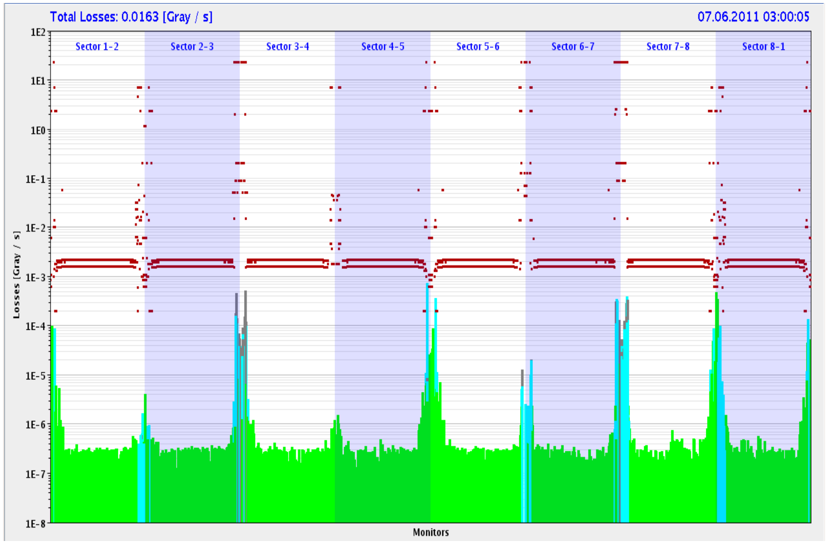
The LHC Beam Loss Monitoring system

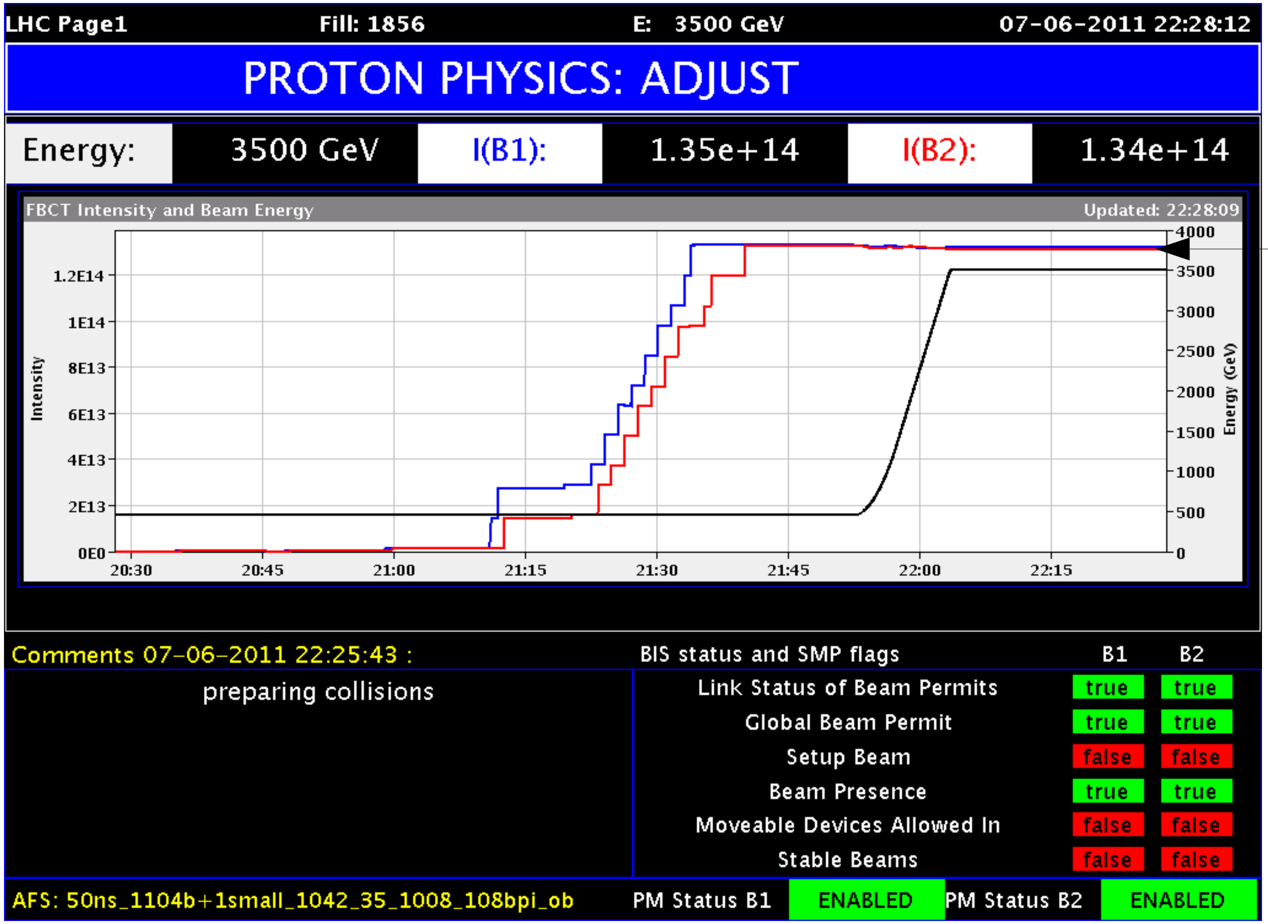


Mariusz Sapinski (BE/BI/BL) for BLM team

PH Detector Seminar

CERN, June 10th, 2011

LHC beam



76 MJ/beam

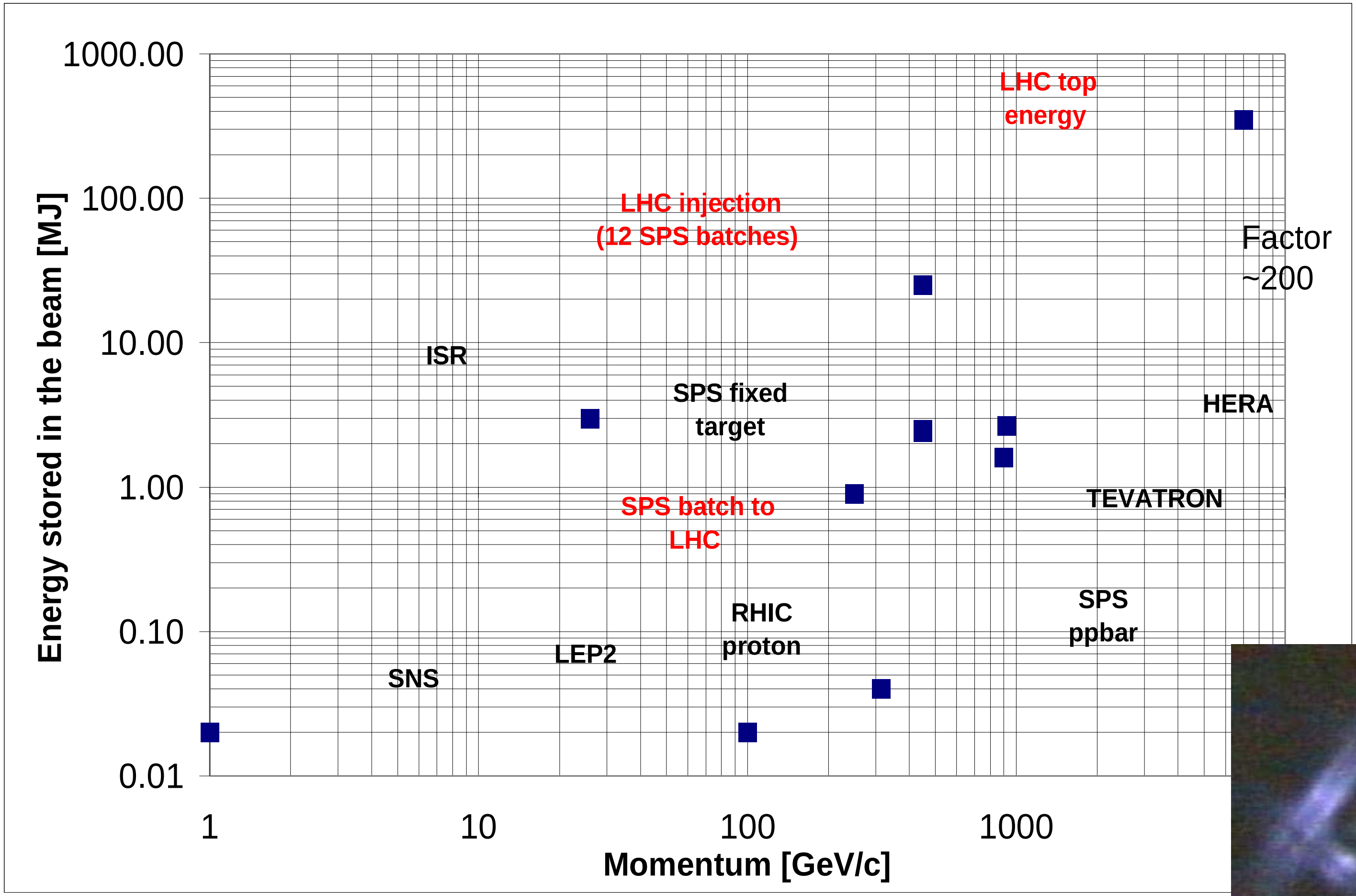
wikipedia.org:
1 MJ is approximately the kinetic energy of a one-tonne vehicle moving at 160 km/h

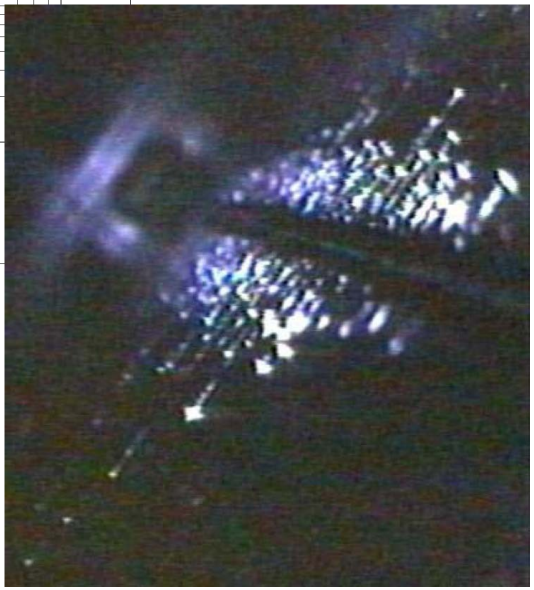
Final energy stored per beam: 362 MJ
but energy in the magnets: 10.4 GJ ... (A380 at 700 km/h)

Outlook

1. Motivation, machine protection
2. Non-LHC system example
3. LHC system specification
4. Reliability
5. Detector technology choice
6. Electronics
7. Data definition and flow
8. Typical loss locations
9. Loss examples (injection losses, UFOs)
10. Beam-abort thresholds
11. Limitations and developments

Motivation





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

Machine protection

Protection scheme against beam losses in superconducting magnets.

LOSS DURATION	PROTECTION SYSTEM
Ultra-fast loss	**Passive Components**
4 turns (356 μs) **Fast losses**	**+ BLM (damage and quench prevention)**
10 ms **Intermediate losses**	**+ Quench Protection System, QPS (damage protection only)**
10 s **Slow losses**	
100 s **Steady state losses**	**+ Cryogenic System**

+ numerous systems protecting against causes of the beam losses...

Beam Loss measurements (I)

BLM systems have 2 functions: protection and diagnostics.

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

Irregular losses can be produced by:
- Obstacles and falling objects (UFOs)
- Orbit changes (for instance due to magnet current error)
- Wrong setting of collimators
- Wrong tune
- Beam processes (luminosity, instabilities)
- Vacuum problems
- ...

Irregular losses may result in:
- Quenching superconducting magnet
- Unnecessary activation of accelerator elements and environment
- Single Event Upsets
- Damage of vacuum chamber

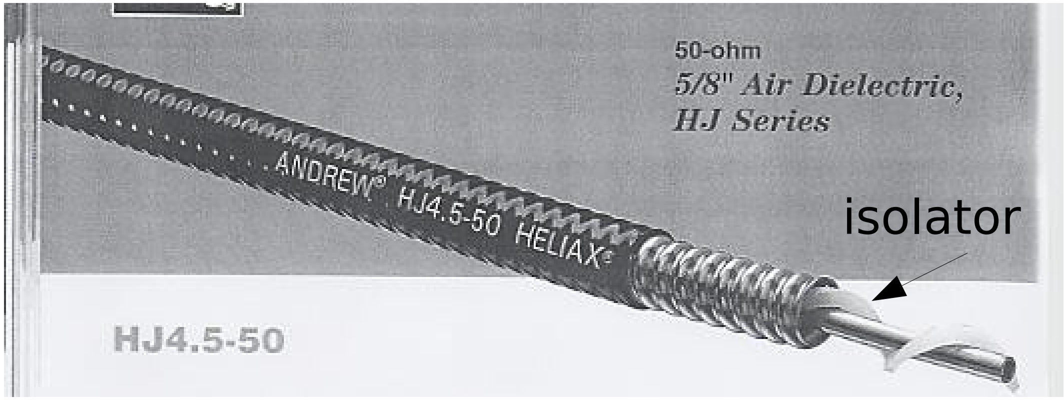
Beam Loss measurements (II)

BLM systems measures number of lost beam particles in a given location and in a given time interval.
One can try to mount BLM inside the vacuum chamber but for many reasons typically they are mounted outside: they measure particle shower.
Loss can be measured also by subtracting the signal of two beam current monitors – limited position resolution.

The most important BLM system parameters:
- Sensitivity
- Dynamic range
- Temporal resolution
- Spatial resolution
- Reliability
- Radiation hardness
- Availability
- Physical size

Non-LHC system example (I)

For instance: SLAC (cable) long ionization chamber



- Cheap, simple, covering 3 km of accelerator
- Isolation not too rad-hard
- Leakage current 0.1 pA/m
- Sensitivity 20 μC/Gy/m
  (LHC chamber 53 μC/Gy)
- Used for 20 years
- Position resolution 1.5 m

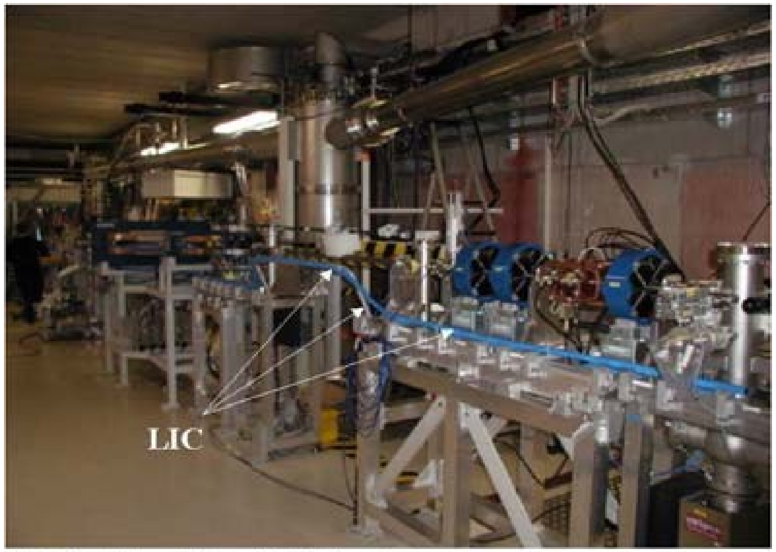
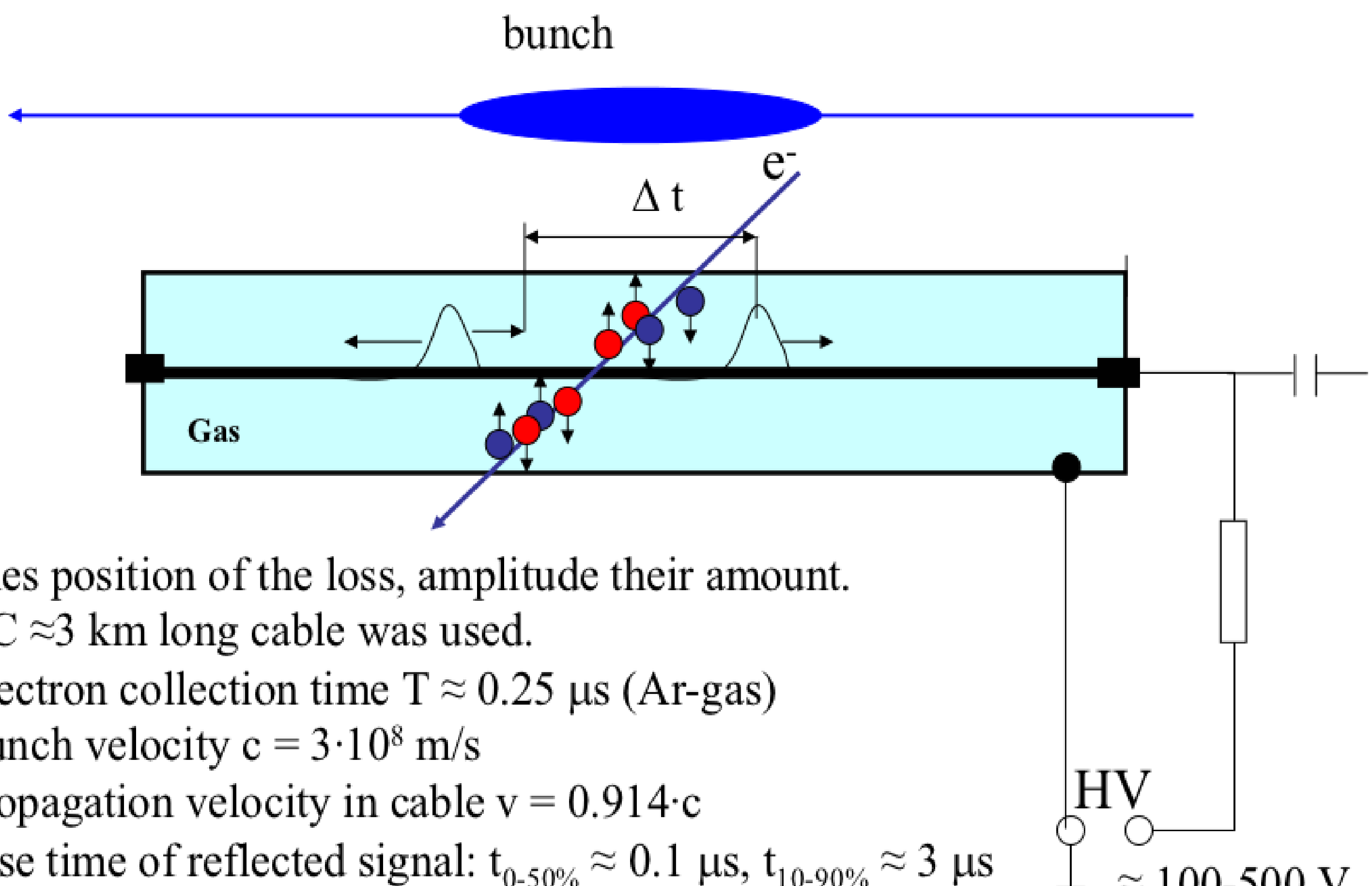


Fig. 1: *Installation of LIC at the ELBE beamline*

Non-LHC system example (II)

SLAC (cable) long ionization chamber – position resolution



Δ t defines position of the loss, amplitude their amount.
At SLAC ≈3 km long cable was used.

- Electron collection time T ≈ 0.25 μs (Ar-gas)
- Bunch velocity $c = 3 \cdot 10^8$ m/s
- Propagation velocity in cable $v = 0.914 \cdot c$
- Rise time of reflected signal: $t_{0\text{-}50\%} \approx 0.1$ μs, $t_{10\text{-}90\%} \approx 3$ μs

Position resolution ≈ 1.5 m (≈ 5 ns) downstream end
≈ 15 m (≈ 50 ns) upstream end (6 km travel)

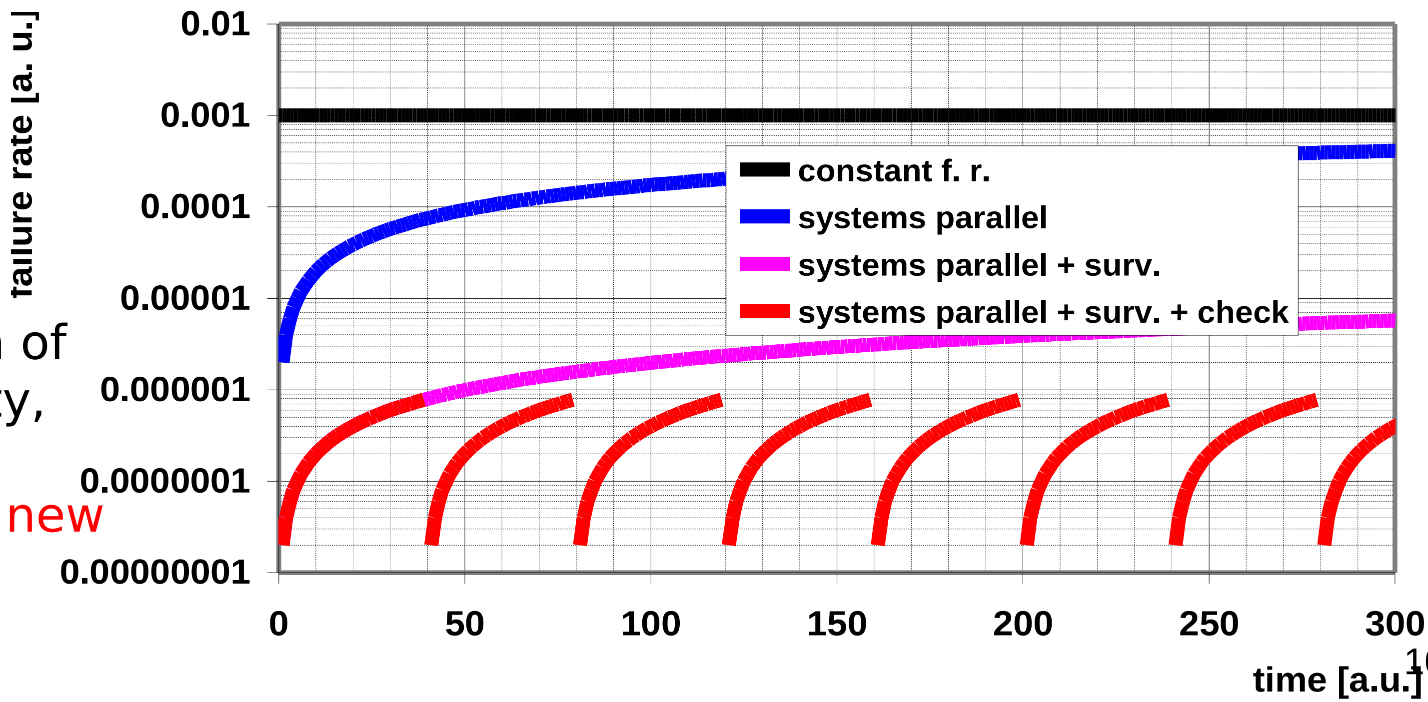
LHC system specification

Main document dates 2002-2004 (based on previous studies).

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:



Verification of functionality, system as good as new

BLM sanity check

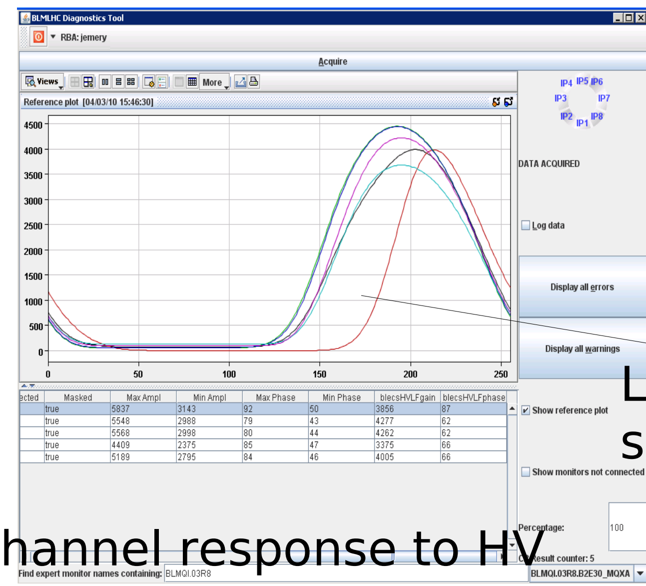
Check which runs before every fill:

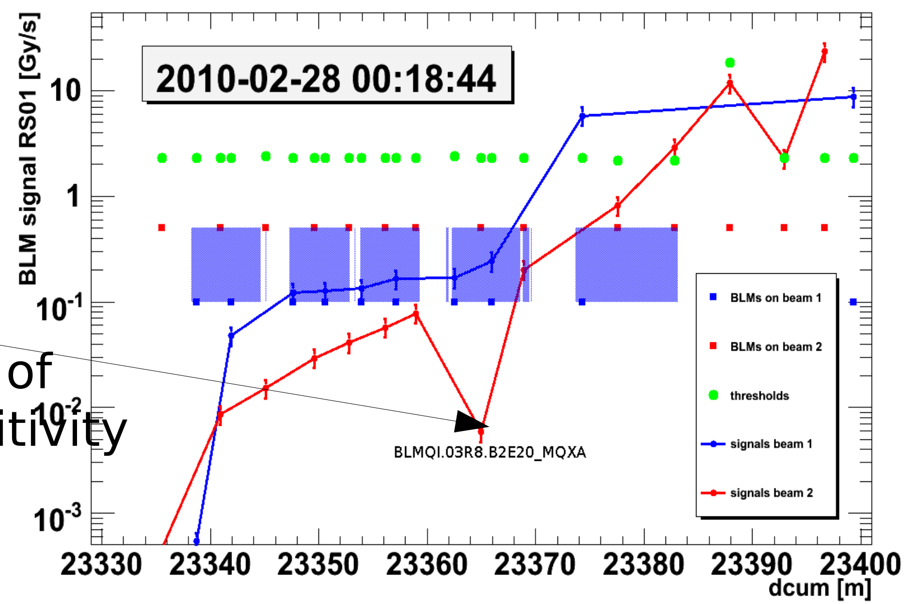
<u>Connectivity check</u>

Detects non-conformities of cabling, verify HV, can detect issues in the tunnel electronics.

<u>Internal beam permit check</u>

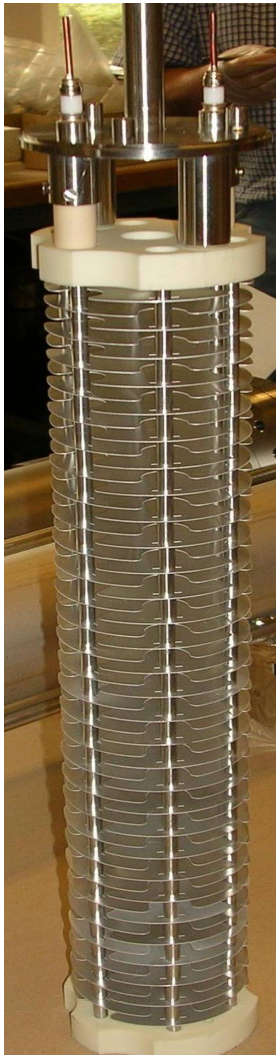
Verify ability of every threshold comparator to send beam dump request.





Loss of sensitivity

channel response to HV modulation



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

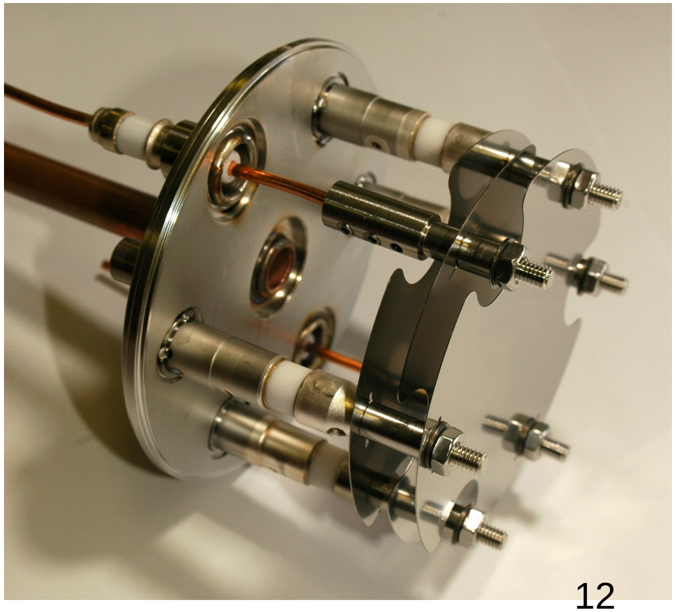
Low pass filter at the HV input

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)

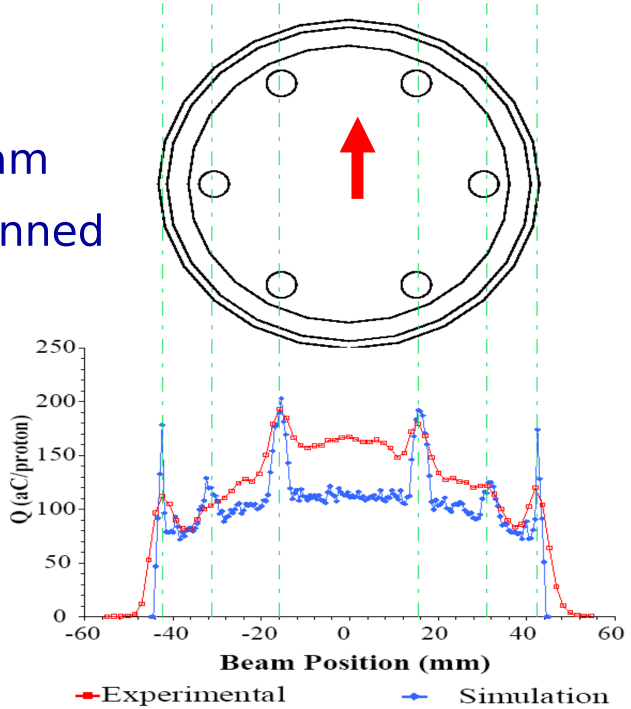


LHC Detector choice (II)

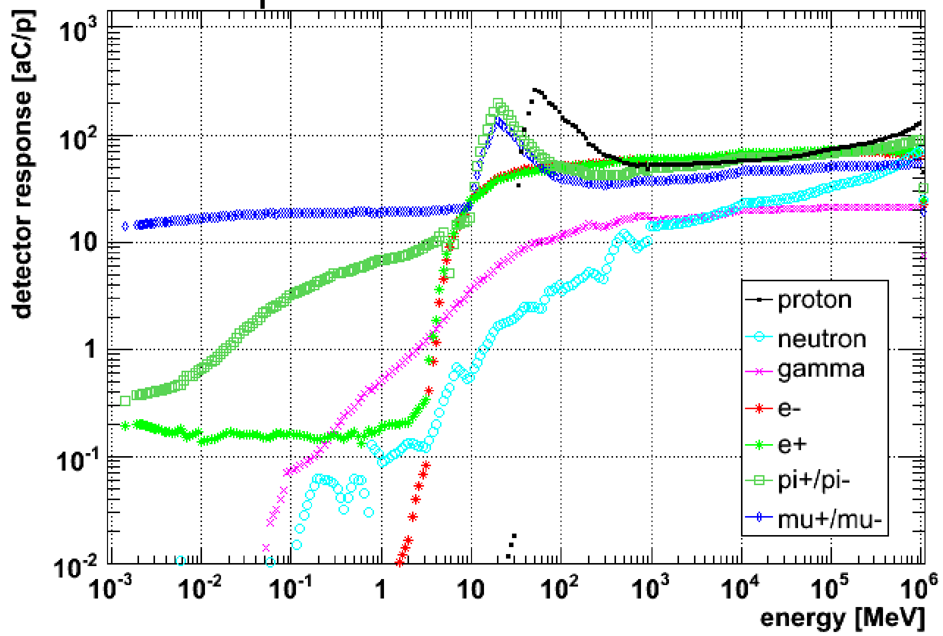
Ionization chamber properties

Beam

scanned



response functions

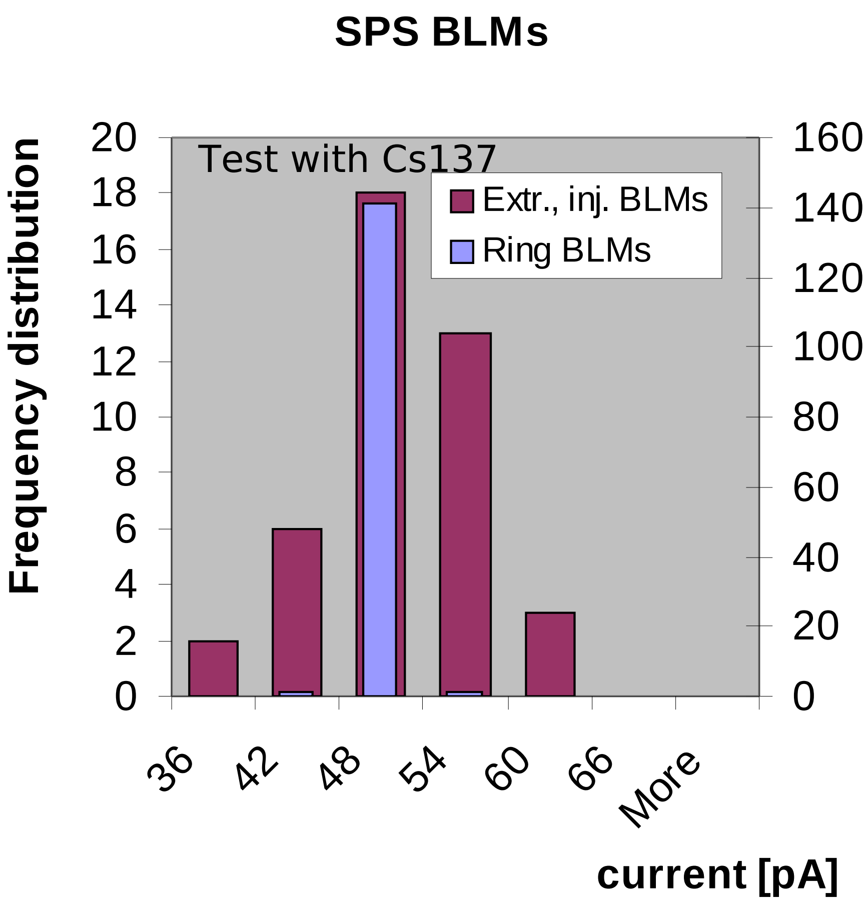


beam tests

simulations

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

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

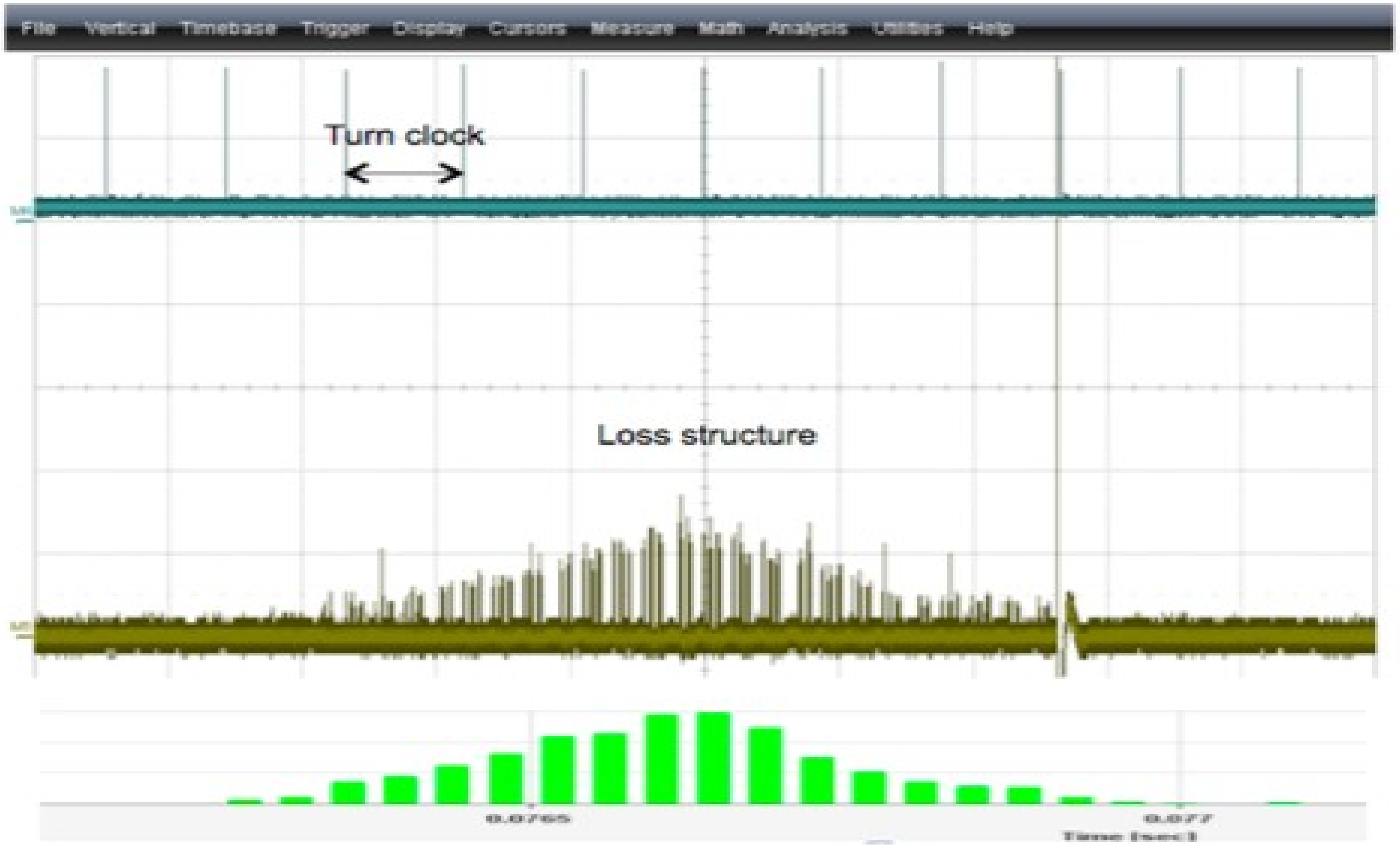
Reliable component

LHC Detector choice (IV)

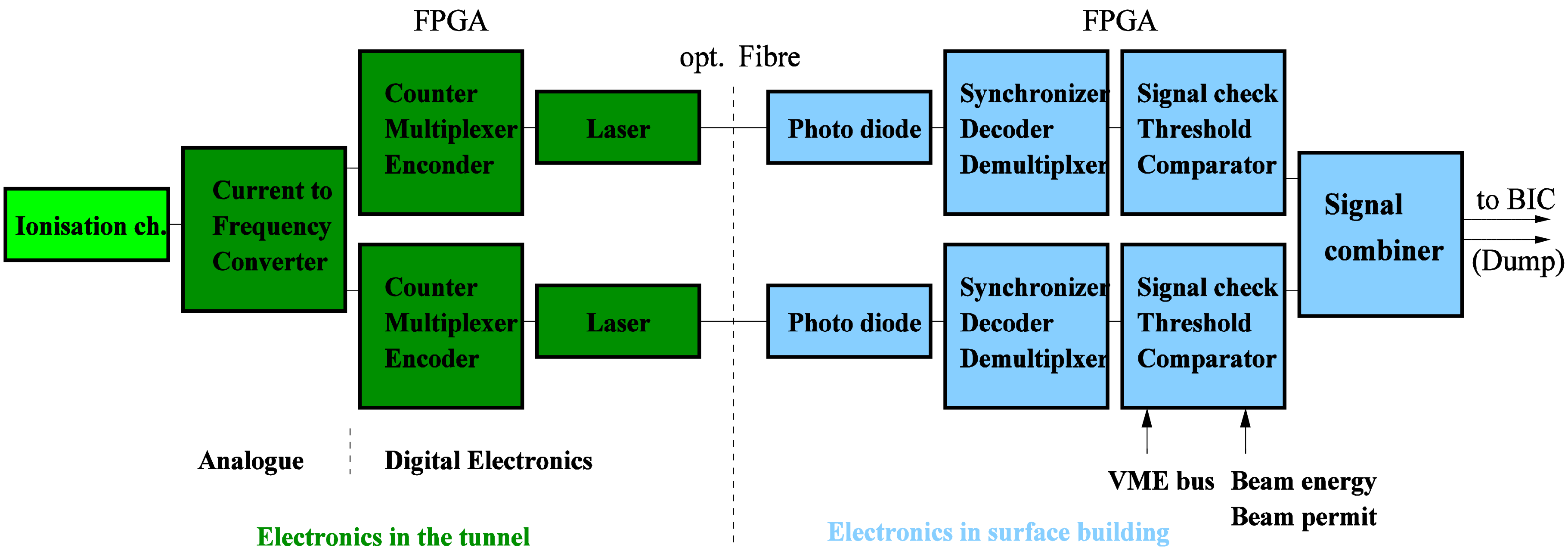
New detectors:

- Little ionization chamber (with lower gas pressure) – lower sensitivity
- Fast diamond detectors (like beam condition monitors of CMS/ATLAS)

  - they allow bunch-by-bunch measurement of beam loss.



Electronics



Analog front-end FEE

Current to Frequency Converters (CFCs)
Analogue to Digital Converters (ADCs)
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

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

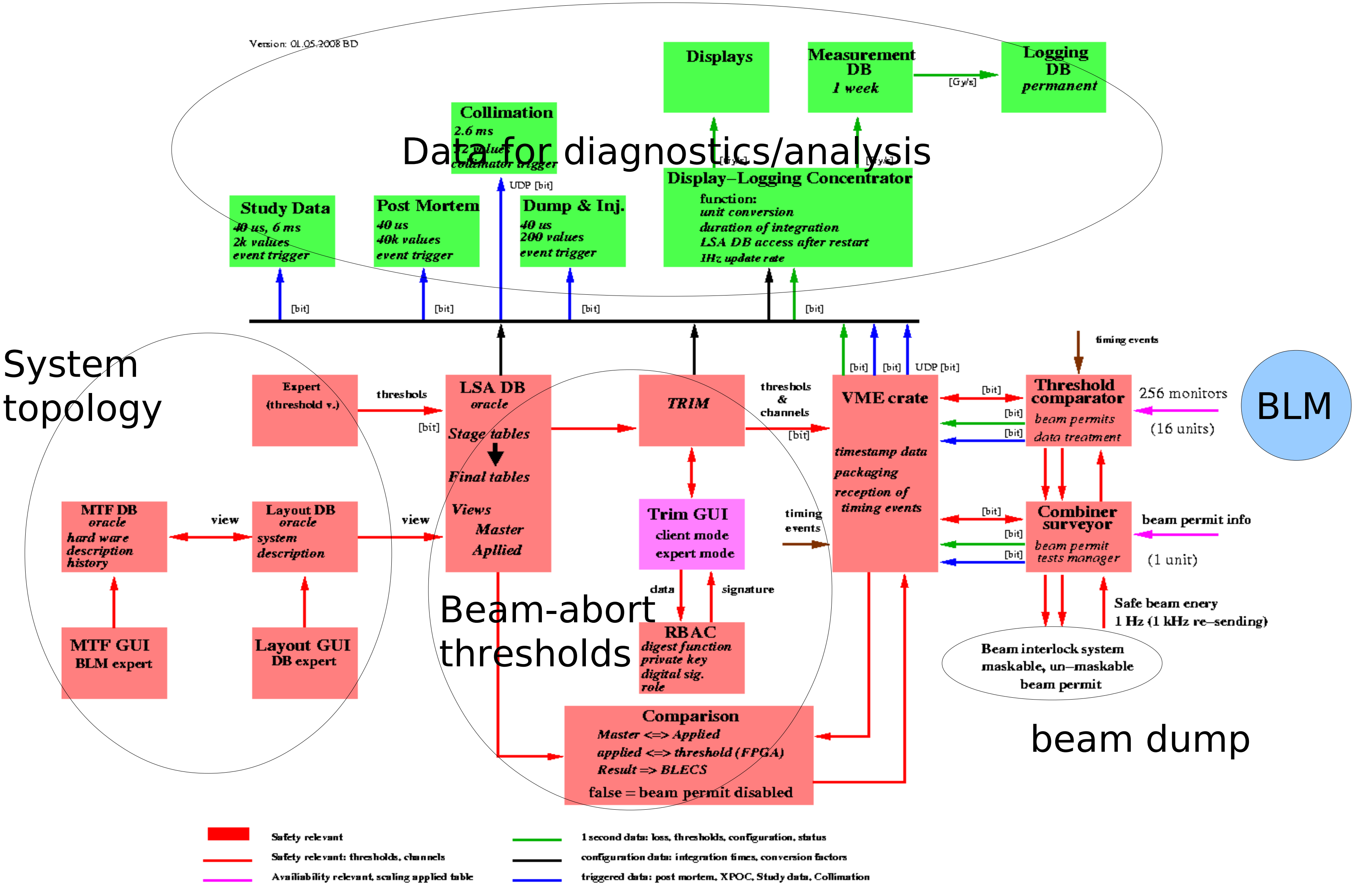
The 40 µs time windows are assembled into 12 running sums:
40 µs, 80 µs, 320 µs, 640 µs, 2.56 ms, 10.24 ms, 81.92 ms, 0.655 s, 1.31 s, 5.24 s. 20.97 s, 83.89 s.

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

We cannot save all data.
Data are logged in LHC Logging DB with initial frequency of 1 Hz, further reduced after 1 week for permanent storage.
(Logging DB is Oracle, solutions more adequate for large-scale data mining are being investigated).

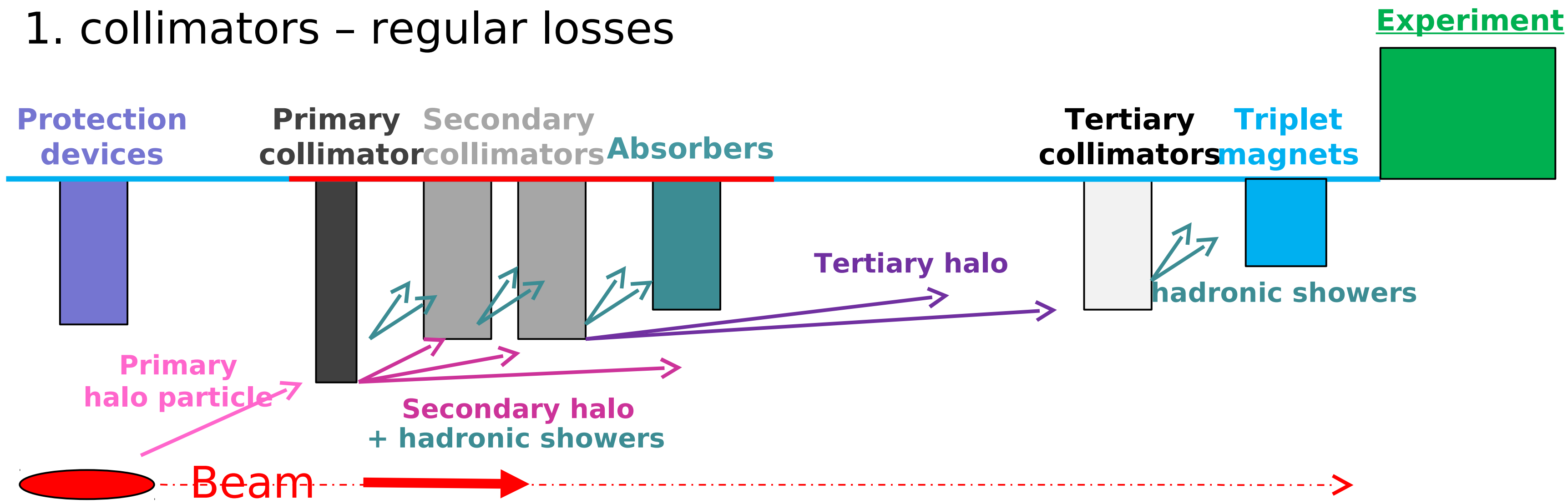
In addition there are special buffers (PostMortem, Study) which store a given number of 40 µs time windows and which can be recovered under special conditions (eg. beam dump).

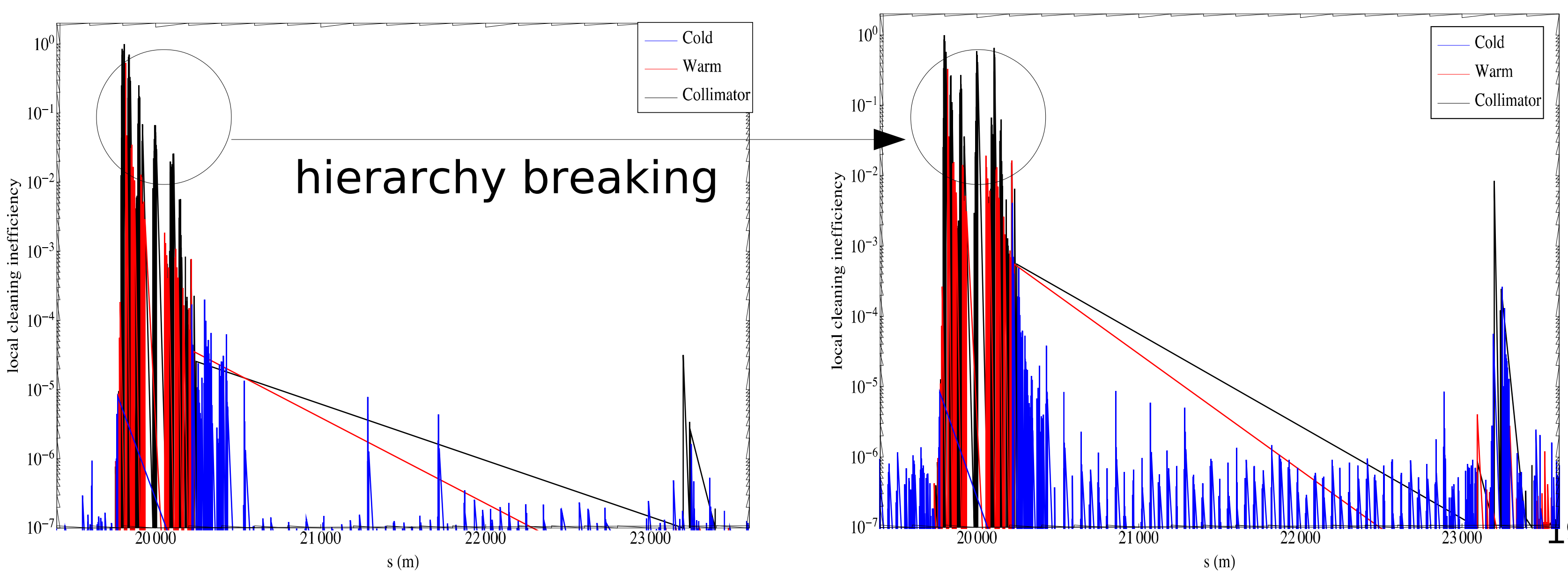
Data diagram



Typical loss locations (I)

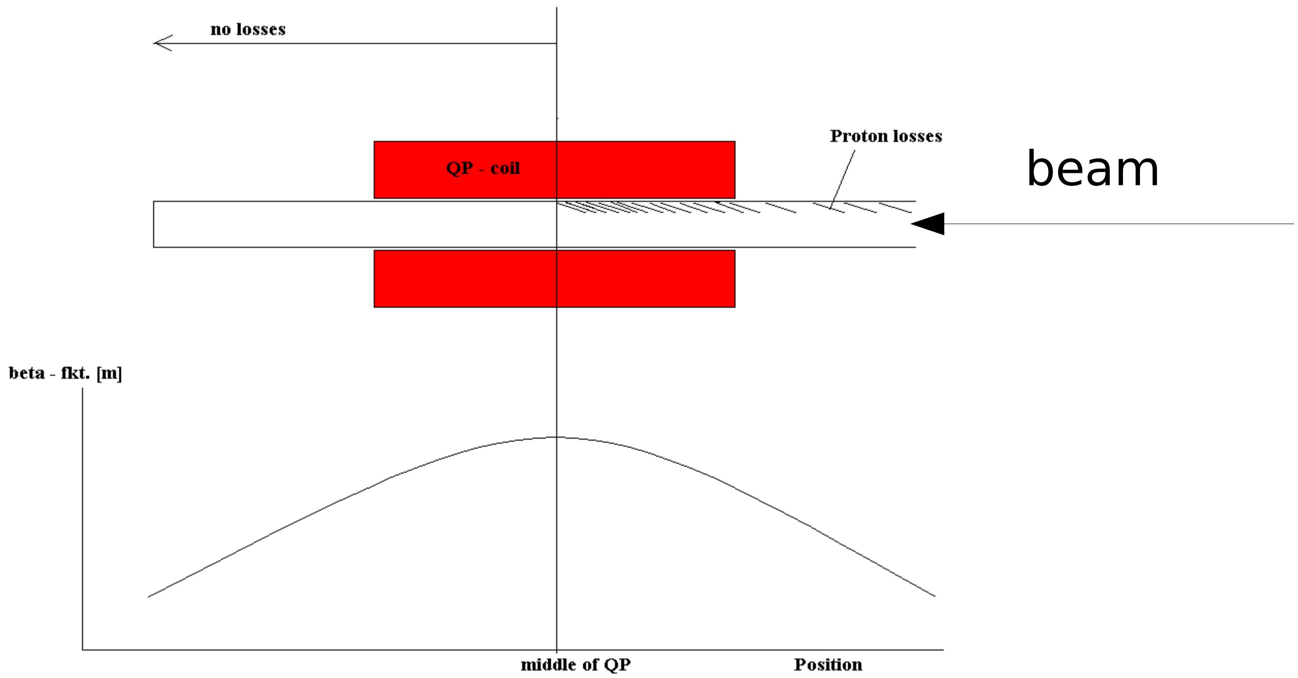
1. collimators – regular losses





Typical loss locations (II)

2. quadrupole magnets – more probable losses

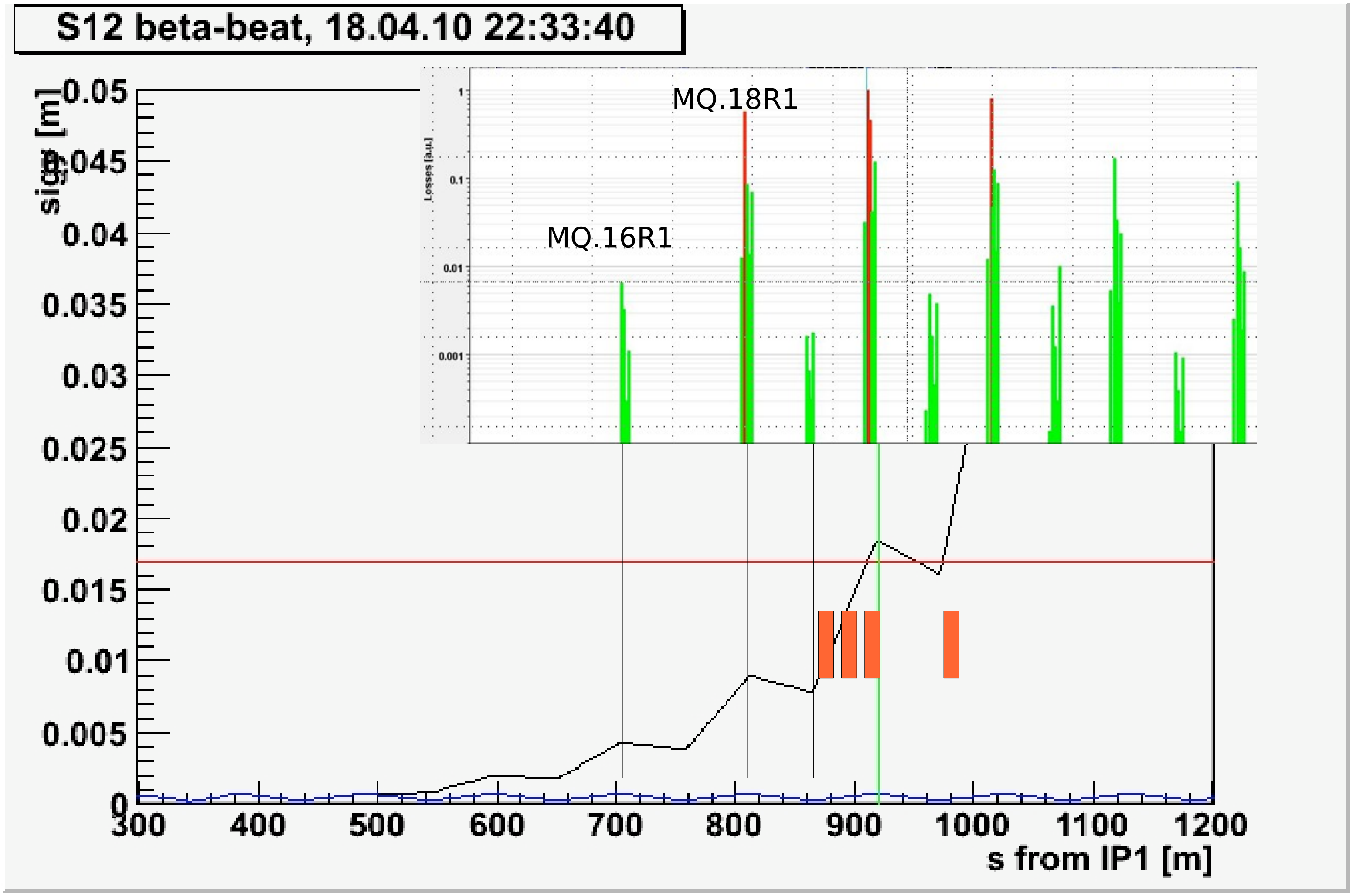


Due to optics functions, for norminal orbit, particles are first lost in places with a large β-function and/or dispersion: quadrupoles and dispersion suppressor.

3. In addition: in the injection region, around the experiments (luminosity losses).

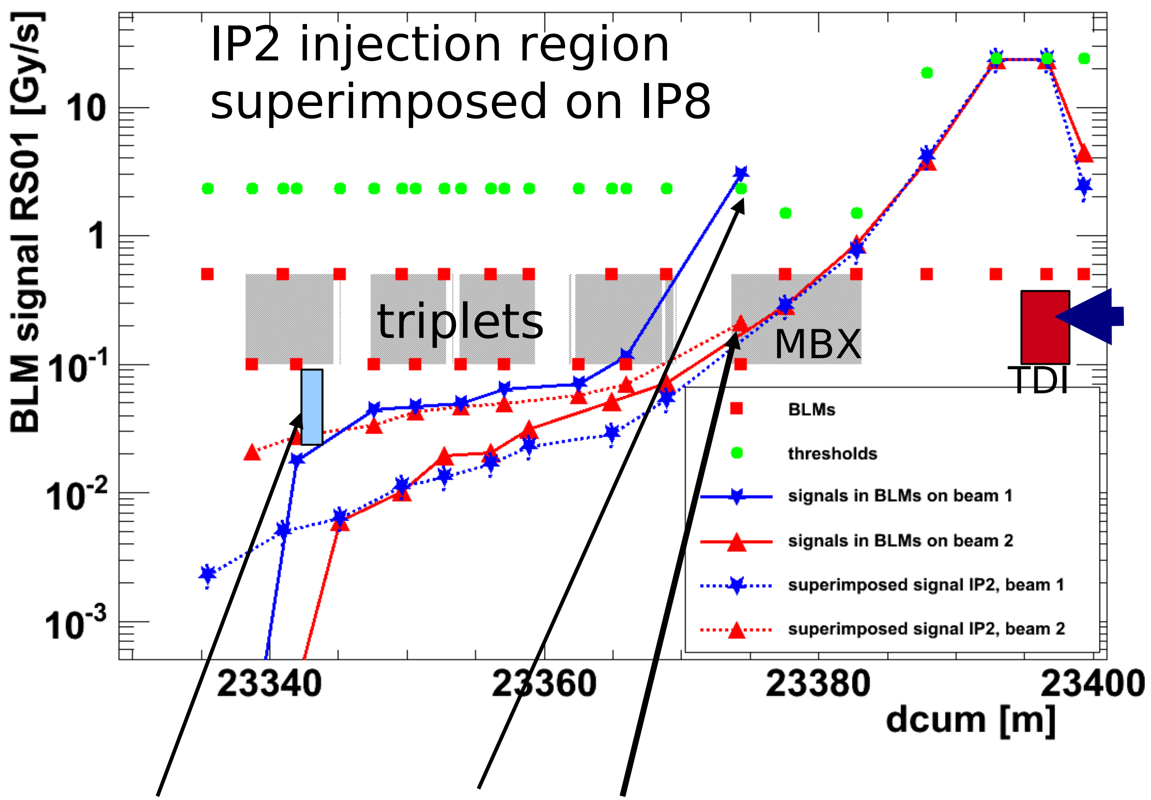
Examples of losses (I)

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



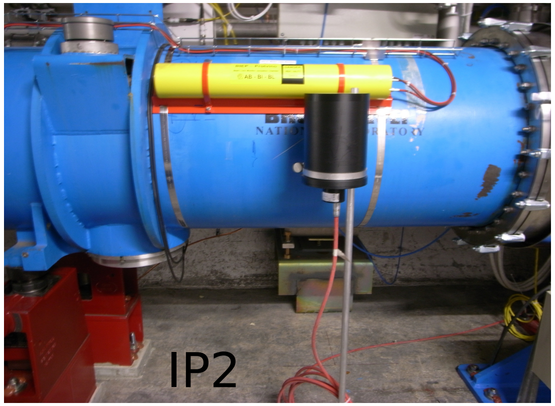
Examples of losses (II)

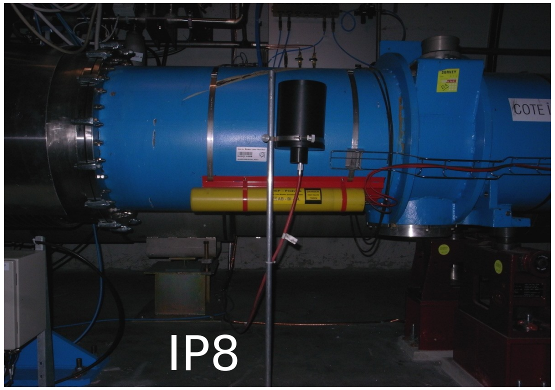
Loss at overinjection



chicane in IP8

IP8 and IP2 asymmetry
at overinjection



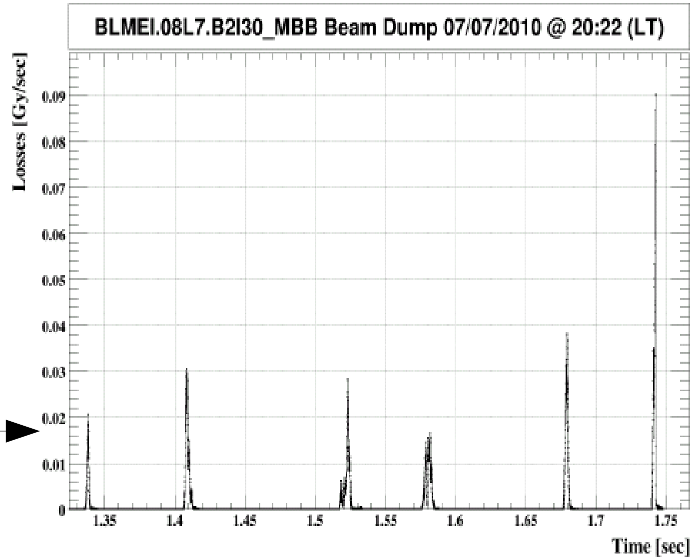


Examples of losses (III): UFOs

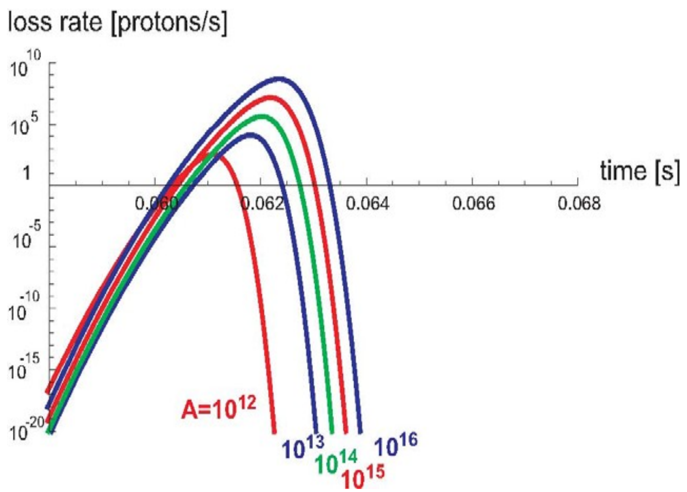
UFOs are sudden losses lasting about 0.5-2 ms.

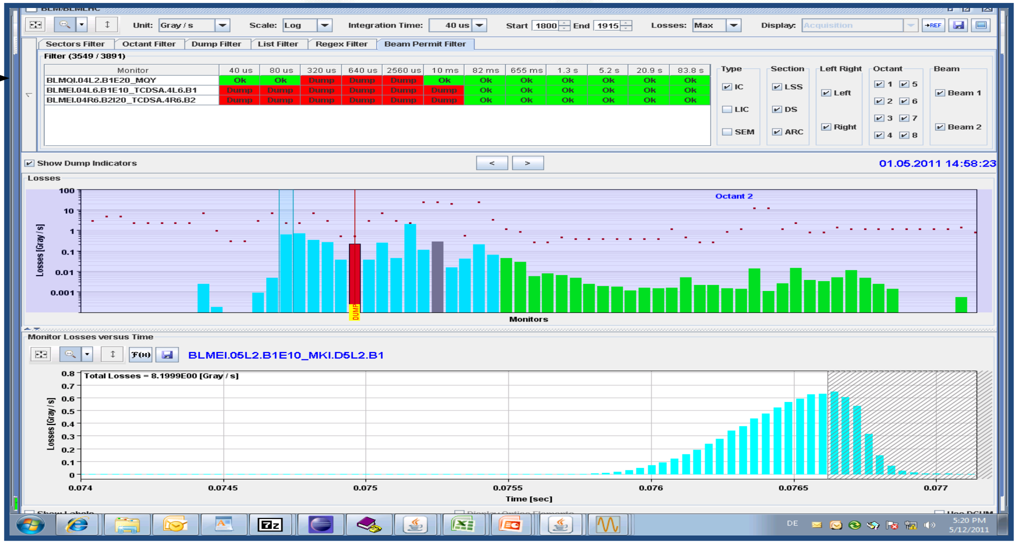
Sometimes they dump the beam (exceeding BLM thresholds).

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



UFO from May 1st, 2011



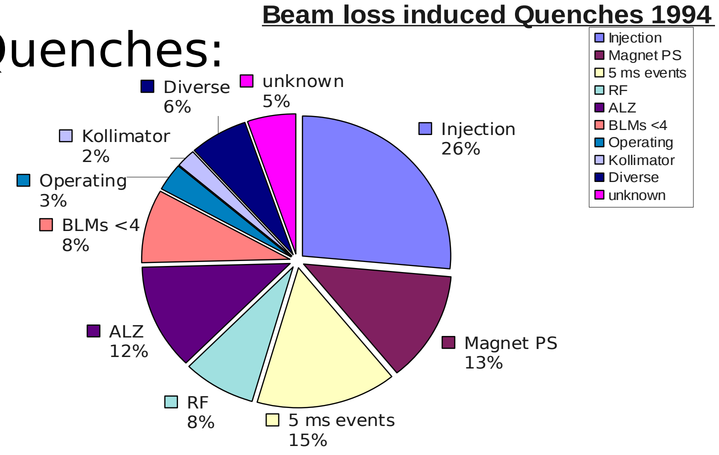


Beam-abort thresholds (I)

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

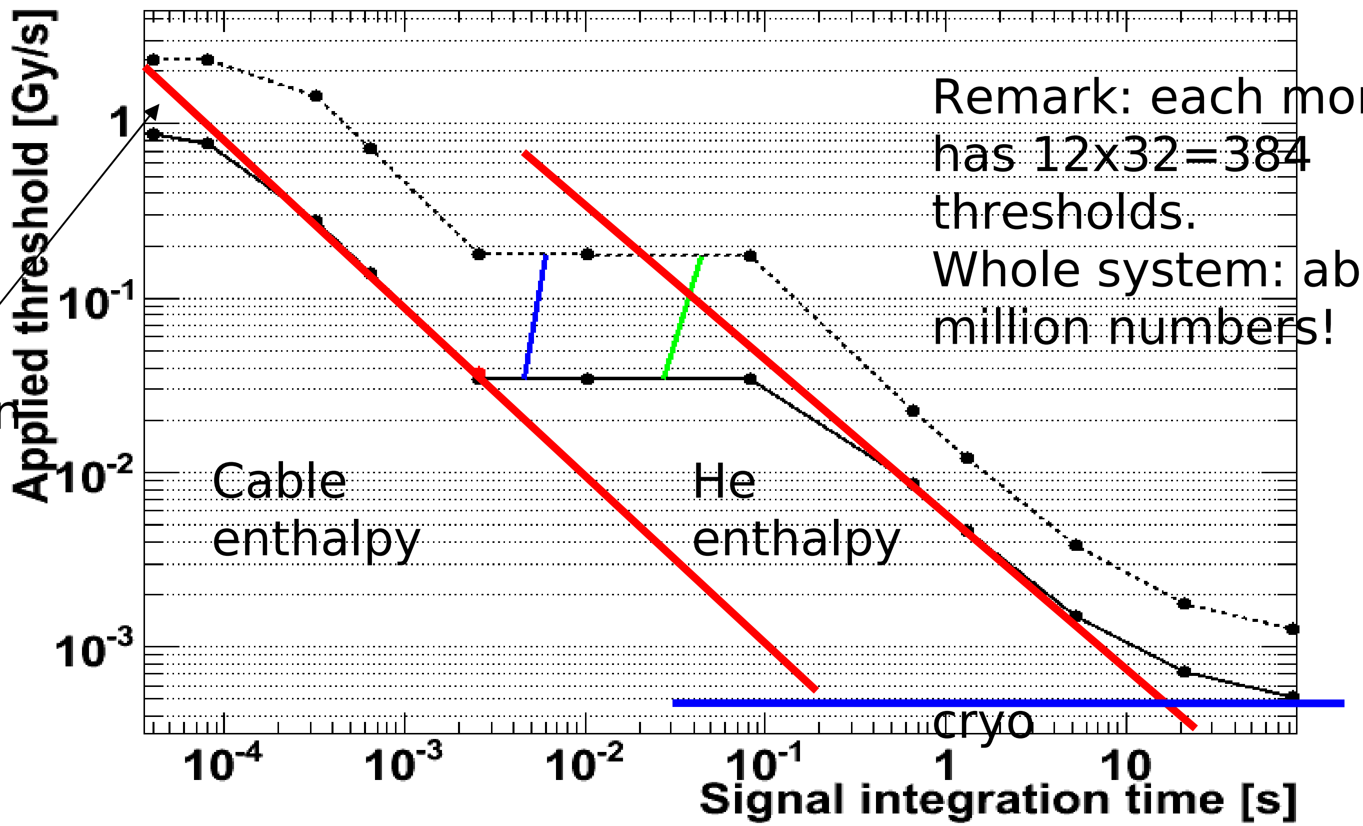
LHC, since injection tests in 2008: 11 quench events, only two at 3.5 TeV (intentional - both tests)

It came as a surprise that LHC is not quenching – because of a very good orbit stability (and other reasons).

Beam-abort thresholds (II)

Typical threshold on cold magnet based on LHC Note 44:

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



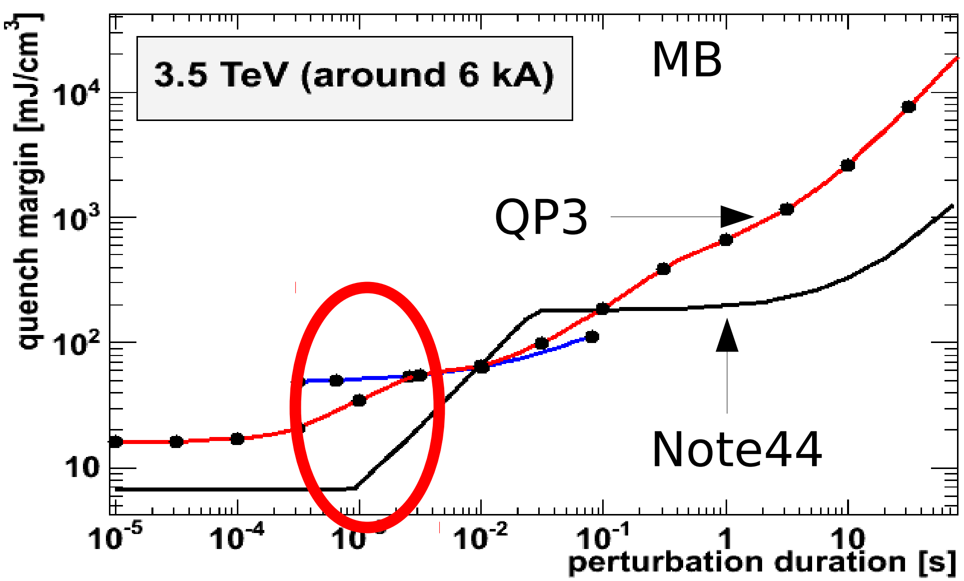
filter correction

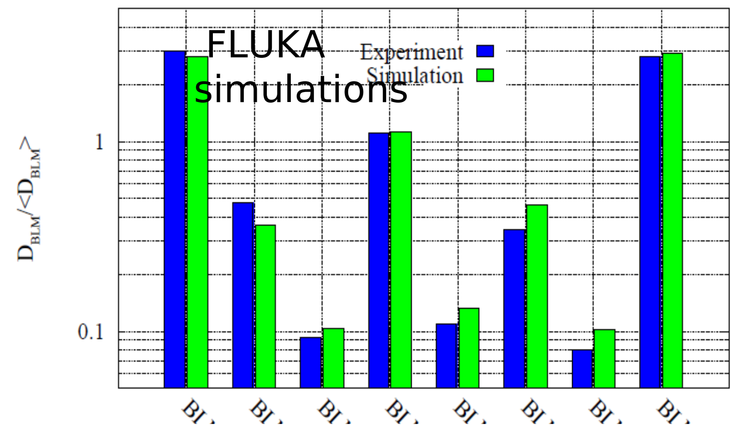
Remark: each monitor has 12x32=384 thresholds.
Whole system: about 1.5 million numbers!

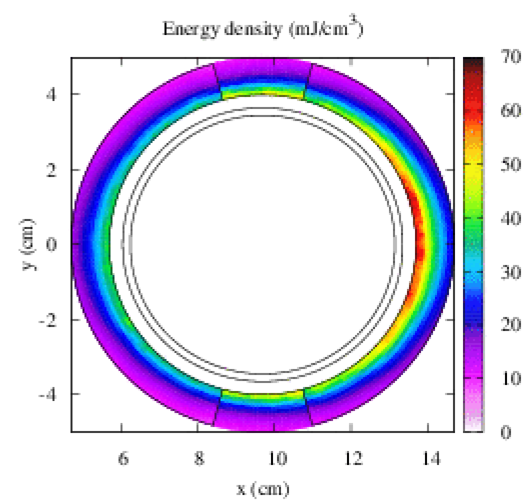
Based on Monte-Carlo, heat transfer codes and quench tests.

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





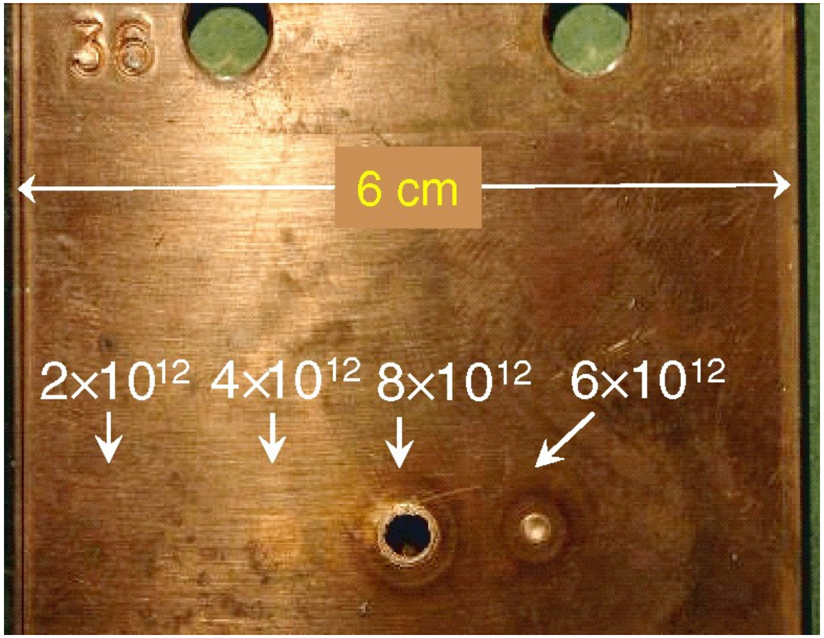


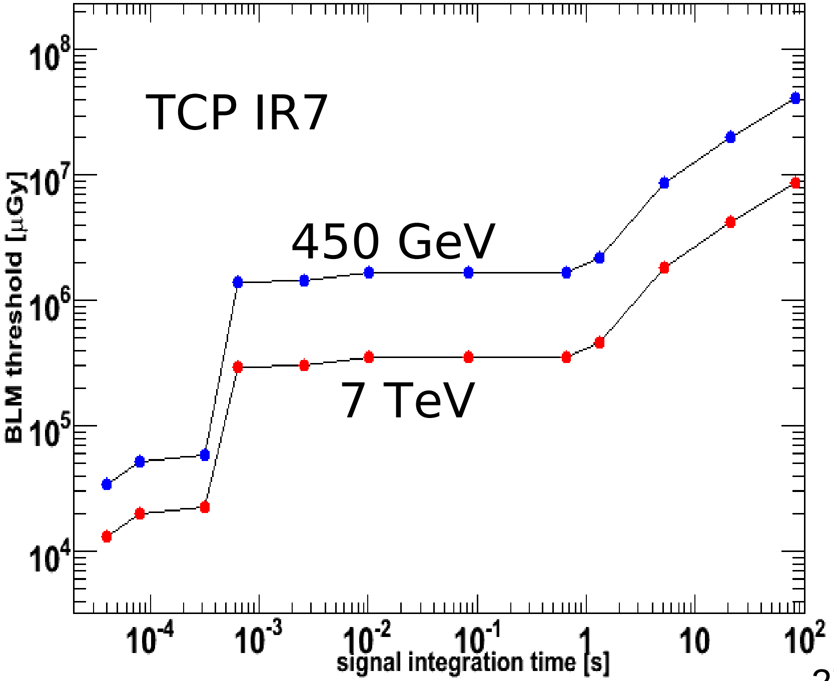
Max E_{dep}
FLUKA: 62.5 mJ/cc
QP3: 38 mJ/cc (preliminary)
we call it a good agreement

Beam-abort thresholds (IV)

Warm magnets – conditions to compute thresholds:
- short loss: should not be damaged
- long loss: should not be overheated (about 100 C)

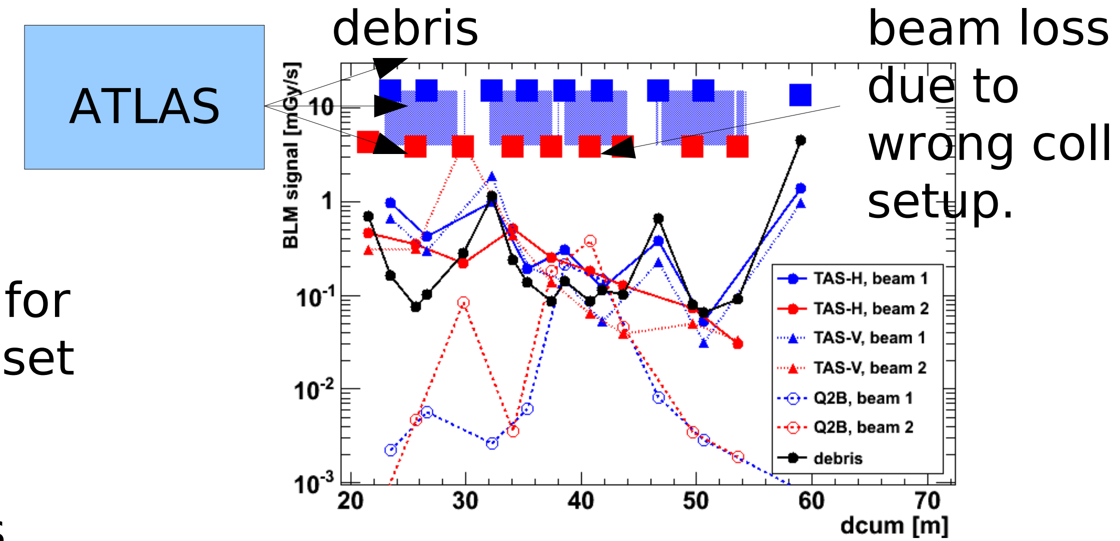
Collimators:
thresholds typically far from damage level, determined by assumed beam lifetime and hierarchy.





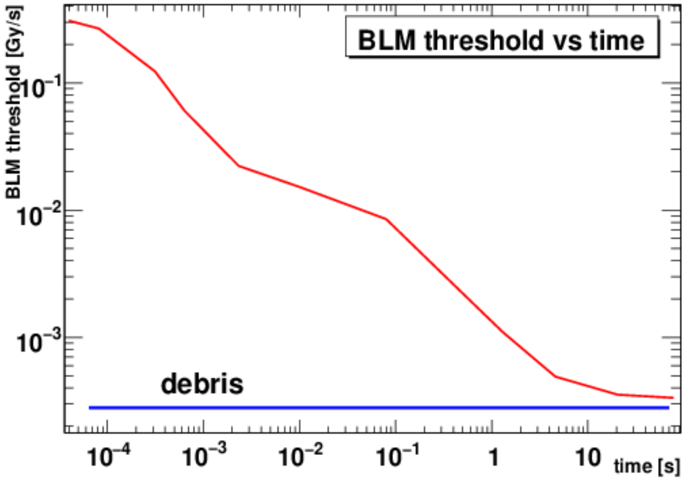
Limitations

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.



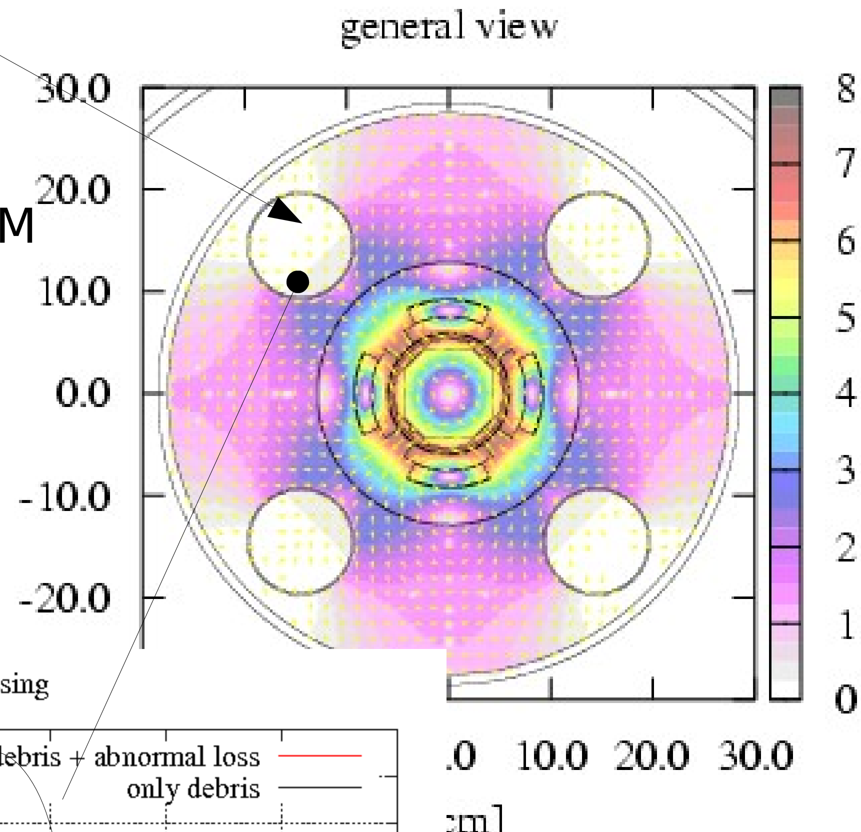
Development

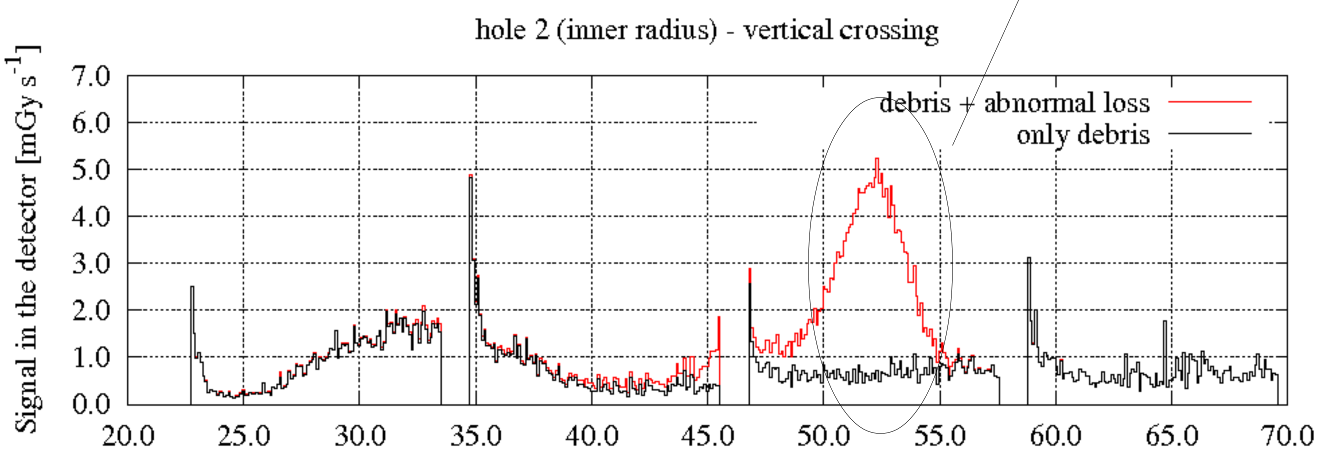
Idea: put BLM detectors closer to magnet coil.

Cryogenic BLMs undergo first tests right now at T9 beamline in East Hall.

Yesterday signals from Si and Diamond detectors were measured at 1.9 K.

current BLM position





Summary

Beam Loss Monitoring system is crucial for safety of LHC machine.

It plays a crucial role in beam diagnostics.

It is a complex but very reliable system (basically no spurious beam dumps have been observed up to now).

There are interesting developments ongoing.

Thank you for your attention!

Additional slides