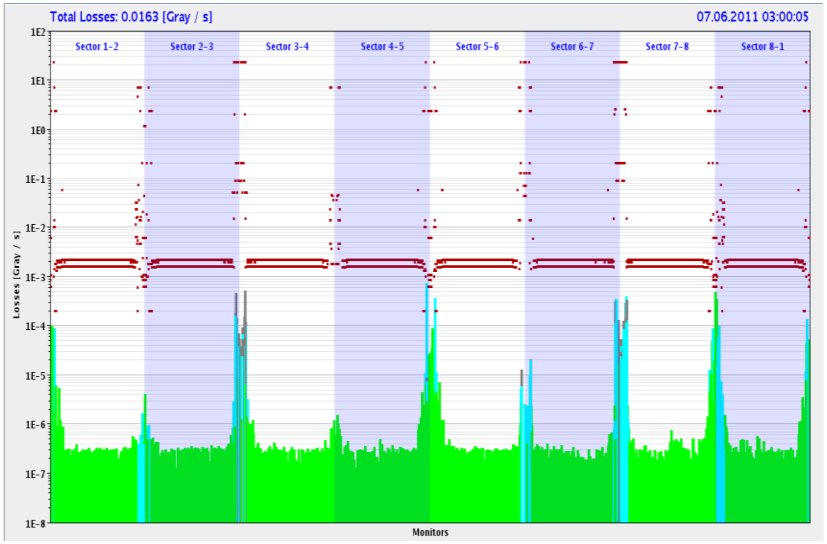
Experience with LHC Beam Loss Monitoring system (and lessons for FAIR)

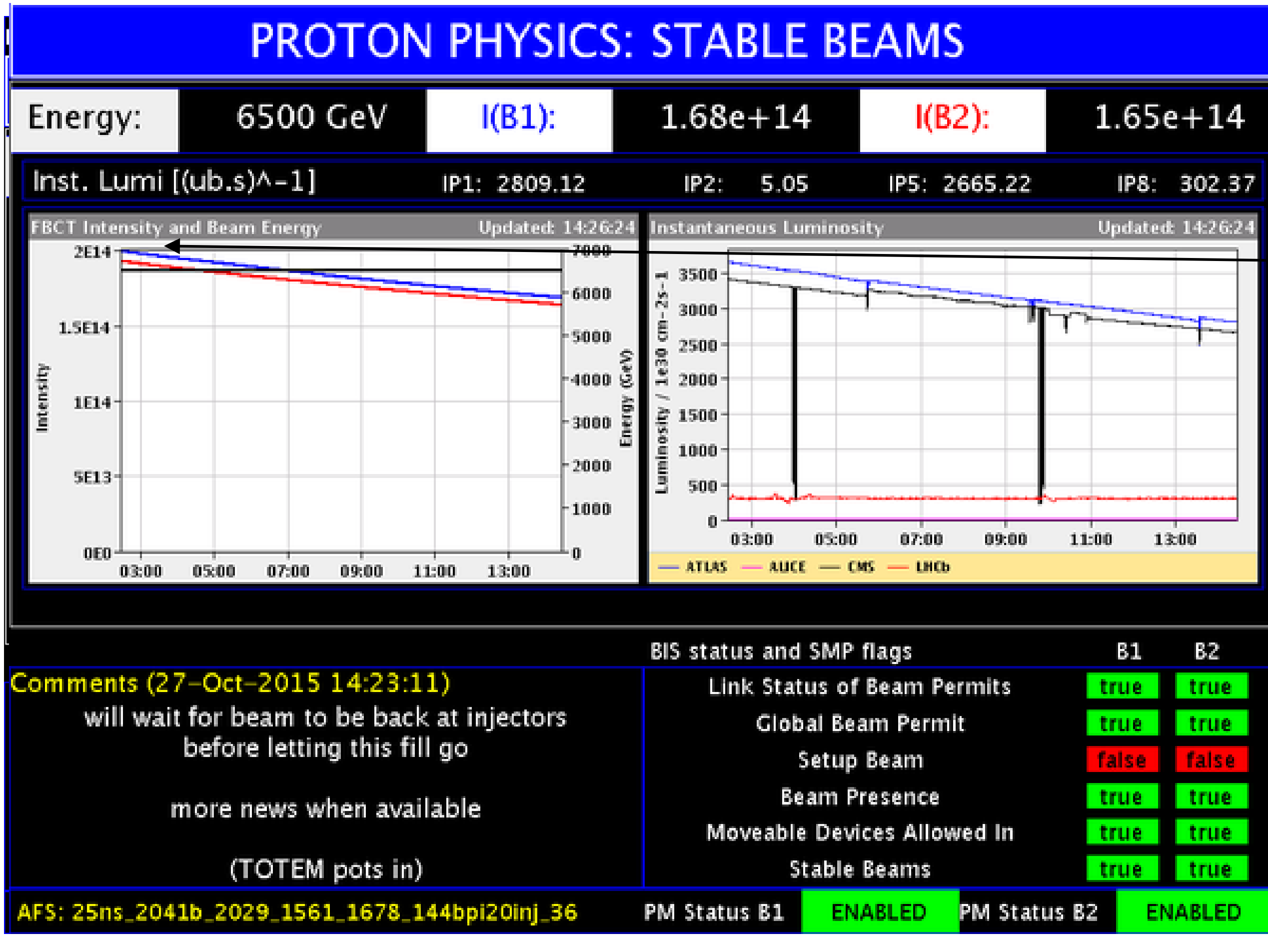


Mariusz Sapinski (LOAO)
FAIR Commissioning and Control WG
GSI, November 18th, 2015

Outlook

1. Motivation : LHC beam and machine protection
2. System specification
3. Reliability
4. Choice of detector technology
5. Electronics
6. Data definition and flow
7. Loss examples (injection losses, UFOs)
8. Beam-abort thresholds
9. New developments

Motivation: LHC beam



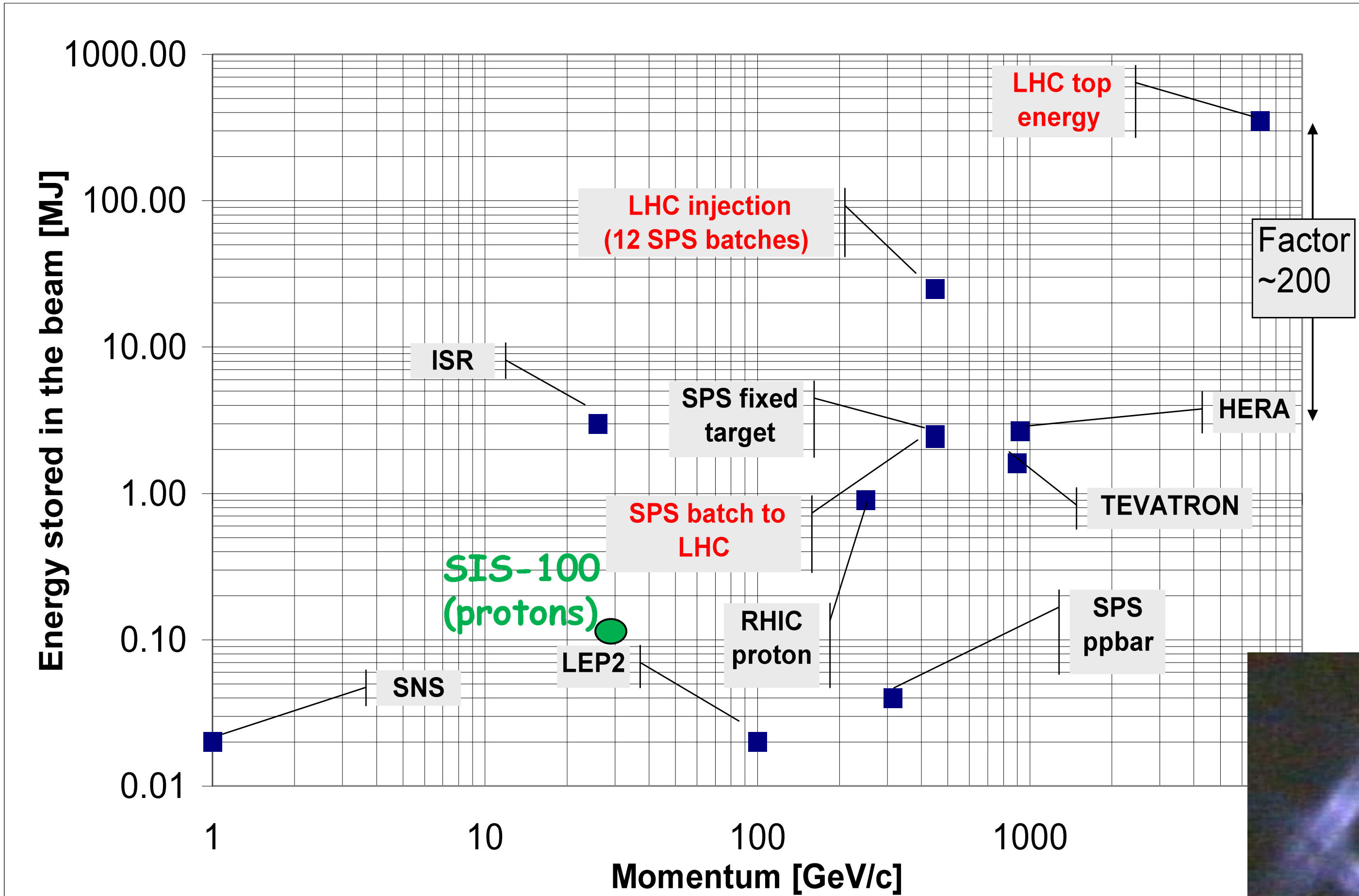
250 MJ/beam

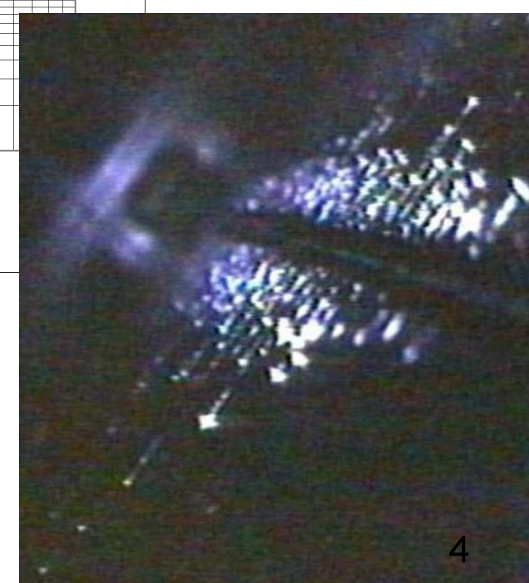
(a few weeks ago)

wikipedia.org:
1 MJ is approximately the kinetic energy of a one-tonne vehicle moving at 160 km/h

SIS-100: only 100 kJ (p)
- pulsing machine, loss-generating processes repeat regularly

Motivation: loss consequences

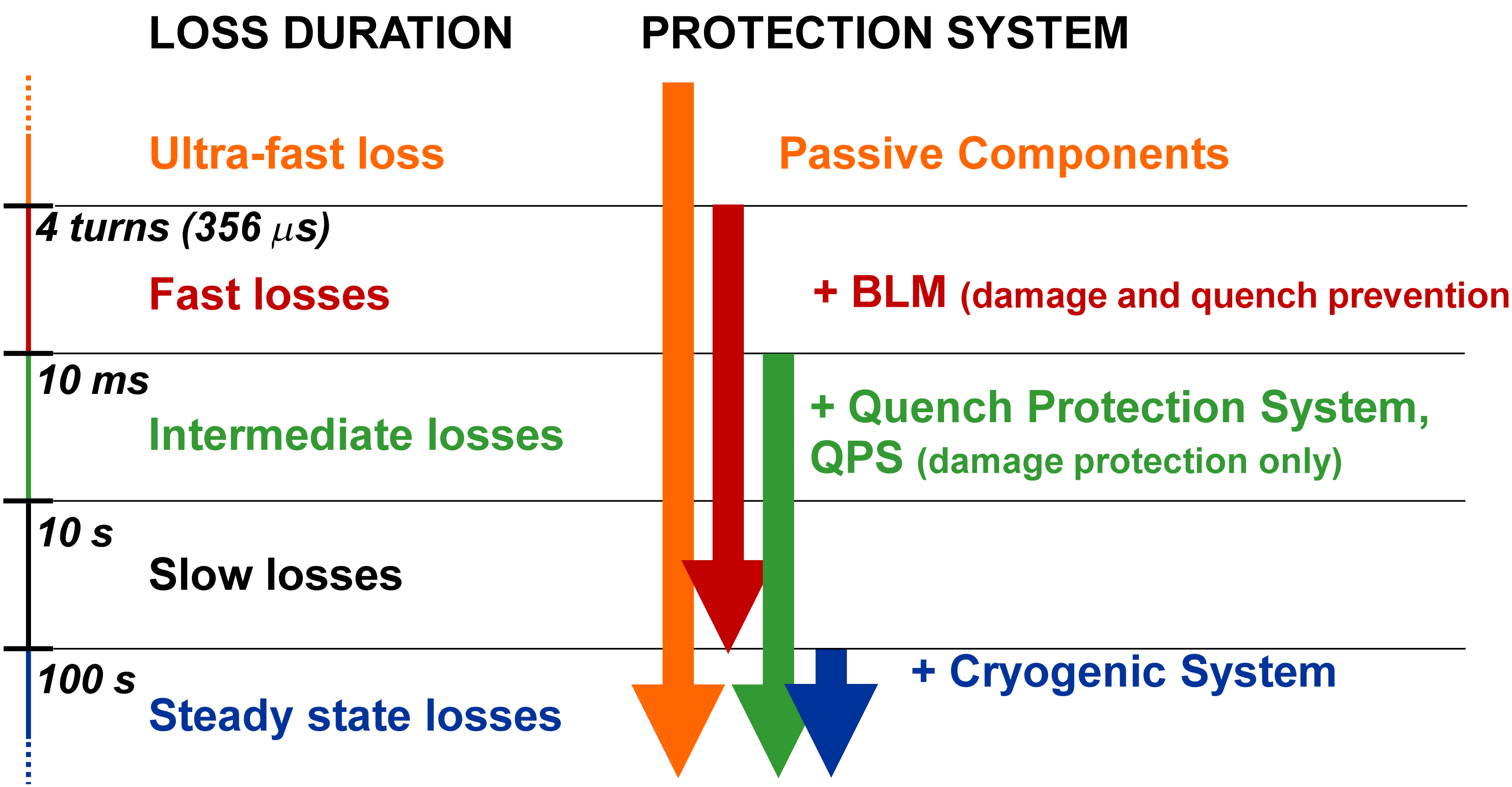




December 5, 2003, 1.5 MJ beam lost on the aperture in TeVatron, causing massive quenches and damage of the vacuum chamber and collimators – 2 weeks to repair.

Machine protection: redundancy

Protection scheme against beam losses in superconducting magnets.



+ other systems (about 20) which can trigger interlock and dump the beam

Beam losses and monitoring objectives

BLM system has 2 functions: protection and diagnostics (measurement).
the two roles have different requirements! - compromises

Beam losses are regular (controlled, slow) and irregular (uncontrolled).

Examples of irregular losses:

- Obstacles and falling objects (UFOs)
- Orbit changes (for instance due to magnet current error)
- Wrong collimators setting
- Wrong tune
- Beam instabilities …

Irregular losses may result in:

- Quenching superconducting magnet
- Unnecessary activation of accelerator elements and environment
- Single Event Upsets in tunnel electronics
- Damage of vacuum chamber

System parameters

The most important BLM system parameters:

• Sensitivity	m
• Dynamic range	m/p
• Response time and temporal resolution	p
• Spatial resolution	m
• Reliability	p
• Radiation hardness	p
• Availability	p
• Physical size	-

System specification

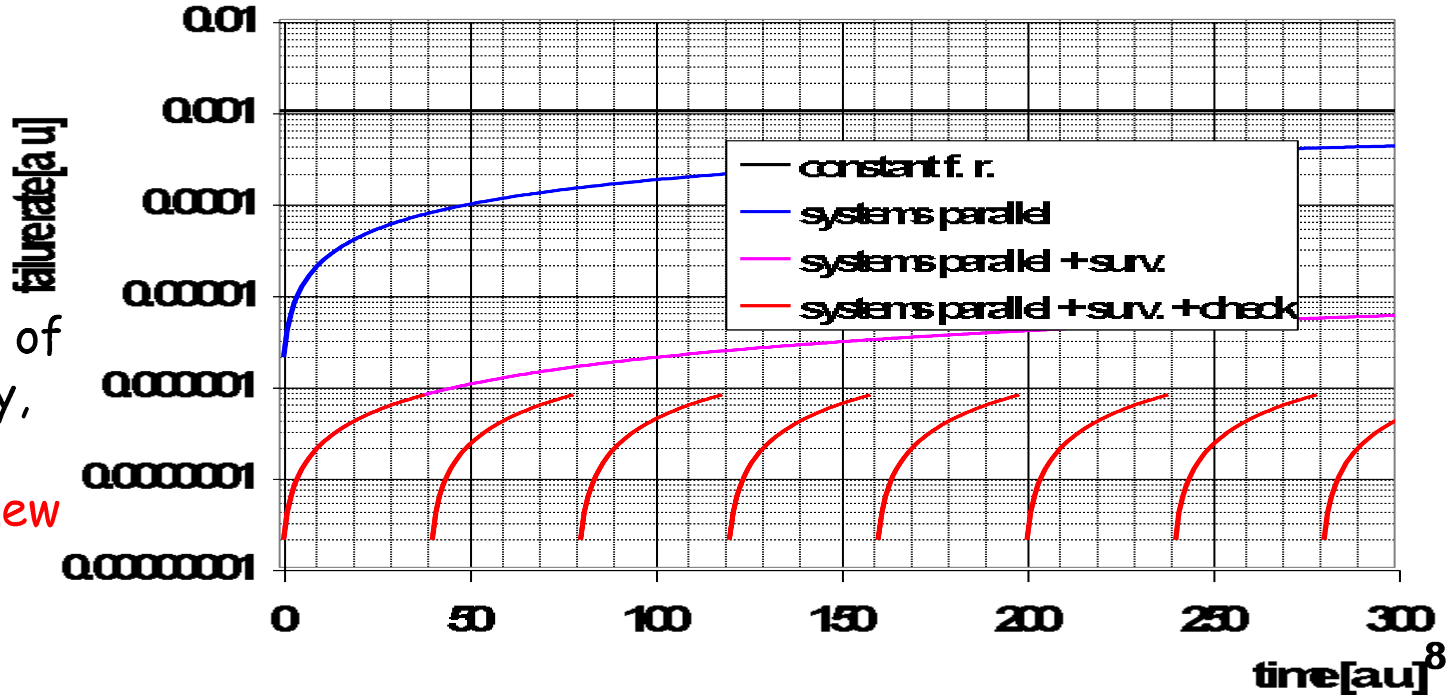
Main document dates 2004, but based on previous studies.
(LSA structures were specified in 2007)

Key parameters:

- Sensitivity: 5% of quench level
- Dynamic range: about 10^5 for signal integration time 40 μs
- Response time ≤ 1 turn (0.1 ms)
- Failure rate (reliability):

SIL3 system

Verification of functionality, system as good as new



BLM sanity check

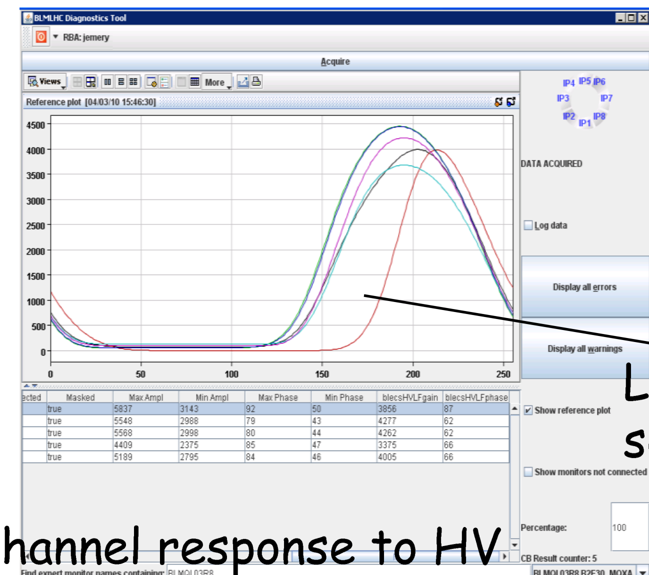
Check which runs before every fill:

<u>Connectivity check</u>

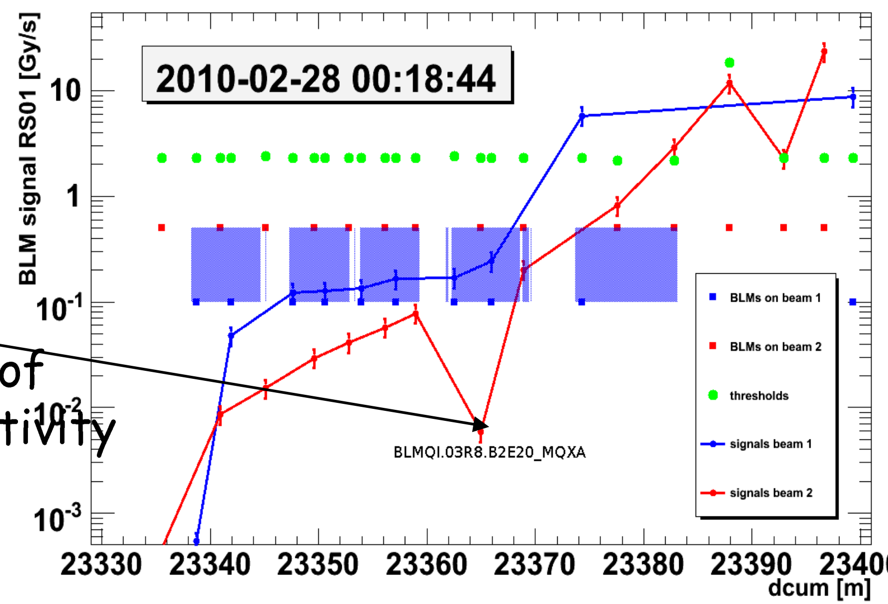
Detects non-conformities of cabling, verify HV, can detect issues in the tunnel electronics. (J. Emery, J. Instrum. 5 (2010) C12044)

<u>Internal beam permit check</u>

Verify ability of every threshold comparator to send beam dump request.

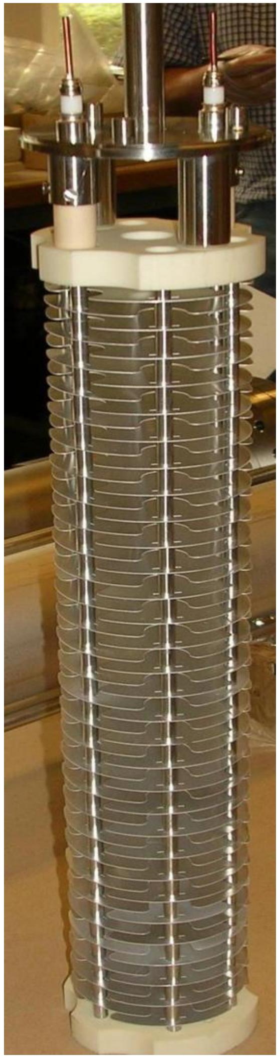


channel response to HV modulation



Loss of sensitivity

Detector choice (I)



Ionization chamber

(similar to the one used in SPS)

Stainless steal cylinder

Parallel electrodes distance 0.5 cm

(Aluminium)

Diameter 8.9 cm

Voltage 1.5 kV

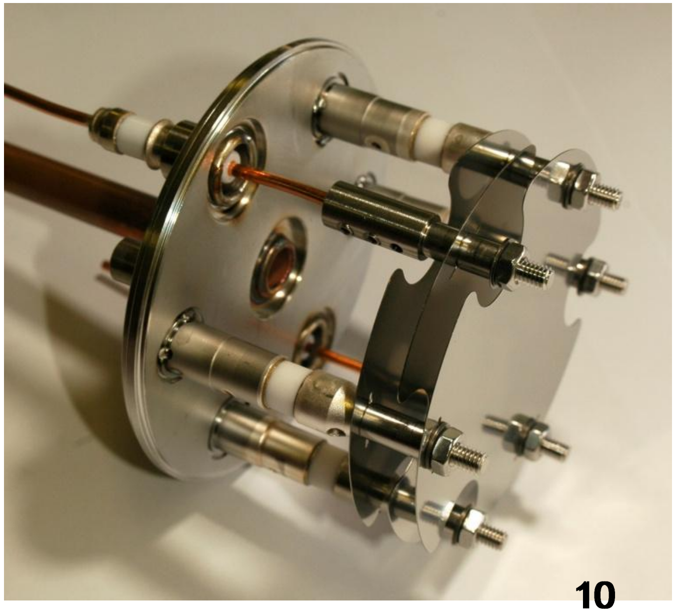
Low pass filter at the HV input

Length 60 cm

N_2 gas filling at 1.1 bar

Sensitive volume 1.5 l

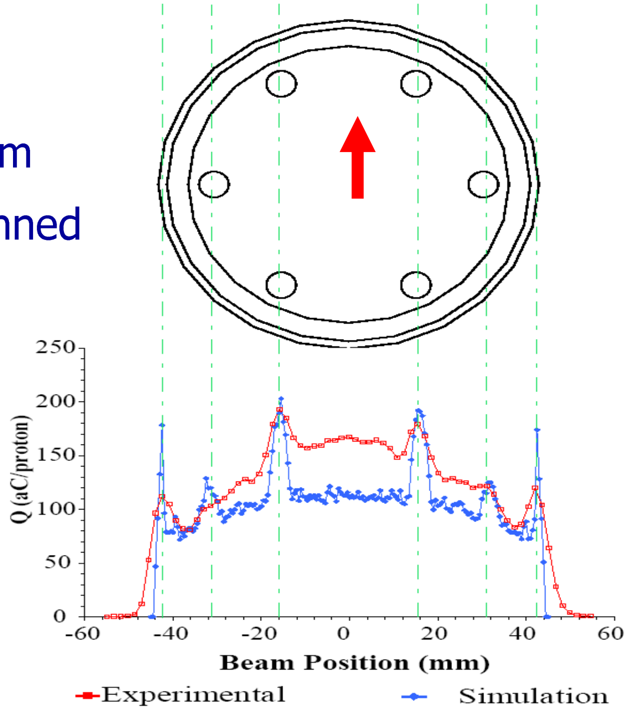
Initial choice for high-rad areas: Secondary Emission Monitor (SEM)



Detector choice (II)

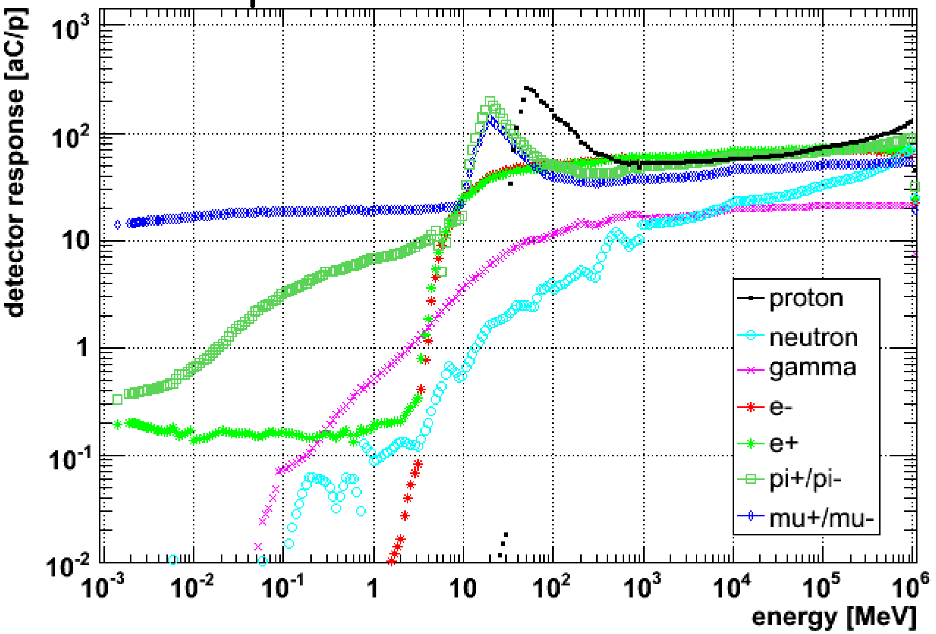
Ionization chamber properties

Beam scanned



beam tests

response functions

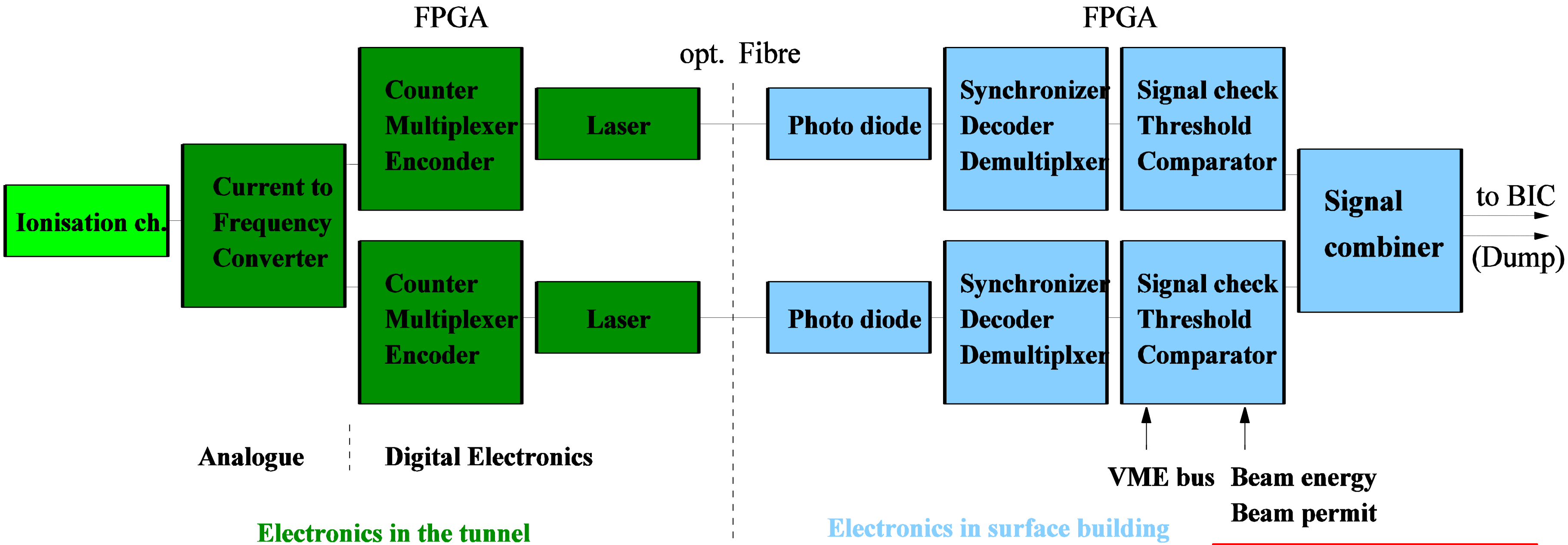


simulations

Well known and reliable component (SPS ionization chambers are in use since 30 years)

Electronics

Parallel, redundant channels:



Safe beam flag - masking

Analog front-end FEE

Current to Frequency Converters (CFCs)
Tunnel FPGAs:
Actel's 54SX/A radiation tolerant.
Communication links:
Gigabit Optical Links.

Real-Time Processing BEE

FPGA Altera's Stratix EP1S40
Mezzanine card for the optical links
3 x 2 MB SRAMs for temporary data storage
NV-RAM for system settings and threshold table storage

Data definition

Signal is integrated in 40 µs time window (25 kHz samplig).

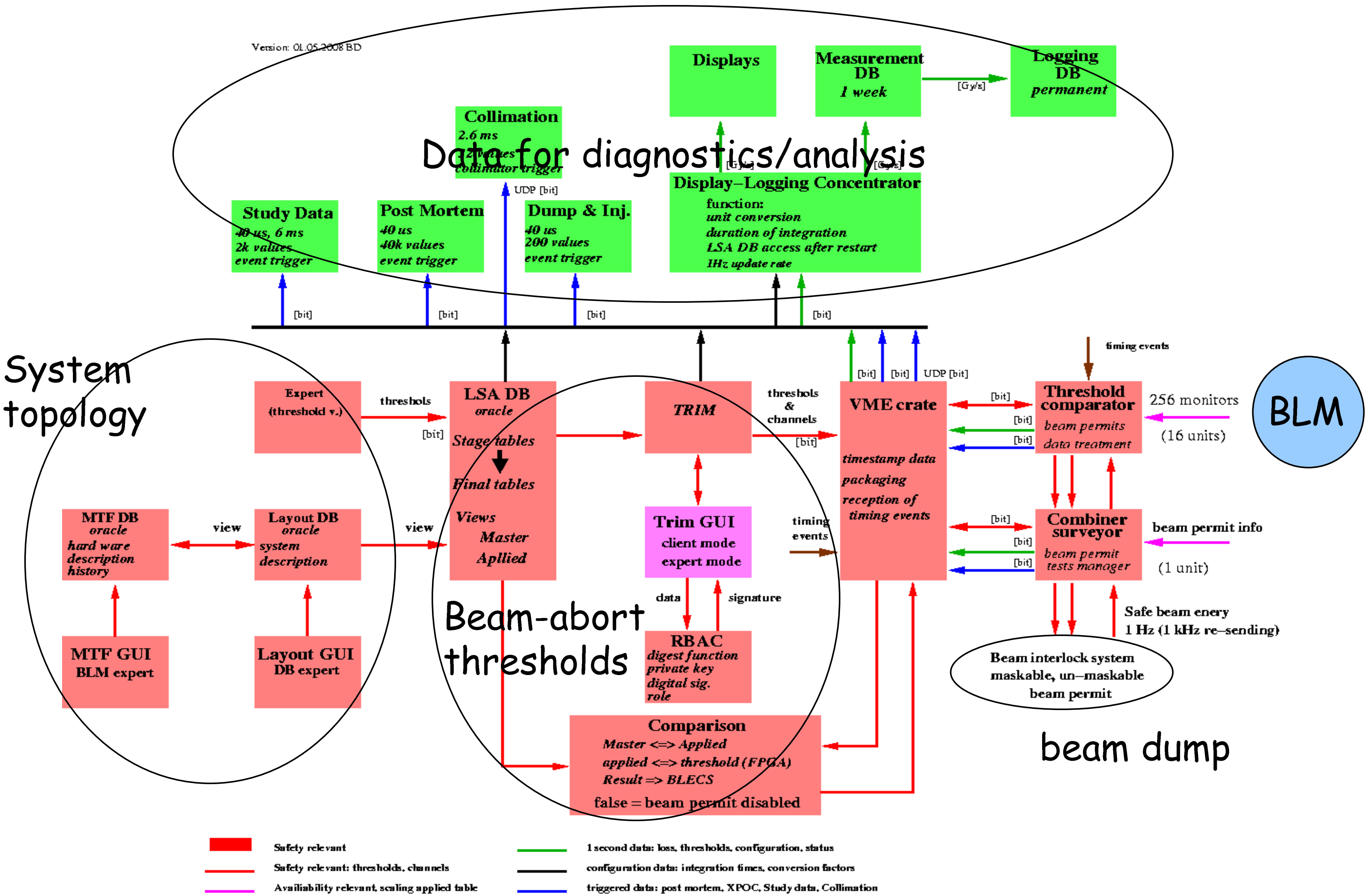
The 40 µs time windows are assembled into 12 running sums:
40 µs, 80 µs, 320 µs, 640 µs, 2.56 ms, 10.24 ms, 81.92 ms, 0.655 s, 1.31 s, 5.24 s. 20.97 s, 83.89 s.

The 12 running sums are compared with 12 thresholds in FPGA.

All data cannot be archieved!
Data are logged in LHC Logging DB with initial frequency of 1 Hz, further reduced after 1 week for permanent storage.

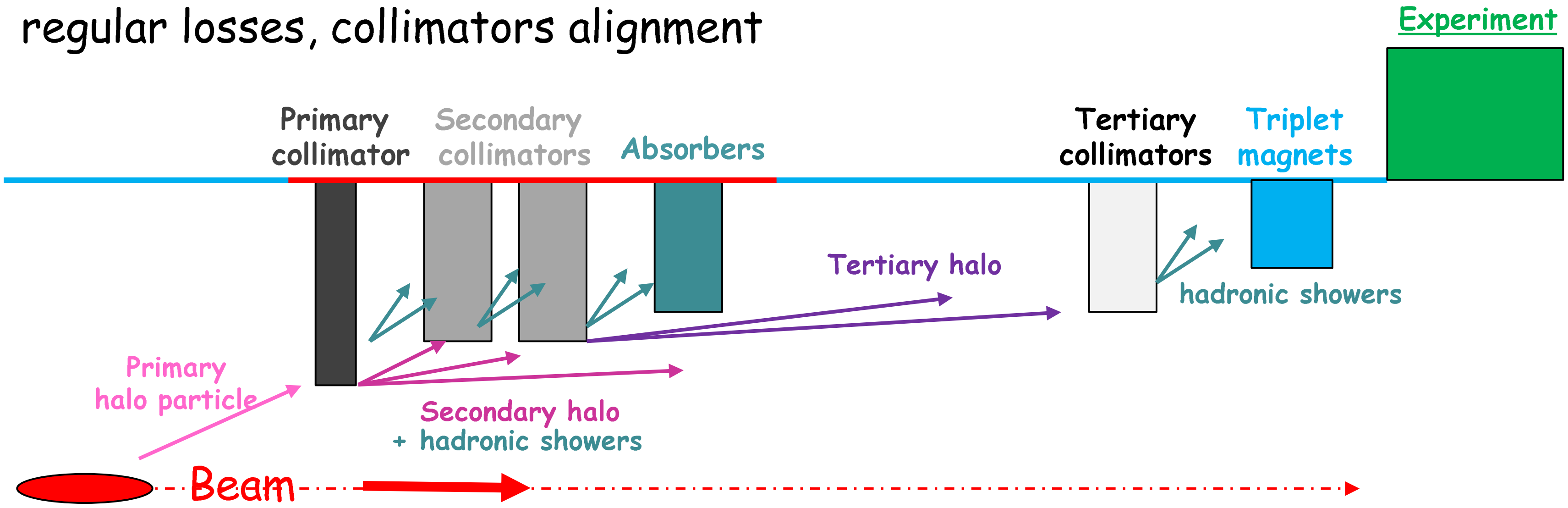
In addition there are special buffers (PostMortem, Study) which store a given number of 40 µs time windows and which can be recovered under special conditions (eg. beam dump).

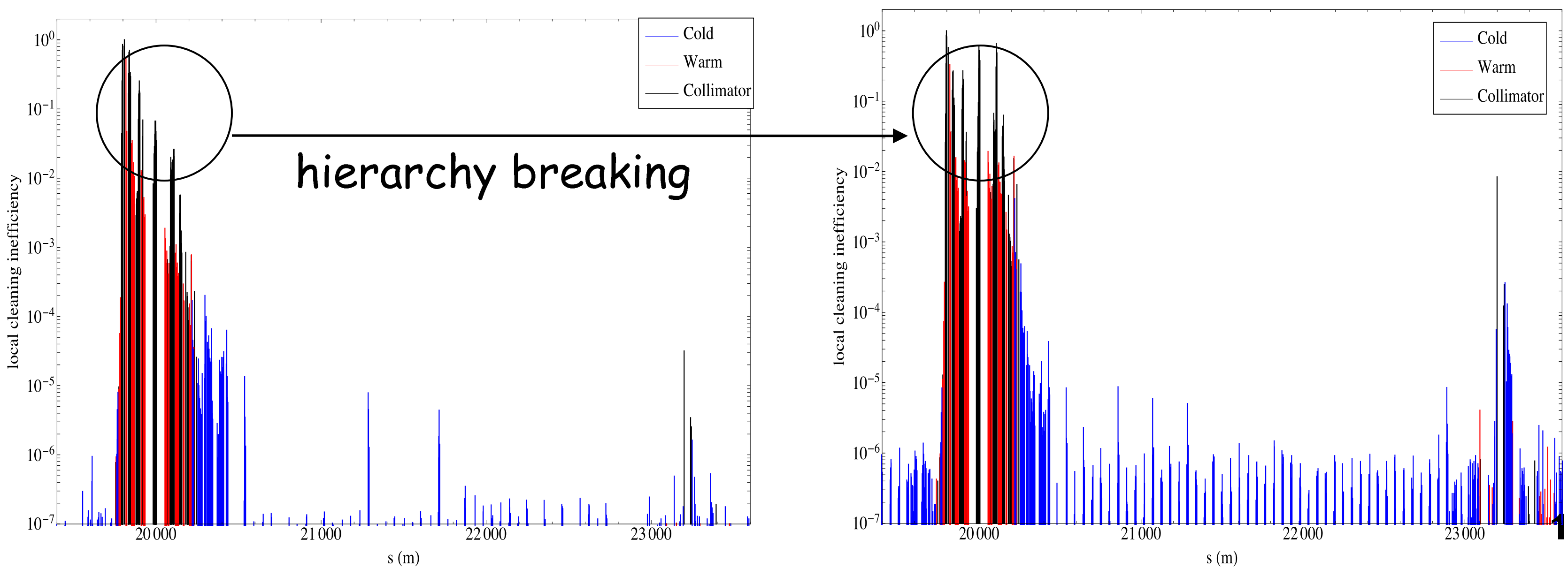
Data diagram



Loss example (I): collimation

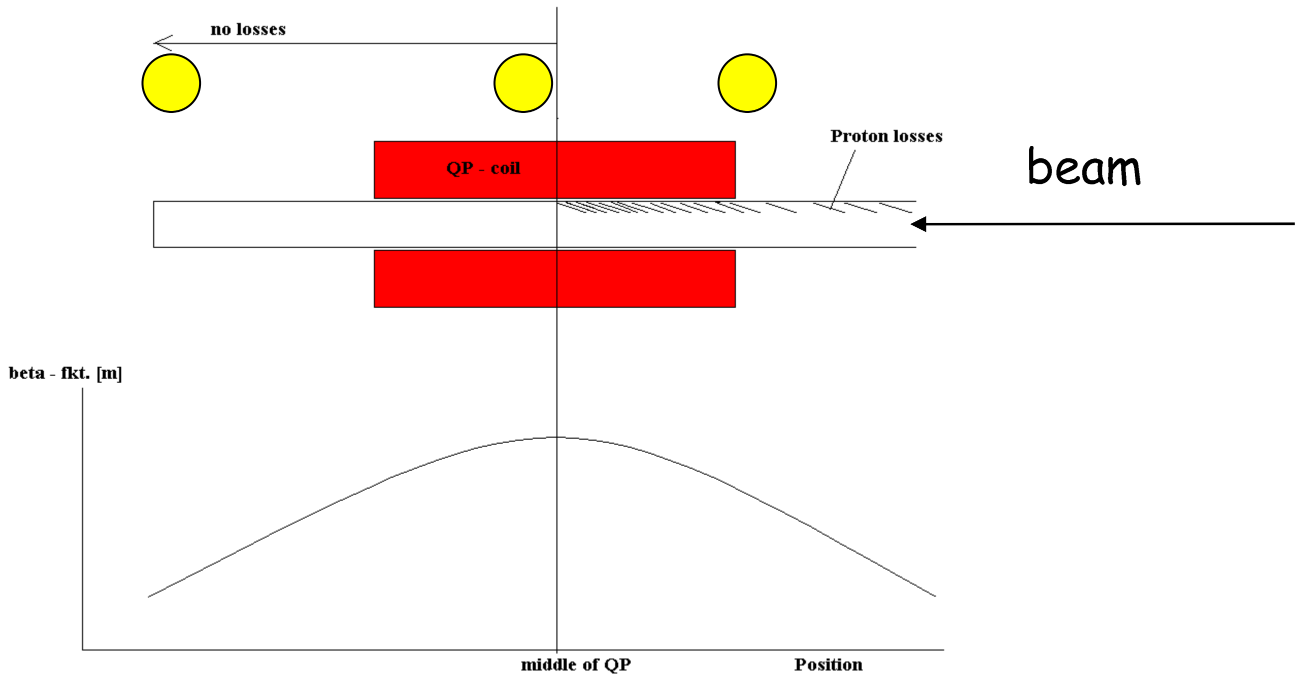
regular losses, collimators alignment





Loss example (II): quadrupole

irregular loss (eg. due to orbit distortion)



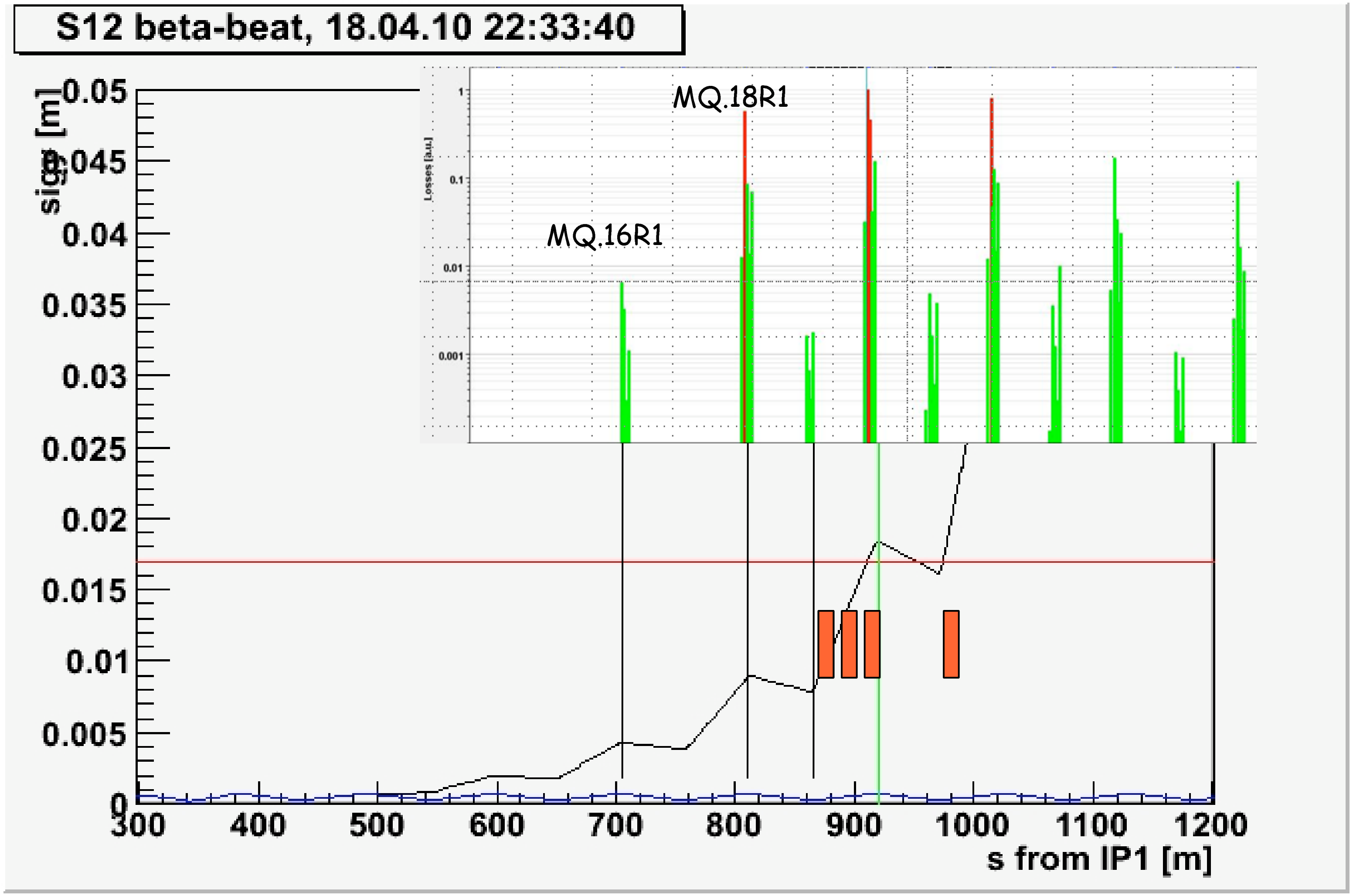
Particles first lost in places with a large β-function and/or dispersion: quadrupoles and dispersion suppressor.

<u>During Run I this loss scenario turned out to be irrelevant!</u>

Every 3rd detector was moved to another location.

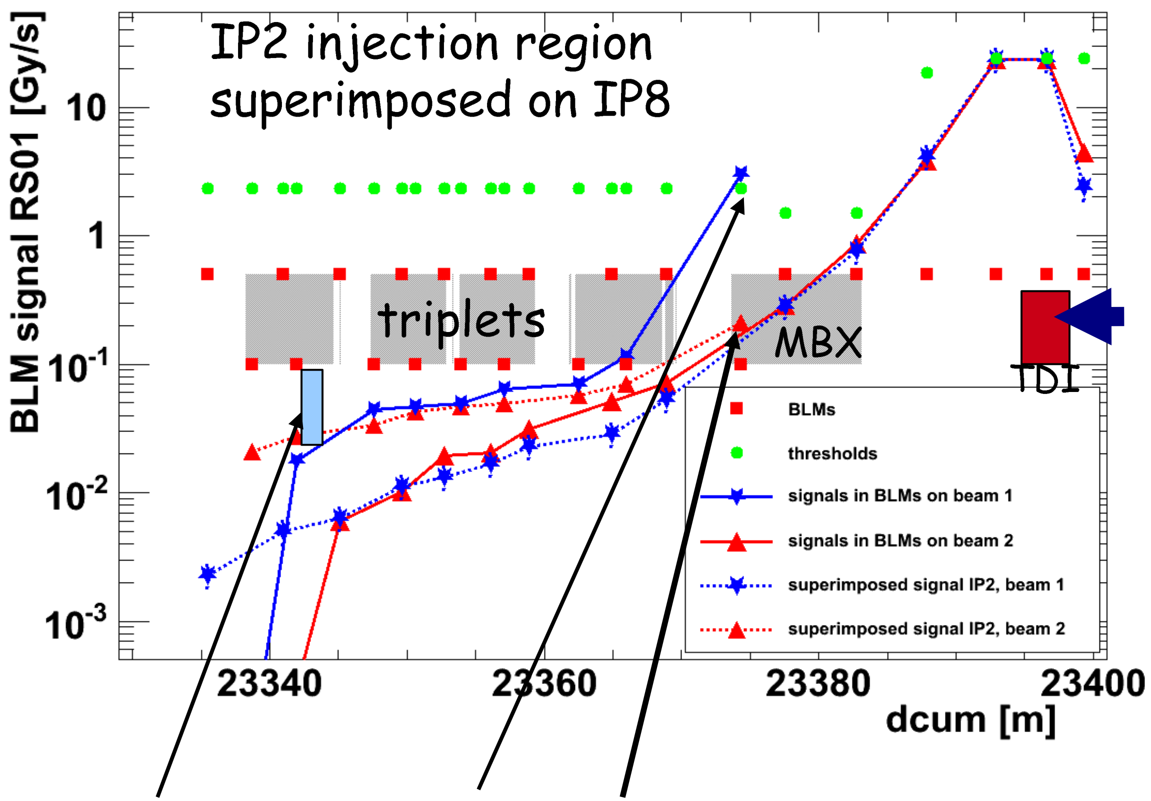
Loss example (III): massive quench at injection

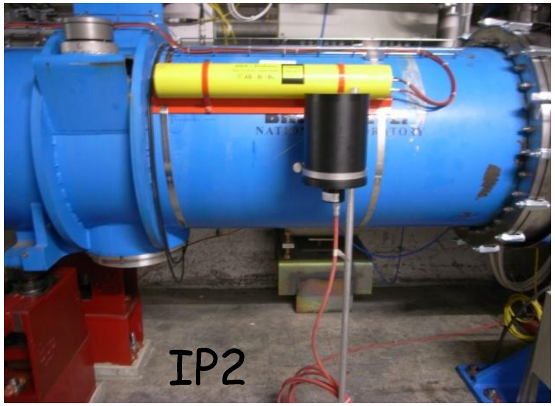
Quench of 4 dipole magnets at injection due to wrong current in MQ magnets. Injected one bunch of 8E9 protons.

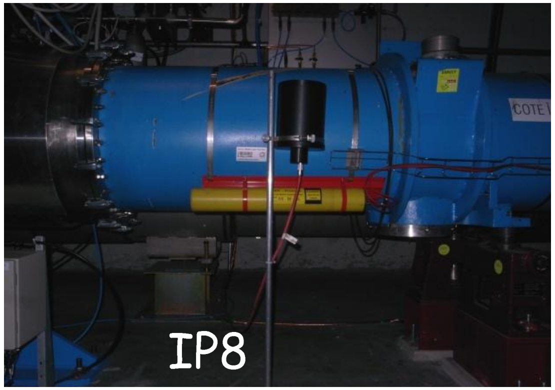


Loss example (IV): nonconformities

Loss at overinjection







chicane in IP8

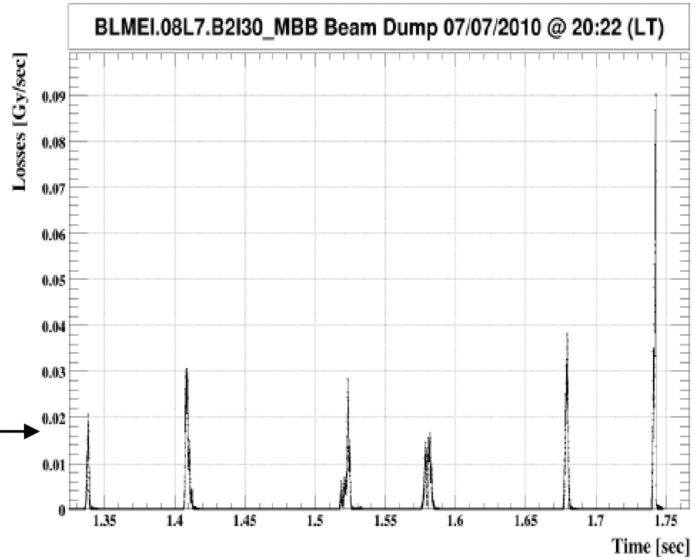
IP8 and IP2 asymmetry at overinjection

Loss example (V): UFOs

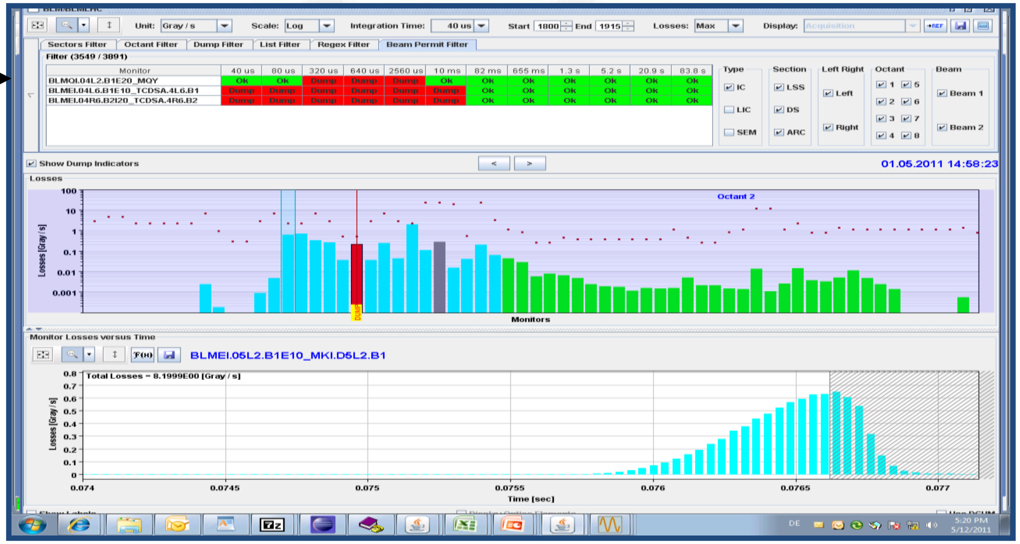
UFOs are sudden losses lasting about 0.5-2 ms.

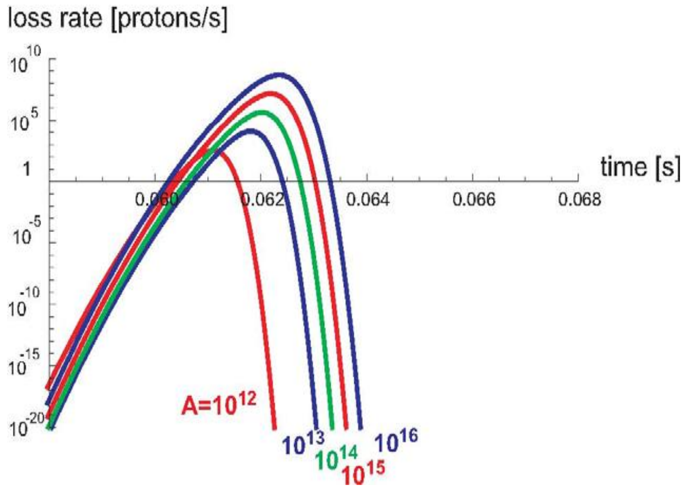
Sometimes they dump the beam (exceeding BLM thresholds).

Post Mortem data of the first UFO which dumped the LHC beam



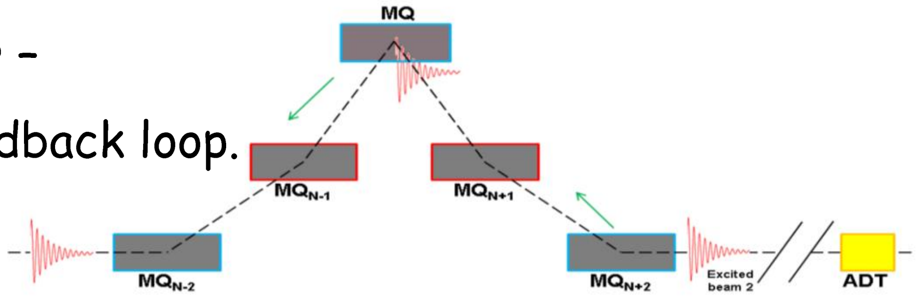
UFO from May 1st, 2011

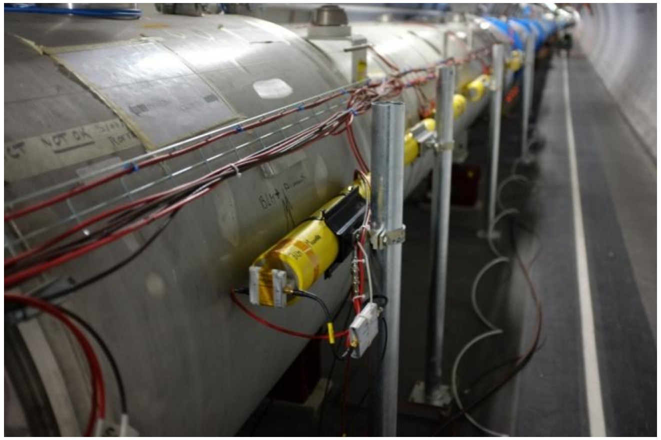




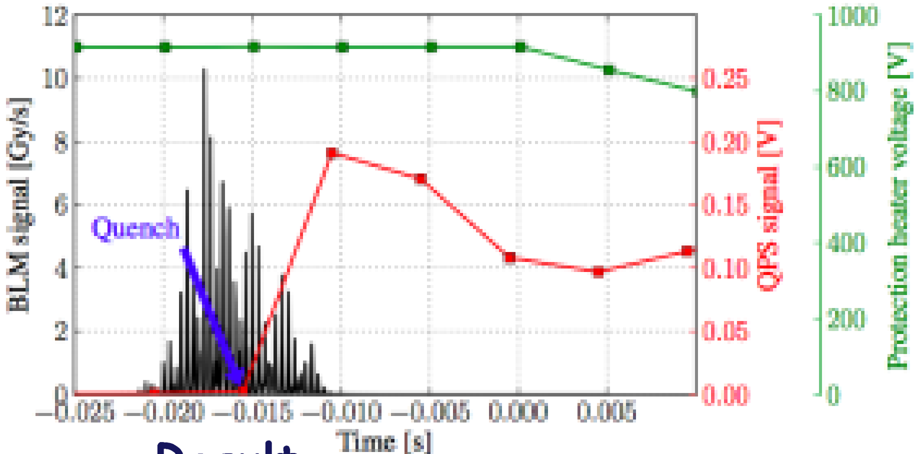
Loss example (V): millisecond quench test

- **Goal:** measure steady-state quench level for UFO-type loss.
- Superconducting machine - not easy to generate beam loss in millisecond timescale (wire scanner test in 2010).
- Help comes from transverse damper – fast magnet with programmable feedback loop.
- Beam intensity below pilot bunch.





Preparation: additional BLMs



Result

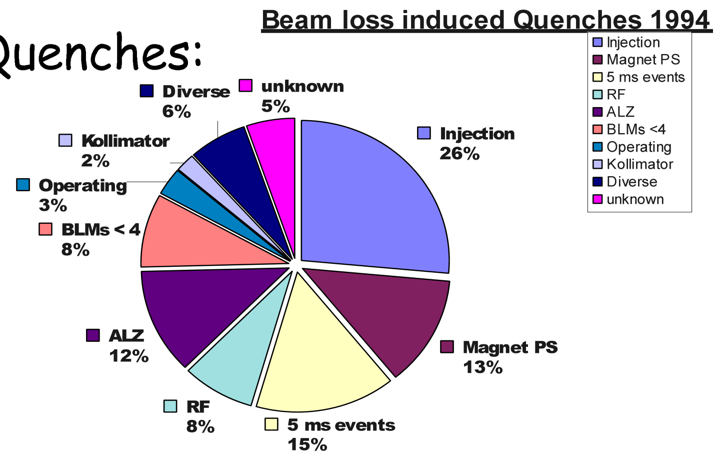
Beam-abort thresholds (I)

The beam should be stopped when:

- Loss level is close to quench level of superconducting magnet
- Loss level is close to damage of accelerator element
- Loss level is abnormally high, showing some problems with settings

(for instance collimation hierarchy breaking).

Quenches:



HERA, total: 189 quenches in 10 years

LHC: most thresholds driven by quench prevention

Quench impact – long recovery (up to 5 hours)
In Tevatron it was worst – refilling antiprotons

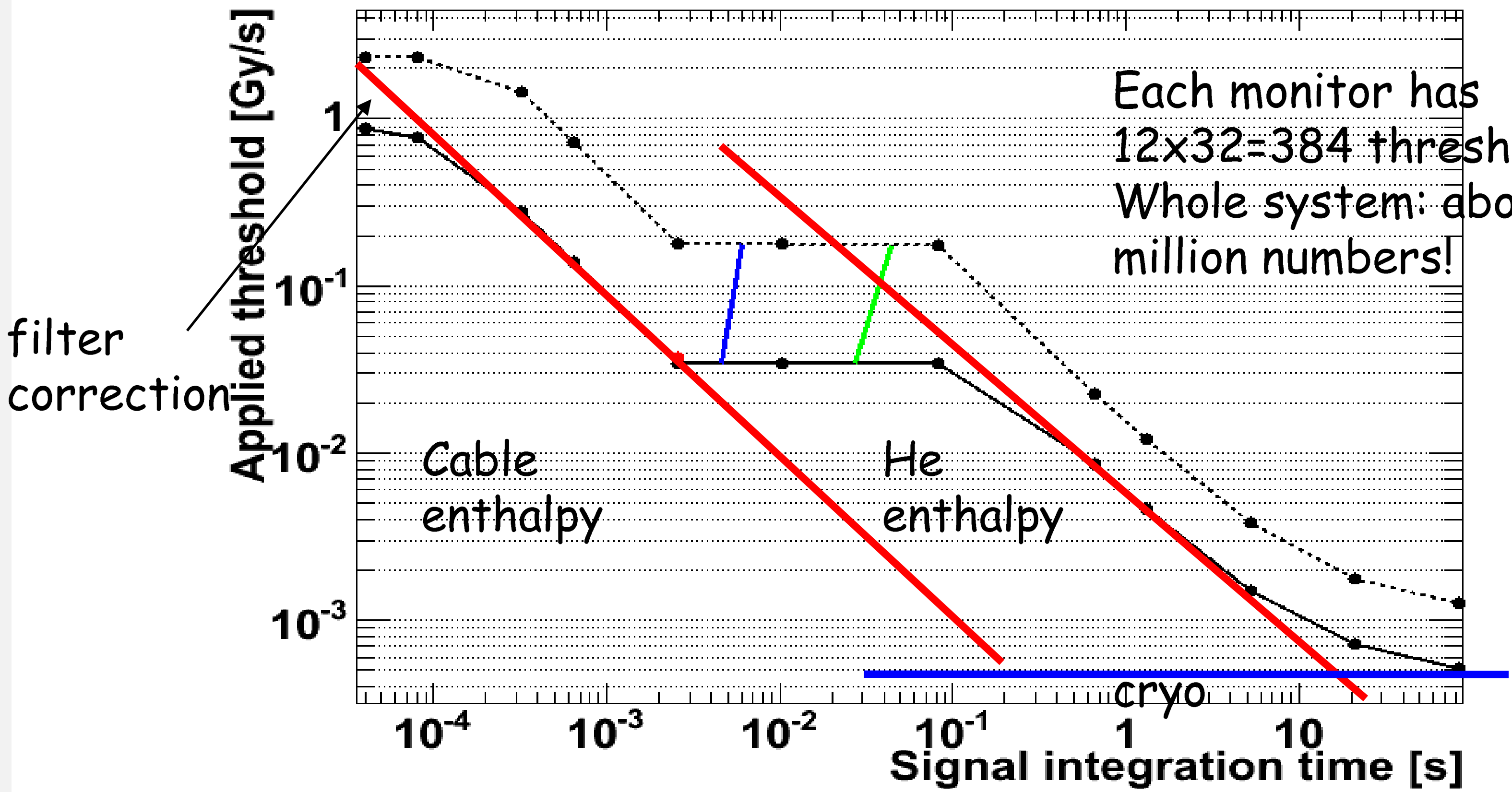
Nice surprise: almost no quenches in LHC:
- good orbit stability
- large stability margin

Beam-abort thresholds (II)

Typical threshold on cold magnet based on LHC Note 44:

$T = Q_{BLM}(E)\,\Delta H(E,t)/E_{dep}(E,t)$

Each monitor has 12x32=384 thresholds.
Whole system: about 1.5 million numbers!



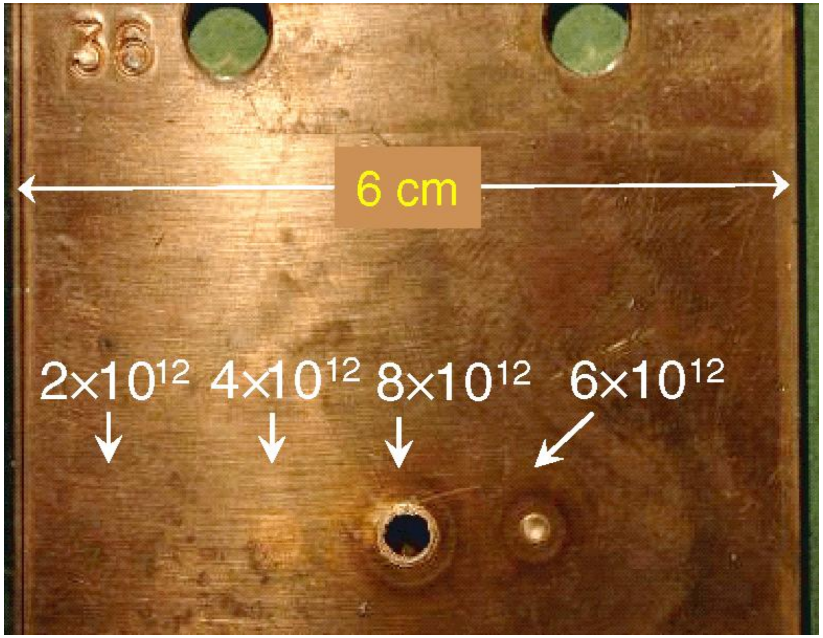
Beam-abort thresholds (III)

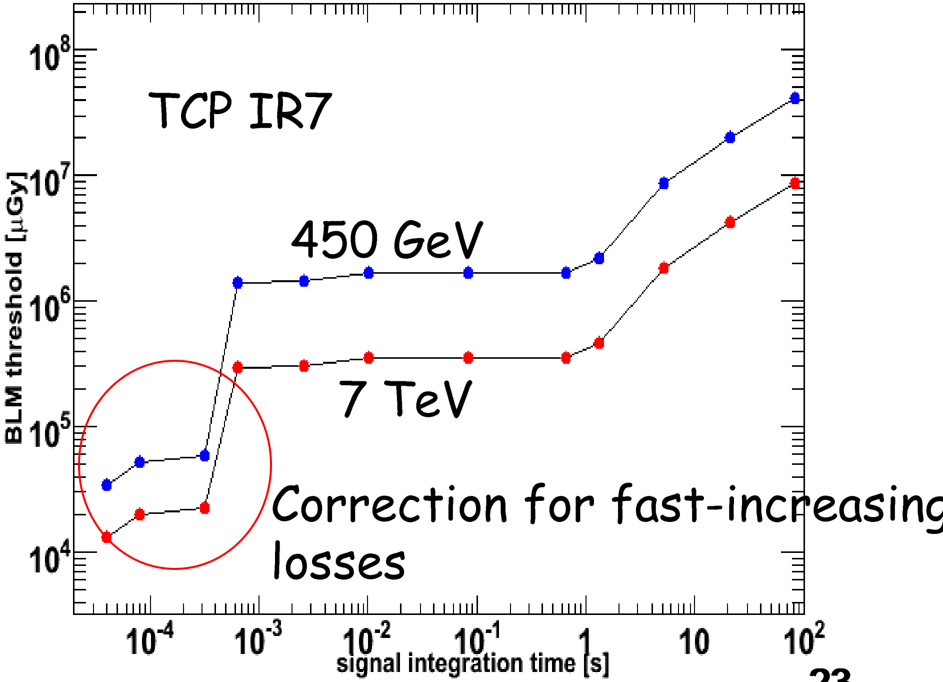
Warm magnets – conditions to compute thresholds:

- short loss: should not be damaged
- long loss: should not be overheated (about 100 C)

Collimators:

thresholds typically far from damage level, determined by assumed beam lifetime and hierarchy.

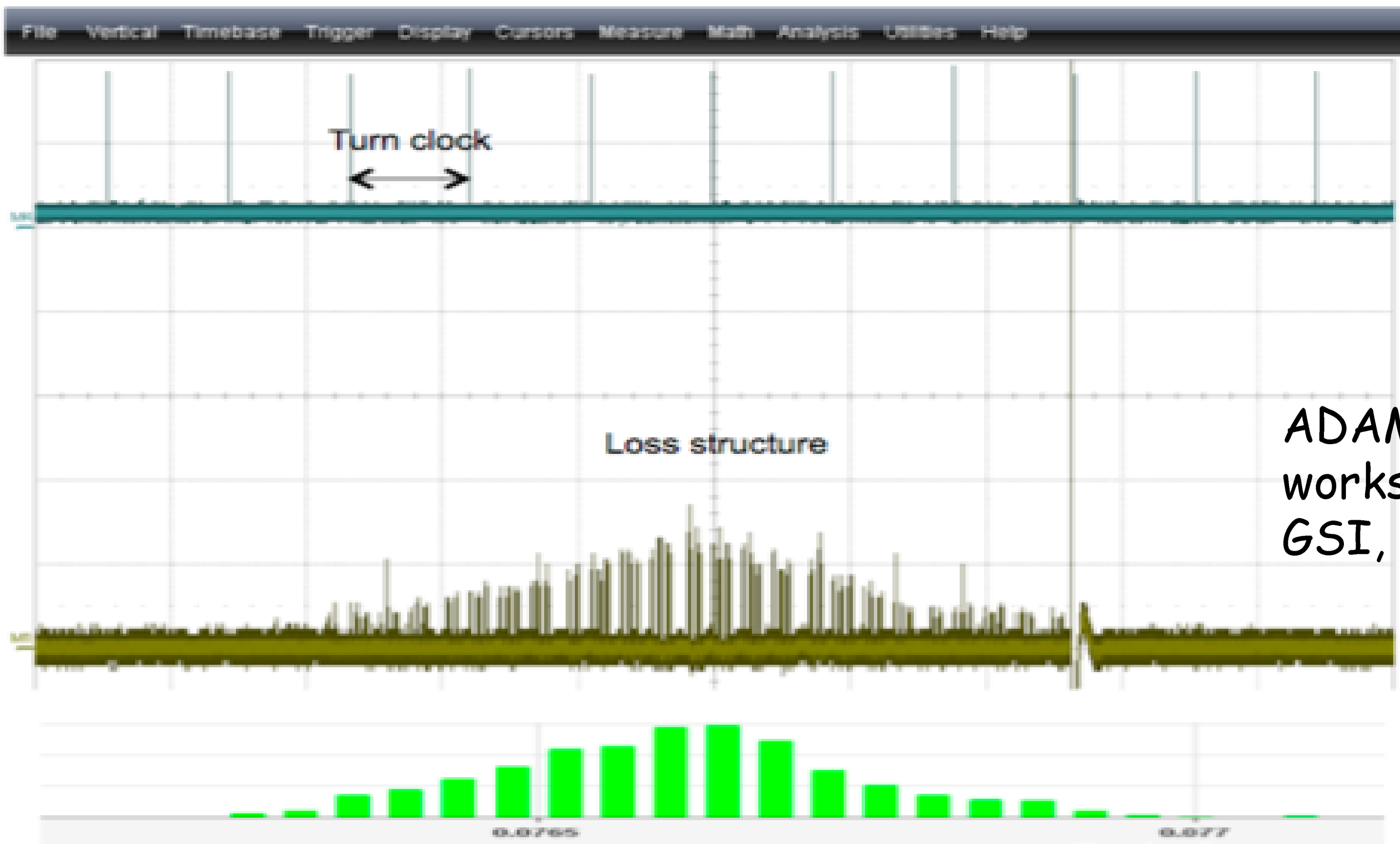




New developments (I)

New detectors:

- Little ionization chamber (with lower gas pressure) – lower sensitivity
- Fast diamond detectors - bunch-by-bunch measurements



ADAMAS workshop, GSI, 3-4 Dec

New developments (II)

Idea: put BLM detectors closer to magnet coil.

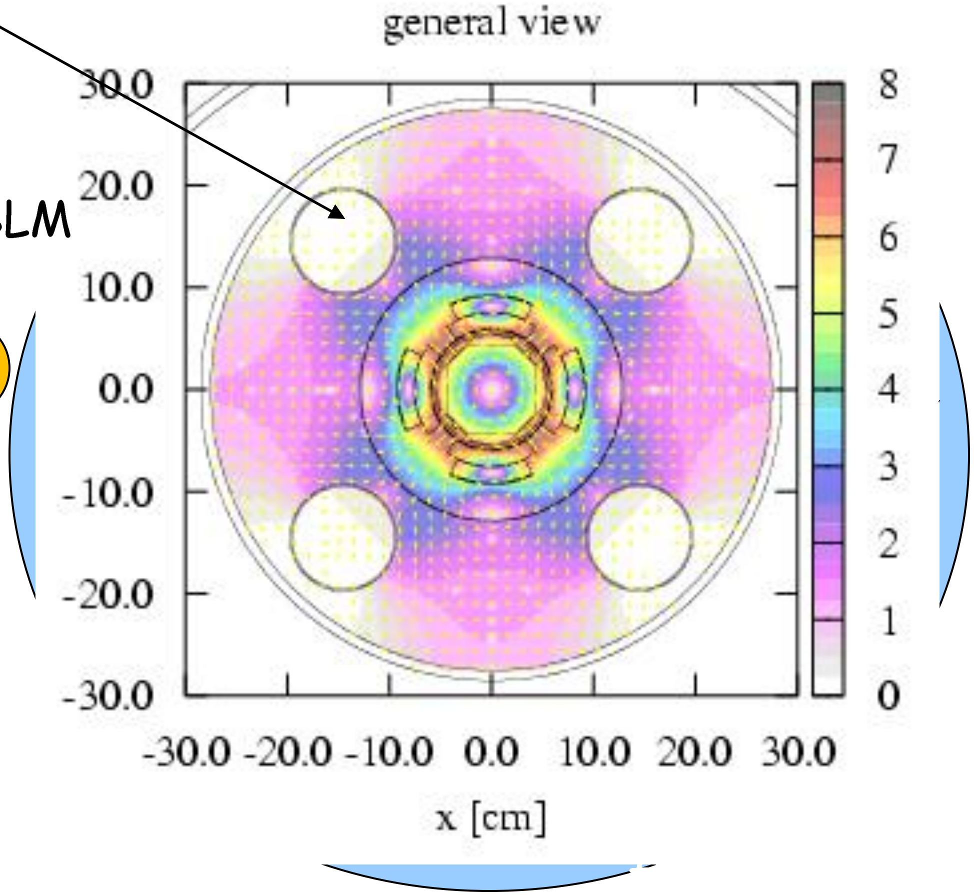
Cryogenic BLMs tested at in various conditions on the beamtest lines.

Signals from Si and Diamond detectors were measured at 1.9 K.

Test installation on the cold mass of LHC magnets.

The same readout electronics as standard system.

current BLM position



Better sensitivity to beam losses (less material in front)

Summary

1. BLM system is critical for safety of LHC machine.
2. It plays a crucial role in beam diagnostics.
3. Complex but very reliable system (no spurious beam dumps).
4. Developments ongoing: CryoBLM, Cerenkov fibers, etc…

For FAIR:

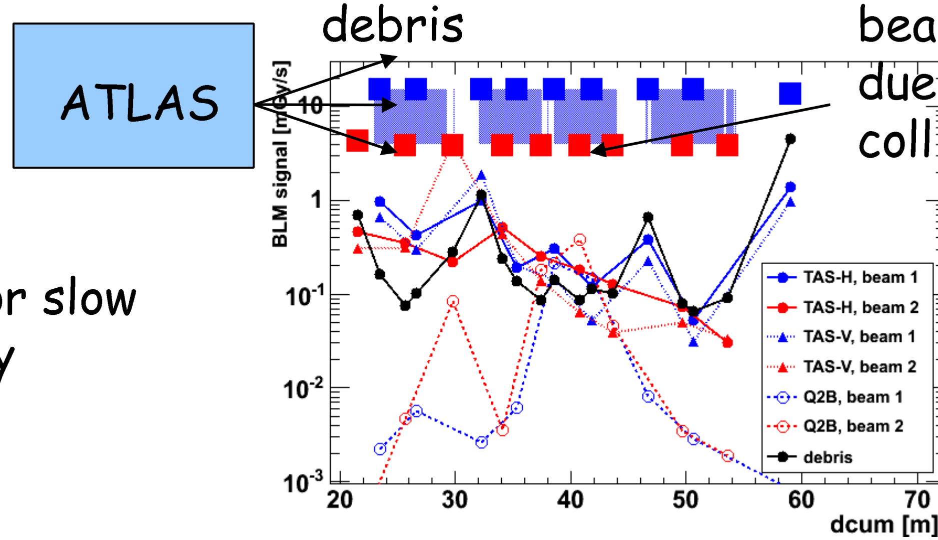
- Complex data definition and flow.
- System self-diagnostics once per day.
- Some loss scenarios turned out irrelevant (but we would not know it without BLM system).
- Unexpected loss scenarios appeared.

Thank you for your attention!

Additional slides

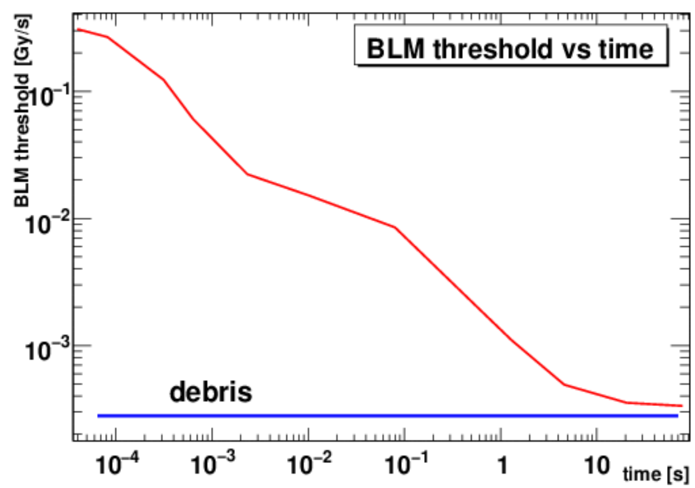
Limitations

Example: debris from ATLAS and slow beam losses in the triplet:



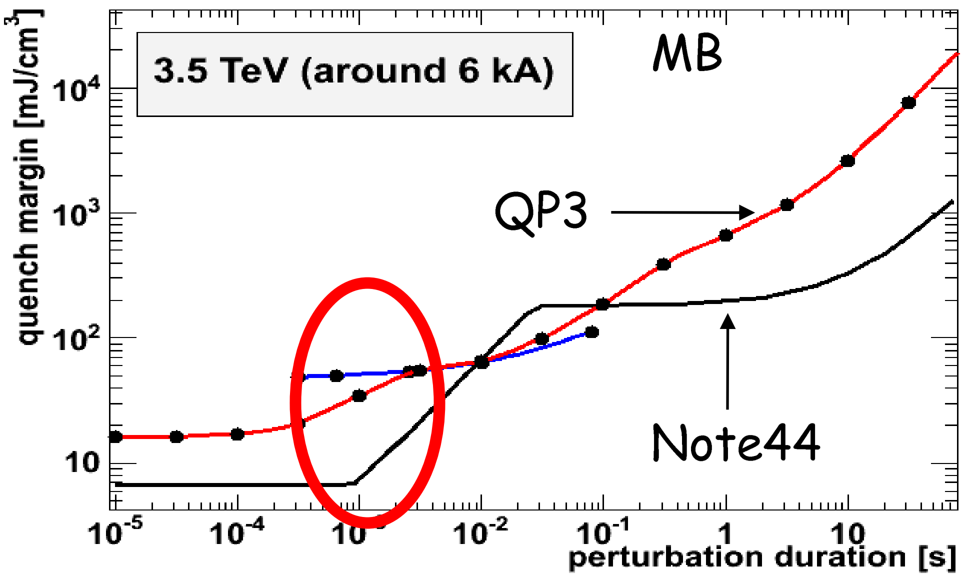
In order to protect Q2 magnet the threshold for slow losses should be set very close to constant debris signal.
Spurious beam dumps would be unavoidable.

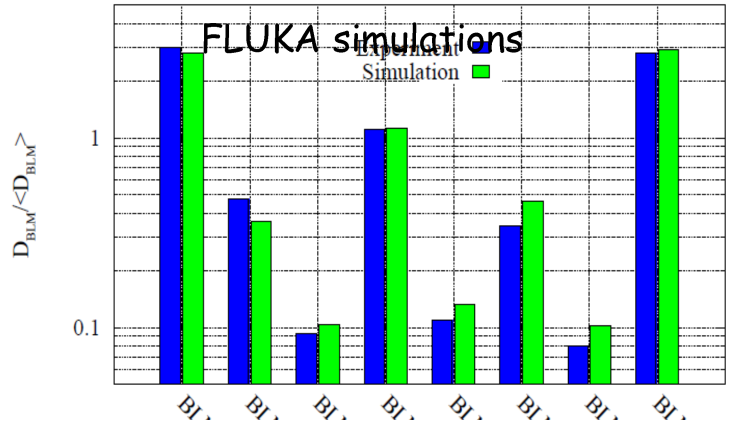
Similar problem of radiation masking signal from dangerous beam loss is observed in other locations on LHC.

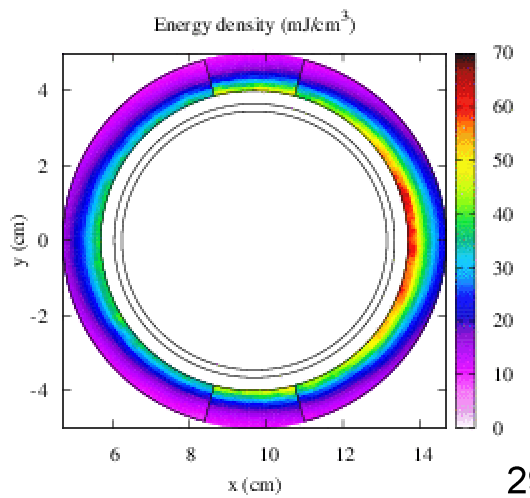


Beam-abort thresholds (III)

One of the most spectacular quench tests: generate millisecond scale losses using with Wire Scanner at 3.5 TeV.
Motivation: explore quench limit for losses similar to UFOs.
Quench occurred after about 10 ms

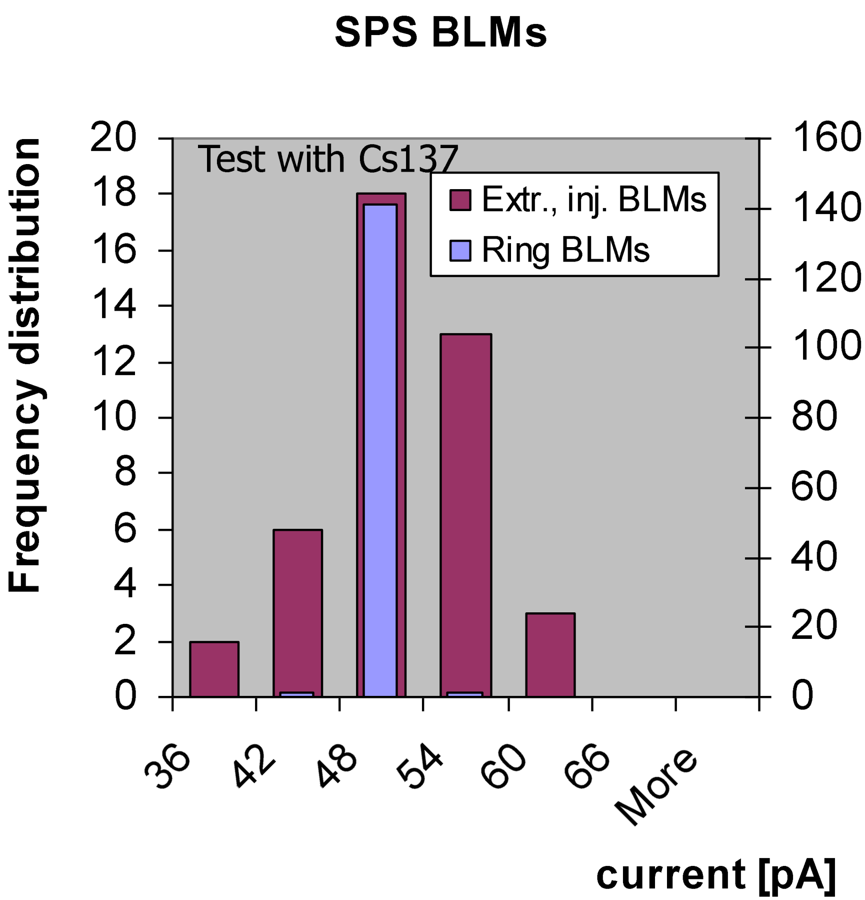






Max E_{dep}
FLUKA: 62.5 mJ/cc
QP3: 38 mJ/cc (preliminary)
we call it a good agreement

LHC Detector choice (III)



30 years of operation

Measurements done with installed electronic

Relative accuracy

- $\Delta\sigma/\sigma$ < 0.01 (for ring BLMs)
- $\Delta\sigma/\sigma$ < 0.05 (for Extr., inj. BLMs)

Gain variation only observed in high radiation areas

Consequences for LHC:

- No gain variation expected in the straight section and ARC of LHC
- Variation of gain in collimation possible for ionisation chambers

Total received dose:

ring 0.1 to 1 kGy/year

extr 0.1 to 10 MGy/year

Reliable component