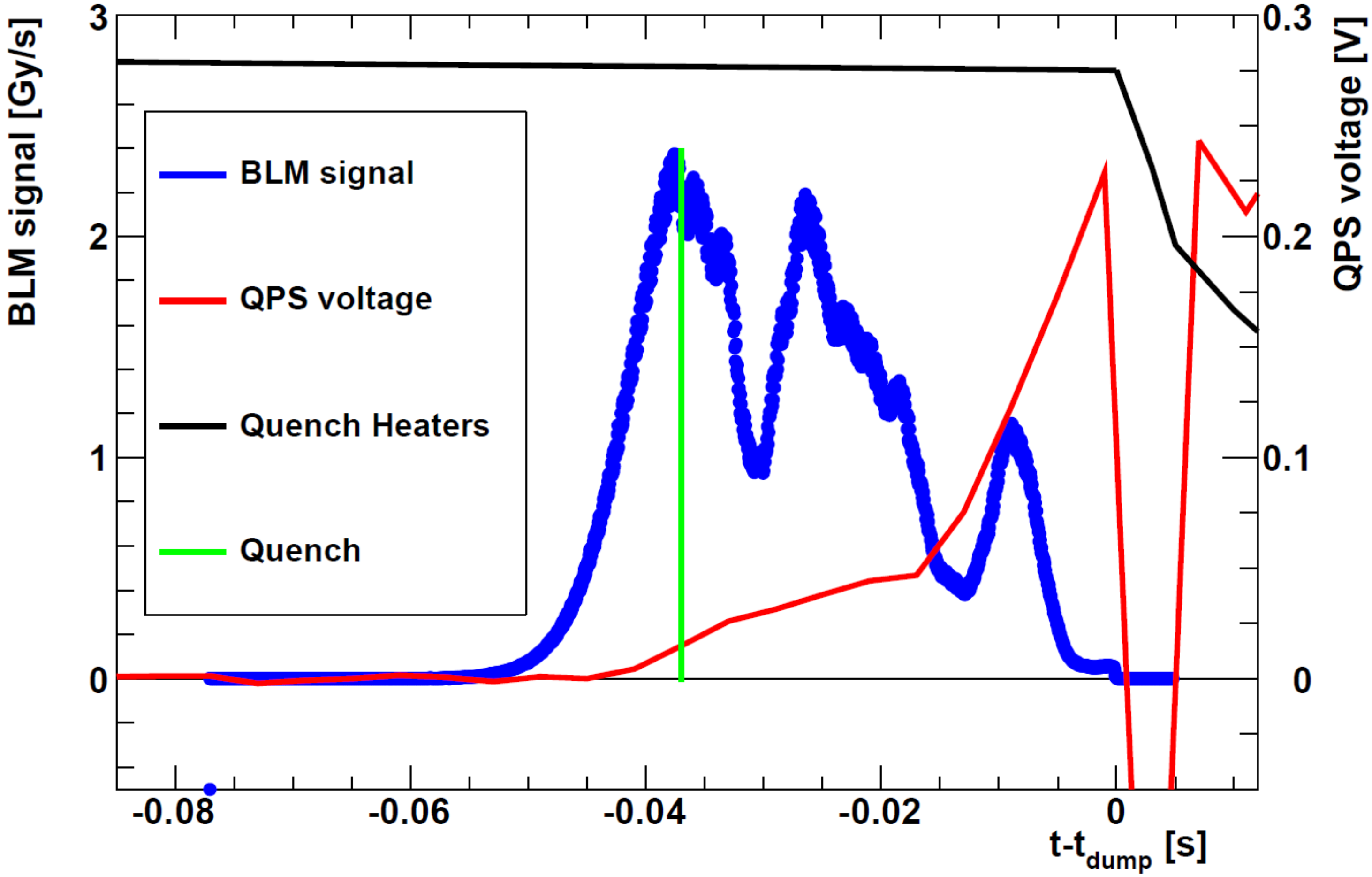


BLM Threshold Change Cold Magnets 2011



Quench Test: Wire Scanner Induced Losses

- BLM signal deviation from Gaussian: wire vibrations, sublimation of 50% of wire diameter (from 34 μm to about 18 μm)
- Voltage drop over the magnet coil (drop below zero due to signal disturbance)



Dependability (Reliability, Availability and Safety)

- **SIL** (Safety Integrity Level) approach to **system design** (Gianluca Guaglio)
- Damage risk:
  - Simulation assumed 100 dangerous losses per year, which can only be detected by **one** BLM

  → 83 BLM emergency dumps in 2 years (only 3 in the last ½ year!) where BLM system dumped first

  → observed **protection redundancy** (several local monitors and aperture limits see beam loss)

per year	Requirement	Simulation	2010 (above 450 GeV)	2011 (beam with damage potential)
Damage risk	$< 10^{-3}$	5×10^{-4}	-	-
False dumps	< 20	10 – 17	**3** (7 – 14 per year of standard operation)	**6**

Dependability (Reliability, Availability and Safety)

- Thresholds:
  - **No avoidable quench** (all beam induced quenches with injected beam)
  - **All exceptionally high losses caught**
- 1 issue detected: power cable cut at surface – detected by internal monitoring, no immediate action on beam permit (only during regular system test) → added to software interlock immediately and later to hardware interlock
- Hardware failures:
  - Mostly, onset of system degradation detected by regular offline checks before malfunction
- Firmware updates: 3 in 2010; 2 (+1 pending) in 2011 → **extensive testing** ('vertical slice' etc.)!

Number of Hardware Failures 2010 + 2011 (during 9 month run)

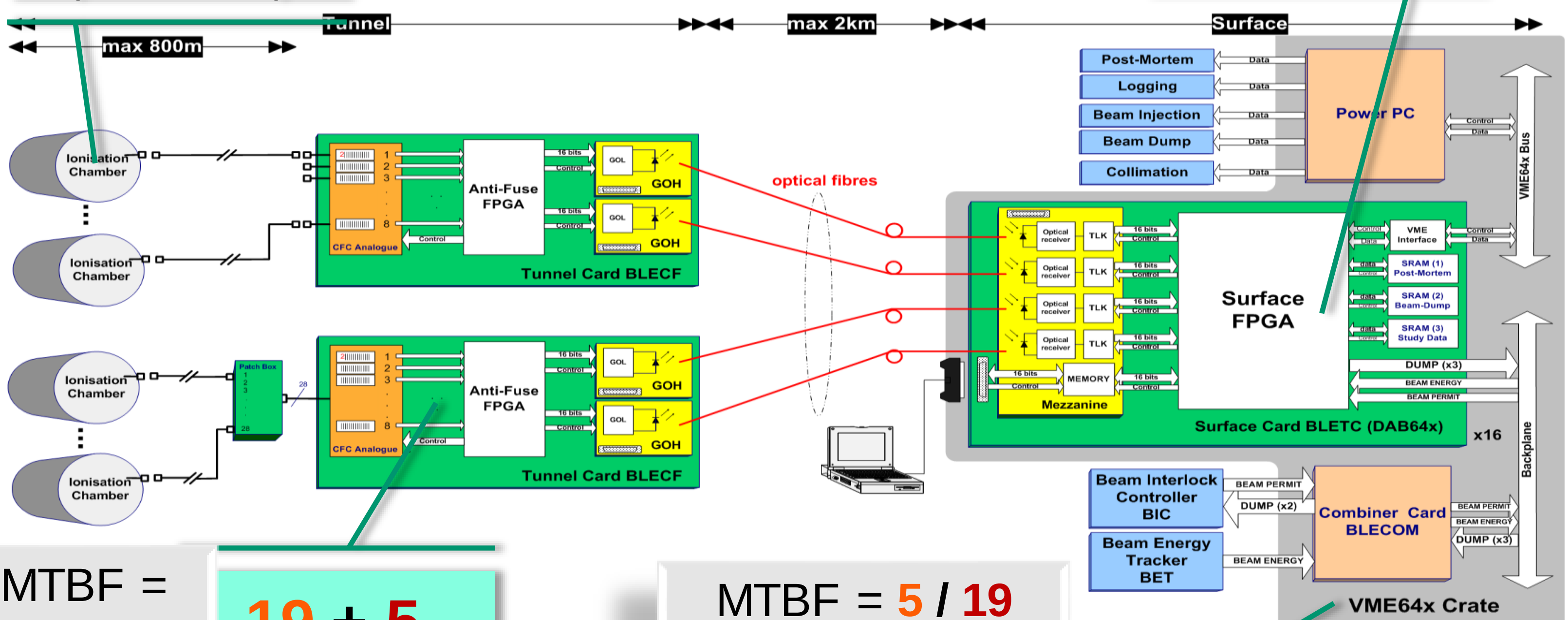
- Number of failures regarded manageable (no availability issue)

MTBF = 225 / years

12 + 0 ICs (out of 3600)

MTBF = 19 / 33 years

14 + 8 Surface cards (out of 350)



MTBF = 30 / 112 years

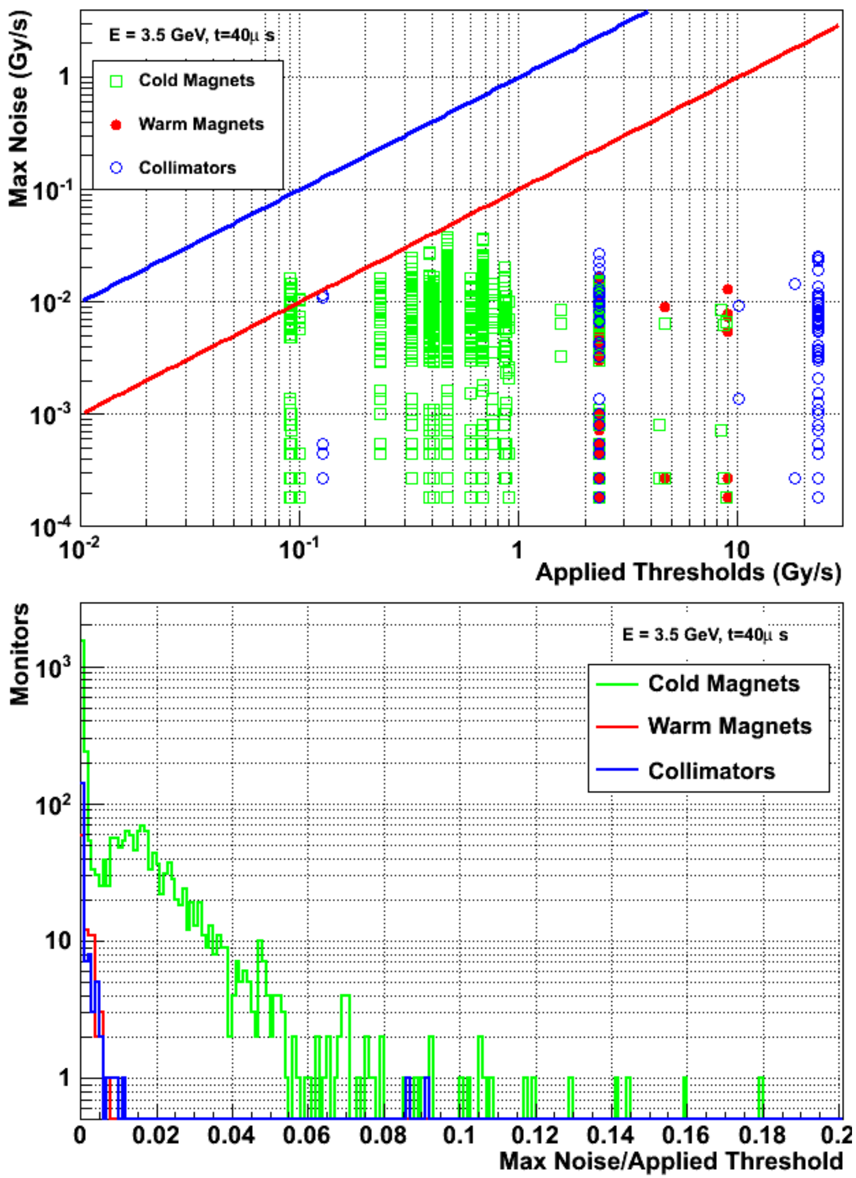
19 + 5 Tunnel cards (out of 750)

MTBF = 5 / 19 years

4 + 1 VME crates (out of 25)

Noise

- Important for availability (false dumps) and dynamic range
- 1 monitor disabled for short term - no dump on noise
- Main source of noise: long cables (up to 800 m in straight section)
- Aim: factor 10 between noise and threshold
- Thresholds decrease with increasing energy → noise reduction before 7 TeV
  - Single pair shielded cables, noise reduction: > factor 2-5
  - **Development of kGy radiation hard readout to avoid long cables**



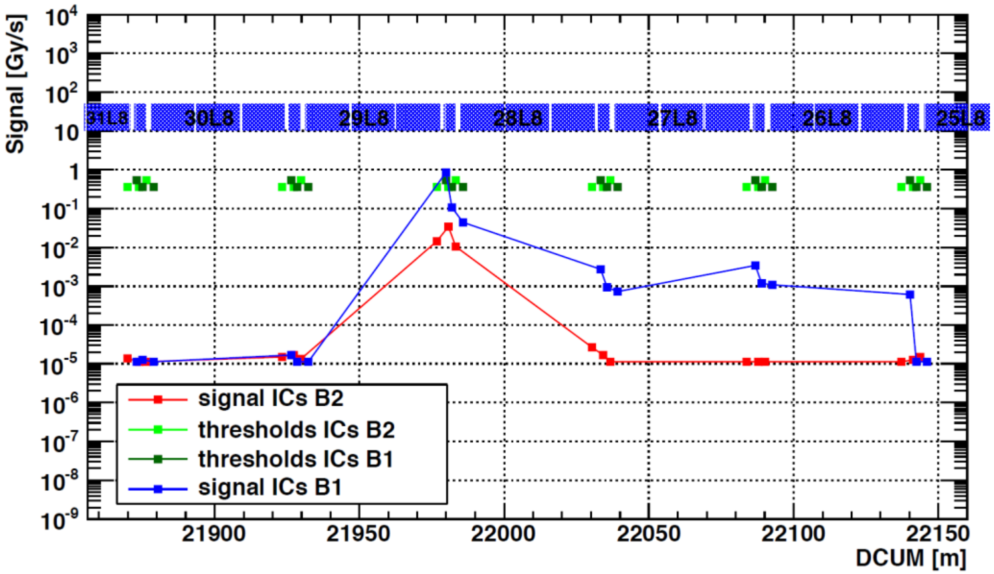
Fast (ms-time-scale) Losses
UFO: Unidentified Falling Object

- MOPS017 *Simulation Studies of Macro-particles Falling into the LHC Proton Beam*, N. Fuster Martinez et al.
- TUPC136 *Analysis of Fast Losses in the LHC with the BLM System*, E. Nebot et al.
- TUPC137 *UFOs in the LHC*, T. Baer et al.

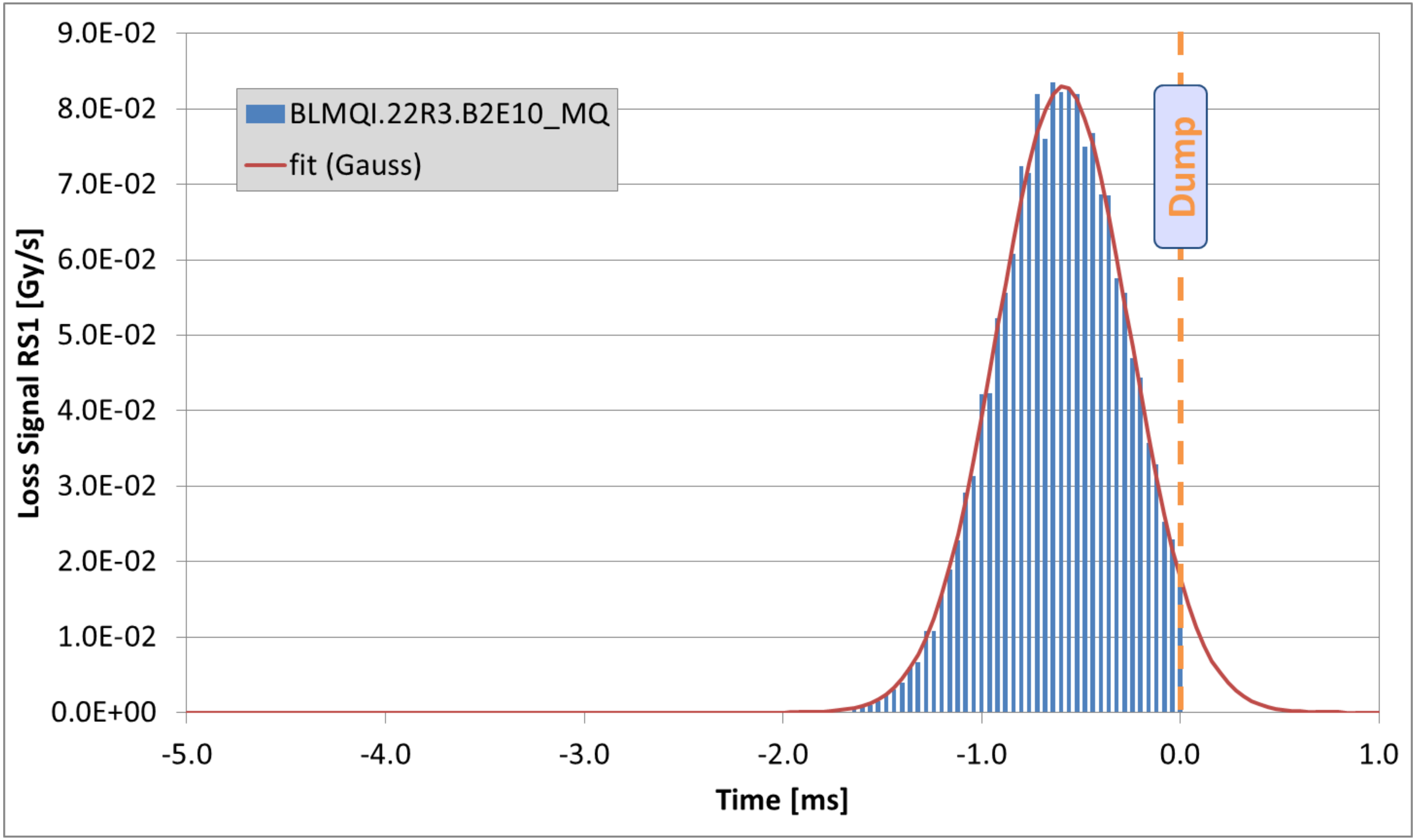
Beam Aborts due to UFOs

- Fast and localized losses all around the ring believed to be caused by macro particles interacting with the beam
- Stepwise increase of BLM thresholds at the end of 2010 run
- New BLM thresholds on cold magnets for 2011 start-up
- Always detected by > 6 local monitors and at all aperture limits (collimators)
- most UFOs far from dump threshold

UFO Beam Aborts	35
of which:	
2010	17
2011	18
Around injection kickers (MKI)	13
Experiments	6
At 450 GeV	1

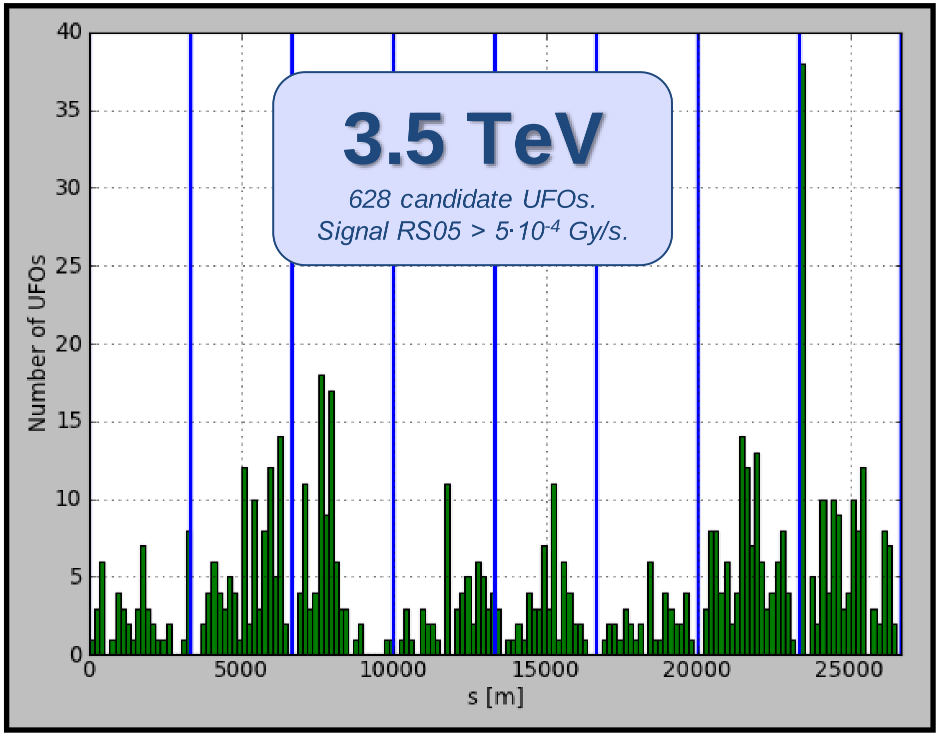


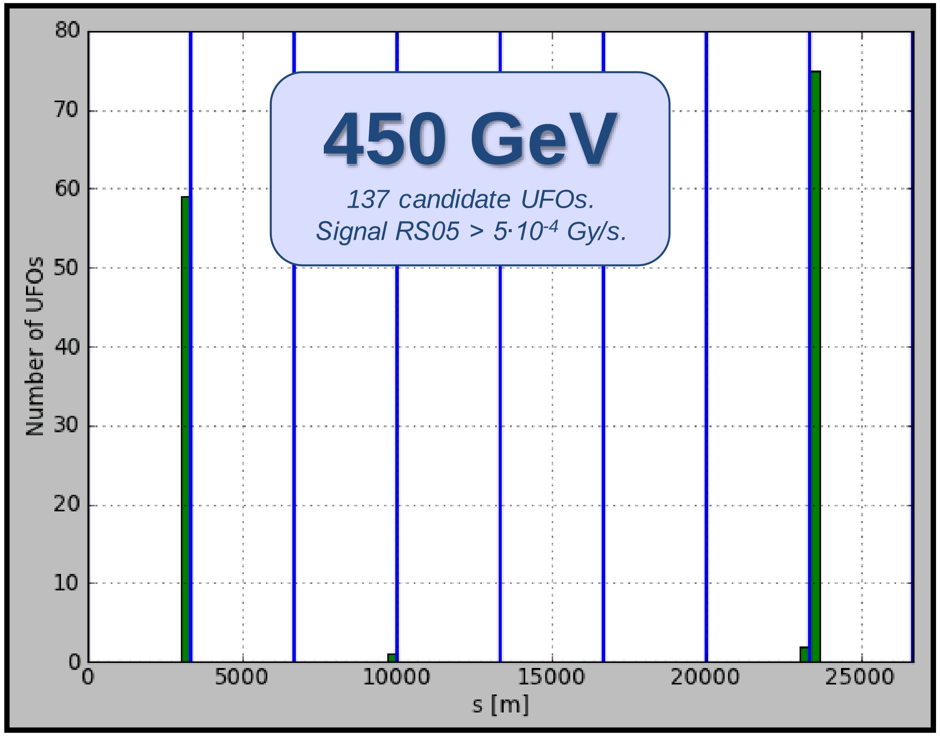
Gaussian Fit to UFO Time Distribution



Spatial UFO Distribution

T. Baer



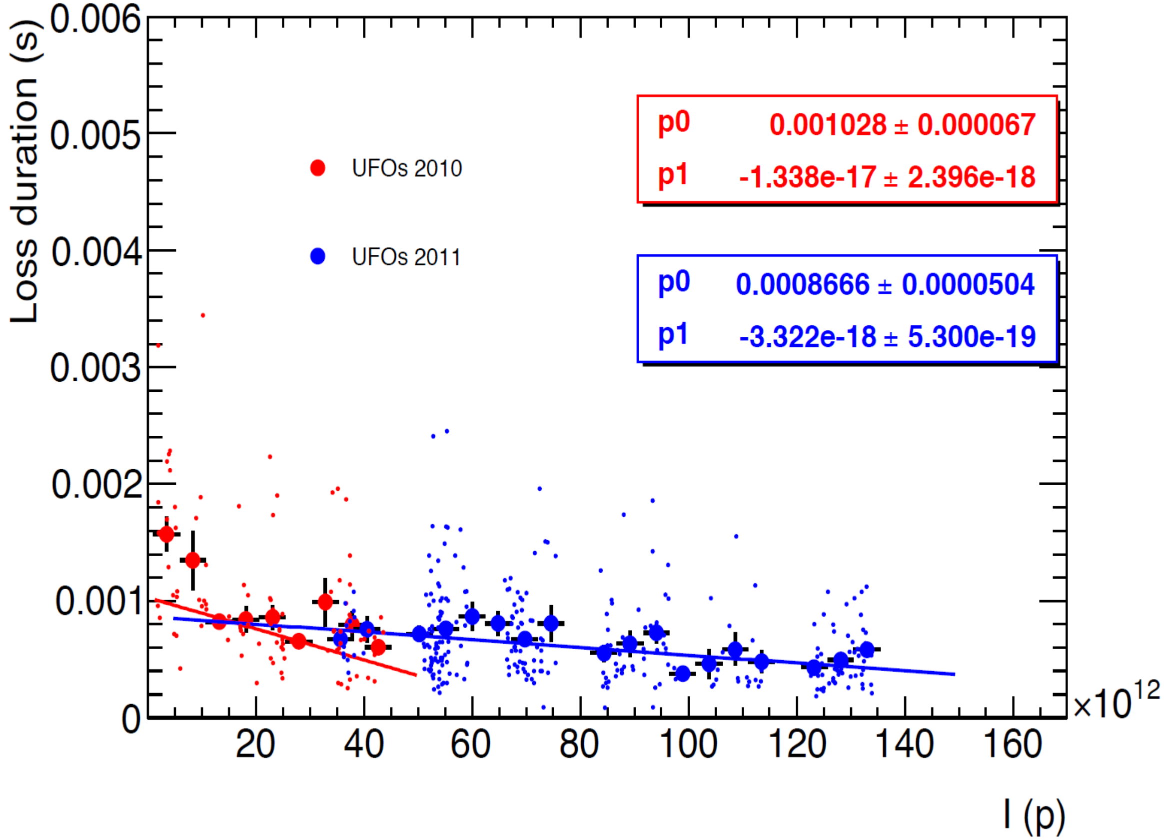


Distributed around the ring
38 UFO Candidates
at Injection Kicker Beam 2

UFOs mainly at Injection Kickers

E. Nebot and T. Baer

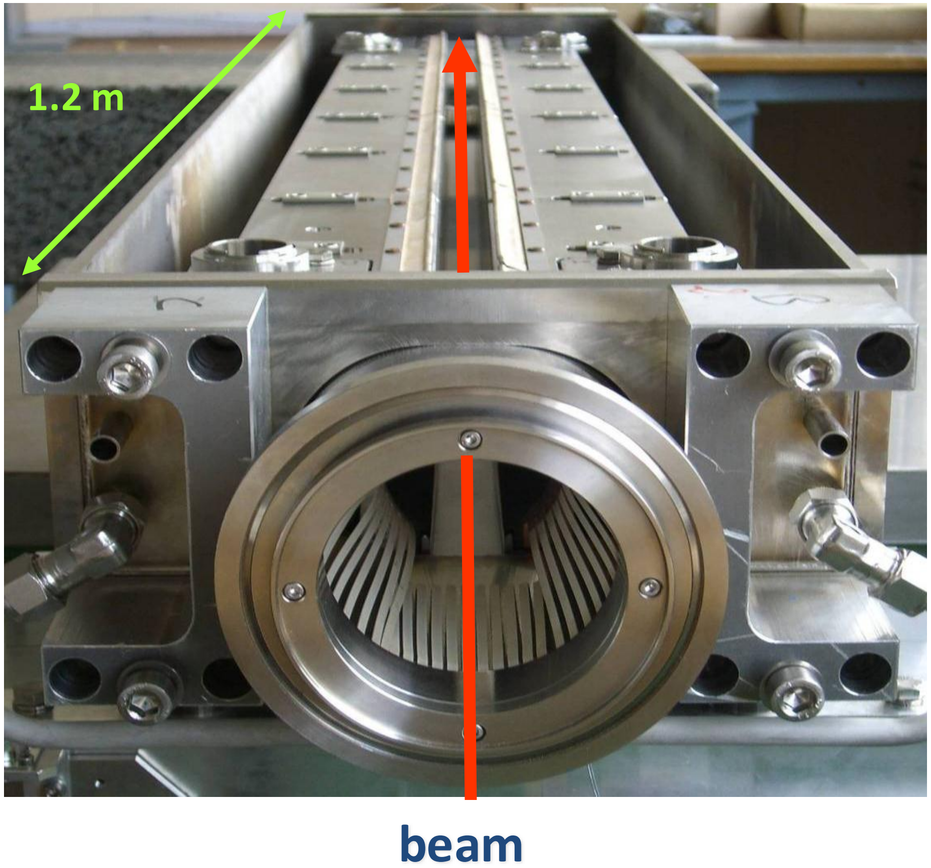
- Average duration: 130 μs at nominal intensity
- The maximum signal does not depend on intensity
- Estimate on signal increase at 7 TeV compared to 3.5 TeV (from wire scanner measurements): factor 2 – 3.5
- 2011 rate decreased from 10 UFOs/h to 5 UFOs/h during ‘stable beams’



Collimation and BLM

Collimation System

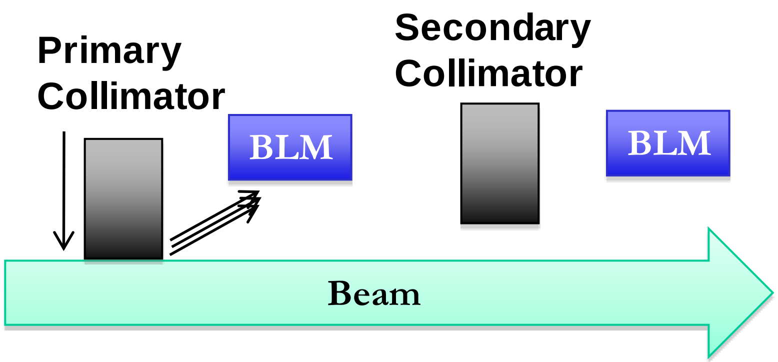
- Three stage collimation system (≈100 collimators and absorbers)
  - Primary: deflection
  - Secondary: absorbtion
  - Tertiary: triplet protection
  - Special dump and injection protection collimators



Collimator Set-Up

G. Valentino
D. Wollmann

1.



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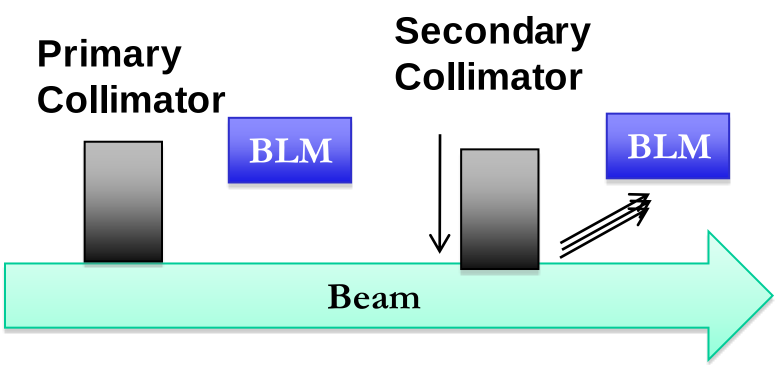


Find center and relative size of beam at collimator location using BLM signal

Set-up procedure:

1. Define beam edge by primary collimator
2. Find beam edge with secondary collimator and center jaws
3. Re-center primary collimator

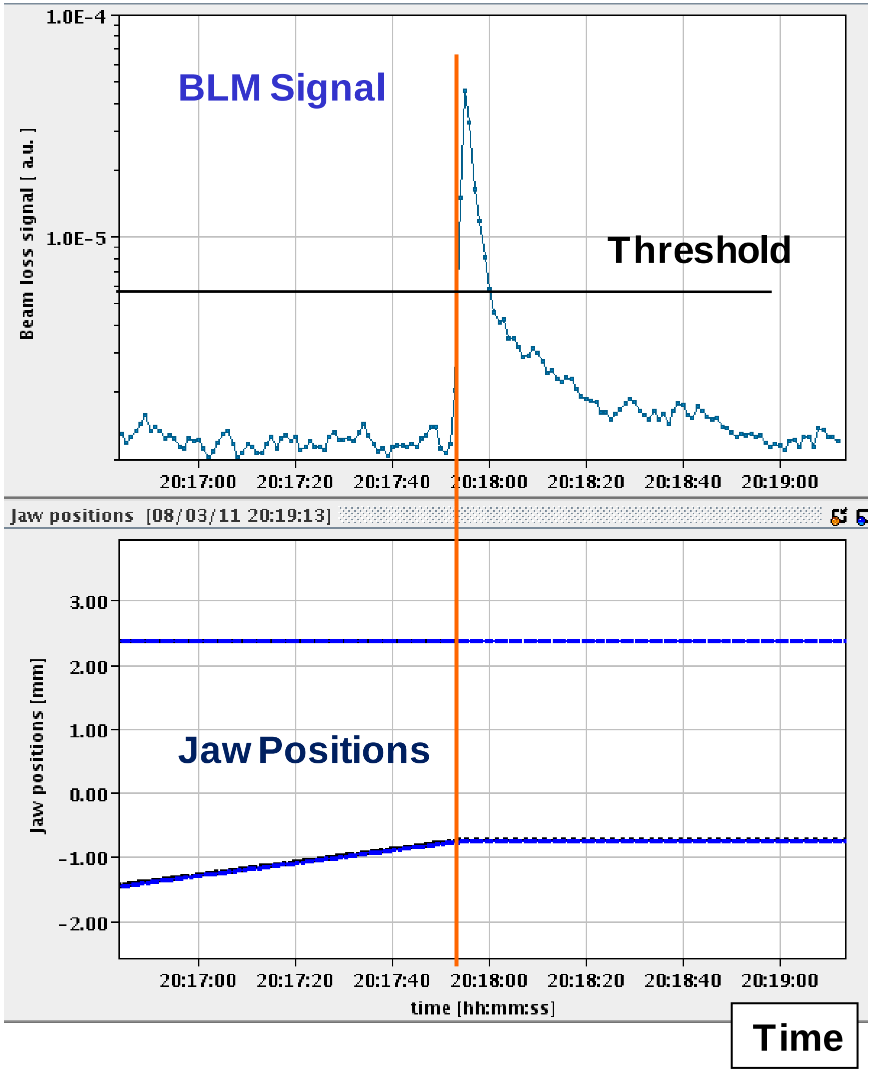
   → Define beam center at collimator positions and the relative beta
4. Open collimators to reference position

Semi-Automatic Setup Procedure

G. Valentino
D. Wollmann

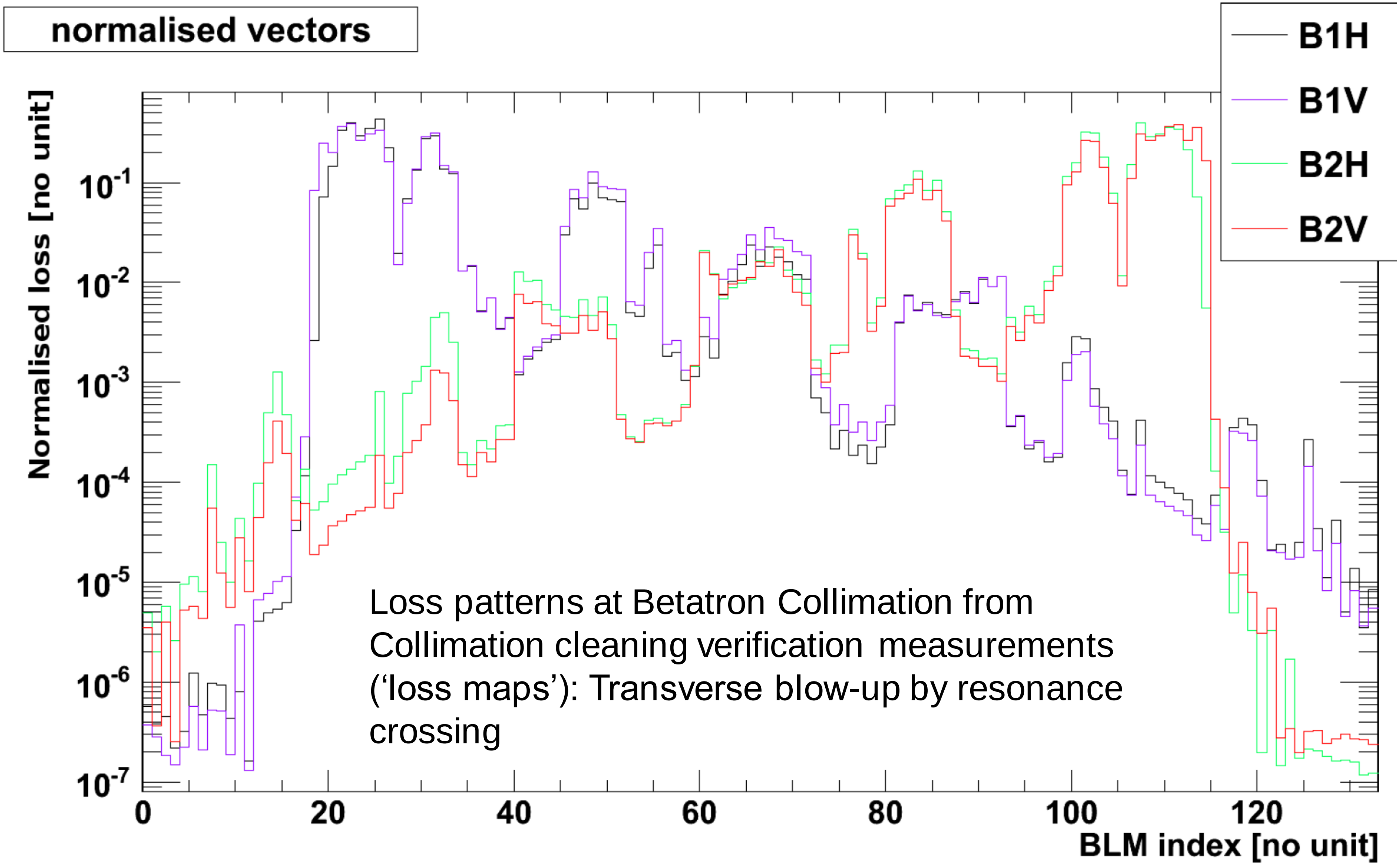
LHC Collimation Project CERN

- Automatic step-wise movement of collimator jaws (user defined 5 – 100 µm steps)
- Stop after reaching user defined BLM threshold (1 Hz logging data)
- Reduction in set-up time up to a factor of 6 with semi-automatic procedure using the BLM (2011) as compared to manual procedure in 2010
- Plan for 2012: use 30 Hz BLM data (special buffer for collimators) to further reduce set-up time



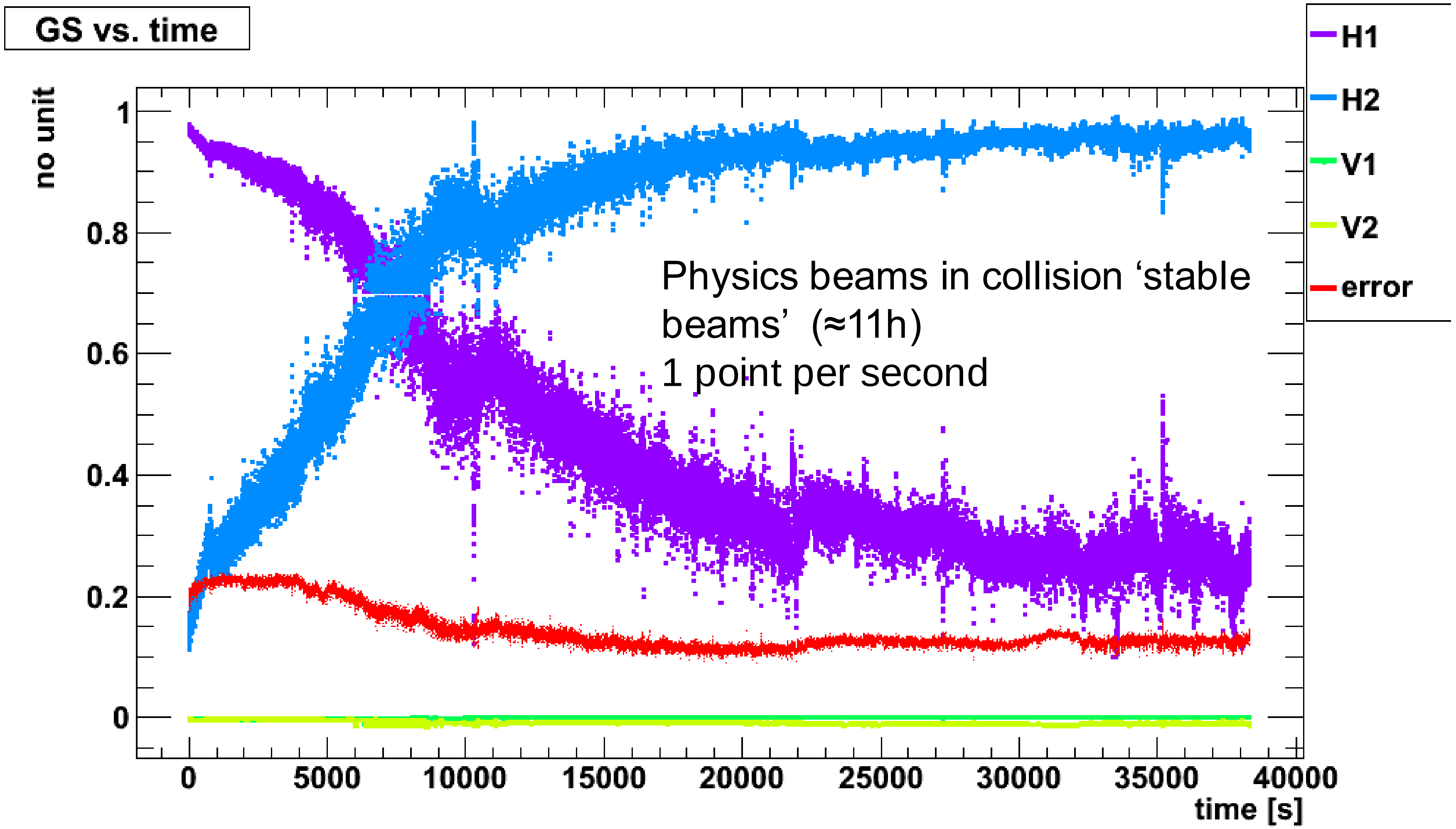
Decomposition of Losses

PhD thesis A. Marsili



Decomposition Prelim. Results

PhD thesis A. Marsili



Summary

Summary

Challenges anticipated

Dependability

(Reliability, Availability, Safety)

Experience

☺ due to rigorous testing

- No evidence of a single beam loss event been missed
- No avoidable quench passed BLM protection
- 1 protection hole found and closed in the design of the tests
- Fewer hardware failures than expected

Non-local losses

😐 → Shielding, different protection approach, 'blinding'?

Summary

Challenges anticipated	*Experience*
Dependability (Reliability, Availability, Safety)	☺
Threshold precision	☺ - Tuning ongoing
Non-local losses	😐 → Shielding, different protection approach, 'blinding'?

- No avoidable quench passed BLM protection
- No dumps on noise
- Initial threshold settings conservative, still appropriate for first year (except non-local losses)

Summary

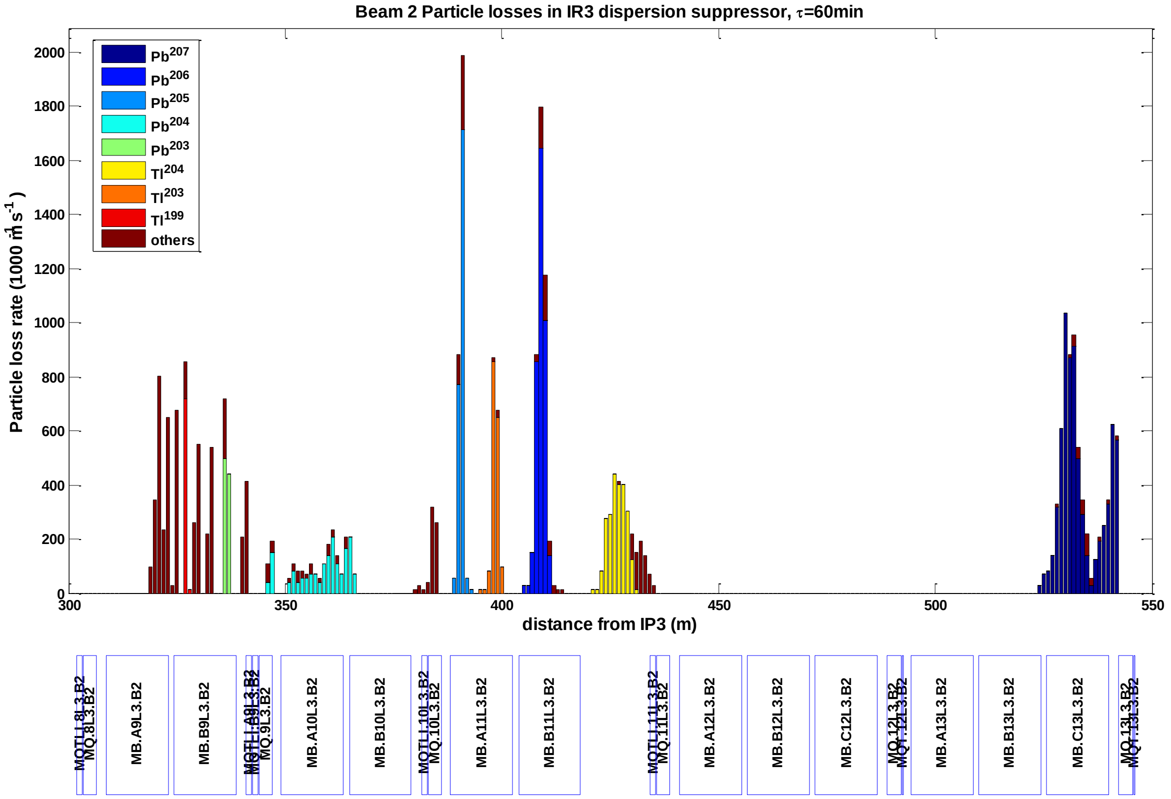
Challenges anticipated	*Experience*
Dependability (Reliability, Availability, Safety)	☺
Threshold precision	☺ - Tuning ongoing
Reaction time 1-2 turns	☺
Dynamic range: 2×10^5 40 µs 10^8 ≥ 1.3 s	😐 short integrals Noise (long cables) → Cables, radiation hard electronics, new less sensitive IC
Non-local losses	😐 → Shielding, different protection approach

End of Presentation

IONS

BLM for Ions I

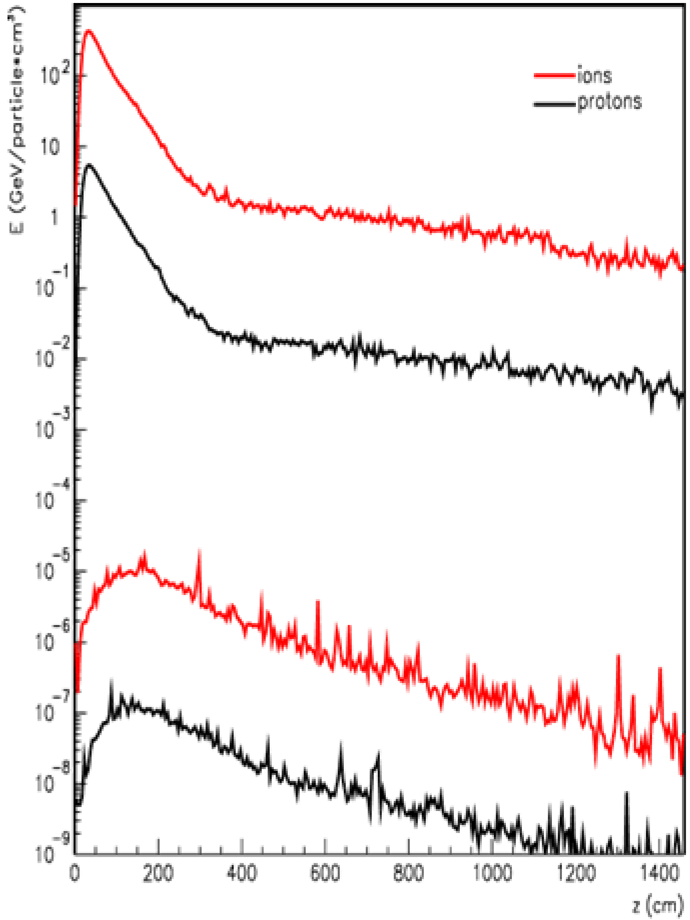
- Considerably less simulations available than for protons at the moment → much higher uncertainty for the BLM system
- Simulations of ion loss maps done (H. Braun) → additional monitors; Error studies still to be done (AB/ABP)



H. Braun

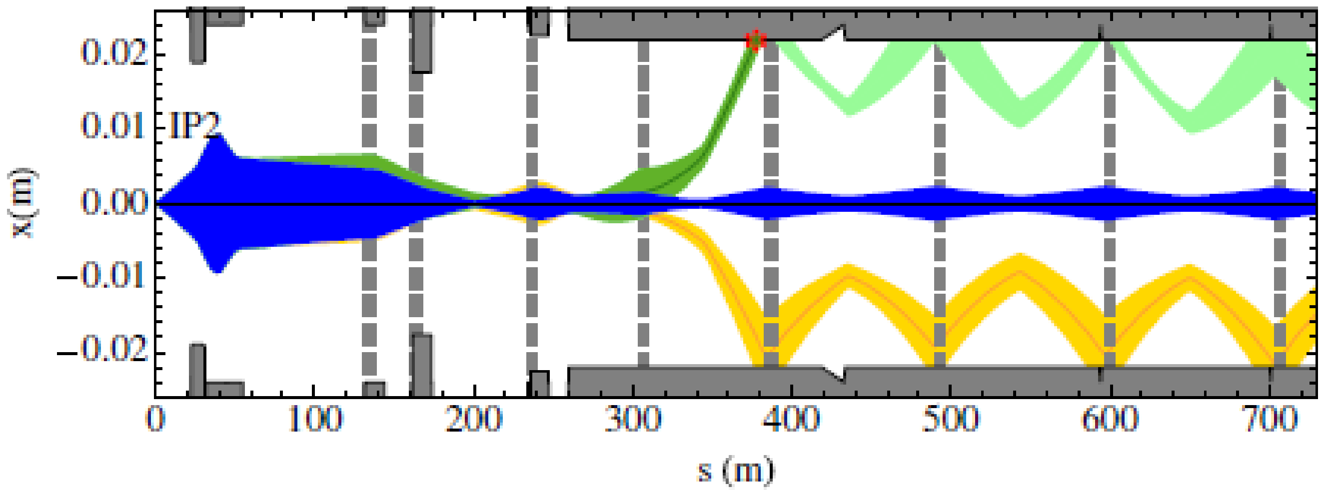
BLM for Ions II

- BFPP simulations for ALICE: loss positions (J. Jowett) and showers through dipole magnet (R. Bruce) → additional monitors
  - Main dipoles: ratio of energy deposited in magnet versus energy deposited in the BLM detector is roughly the same as for protons
    - Ratio of quench (damage) level to BLM signal about the same as for protons → Similar threshold tables for protons and ions
    - standard BLMs (local aperture limitations) at right position
  - Future simulations (other EM processes) might lead to more requests for BLMs

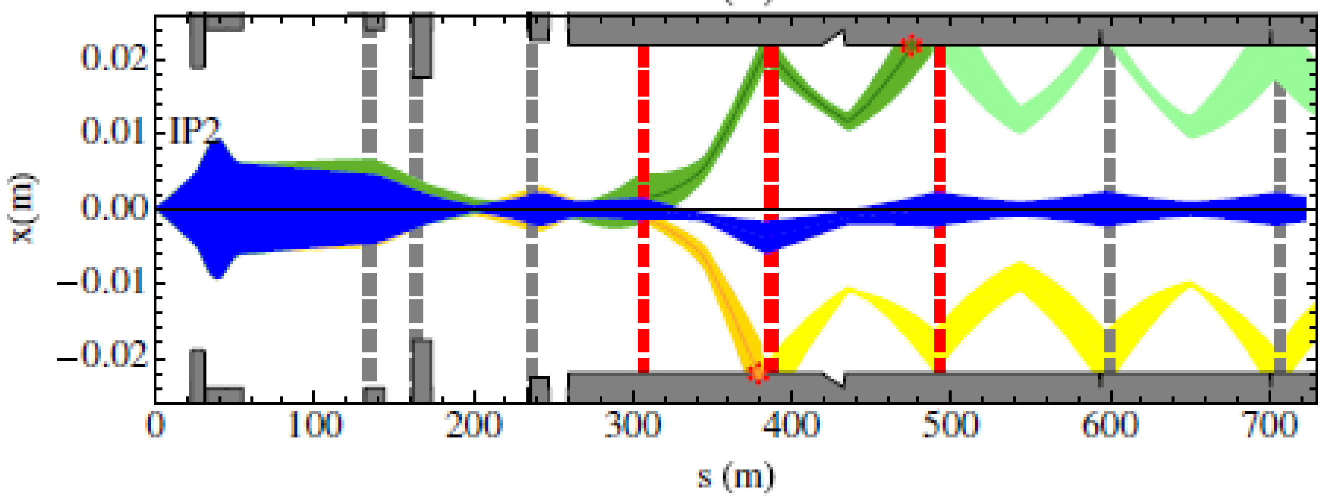


Energy position in the hottest part of the coil and at the BLM location (FLUKA, LHC Project Note 379, R. Bruce et al.)

BFPP

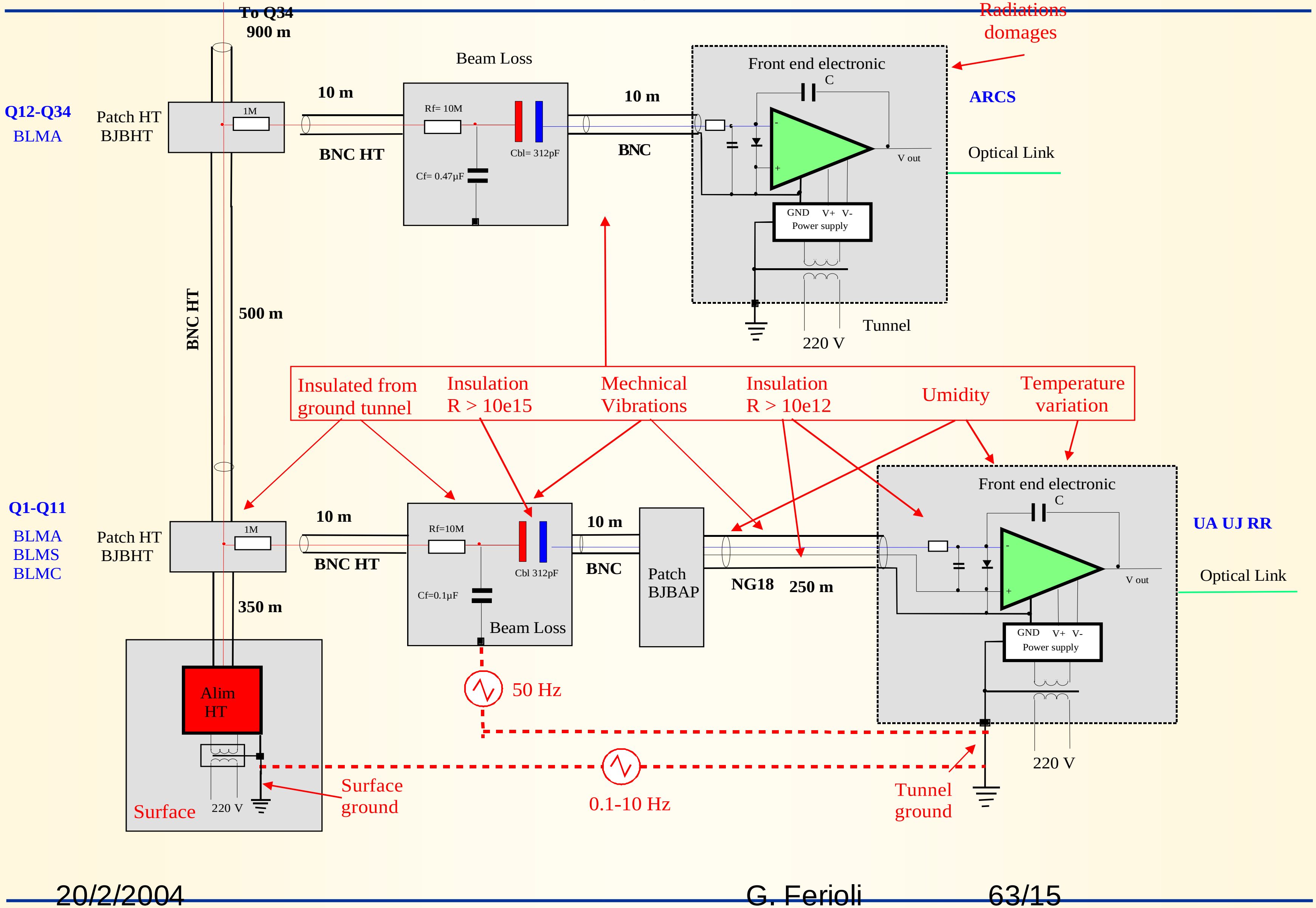


0.02
0.01
IP2
0.00
−0.01
−0.02
x(m)
0
100
200
300
400
500
600
700
s (m)



0.02
0.01
IP2
0.00
−0.01
−0.02
x(m)
0
100
200
300
400
500
600
700
s (m)

Noise and ground loops



Showers on Magnet from Losses on Collimator

- Maximum voltage drop on superconducting magnet coil scales with BLM signal