Beam Loss Monitoring for LHC Machine Protection

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TIPP 2011

June10, 2011

Chicago, USA

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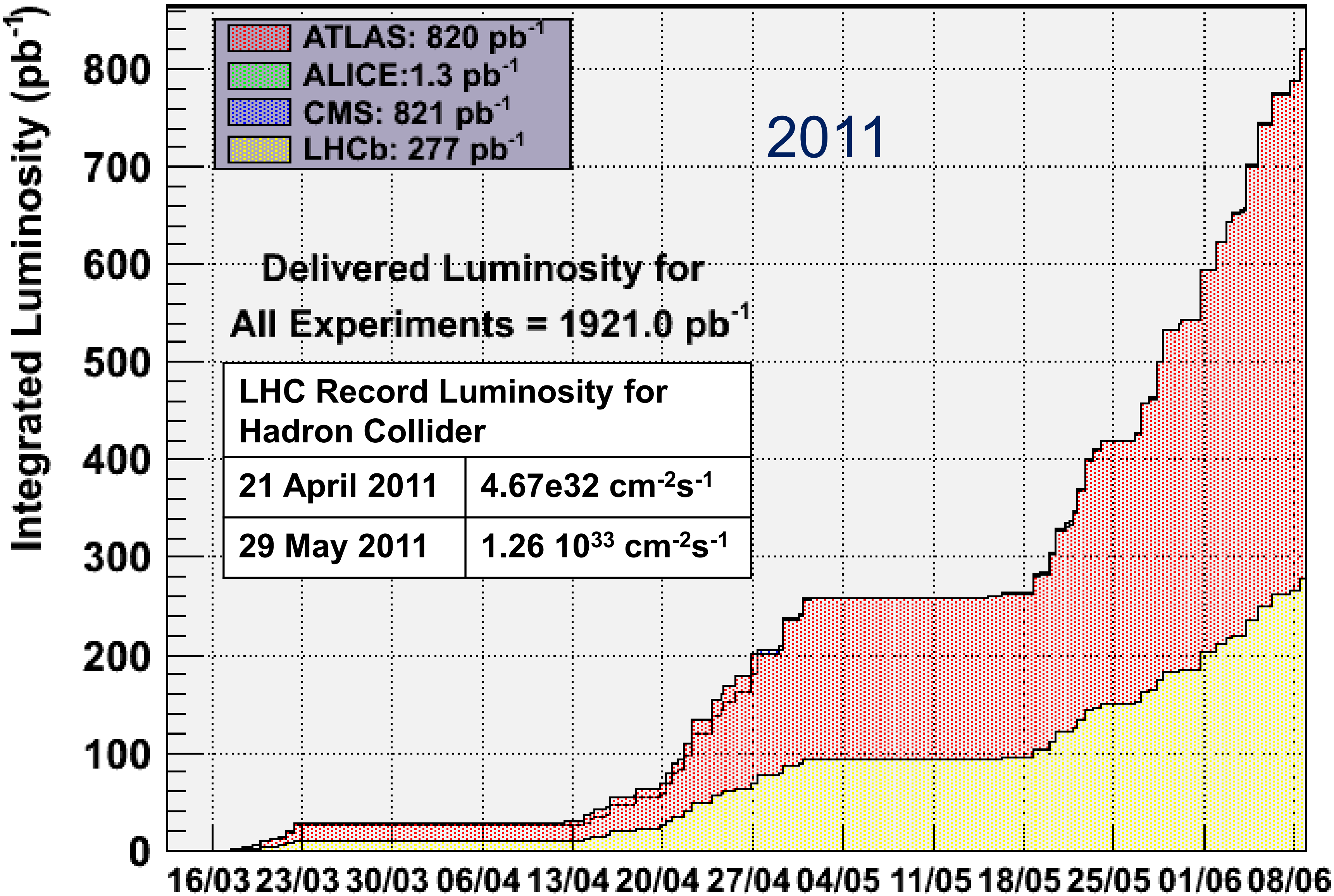
Content

- Status of the LHC
- The BLM system
- Operational experience
- Fast (ms-time-scale) losses, UFO: Unidentified Falling Object
- BLMs and Collimation – Examples
- Summary

Luminosity Production



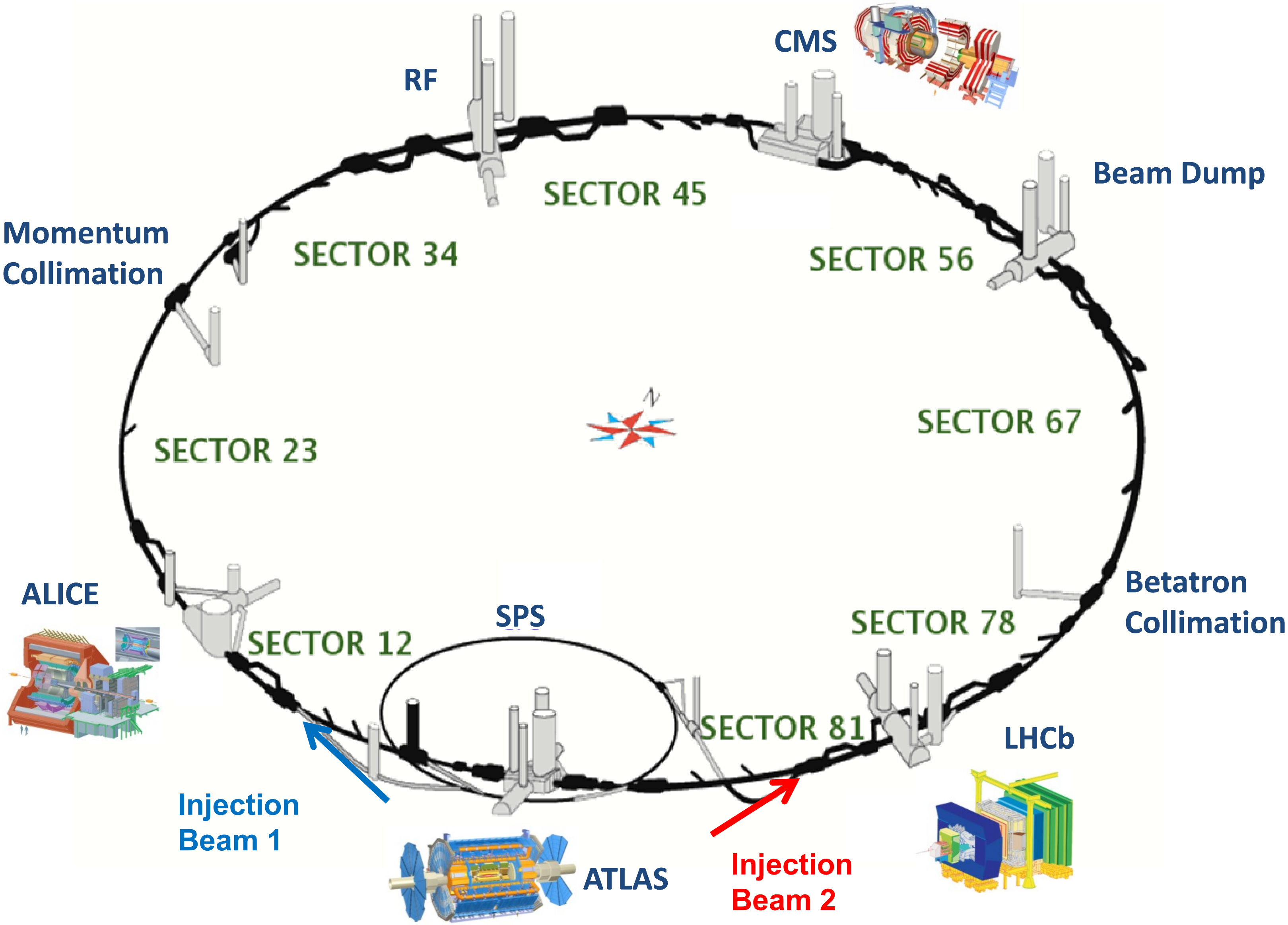
Current LHC Parameters

	Current	Nominal	
Energy/beam	3.5 TeV	7 TeV	
Bunch spacing	50 ns	25 ns	
Bunches/beam	1092 (3.5 TeV)	2808	x 2.6
Bunch intensity	1.2 x 10^{11}	1.15 x 10^{11}	
Intensity/beam	1.3 x10^{14} p	3.2 x 10^{14} p	x 2.5
Peak luminosity	1.26 x 10^{33} $cm^{-2}s^{-1}$	1.0 x 10^{34} $cm^{-2}s^{-1}$	x 8
Long emittance (4σ)	≈ 1.9 eVs (3.5 TeV)	2.5 eVs (7 TeV)	
Trans. Norm. Emittance	≈ 2 – 2.5 μm rad (3.5 TeV)	3.75 μm rad (7 TeV)	
Energy/beam	73 MJ	362 MJ	x 5

Records from Atlas as of 6 June 2011

	Record	Date
Peak Stable Luminosity Delivered	1.26×10^{33}	29 May 2011
Maximum Luminosity Delivered in one fill	46.61 pb^{-1}	1 June 2011
Maximum Luminosity Delivered in one day	46.84 pb^{-1}	2 June 2011
Maximum Luminosity Delivered in 7 days	201.05 pb^{-1}	30 May thru 5 June 2011
Maximum Peak Events per Bunch Crossing	14.01	23 April 2011
Longest Time in Stable Beams for one fill	17.9 hours	23 April 2011
Longest Time in Stable Beams for one day	19.7 hours (82.1%)	27 March 2011
Longest Time in Stable Beams for 7 days	93.0 hours (55.4%)	27 April 2011
Fastest Turnaround to Stable Beams	2.4 hours	16 April 2011

LHC Layout



RF
CMS
Beam Dump
Momentum
Collimation
SECTOR 45
SECTOR 34
SECTOR 56
SECTOR 23
SECTOR 67
N
ALICE
SPS
SECTOR 12
SECTOR 78
Betatron
Collimation
SECTOR 81
LHCb
Injection
Beam 1
ATLAS
Injection
Beam 2

Stored Energy Challenge

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

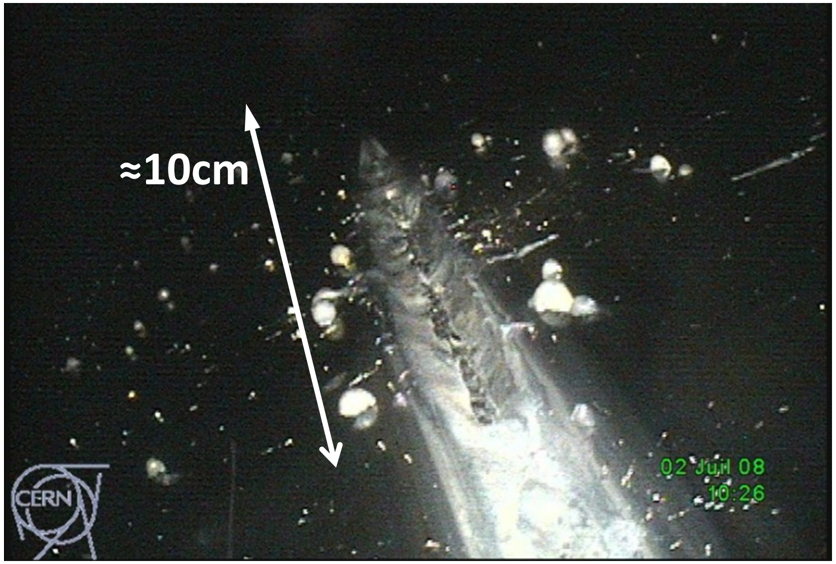
Quench and Damage at 7 TeV	
Quench level	≈ 1mJ/cm^3
Damage level	≈ 1 J/cm^3

- 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

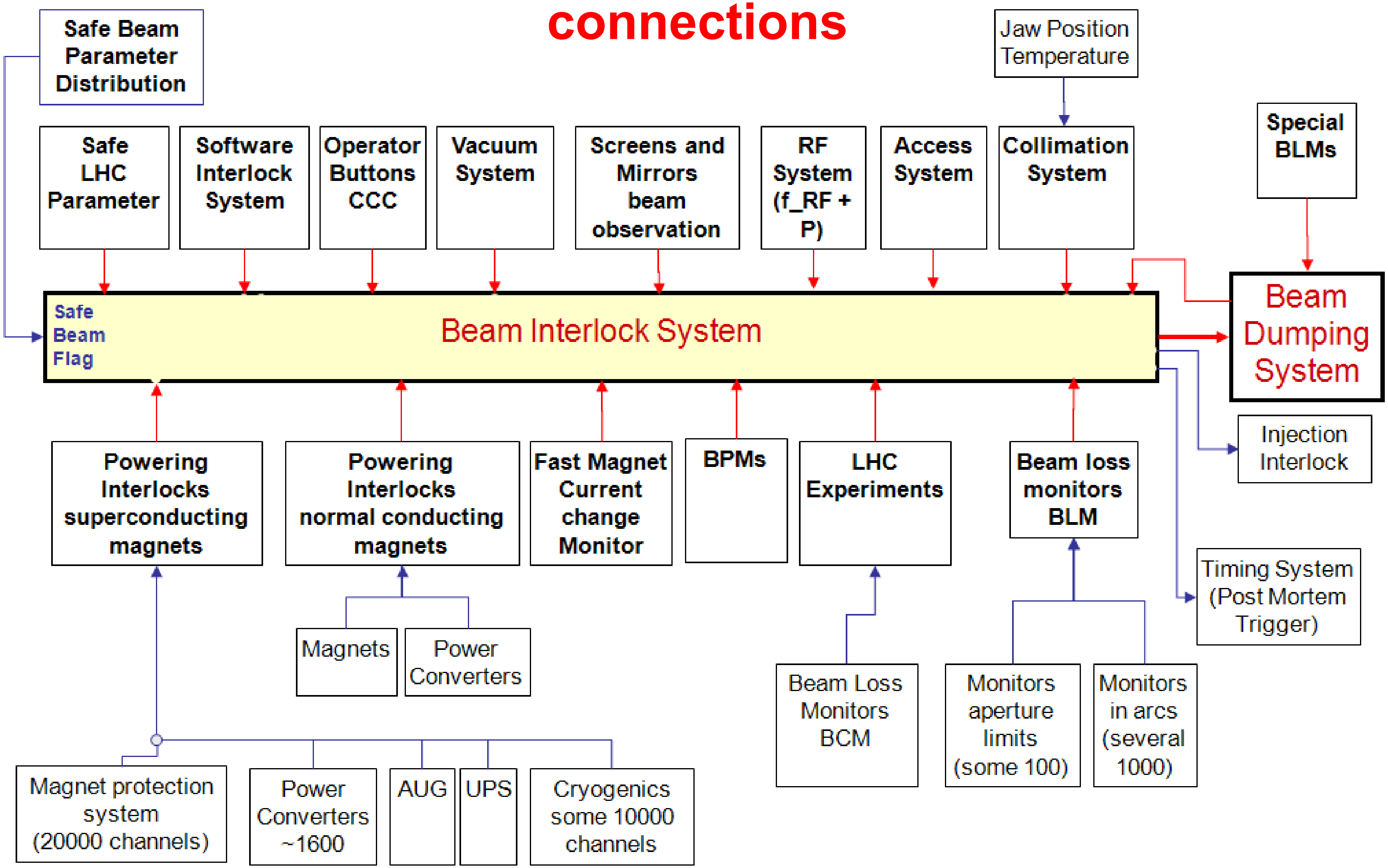
400 GeV beam with **2 MJ**

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

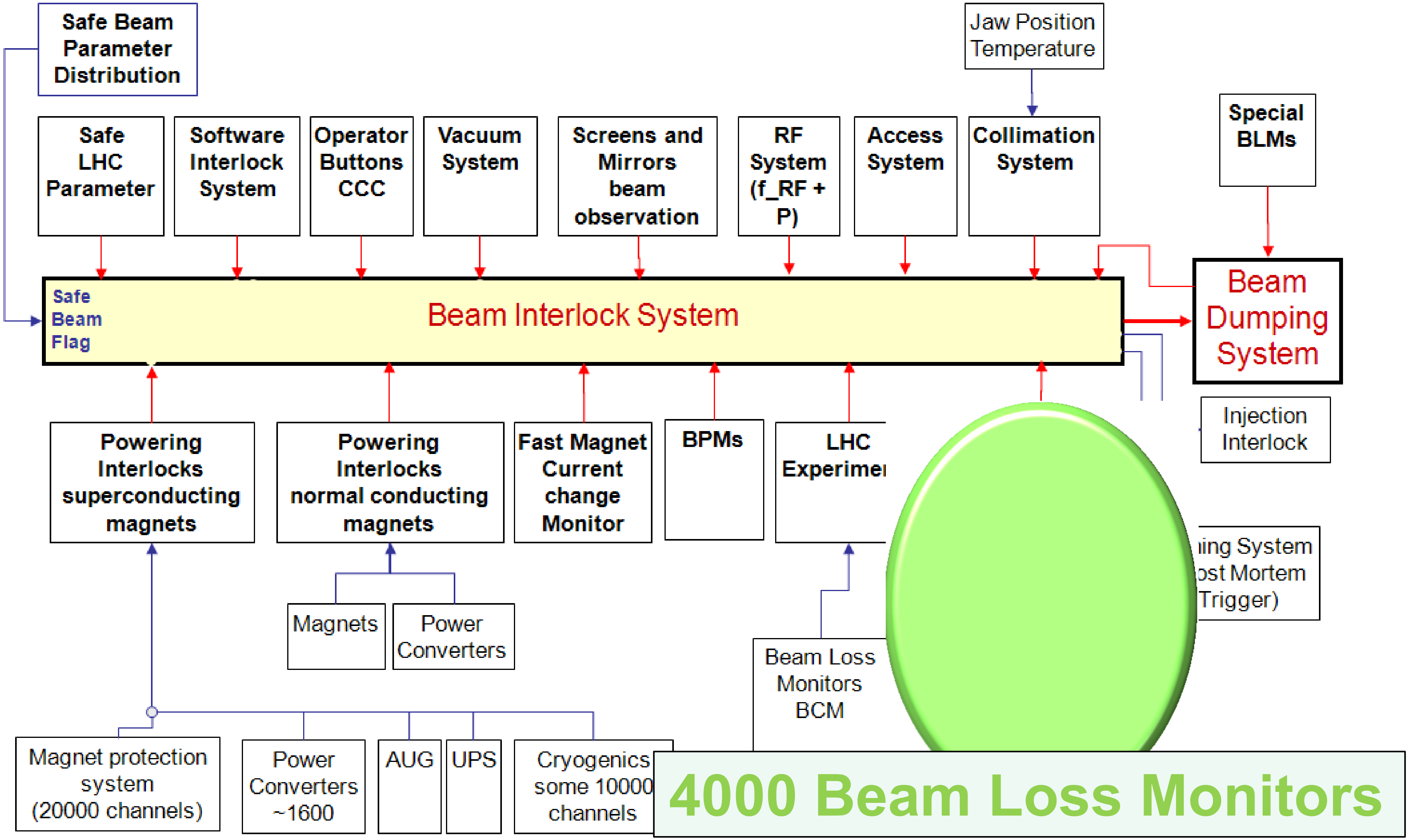


Machine Protection System

Several 10.000 channels from ≈ 250 user input connections



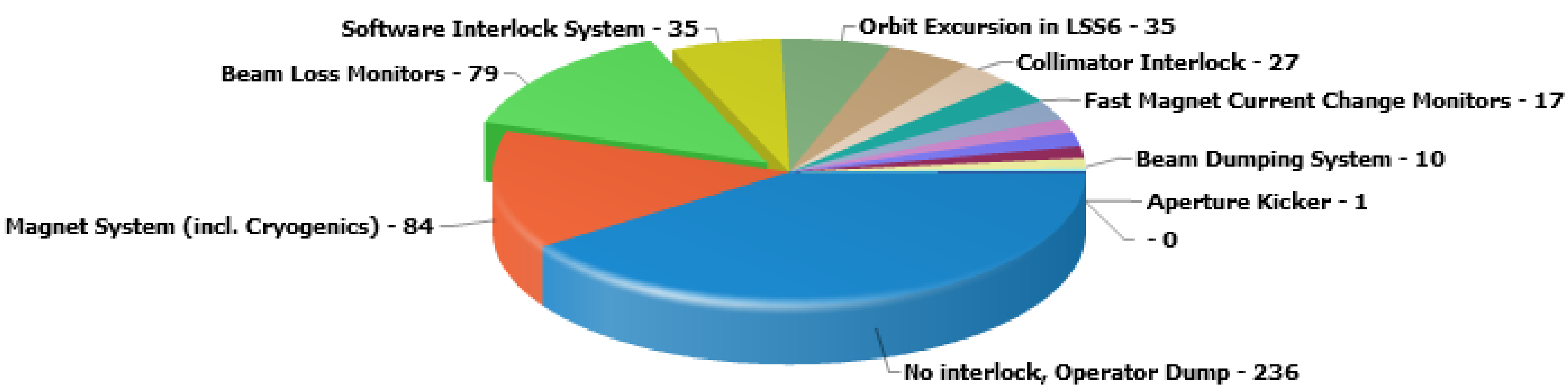
Machine Protection System



2010 and 2011 beam aborts above injection energy

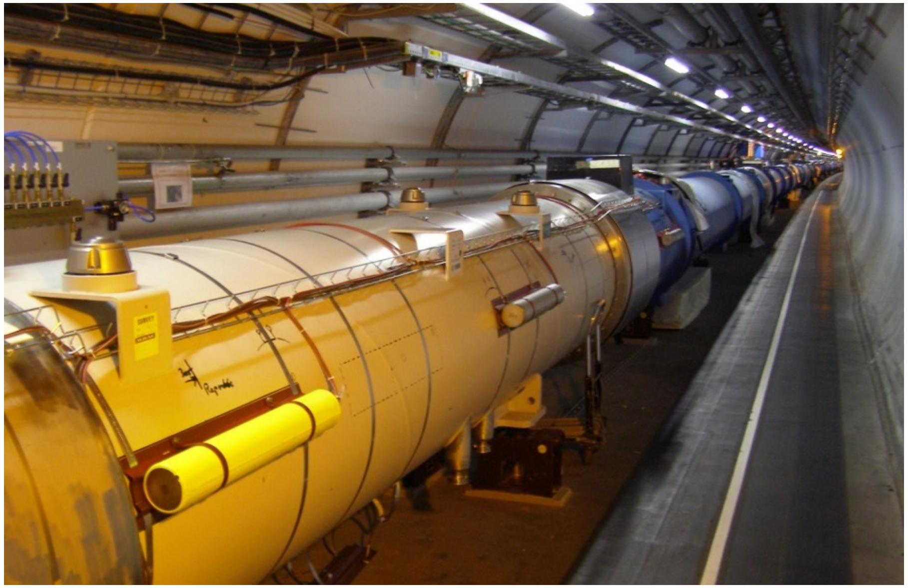
Which system saved us / dumped the beam

BLMs: 23% of the protection dumps

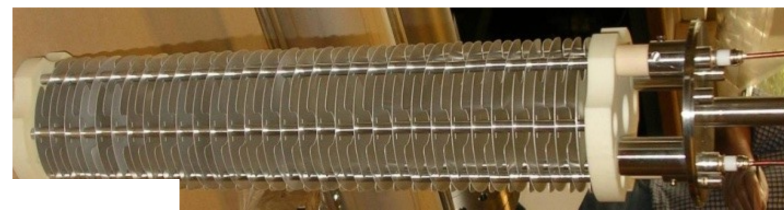


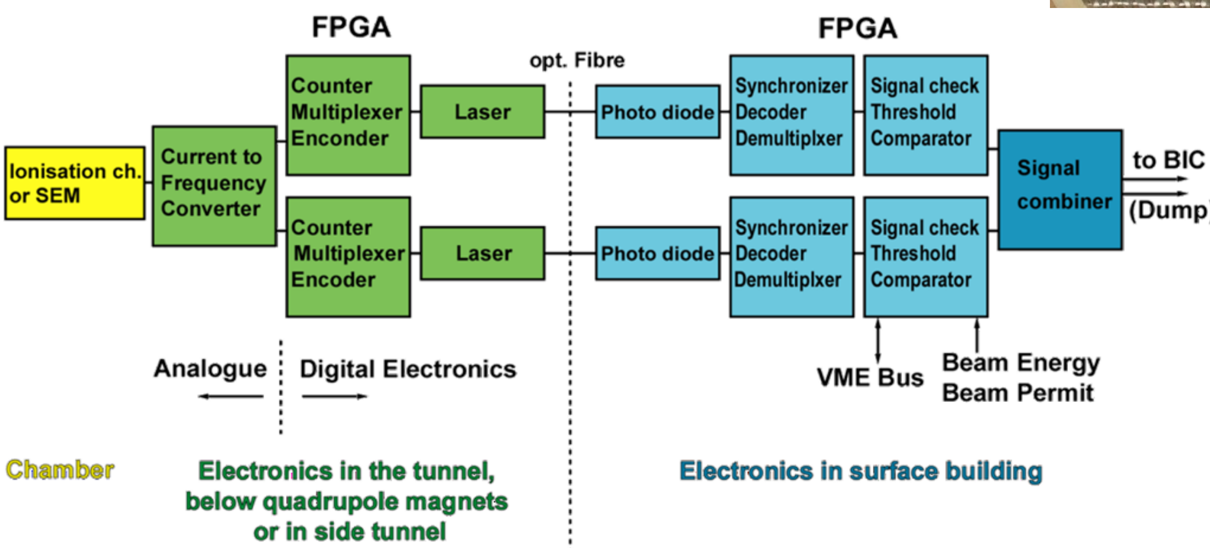
Introduction to the BLM System

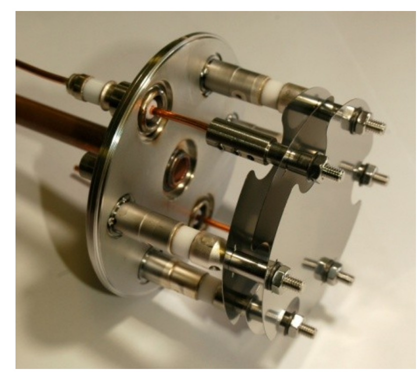
Beam Loss Measurement System Layout



- **Main purpose: prevent damage and quench**
- 3600 Ionization chambers (**IC**) **interlock** (97%) and observation
- 300 Secondary emission monitors (**SEM**) for observation







Beam Abort Thresholds

- 12 integration intervals: 40μs to 84s (32 energy levels)

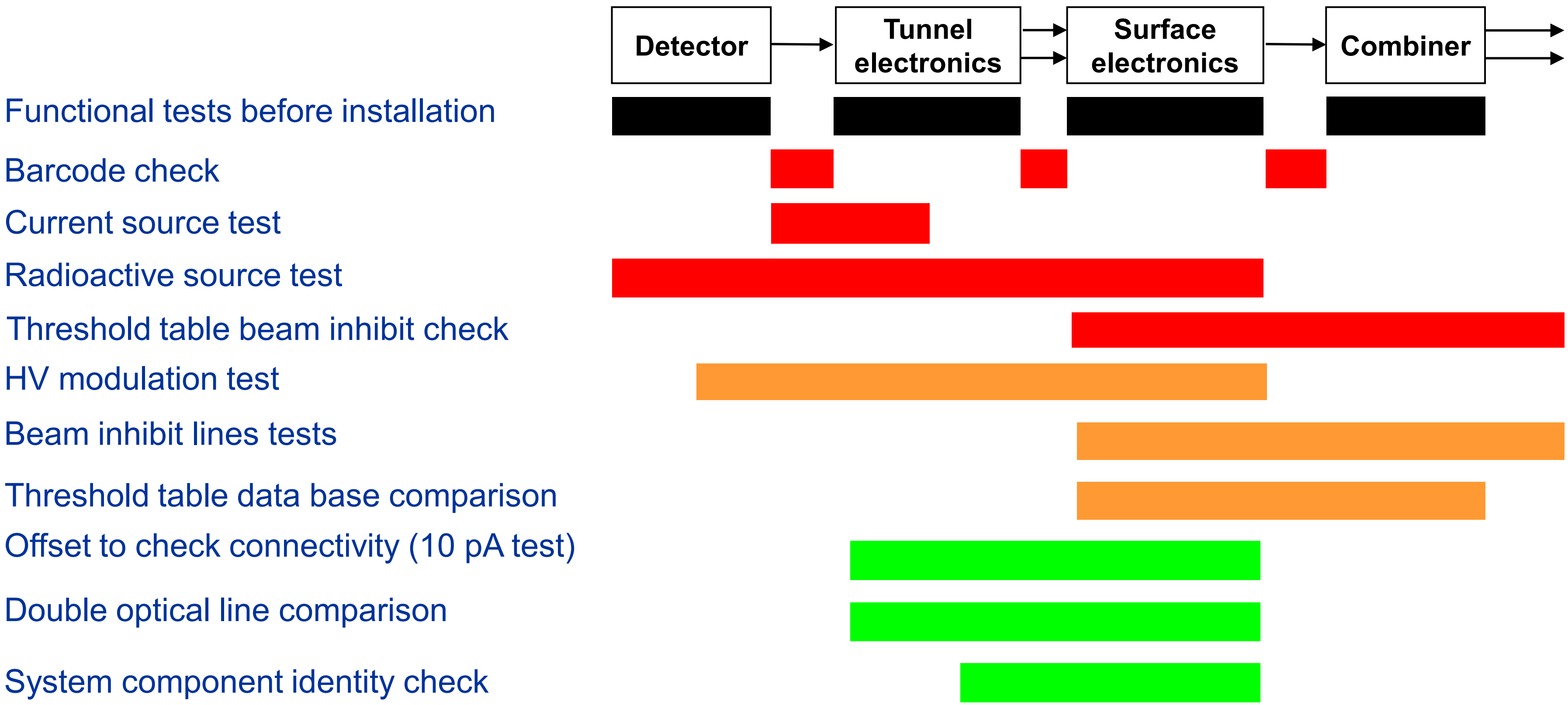
- **Each monitor** (connected to interlock system BIS) aborts beam:
  - One of 12 integration intervals over threshold
  - Internal test failed

- Local protection strategy

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

Regular Validation Tests

PhD thesis Gianluca Guaglio

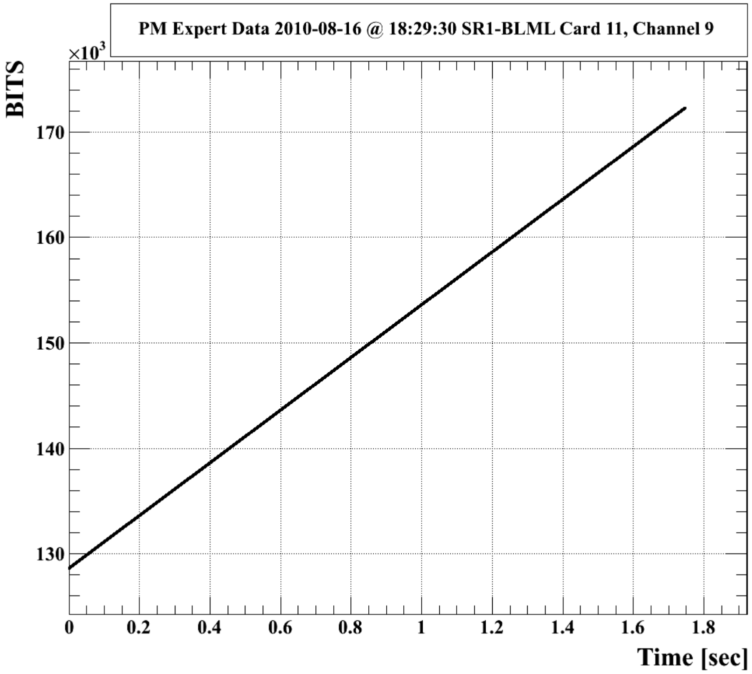


Inspection frequency:

■ 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.)



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:

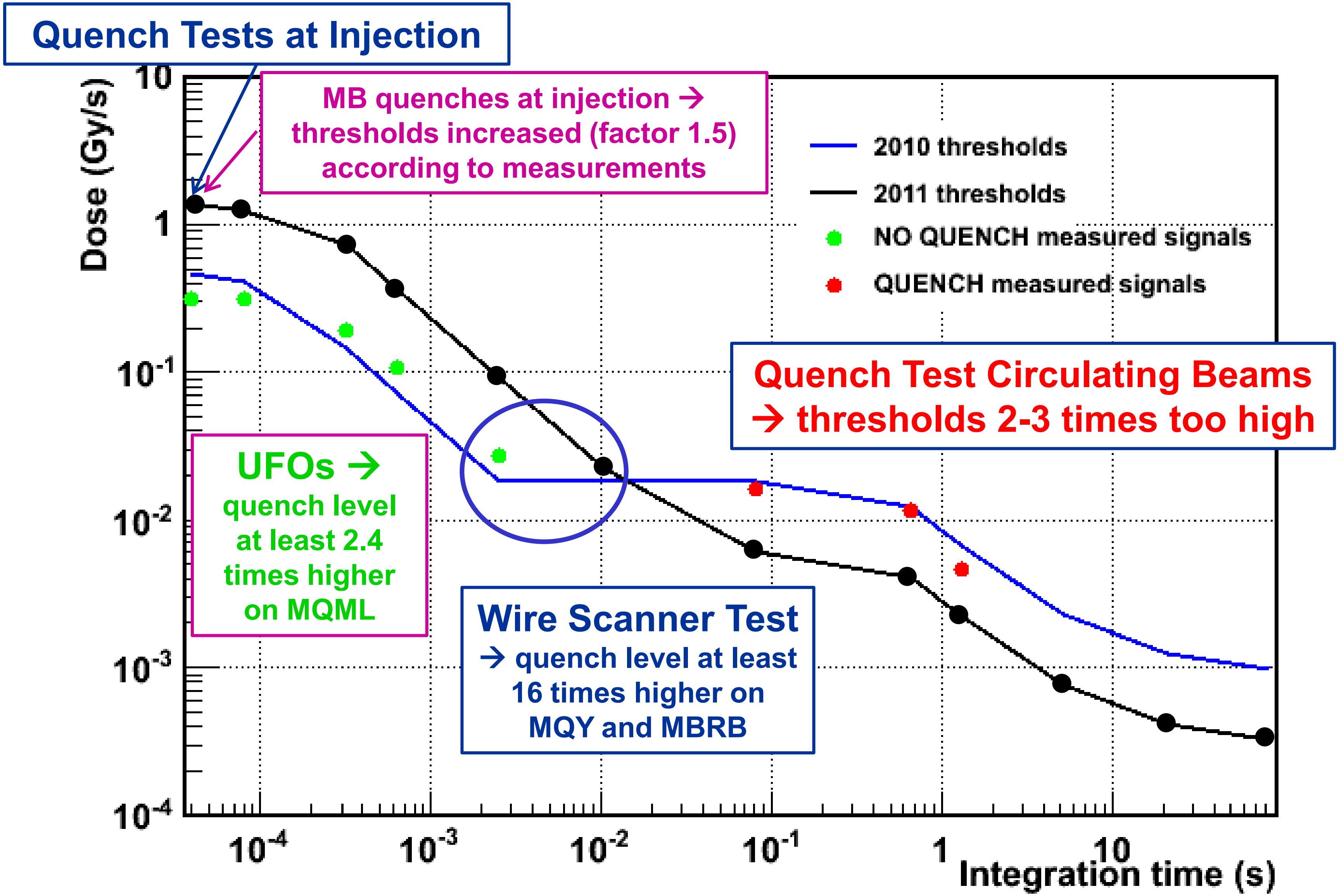
   Thresholds defined according to operational scenario - Deviate from local protection scheme on a few monitors

   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

BLM Threshold Change Cold Magnets 2011



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

  → 80 BLM emergency dumps in 1.5 years

  → 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)	**3**

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.)!

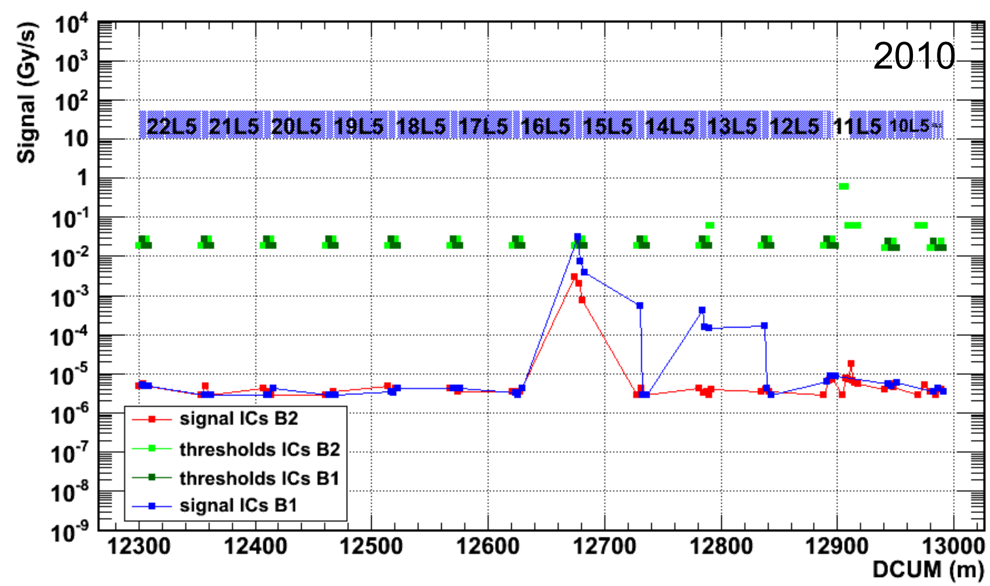
Fast (ms-time-scale) Losses
UFO: Unidentified Falling Object

Beam Aborts due to UFO's

- Stepwise increase of BLM thresholds at the end of 2010 run
- New BLM thresholds on cold magnets for 2011 start-up
- 11 UFO dumps 27 May – 8 June

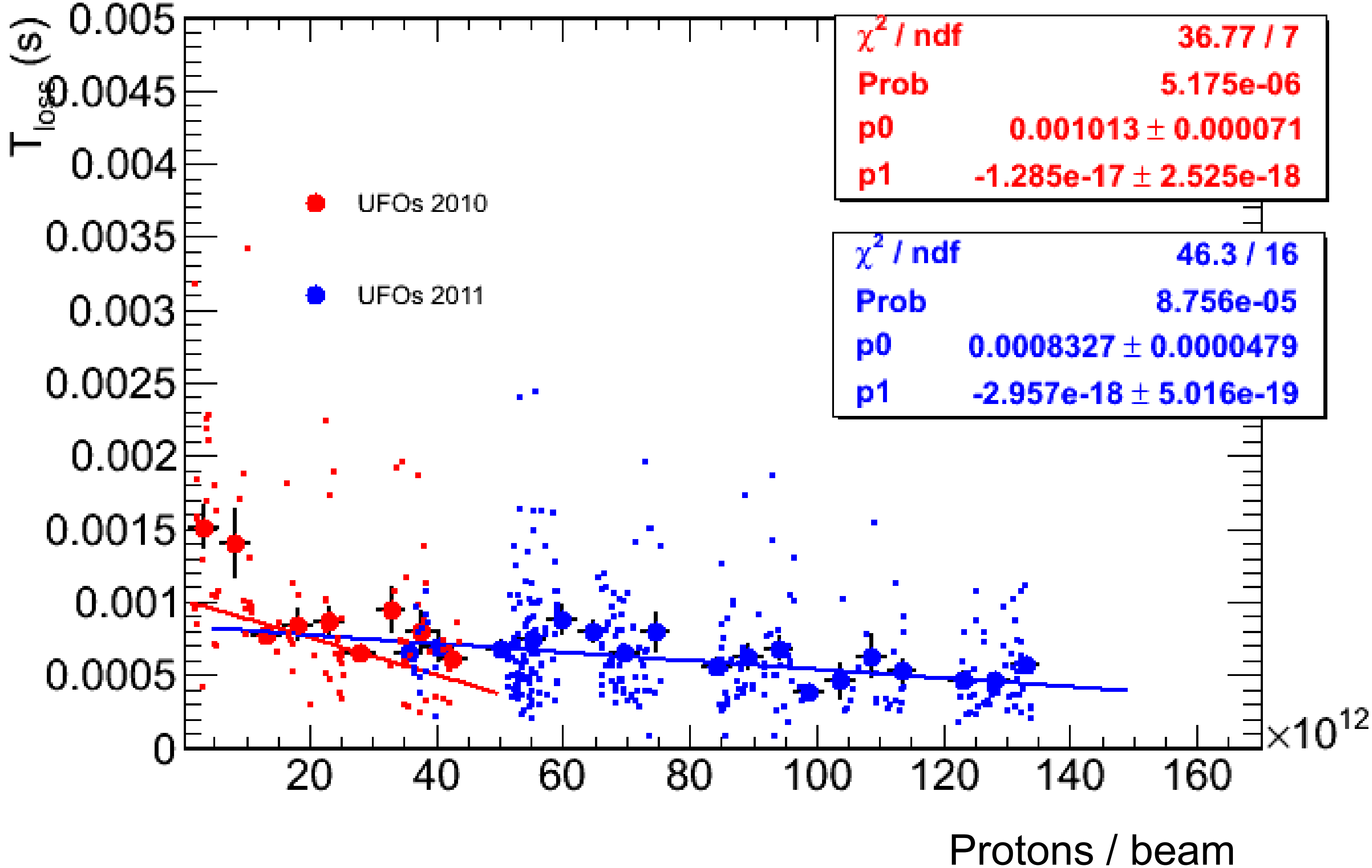
	Beam Aborts	
	BLM	Other
2010	9	1 (LHCb)
2011	10	3 (LHCb, Alice, RF arc detection)

- Always detected by > 6 local monitors (at least 3 close to threshold) and at all aperture limits (collimators) → redundancy
- most UFOs far from dump threshold



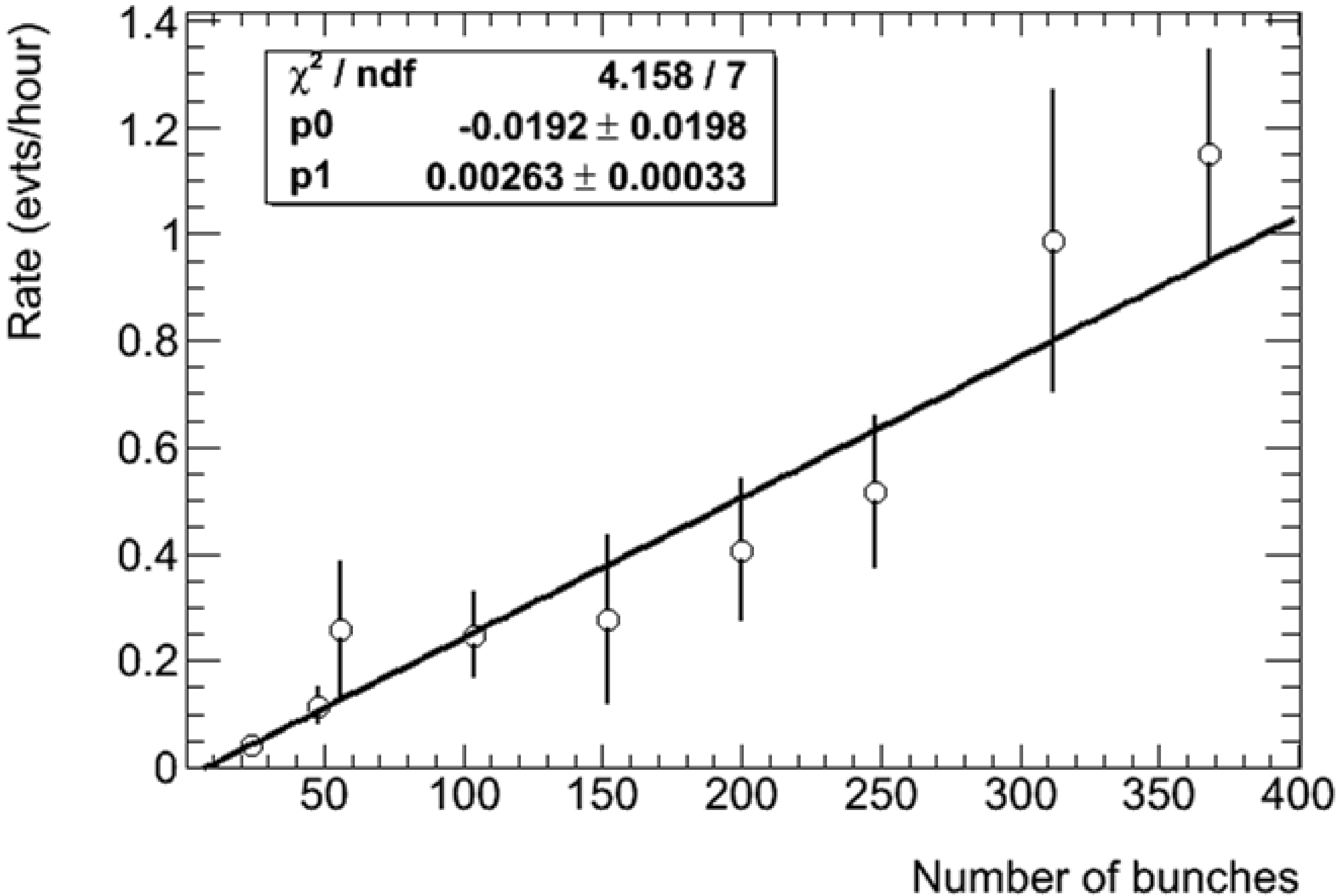
UFO Duration 2010 and 2011

E. Nebot



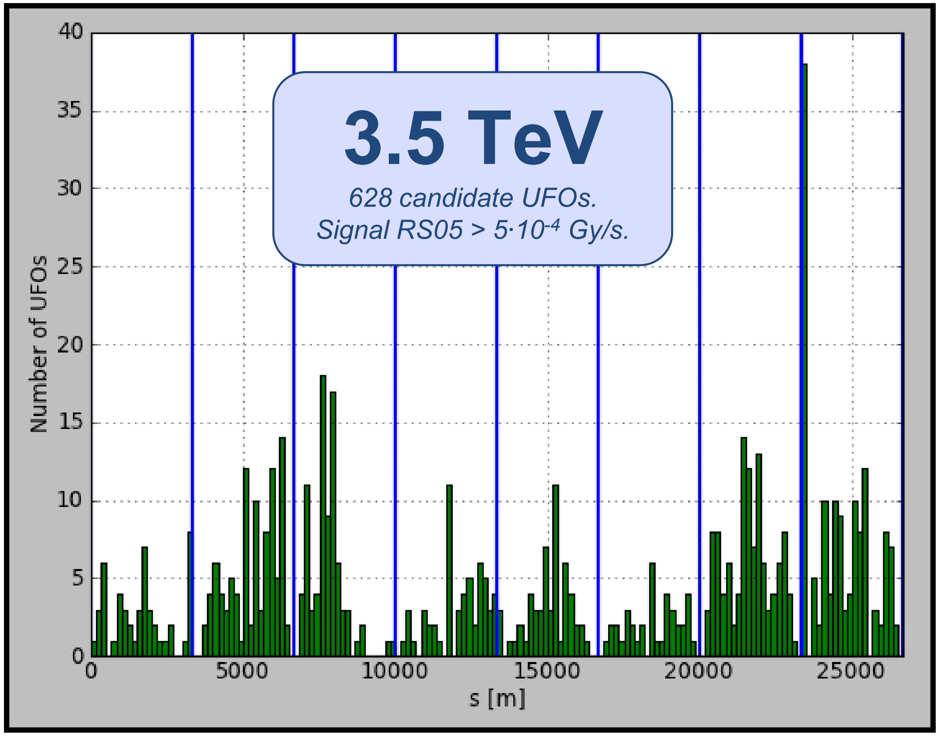
Intensity Dependence – UFO Rate 2010 E. Nebot

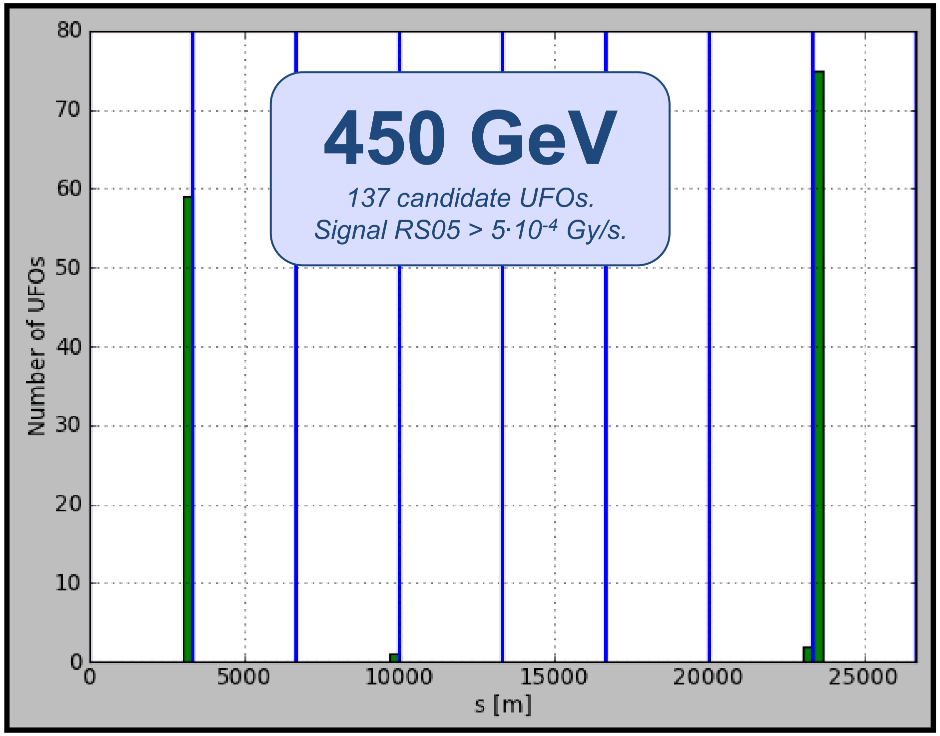
- Rate increases with intensity; prediction from 2010 data:
  2000 Bunches → ≈ 5.2 events/hour



Spatial UFO Distribution

T. Baer



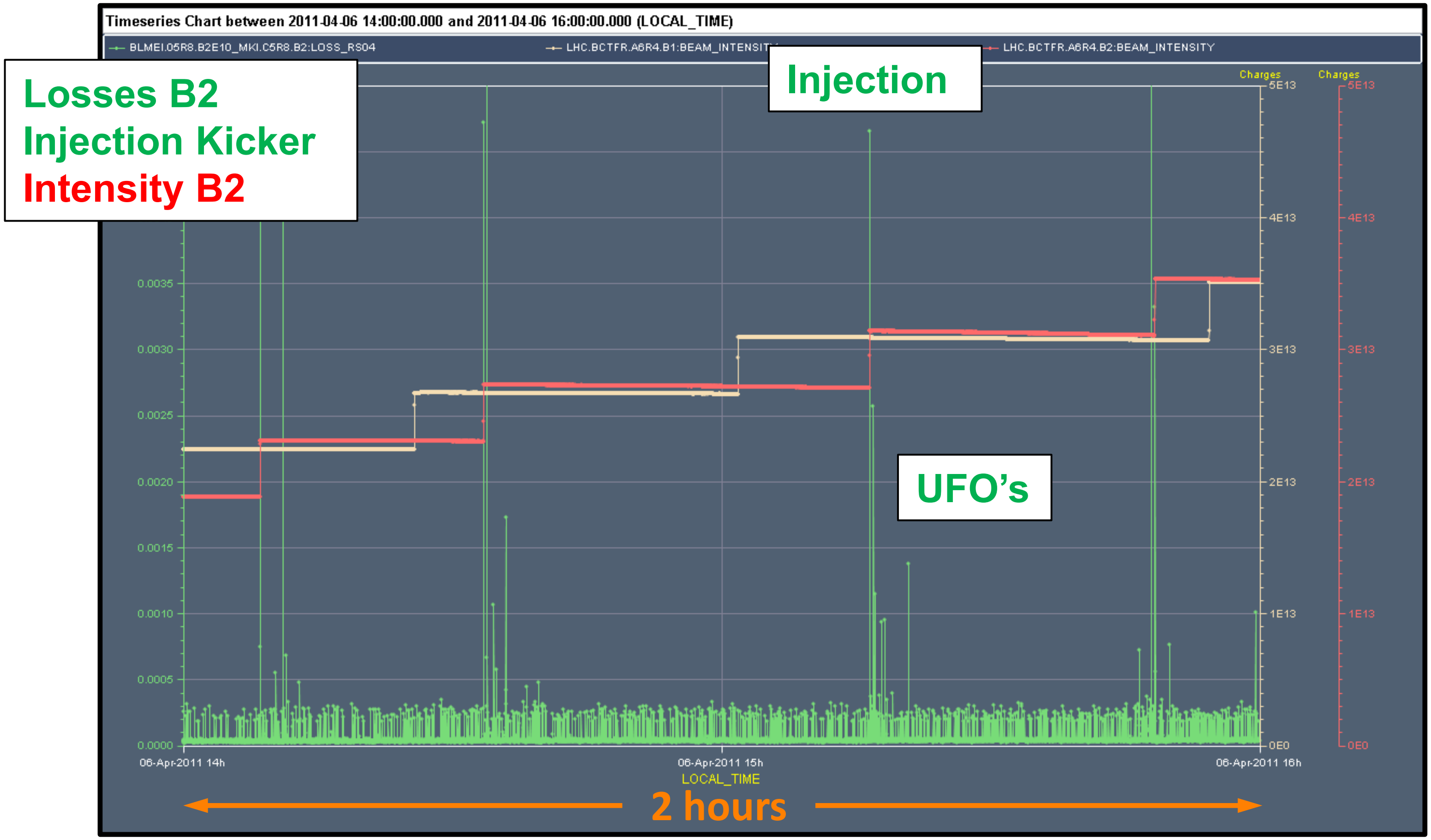


Distributed around the ring
38 UFO Candidates
at Injection Kicker Beam 2

UFOs mainly at Injection Kickers

Injection Kicker UFOs During Scrubbing

- Injection Kicker UFOs during scrubbing run: Loss spikes during first few minutes after an injection

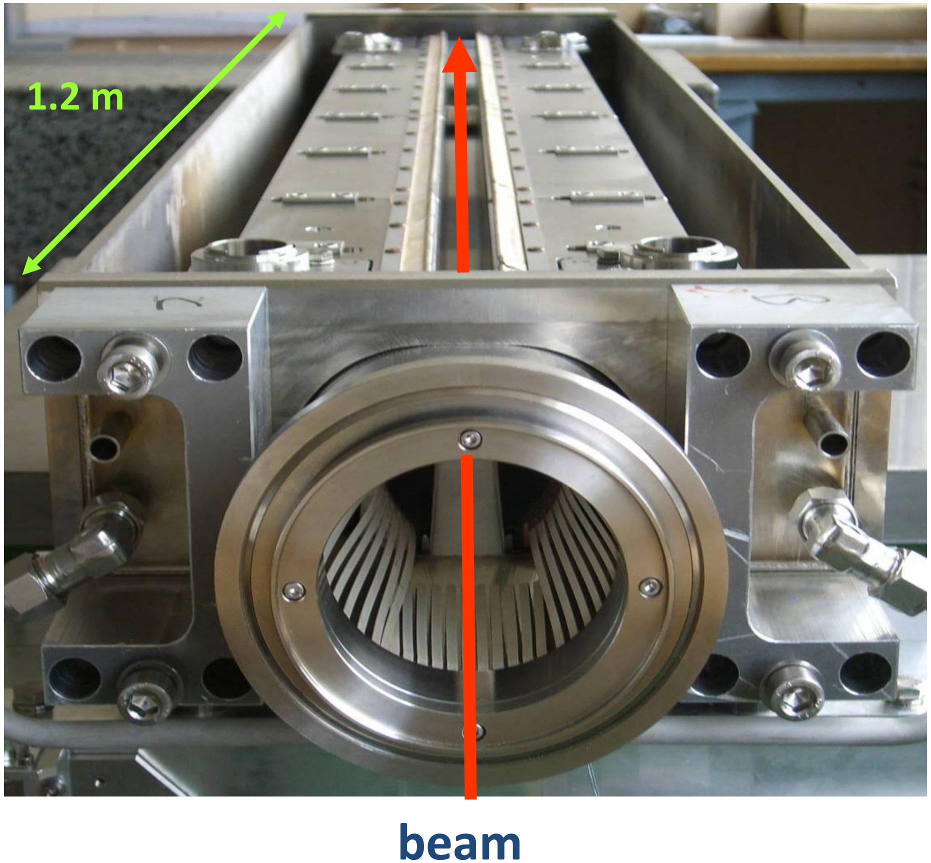


BLMs and Collimation - Examples

- Collimator set-up
- Collimation performance verification

Collimation System

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

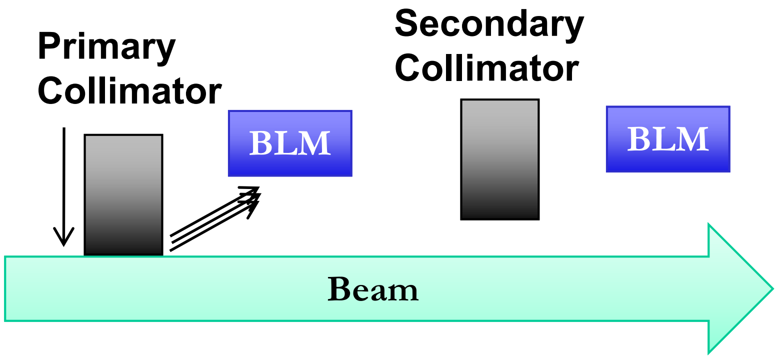


Collimator Set-Up

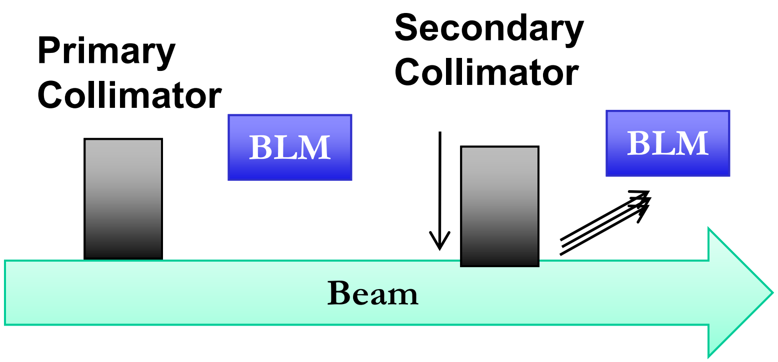
G. Valentino
D. Wollmann

LHC Collimation Project CERN

1.



2.



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

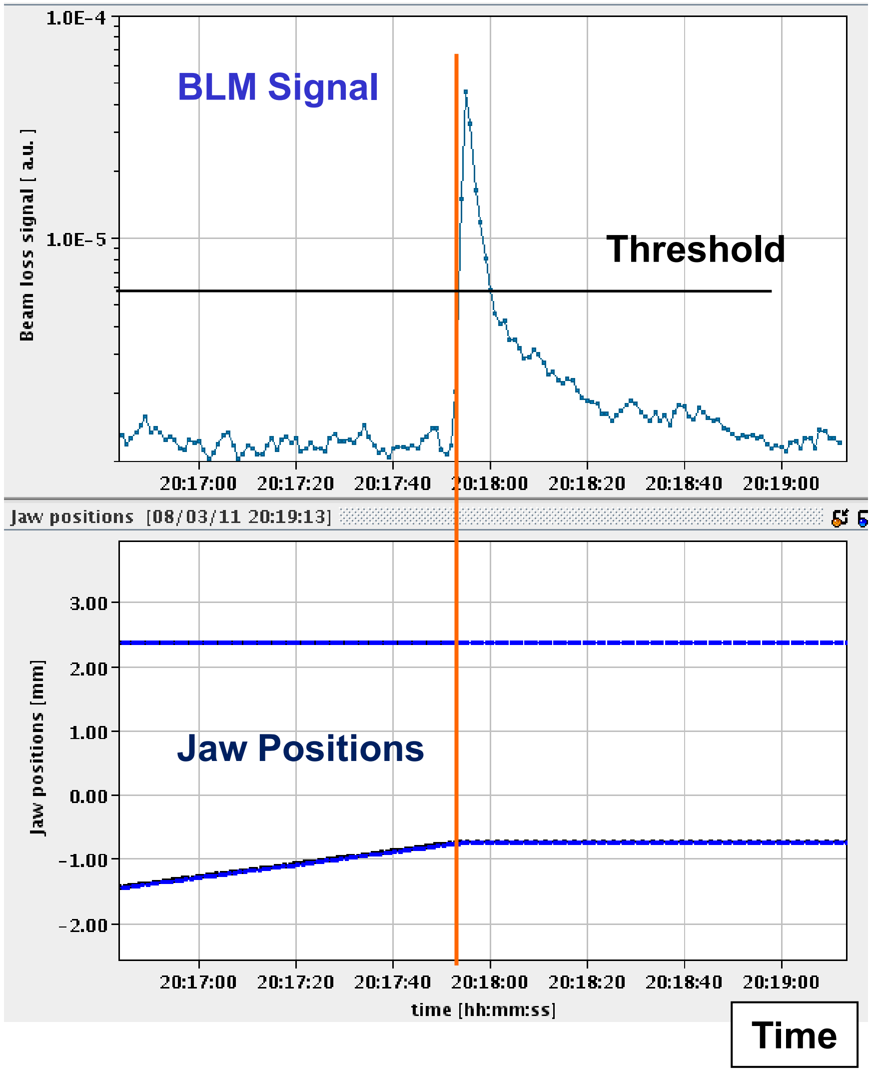
   → Define beam center at collimator positions and the relative beta
4. Open collimators to reference position

Semi-Automatic Setup Procedure

G. Valentino
D. Wollmann

- 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



Machine Study I

R.W. Assmann et al.

LHC Collimation Project CERN

CERN-ATS-Note-2011-036 MD

2011-05-24

Roderik.Bruce@cern.ch
Adriana.Rossi@cern.ch
Benoit.Salvant@cern.ch

Summary of MD on nominal collimator settings

R.W. Assmann, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, L. Lari, E. Metral, N. Mounet, S. Redaelli, A. Rossi, B. Salvant, G. Valentino, D. Wollmann

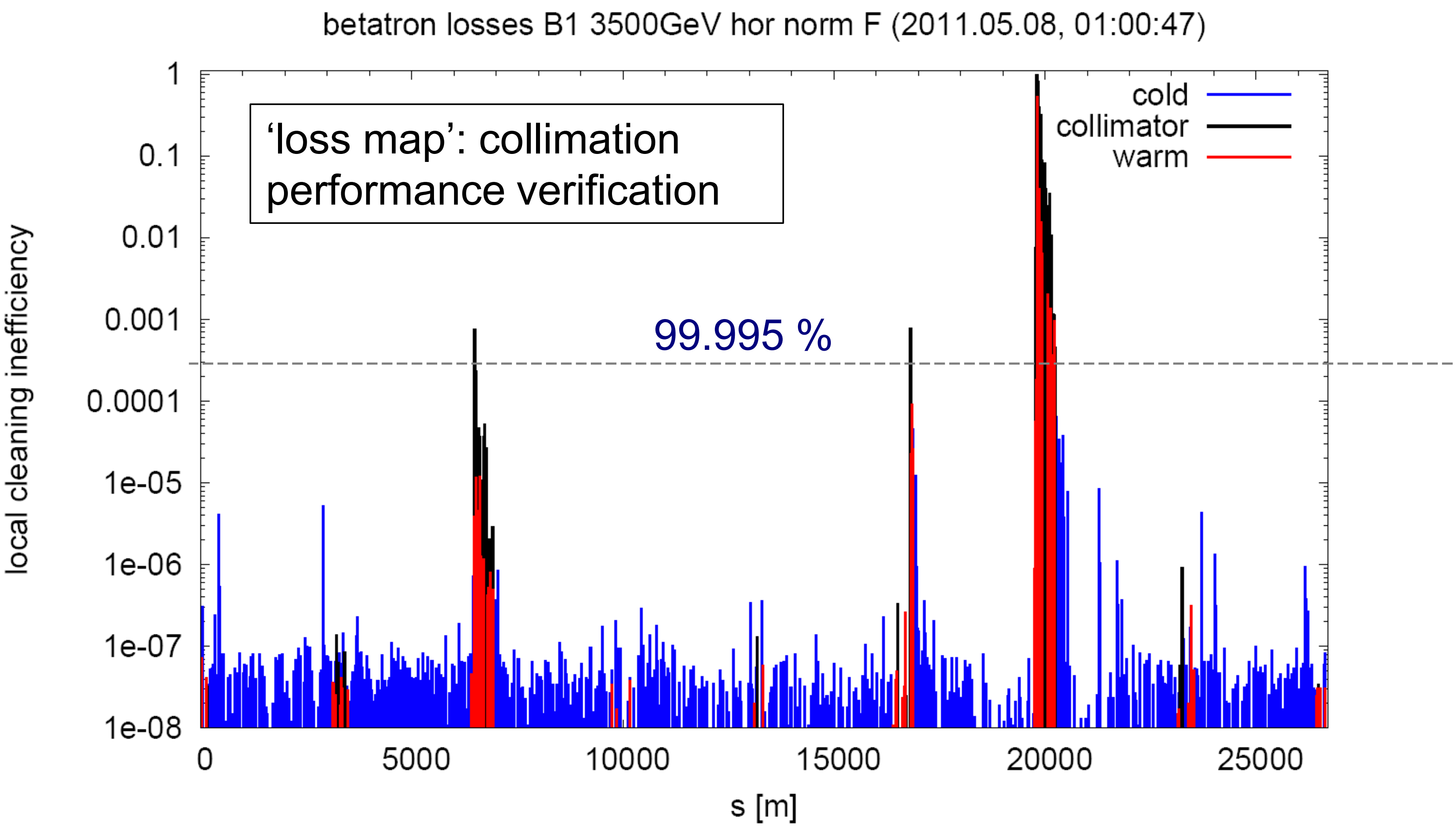
Keywords: Collimator settings, collimator impedance

	TCP IR7	TCSG IR7	TCLA IR7	TCSG IR6	TCDQ IR6
2010 settings	5.7	8.5	17.7	9.3	10. - 10.6
Nominal	5.7	6.7	9.7	7.2	7.7
Tight B1	4.0	6.0	8.0	7.0	7.5
Tight B2	4.0	5.0	7.2	6.2	6.7

Settings in nominal beam sigma at 3.5 TeV

Observed Losses (Normalized to Primary Collimator)

R.W. Assmann et al.



(In-) Efficiency Reached (Coll → SC Magnet)

R.W. Assmann et al.

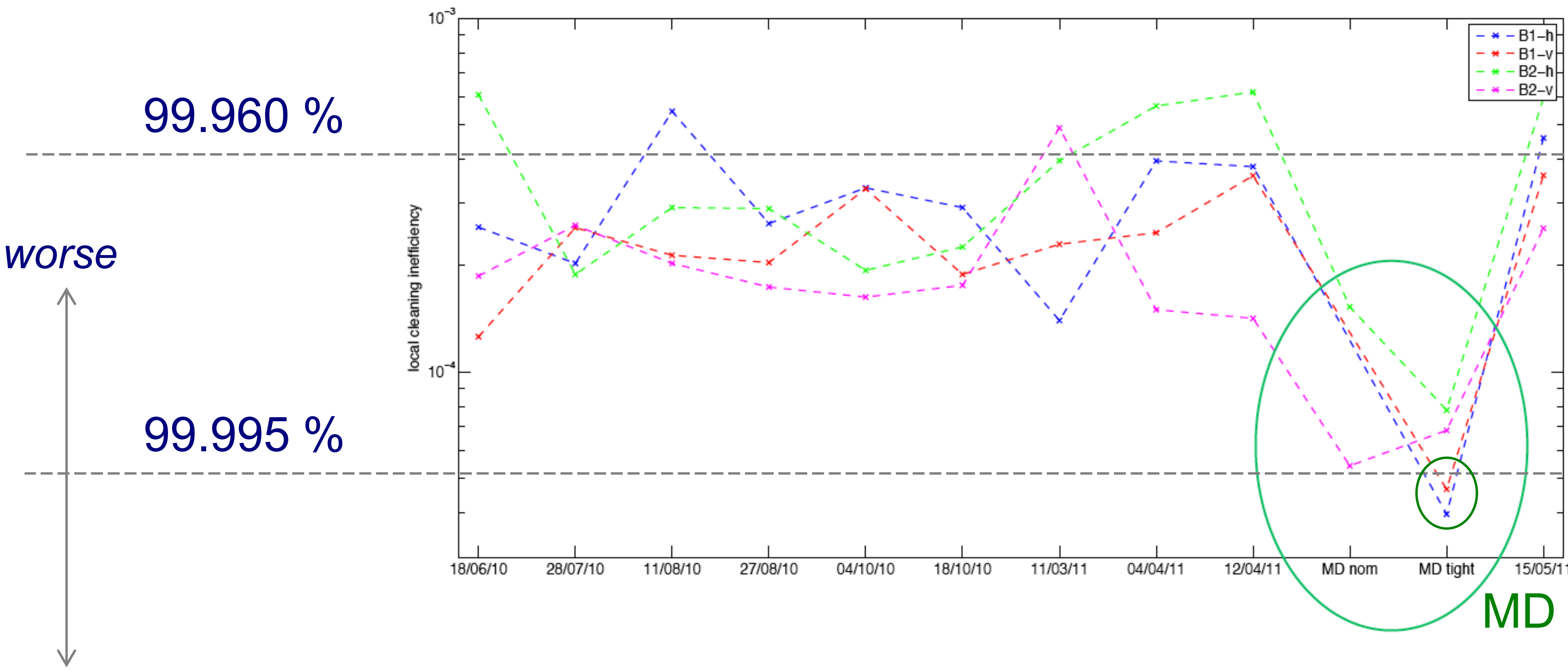


Figure 5: Beam 1 and Beam 2 maximum local cleaning inefficiency in the cold parts of the LHC at 3.5TeV over about one year operation. The results from this MD are contained in the second and third sets of points from the right, where a clear decrease can be observed.

Machine Study II

R.W. Assmann et al.

- Plan maximizing the loss rates on primary collimator
  - either: **up to design loss rate of 500 kW**
  - or: until quench in the dispersion suppressor
- Loss by crossing 1/3 resonance
- 16 bunches, 3.5 TeV

CERN-ATS-Note-2011-042 MD (LHC)

May 24, 2011
Stefano.Redaelli@cern.ch

Collimator losses in the DS of IR7 and quench test at 3.5 TeV

R.W. Assmann, R. Bruce, F. Burkart, M. Cauchi, D. Deboy, B. Dehning, E.B. Holzer, E. Nebot del Busto, A. Priebe, S. Redaelli, A. Rossi, R. Schmidt, M. Sapinski, G. Valentino, J. Wenninger, D. Wollmann, M. Zerlauth,
CERN, Geneva, Switzerland

Machine Study II

R.W. Assmann et al.

- Plan maximizing the loss rates on primary collimator
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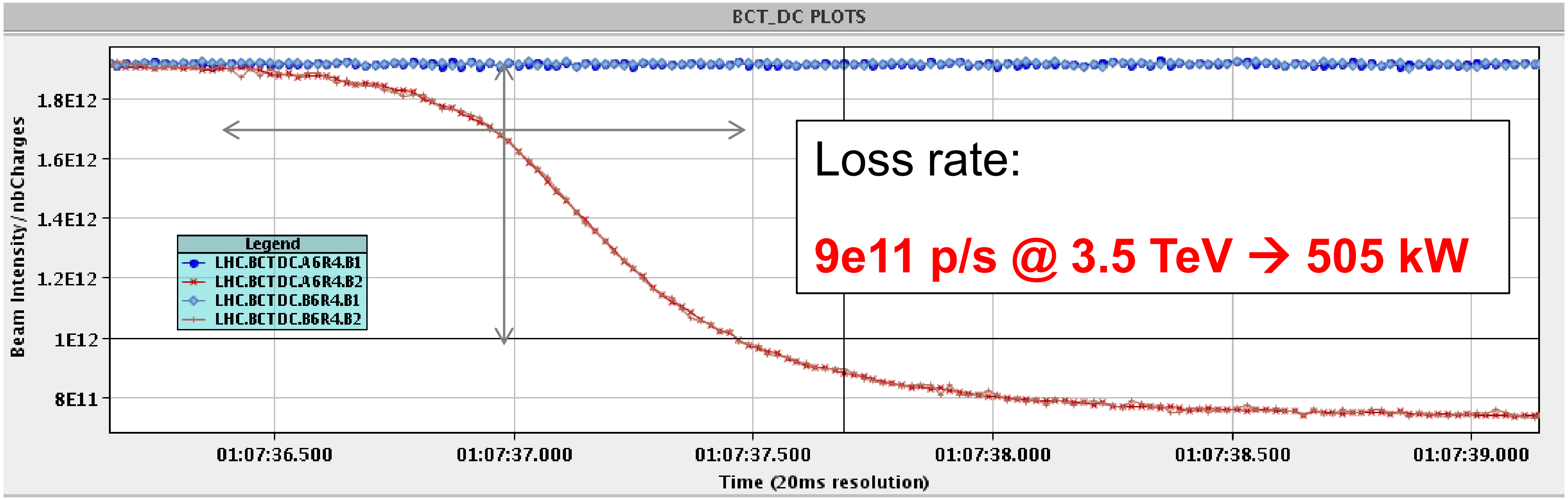

Leakage into Cold Magnets

R.W. Assmann et al.

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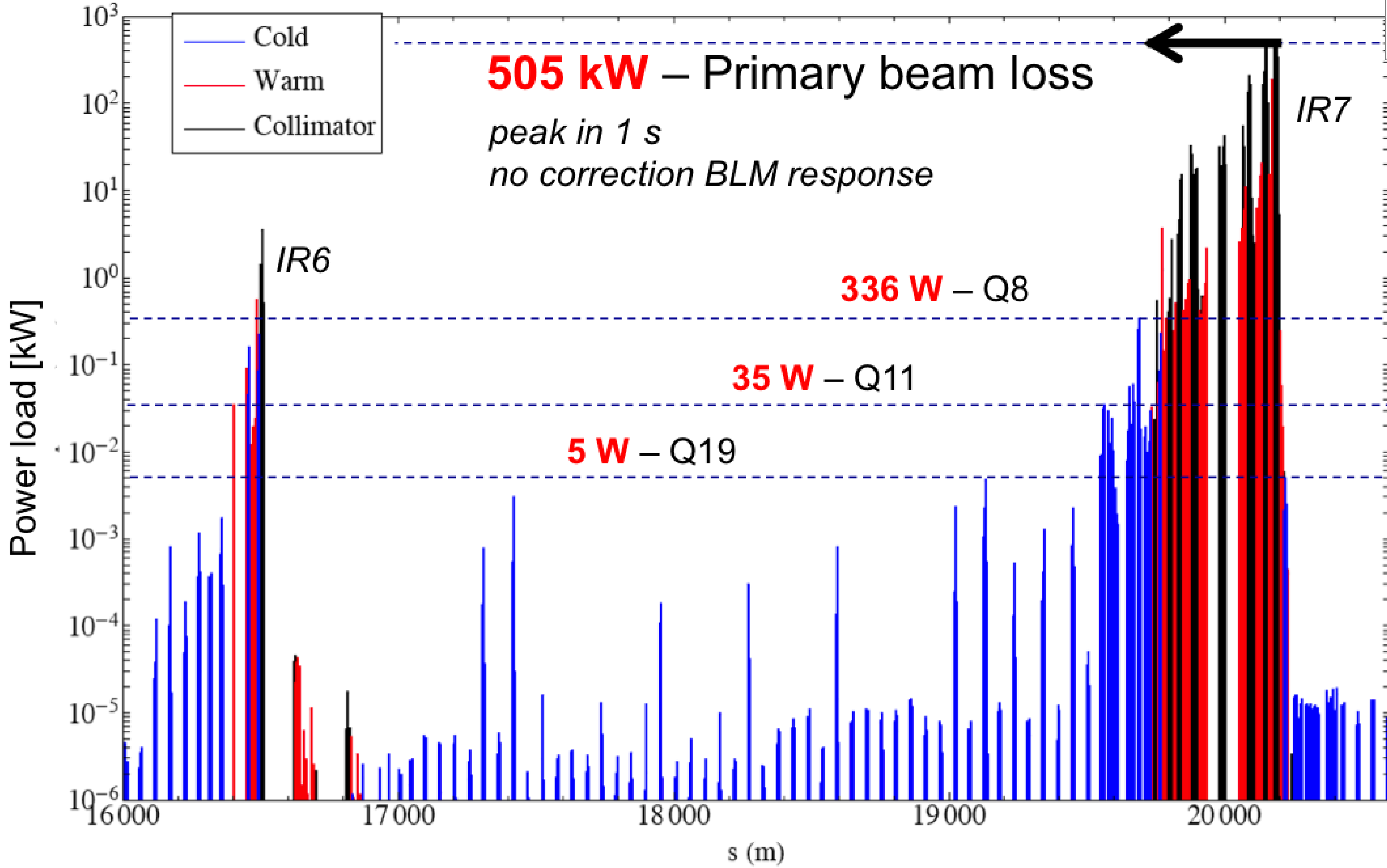
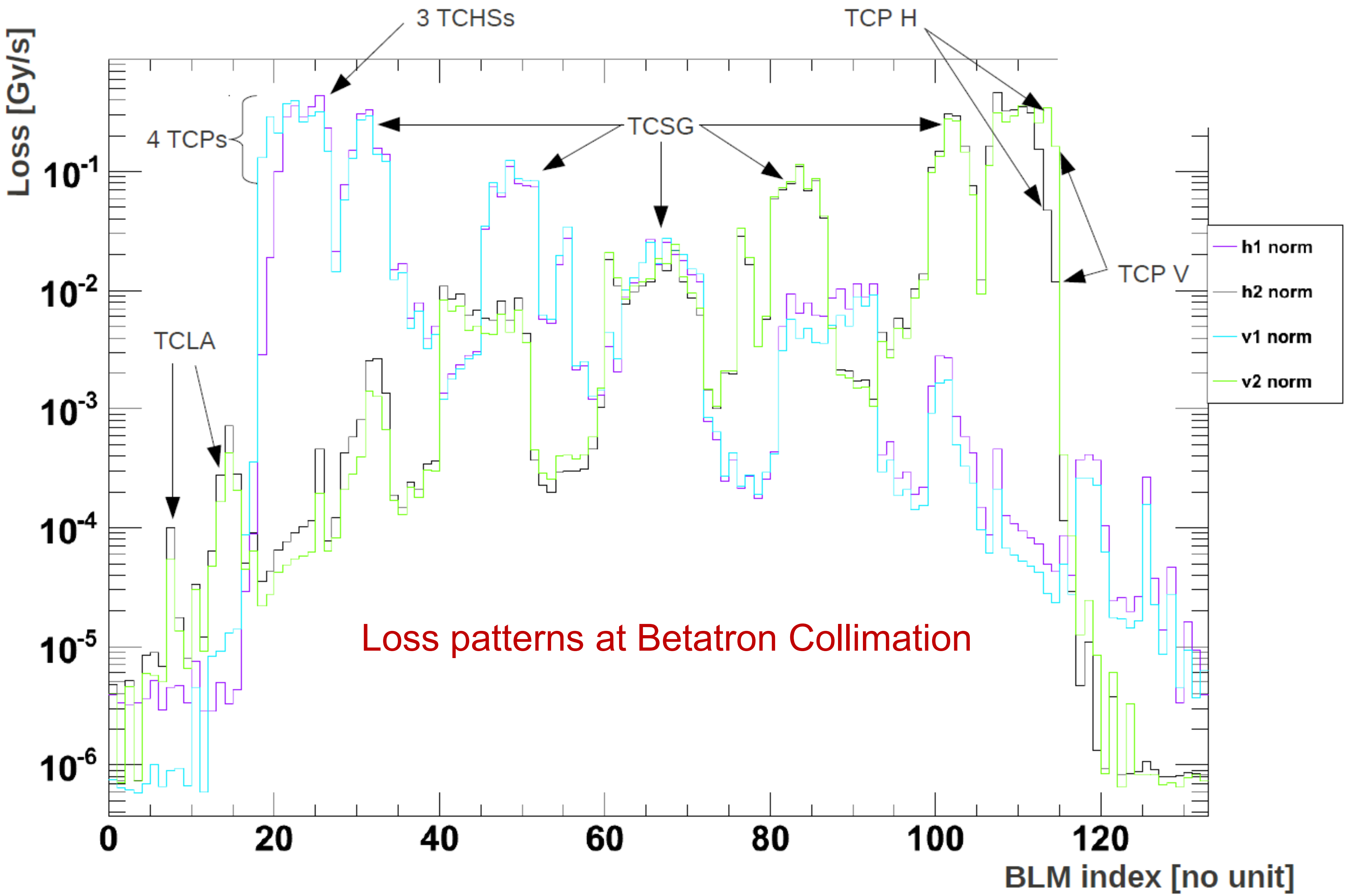


3.5 TeV operational collimator settings (not best possible)

No quench – consistent with BLM readings (64% of assumed quench level)

Decomposition of Losses

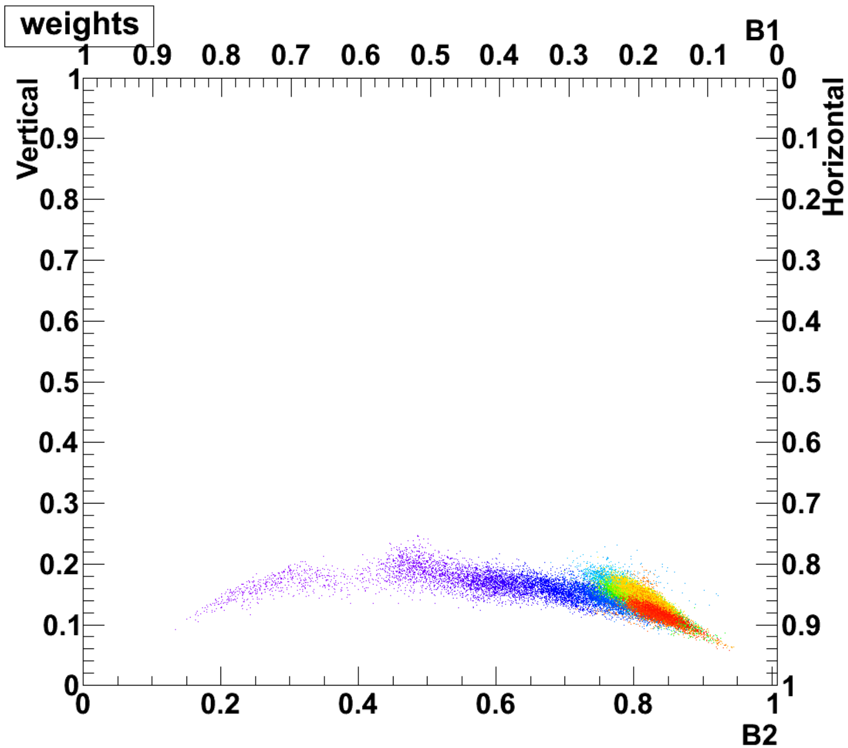
PhD A. Marsili

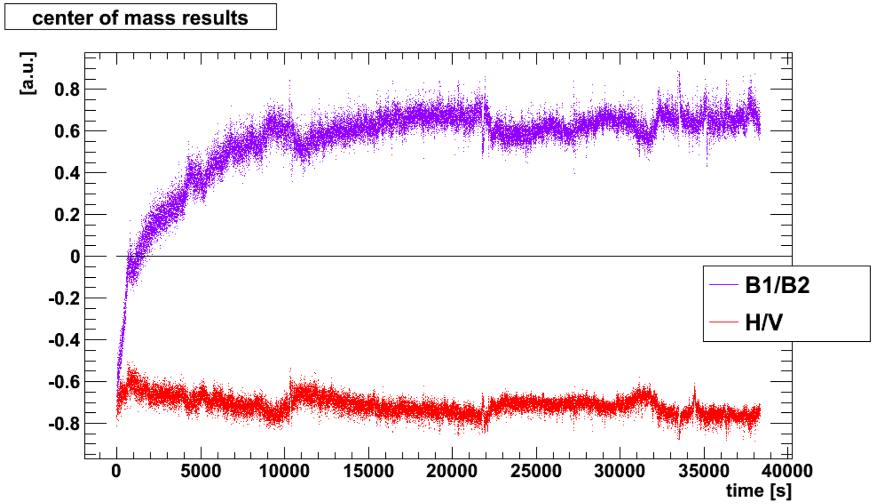


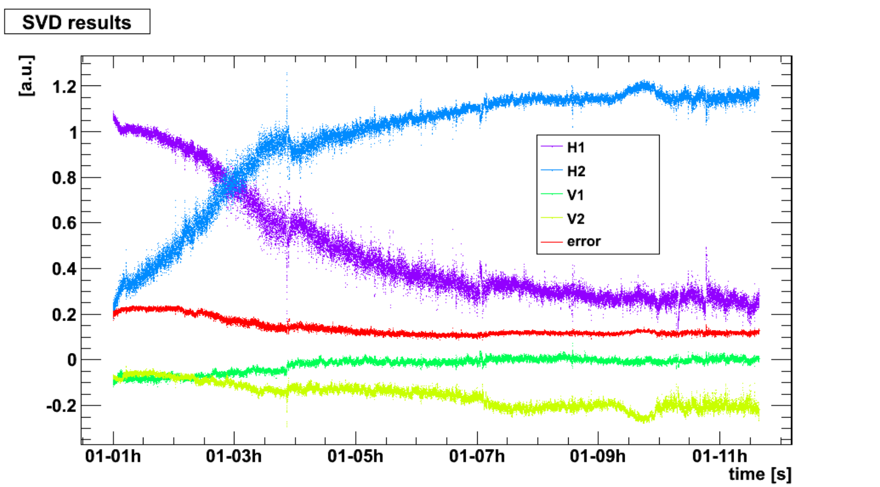
Decomposition Results

PhD A. Marsili

Work in progress







Physics beam, 1 point per second

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

→ Shielding, different protection approach, 'blinding'?

Summary

Challenges anticipated	*Experience*
Dependability (Reliability, Availability, Safety)	☺
Threshold precision	☺ - Tuning ongoing

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

protection approach, 'blinding'?

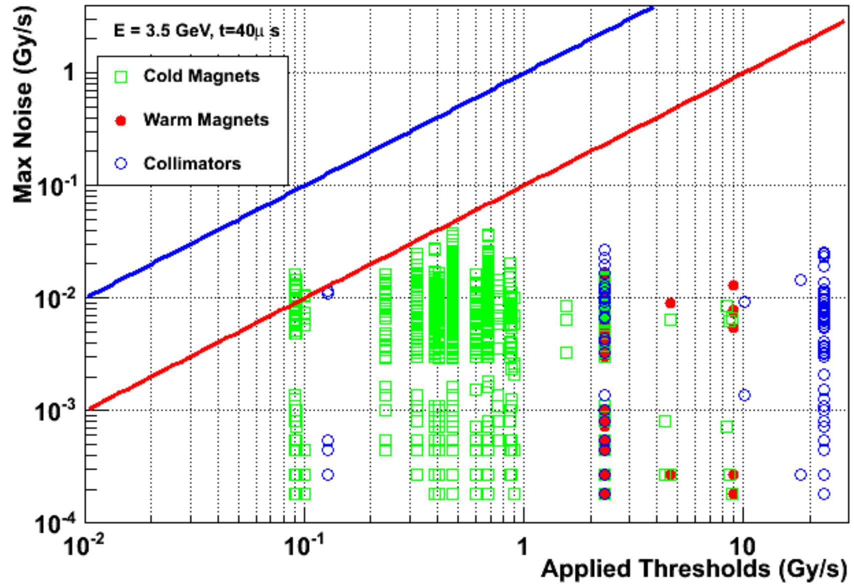
Summary

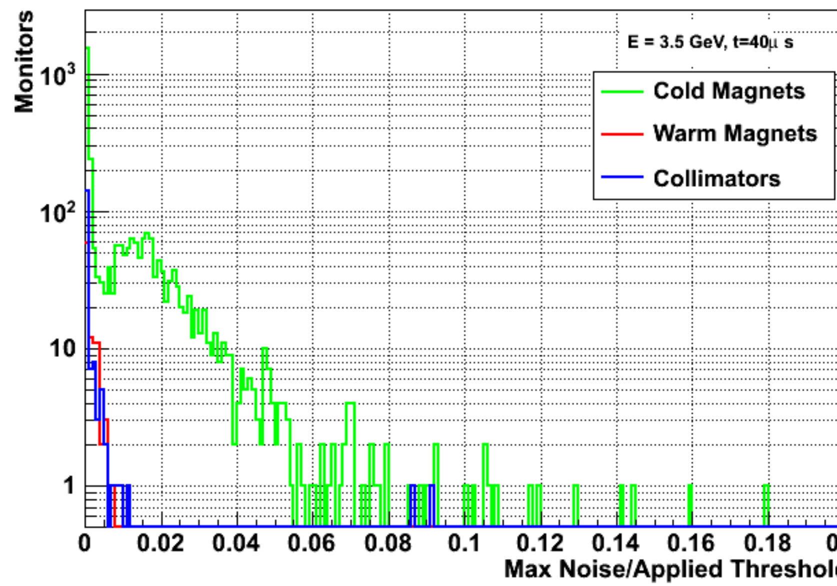
Challenges anticipated	*Experience*
Dependability (Reliability, Availability, Safety)	☺
Threshold precision	☺ - Tuning ongoing
Reaction time 1-2 turns	☺
Dynamic range: 2×10^5 40 µs 10^8 ≥ 1.3 s	😐 short integrals Noise (long cables) → Cables, radiation hard electronics, new less sensitive IC
Non-local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

Spare Slides

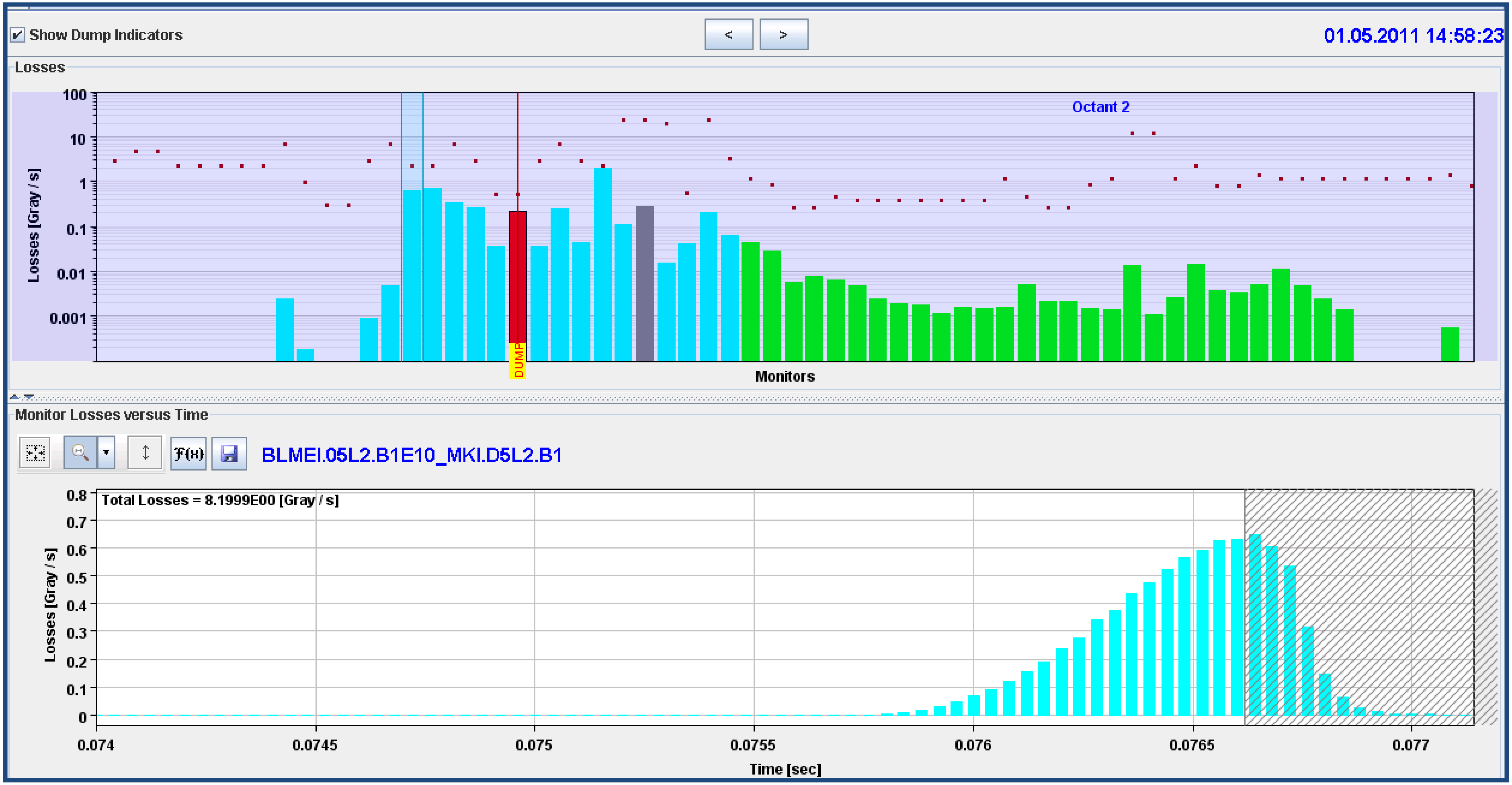
Noise

- 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 5
  - **Development of kGy radiation hard readout to avoid long cables**





Dump on 01.05.2011



Dump of BLMQI.04L2.B1E20_MQY on RS 3, 4 and 5

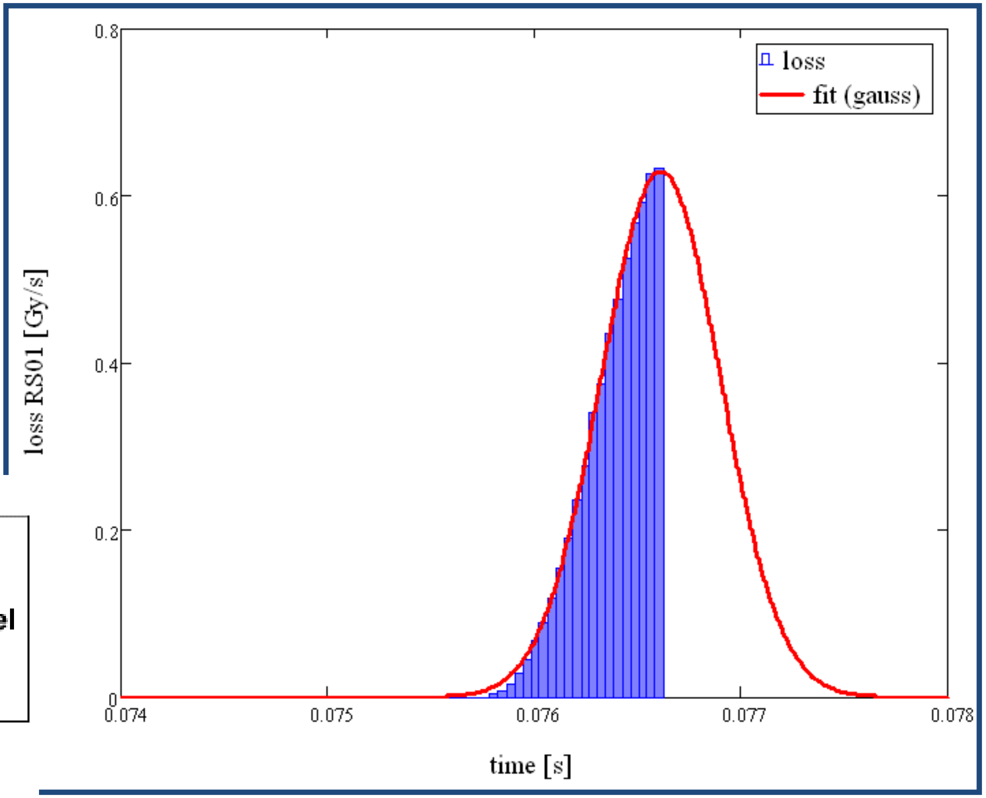
Dump on 01.05.2011

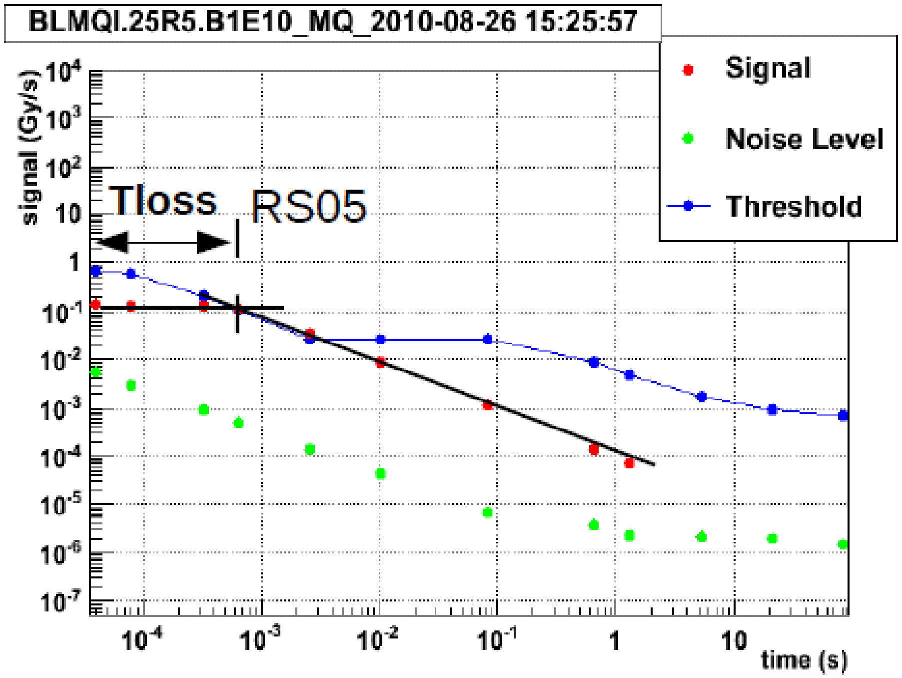
From fit of PM data

(BLMEI.05L2.B1E10_MKI.D5L2.B1):

Amplitude: 0.63 Gy/s

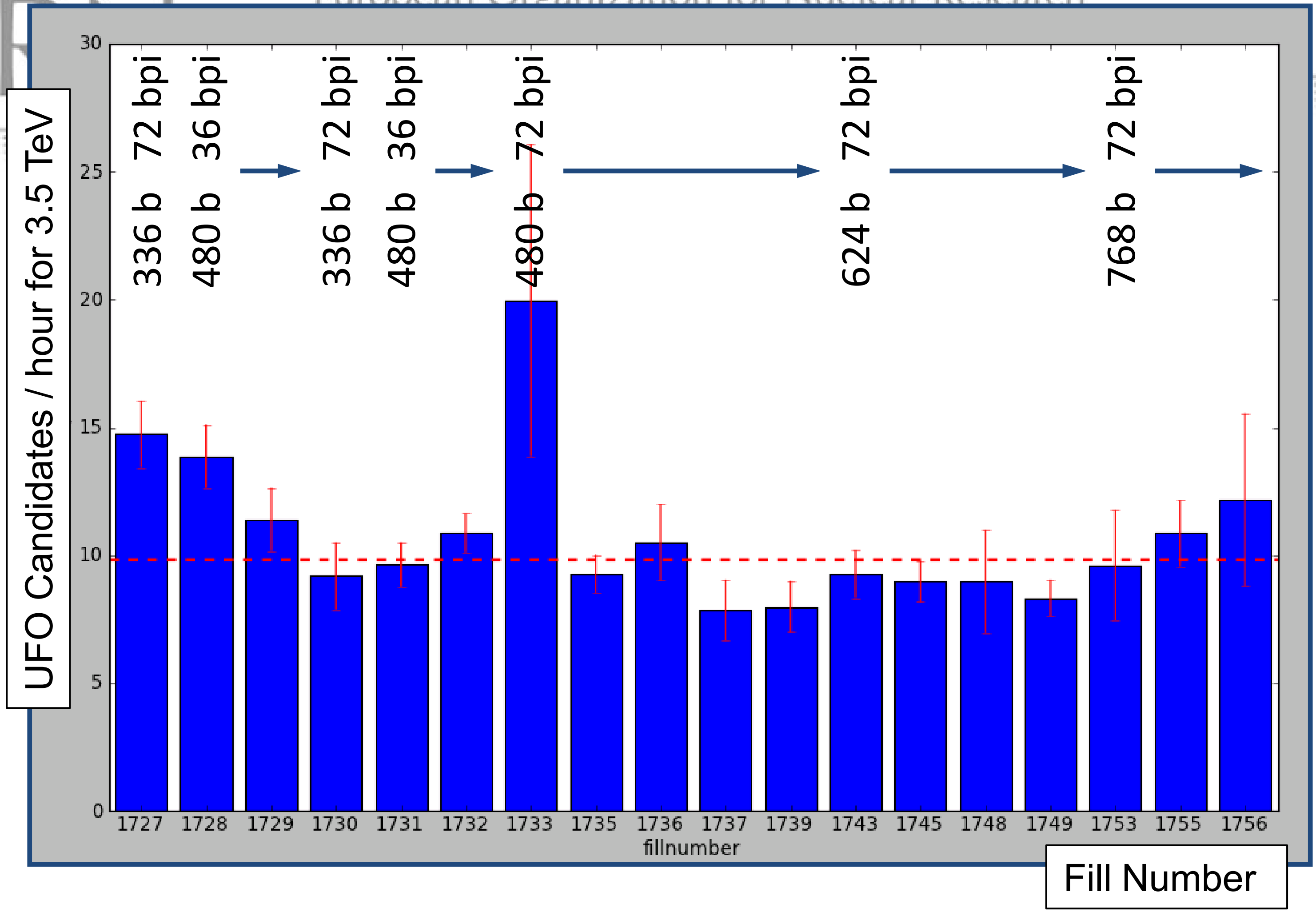
Width: 0.29 ms





2011 Rate of UFO Candidates

T. Baer

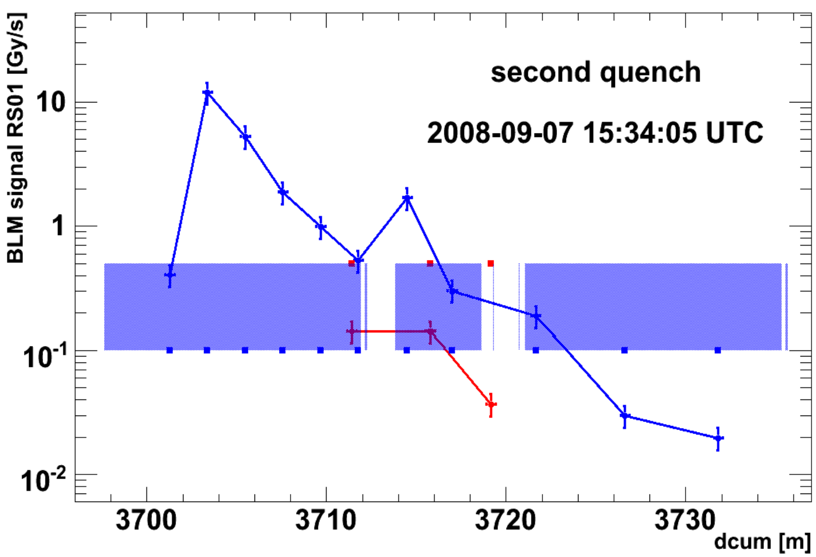


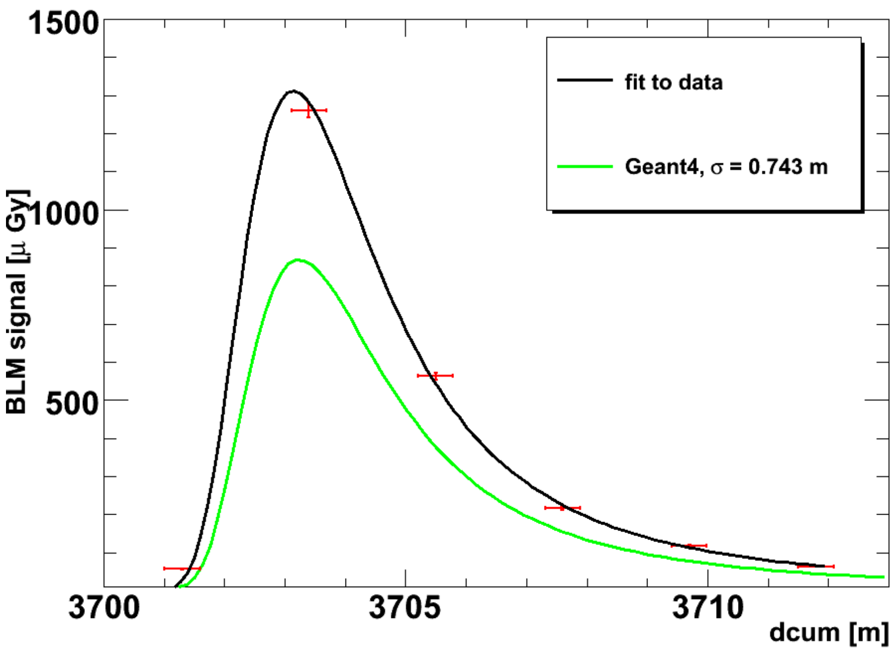
Accuracy of Thresholds

- All quenches so far on dipoles with injected beam.
- 2 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





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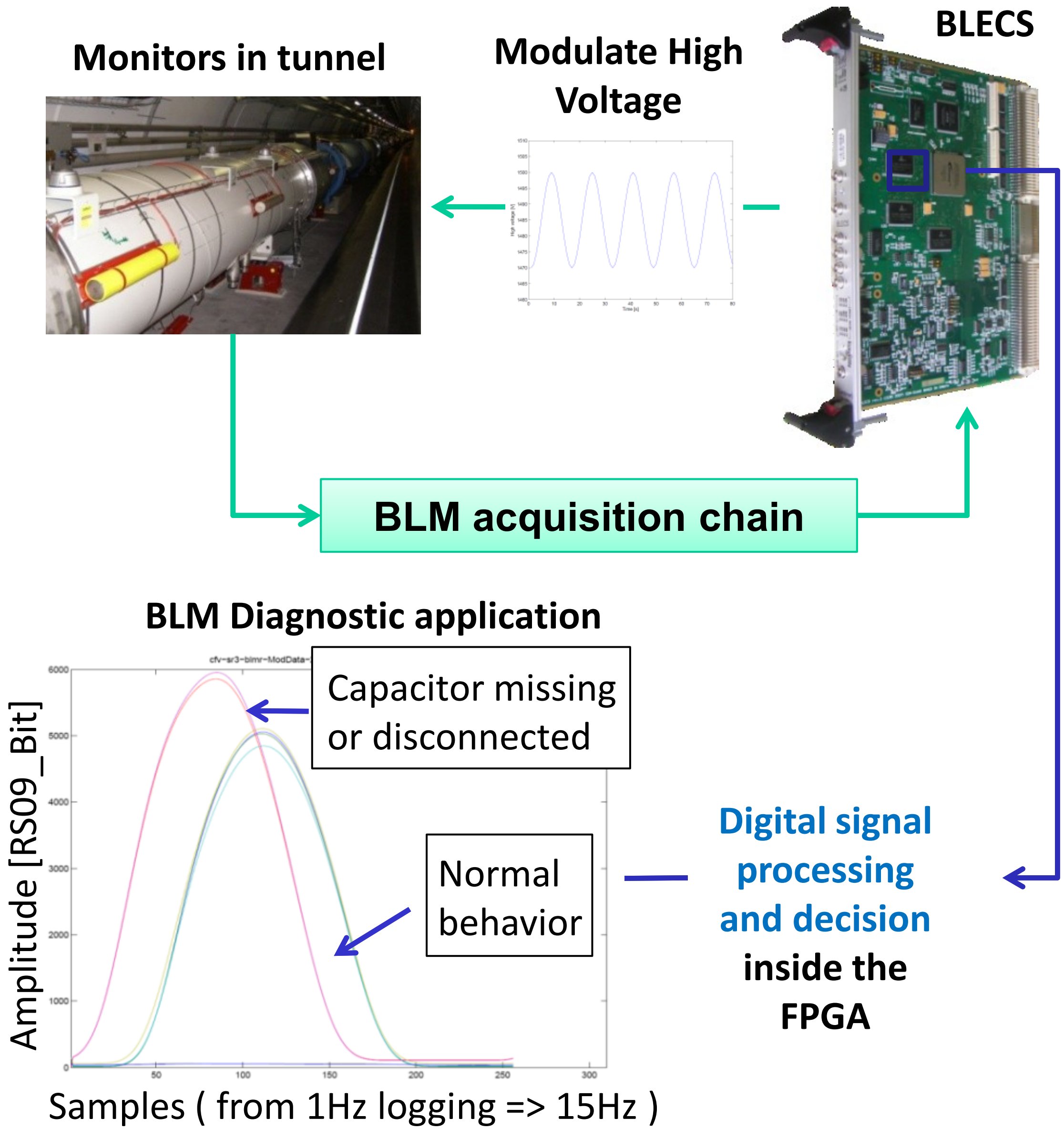
Regular Tests – HV Modulation Test



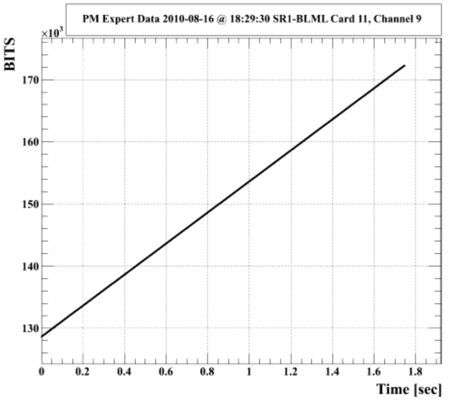
- Decision of pass or fail in surface electronics FPGA (combiner)
- Duration: 7 minutes

Tests:

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

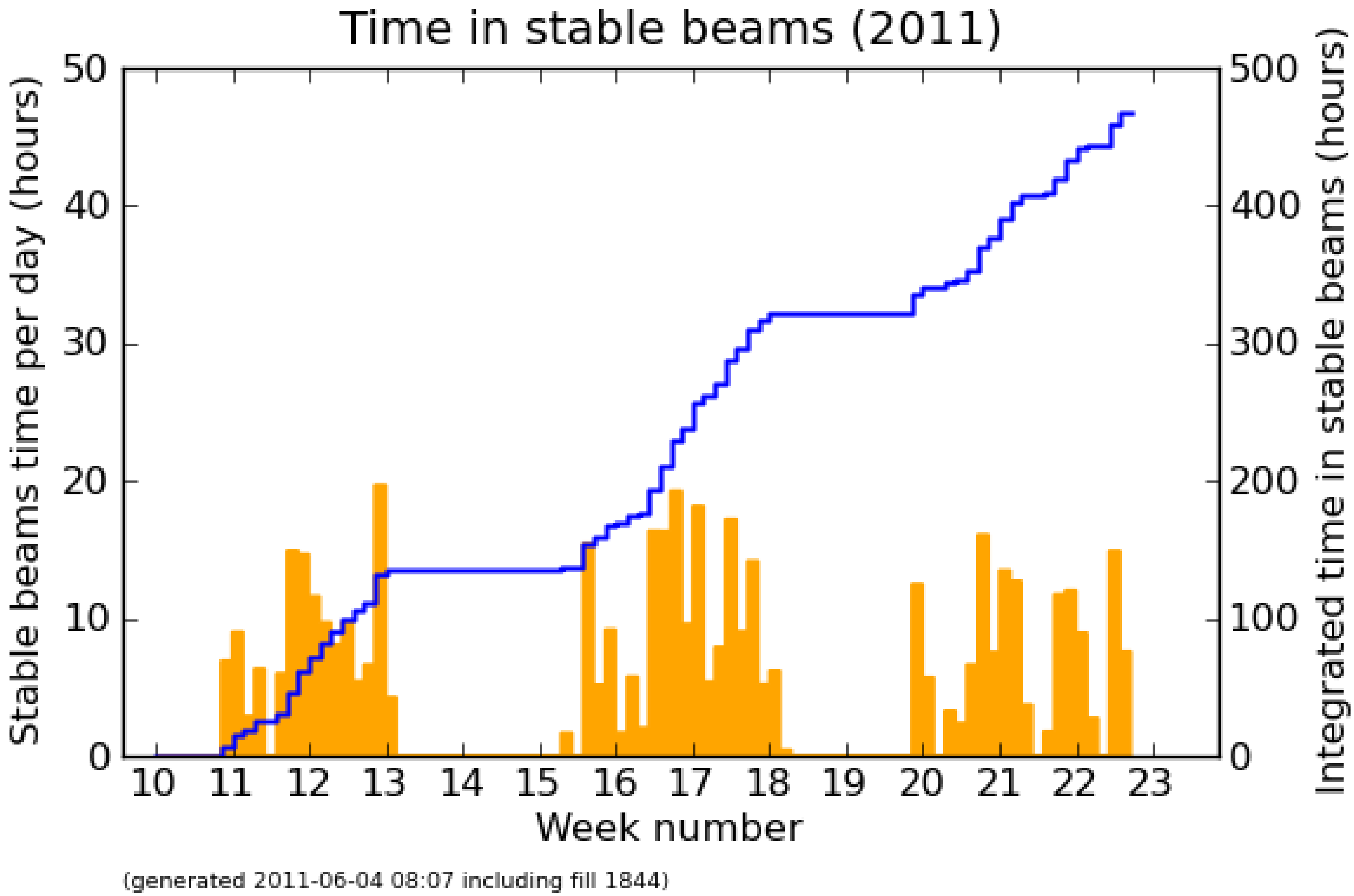
System Validation Tests — Examples

- Extensive firmware test (including all issues of previous versions) – before new release: all operational functionalities
- `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.)

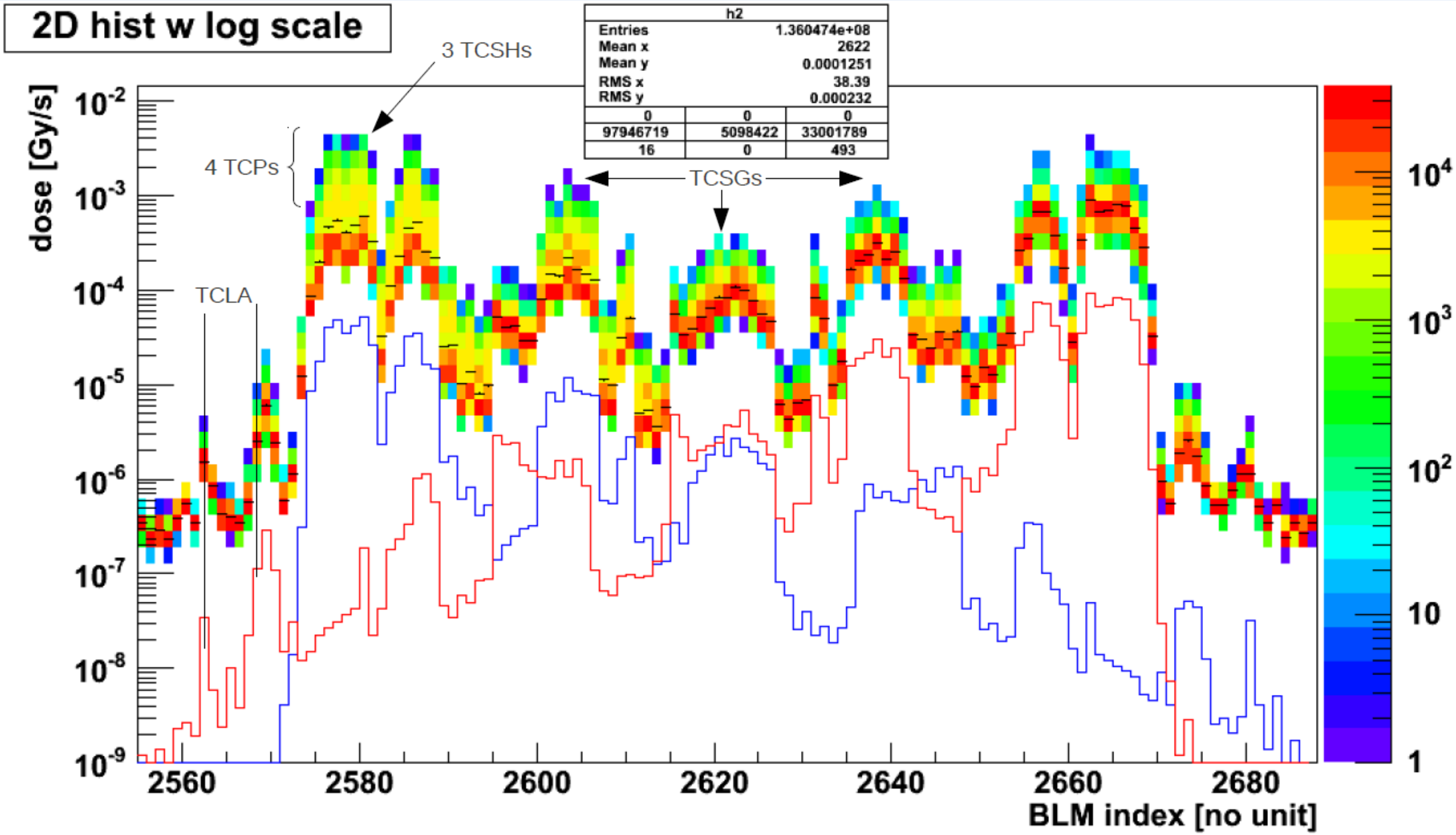


- Performance tests with beam include:
  - Beam abort with injection losses on closed collimator
  - BLM reaction time (injection kicker to break of beam permit): **100 – 130 µs.**

Stable Beams Duration 2011



Point 7: loss scenarios



MPP, CERN, 27/05/2011 A. Marsili, BE-BI-BL 17/19

Hardware Failures (2010)

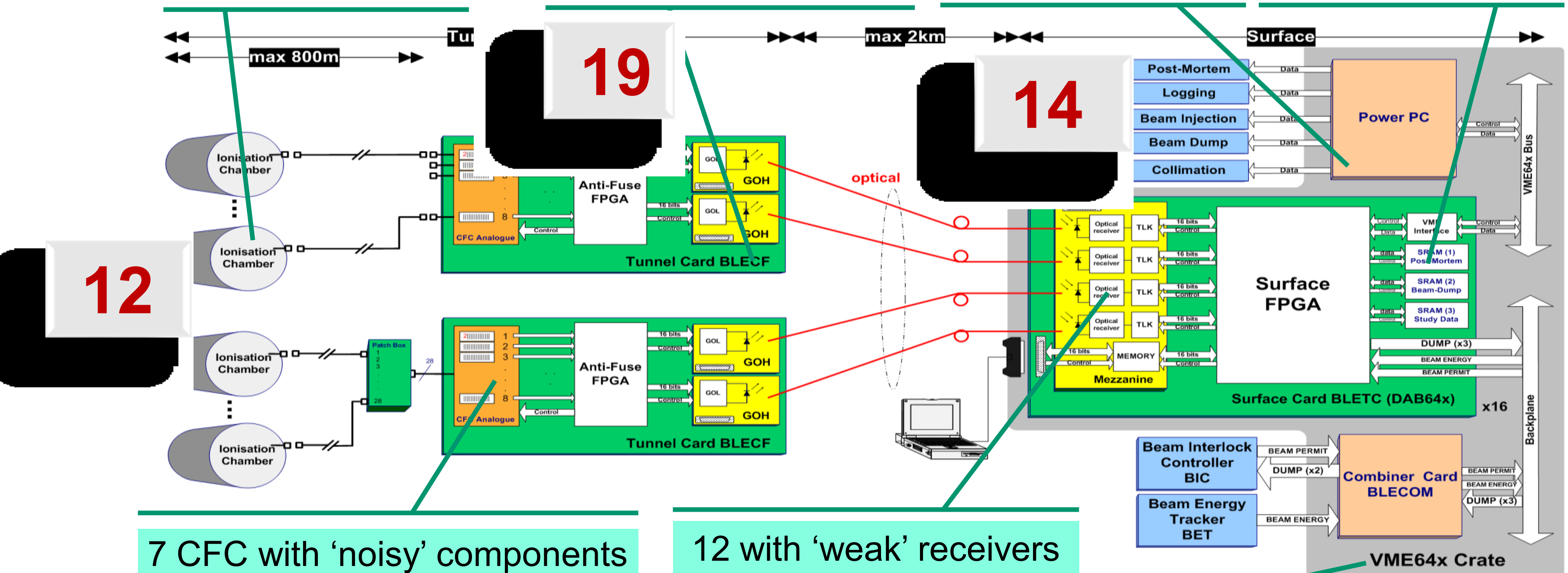
- Mostly, onset of system degradation detected by regular offline checks before malfunction
- Number of failures regarded manageable (no availability issue)

12 IC with bad soldering (out of 3600)

9 GOH with low power
1 damaged connector
out of 1500

3 failed CPU RIO3 out of 25

2 with failed SRAM out of 350



7 CFC with 'noisy' components
2 cards with bad soldering
out of 750

12 with 'weak' receivers
out of 1500

1 VME Power Supply, out of 25

4