(First) Operational experience with LHC Machine Protection

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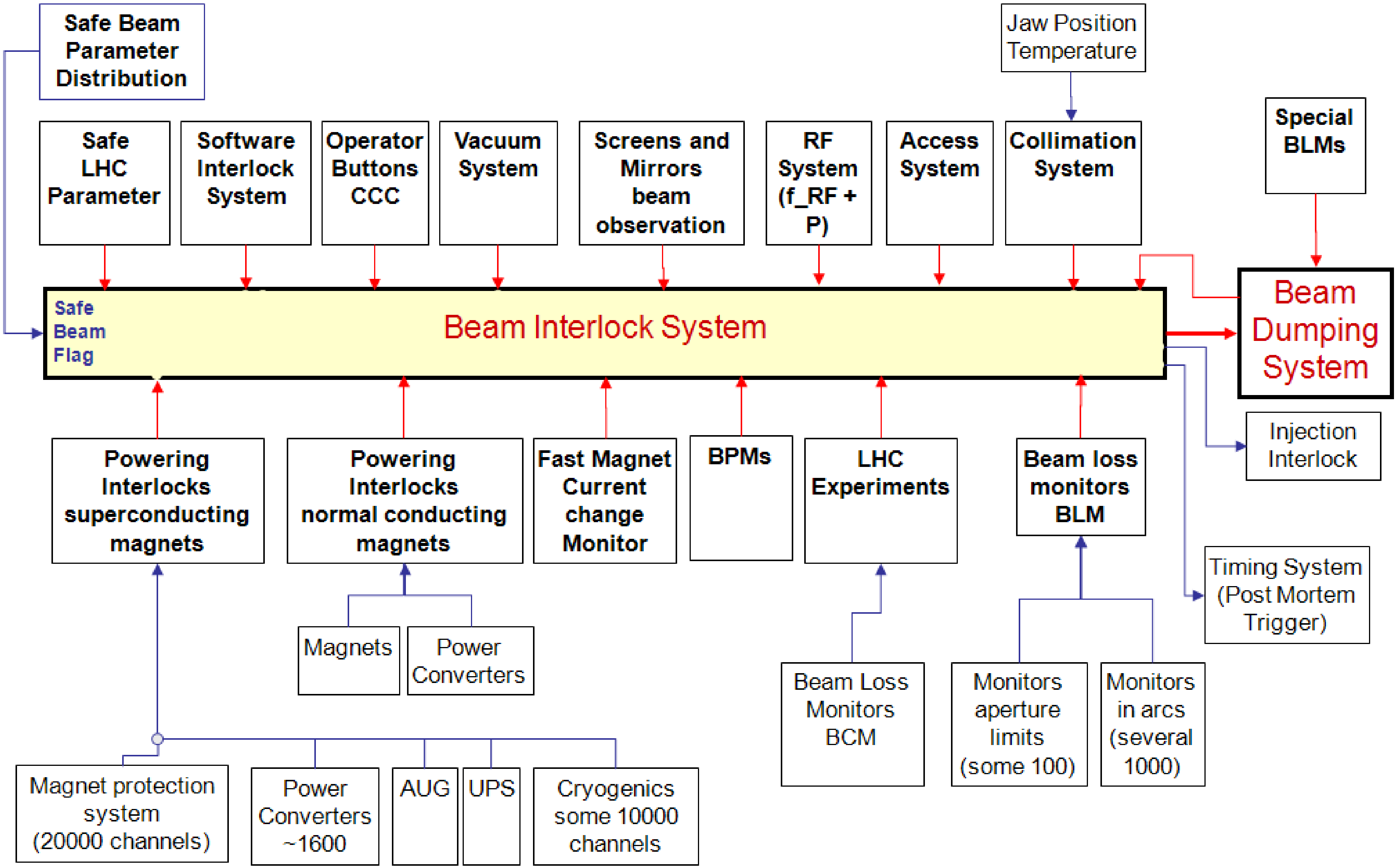
External Review on LHC Machine Protection

Sept 2010

- Failures, beam losses and beam dumps during 3.5 TeV operation
- What caused the failure and what captured the failure?
- Diagnostic tools to analyze beam dump events and evaluate MPS
- What is understood, what remains to be understood?

1v0

From this morning...



Activation of MPS in 2010

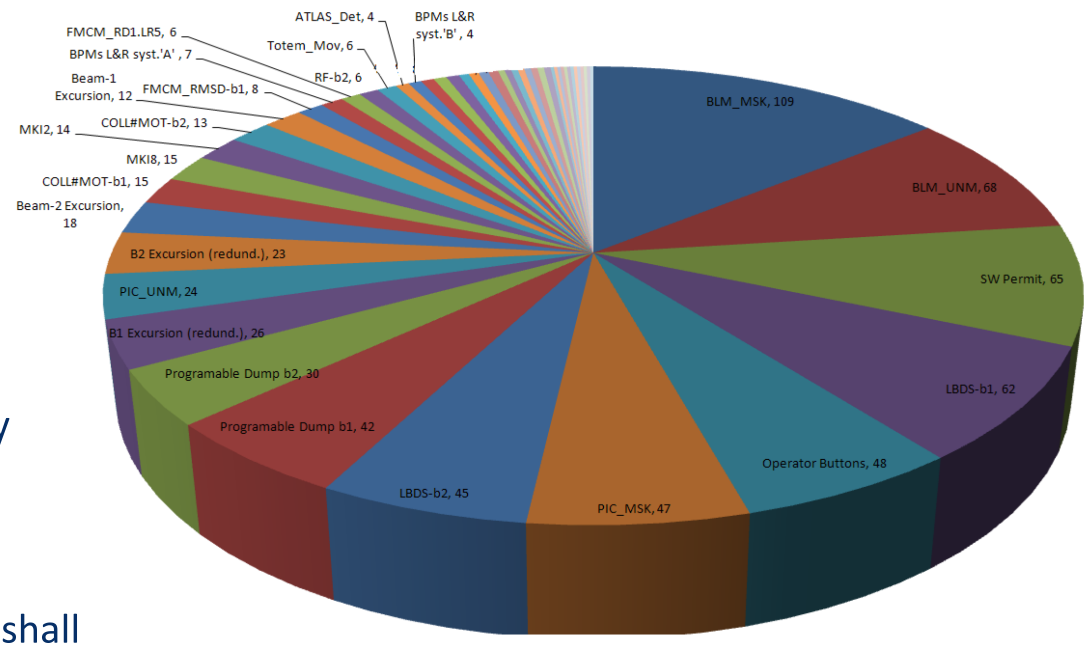
Every beam dump request exercises (parts of) the machine protection system and is being used to evaluate and improve its performance

LHC Machine Protection System has > 250 user input connections, for most frequent failure cases more than one system will/would request a dump of the particle beams

Majority of the events result in avalanches of interlocks, machine interlock systems play a central role for the identification of initiating event and event sequence

So far in 2010 >= 900 activations of the (armed) Beam Interlock System, mostly @ injection and/or for MPS tests

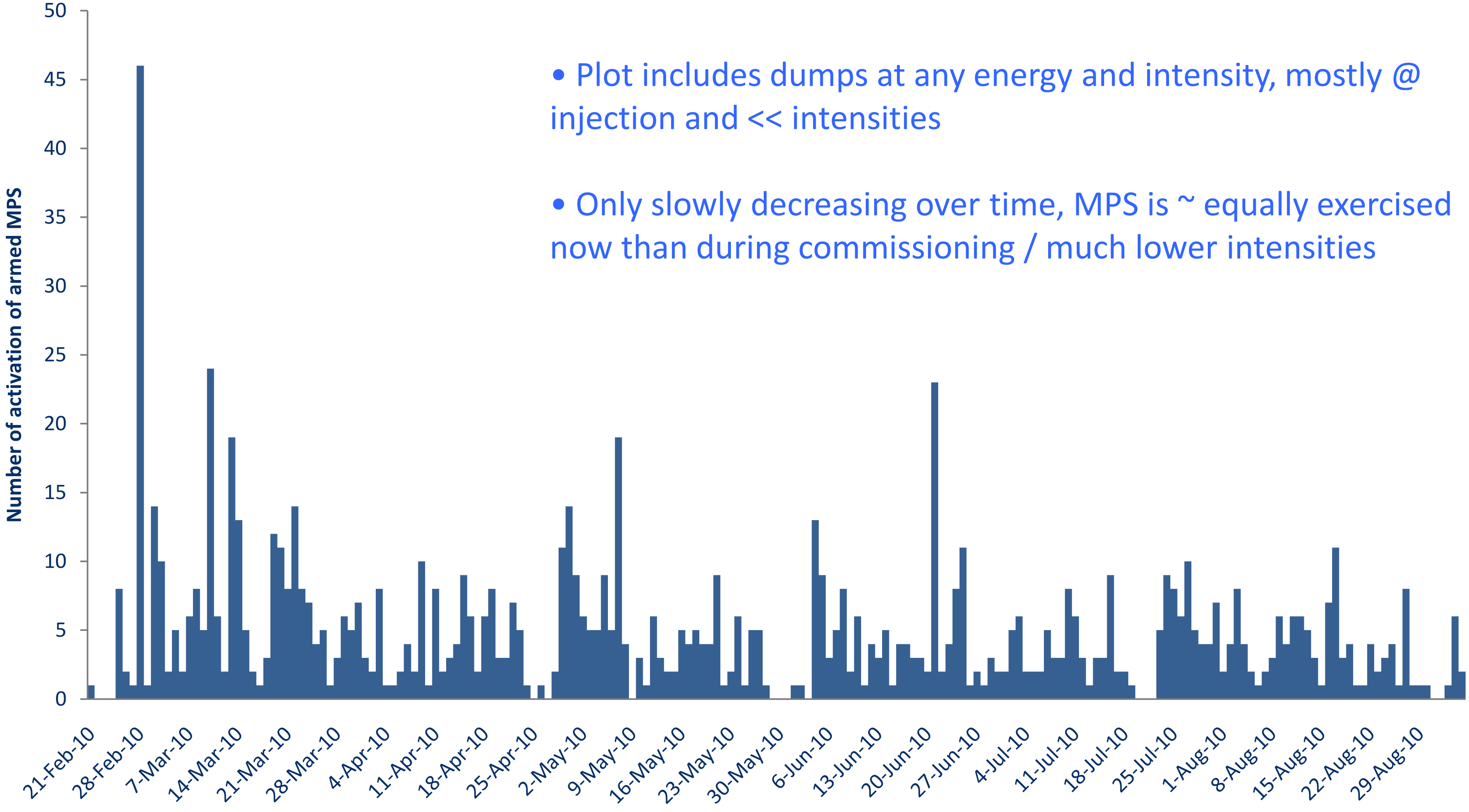
Some 212 beam dumps happened AFTER the start of the energy ramp, on which we shall concentrate hereafter



User inputs requesting a beam dump in the LHC (since Jan 2010)

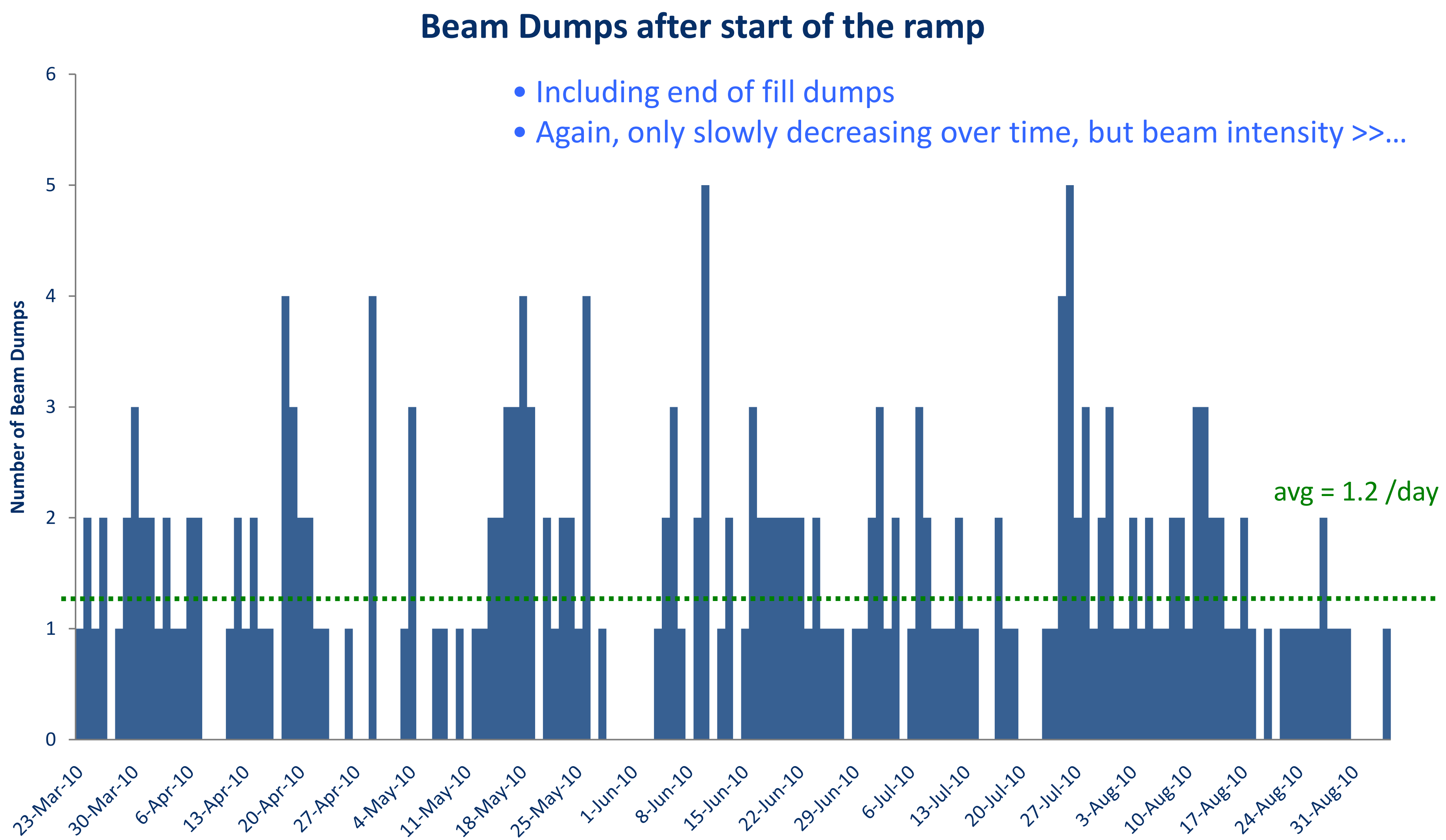
A bit of statistics # 1 …

Activation of (armed) MPS for 2010



- Plot includes dumps at any energy and intensity, mostly @ injection and << intensities
- Only slowly decreasing over time, MPS is ~ equally exercised now than during commissioning / much lower intensities

A bit of statistics # 2…



Detailed analysis of Machine Protection performance

- Detailed analysis of beam dumps in the LHC are vital for the further understanding of the machine protection system and for unveiling possible loop holes in the protection (beware of combined or rare/unforeseen events)
- MPS strategy (especially before increasing intensity): Every beam dump needs to be clean and/or understood before next injection
- Key to efficient and easy understanding of beam dumps are
  - Complete and accurate data acquisition within every MPS sub-system, following common standards and naming conventions
  - Common data acquisition systems and repositories, allowing for easy correlation of data
  - Powerful data archiving, extraction and (automated) analysis tools for repetitive tasks
- For MPS system, two of the available data acquisition/extraction tools are mostly in use, specialized for continuous data logging (for relatively slow change rates) and transient data recordings in case of beam dump events

[11]

Main Data Acquisition Systems for LHC

DATA ACQUISITION SYSTEM	PURPOSE	Acquisition Rate	Data Volume	Importance for MPS
SCADA supervisory systems	**Real-time supervisory tools** (Java, PVSS)	On change	> 10s of kB / day, local archive, then sent to long term storage	Medium – Used daily for supervision of MPS systems
DIAMON	**Diagnostic and monitoring of controls infrastructure**	infrequent	Few 10s of changes per day	Medium, used for online monitoring of red power supplies, FE processes, ….
ALARM System	**Alarms service** (for technical infrastructure,..)	infrequent	> 10.000 Alarms per day	Not used (yet), no efficient alarm filtering yet…
Measurement Database	Continuous Logging of equipment system	**Few Hz**	> GB /day, kept for 7 days only	Not used for MPS (but identical concept as Logging DB)
Logging Database	Logging system for equipment systems, slower response time	On change, but typically <1Hz	**> 100 GB / day**, kept for LHC lifetime	High – Used regularly for performance evaluation
Post Mortem	**Transient data analysis** after powering or beam dump events	**>kHz/MHz**, < intervals around interesting events	> 1 GB / beam dump event, kept for LHC lifetime	Very High – Used daily for performance evaluation

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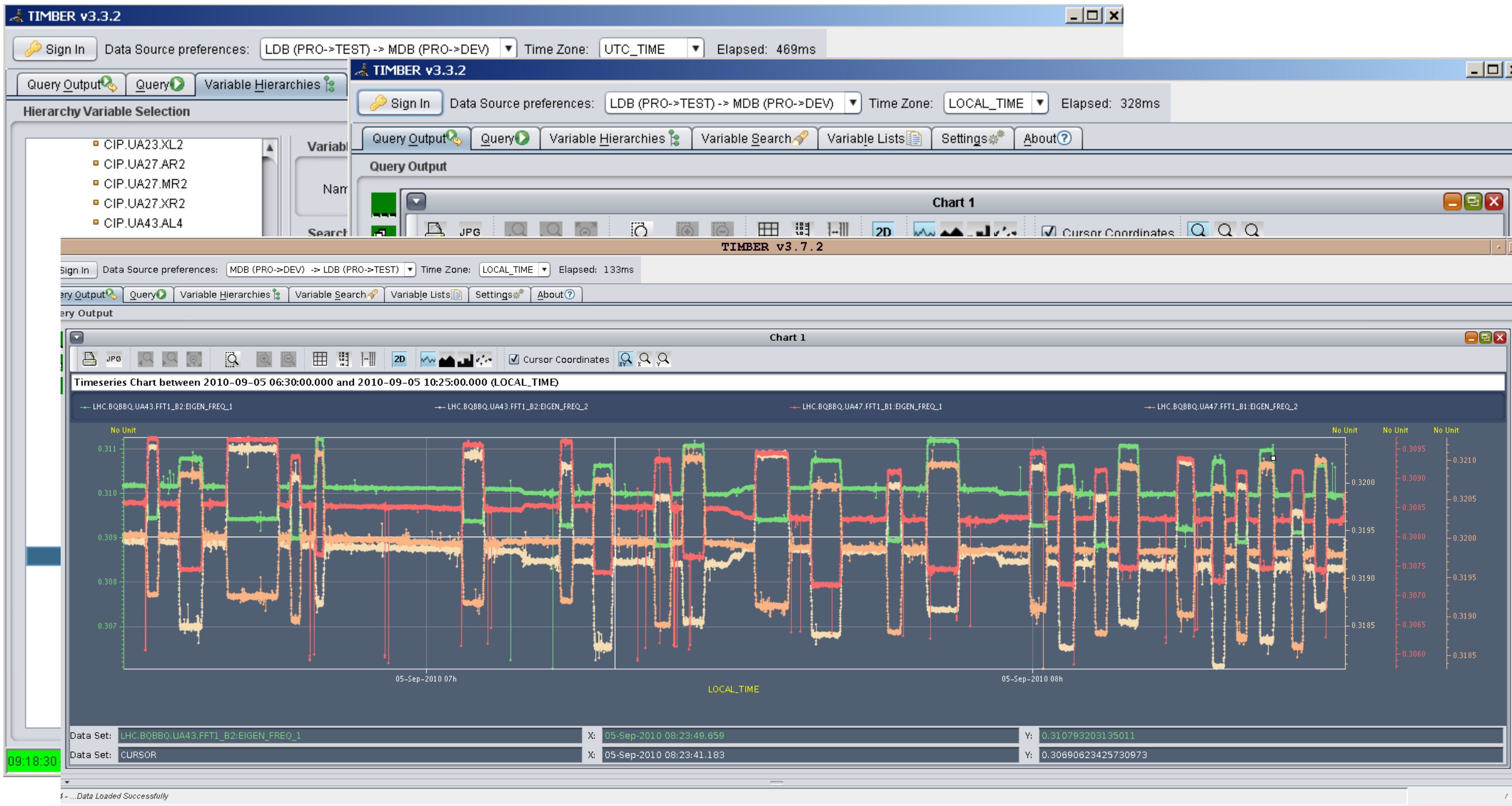
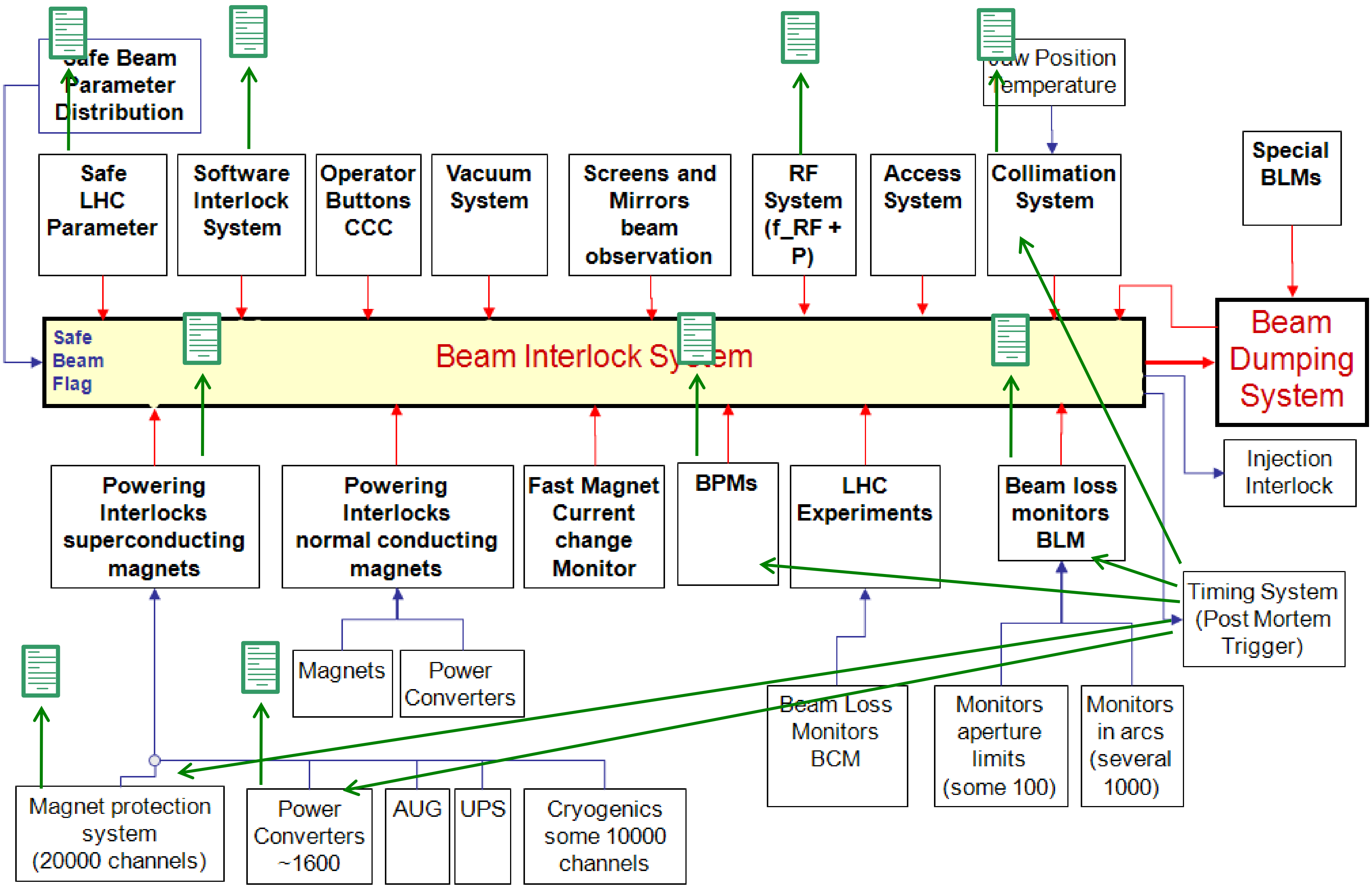
Common repository for all equipment systems, allowing for direct correlation of data

Variable searches based on common variable/system naming

Huge data storage capacity, data maintained throughout complete LHC lifetime



Transient data recording after a beam dump (PM)



Operation - Post-Mortem

LHC Post Mortem system is an automated post-operational analysis of transient data recordings from LHC equipment systems

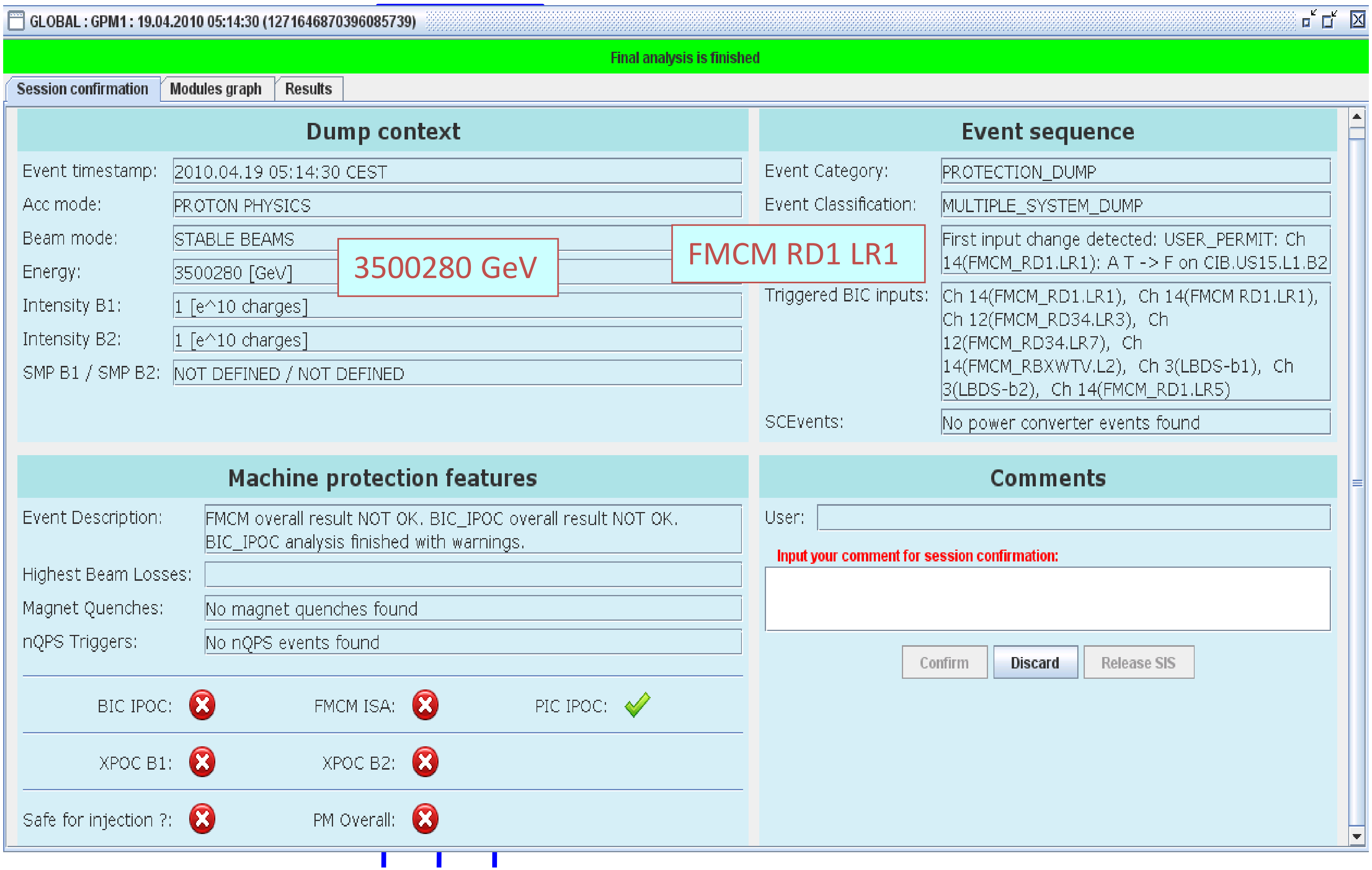
Meant to support machine protection by helping the operations crews and experts in understanding the machine performance and beam dump events and answer fundamental questions:

- What happened? (ie the initiating event / event sequence leading to dump/incident)
- Did the protection systems perform as expected (automated Post operational checks)?
- Assist in trend analysis, statistics of machine performance, …

Basis is a reliable and performing data transmission and storage layer

Each beam dump generates ~ 1GB of PM data which is automatically analysed in typically < 1 min

PM Server Architecture



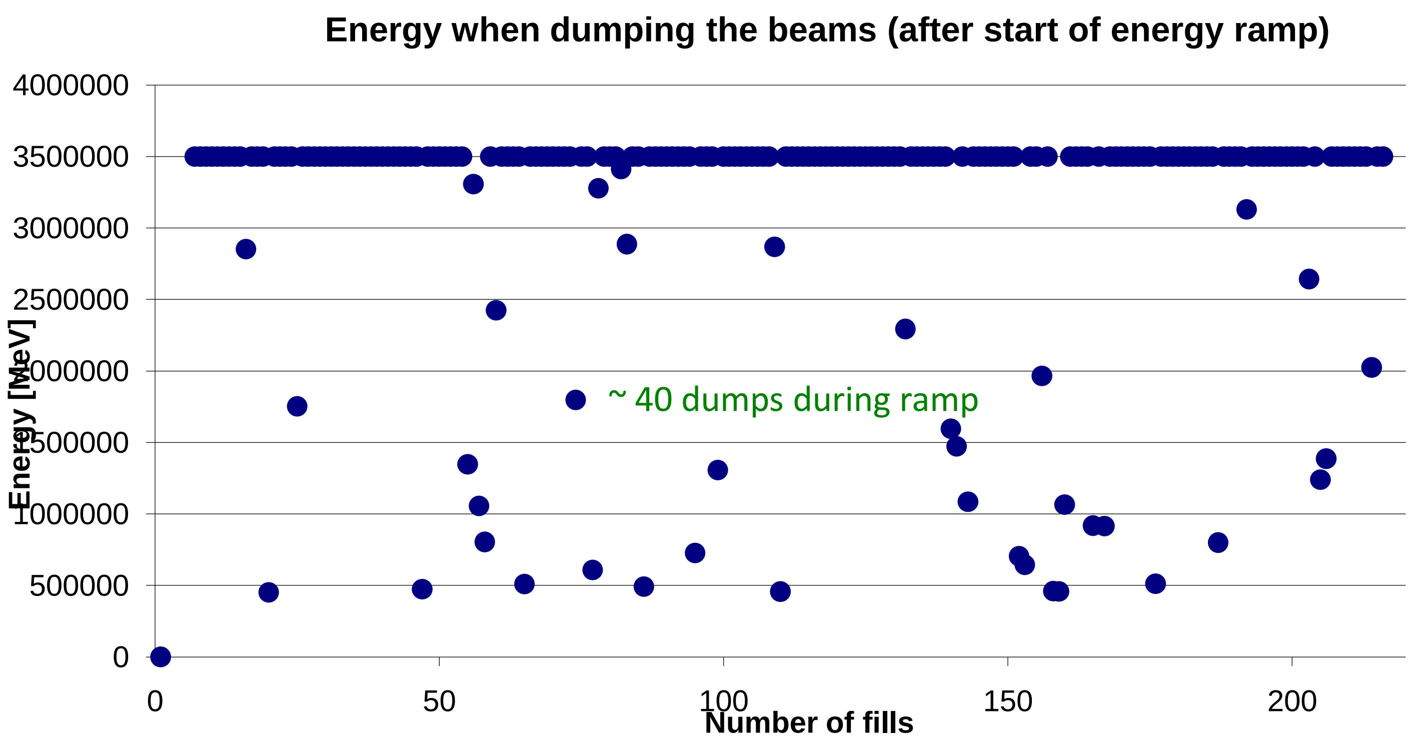
PM buffers

Analysis of global events…

Beam dump events after start of ramp

In the following, some statistics and observations for the ~200 beam dumps which happened AFTER the start of the energy ramp is shown

Statistics are (largely) based on Post Mortem analysis archives and additional manual analysis of MPS experts



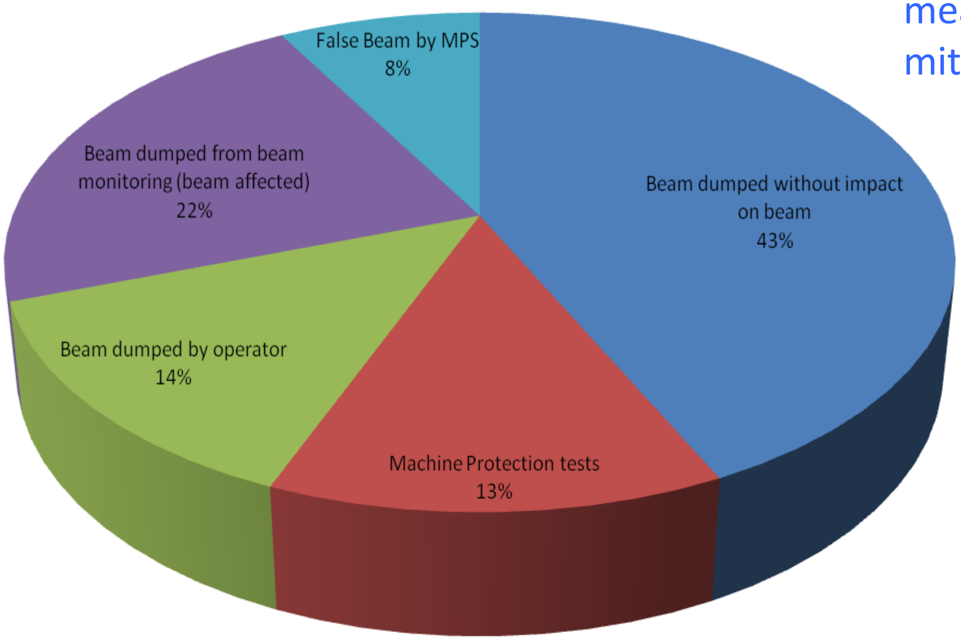
Original Data for following plots courtesy of R.Schmidt

Beam dump events by Category

More than 75% of beam dumps without effects on the beam

Only small fraction of programmed (end of fill) dumps by operations

False beam dumps by MPS will decrease in longer term (initial HW problems in one sub-system)

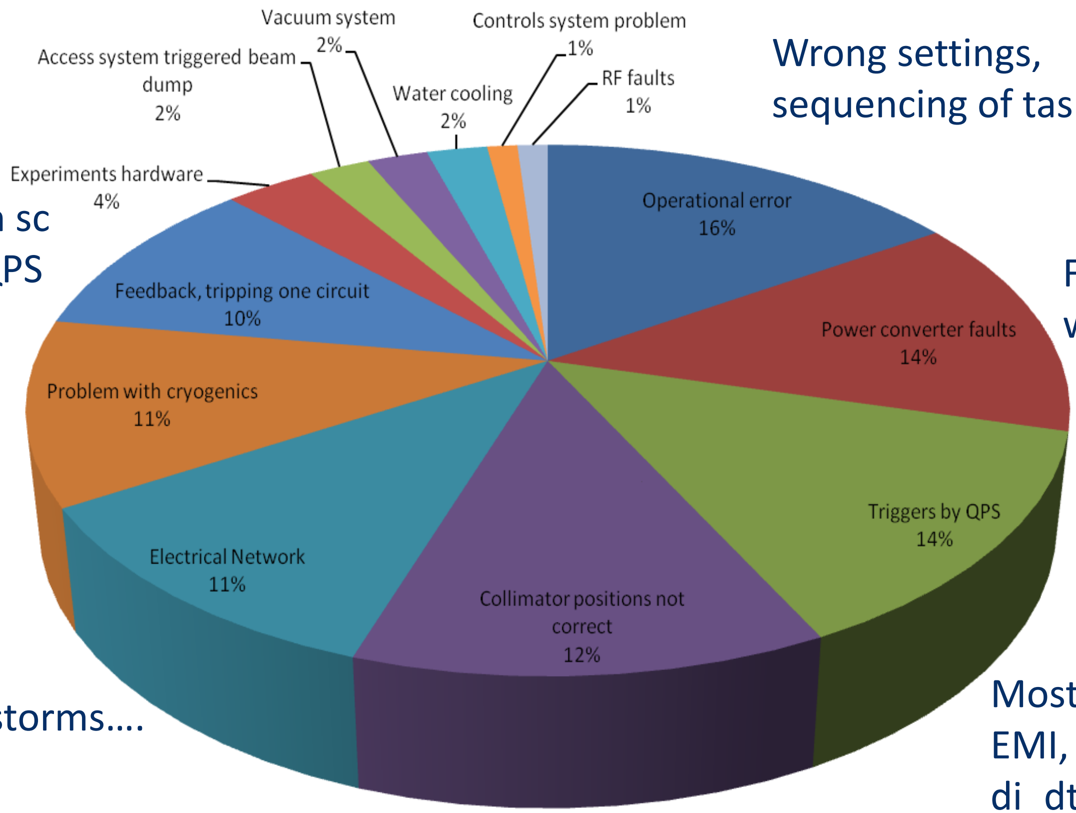


Additional (hardware and software) measures have been and will be added to further mitigate failure cases with effects on the beam, e.g.

- Fast Magnet Current Change Monitors for nc magnets
- DIDT interlock for beam current
- Additional SIS checks on equipment settings, beam position, etc…

Redundancy /protection of failures by 2 independent channels (for circulating beam) works very nicely (e.g. interlocks from magnet powering fast enough to avoid effects on beam, beam cleaning / BLM very well set so no quenches yet, etc…

Beam dumps NOT affecting the beam



Wrong settings, sequencing of tasks,..

Tuning to comply with sc circuit parameters / QPS

Faulty power modules / water cooling,…

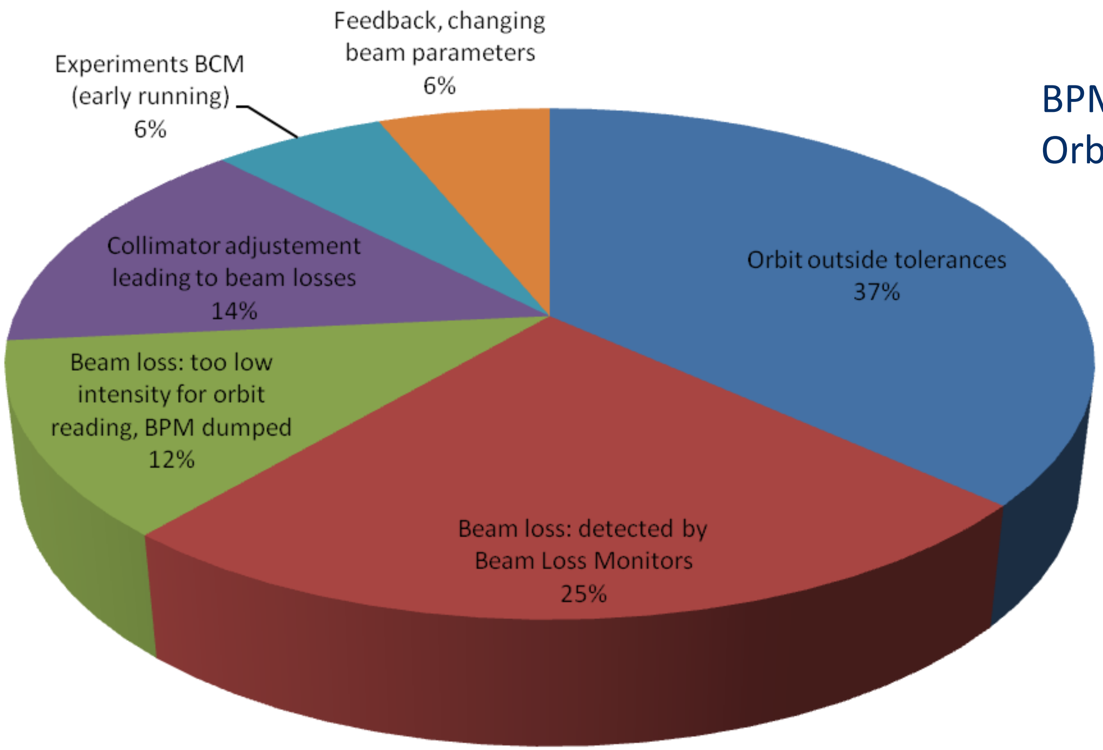
Few losses of cold compressors, often instrumentation or transient signals

Thunderstorms….

Mostly no real quenches, but EMI, too tight thresholds, di_dt/acceleration issues,…

Mostly during initial setup / adjustment

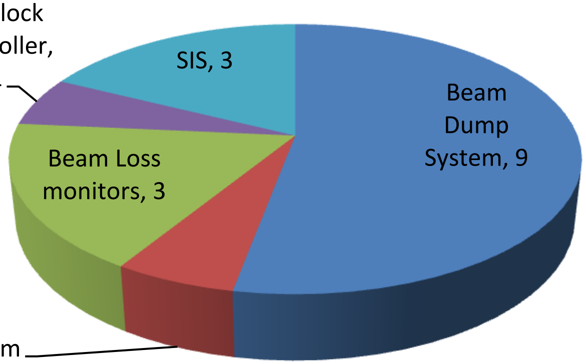
Beam dumps by interlocks affecting the beam

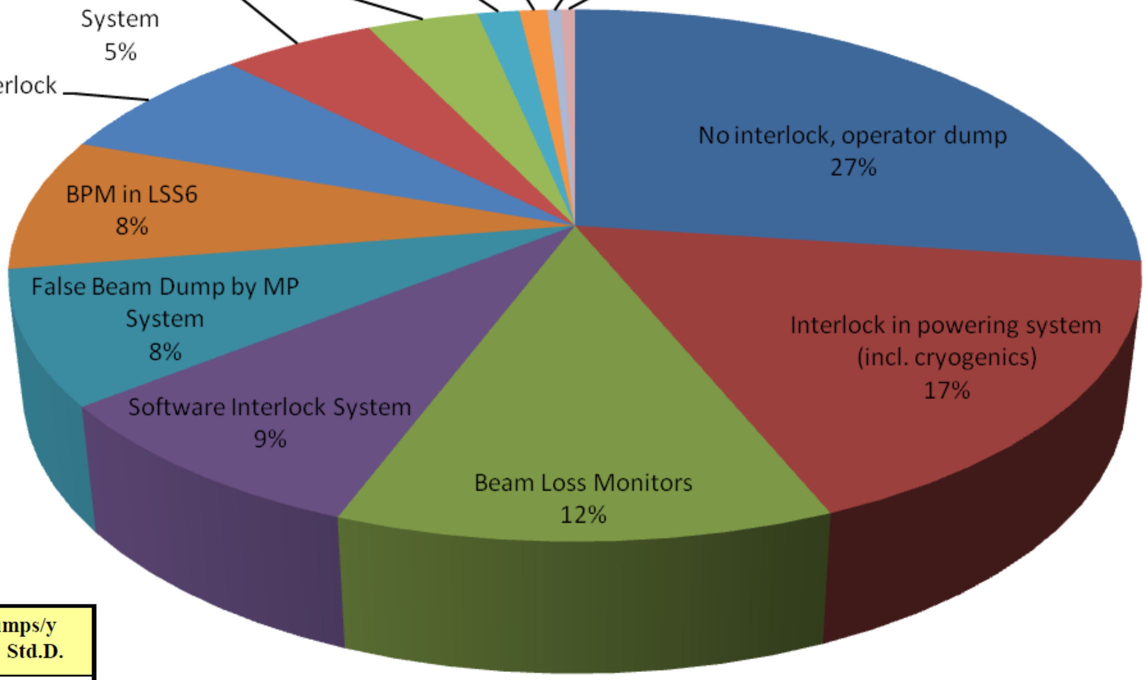


BPMs in IR6 / TCDQ
Orbit feedback / corrector trips

7 fast beam loss events (UFOs? - see later on)
Beam loss on resonance or during scraping
Octupole studies
Wire scanner

What saved us (who dumped the beam)?

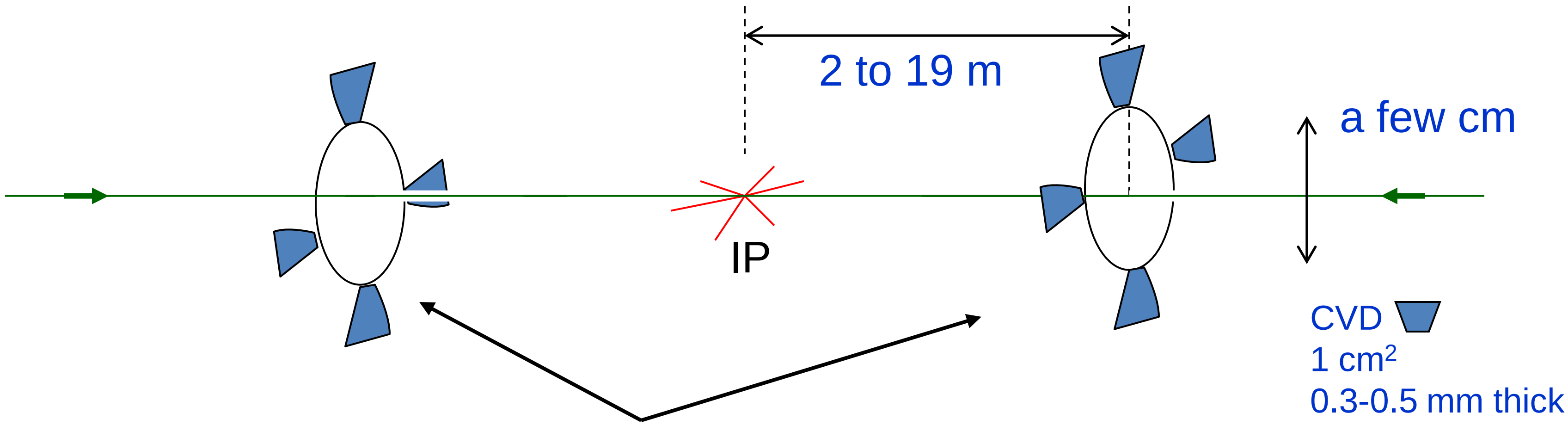




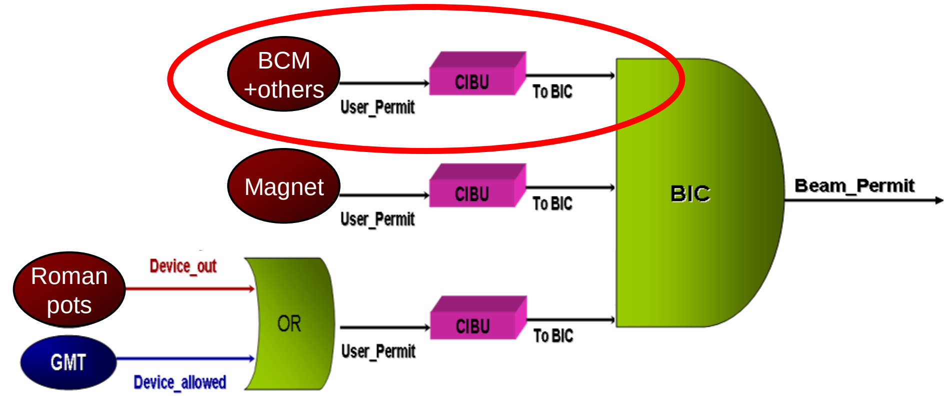
System	Unsafety per year	False dumps/y Average	Std.D.
LBDS[RF][1]	1.8×10^{-7}(2x)	3.8(2x)	+/-1.9
BIC [BT][2]	1.4×10^{-8}	0.5	+/-0.5
BLM [GG]	1.44×10^{-3} (Front-end) 0.06×10^{-3} (Back-end VME)	17	+/-4.0
PIC [MZ]	0.5×10^{-3}	1.5	+/-1.2
QPS[AV]	0.4×10^{-3}	15.8	+/-3.9
MPS	**2.3×10^{-4}** **5.75×10^{-8}/h is SIL3**	**41**[3]	**+/-6.0**

So far ~ 6 months of operation
Dependability studies for MPS systems seem to be confirmed (or be better)

Typical LHC Experiment Protection System



- One Beam Condition Monitor (BCM) on each side of IP:
  - Stand-alone system using a few polycrystalline CVD diamond pads
  - Post-Mortem analysis capability
  - FPGA-based dump logic:
    - input: measured rates
    - output: `UserPermit` signal
  - Unmaskable input to local BIC
  - On trigger, dump both beams



- BCM protects against circulating beam failures, not against injection and extraction failures, though it will be ON during injection (for fast feedback).

Courtesy of M.Ferro-Luzzi

LHC Exp Protection - summary

- All Experiment protection systems are operational
  - Teething/learning issue: overprotection by ATLAS BCM low threshold (startup 2009, solved by replacing with ATLAS BLM)
- No threshold-exceeding beam losses in experiments observed so far during stable beams
- So far, beam conditions are excellent, negligible background rates
- Observations (to be watched out / followed up):
  - ALICE gaseous detector trips (correlated with beam presence, but no correlation with beam loss could be established)
  - LHCb seeing increasing losses when piling up bunch injections
    - Much less this year than in 2009, but still visible
  - IR BPMs currently not reliable ("soft" protection issue, used to monitor beam drifts => especially relevant for VELO/LHCb, but not crucial)

Courtesy of M.Ferro-Luzzi

Fast Beam Losses – UFOs?

So far 7 beam dumps due to fast beam losses (<1% of beam intensity) have been observed, events on both beams and most of the machine

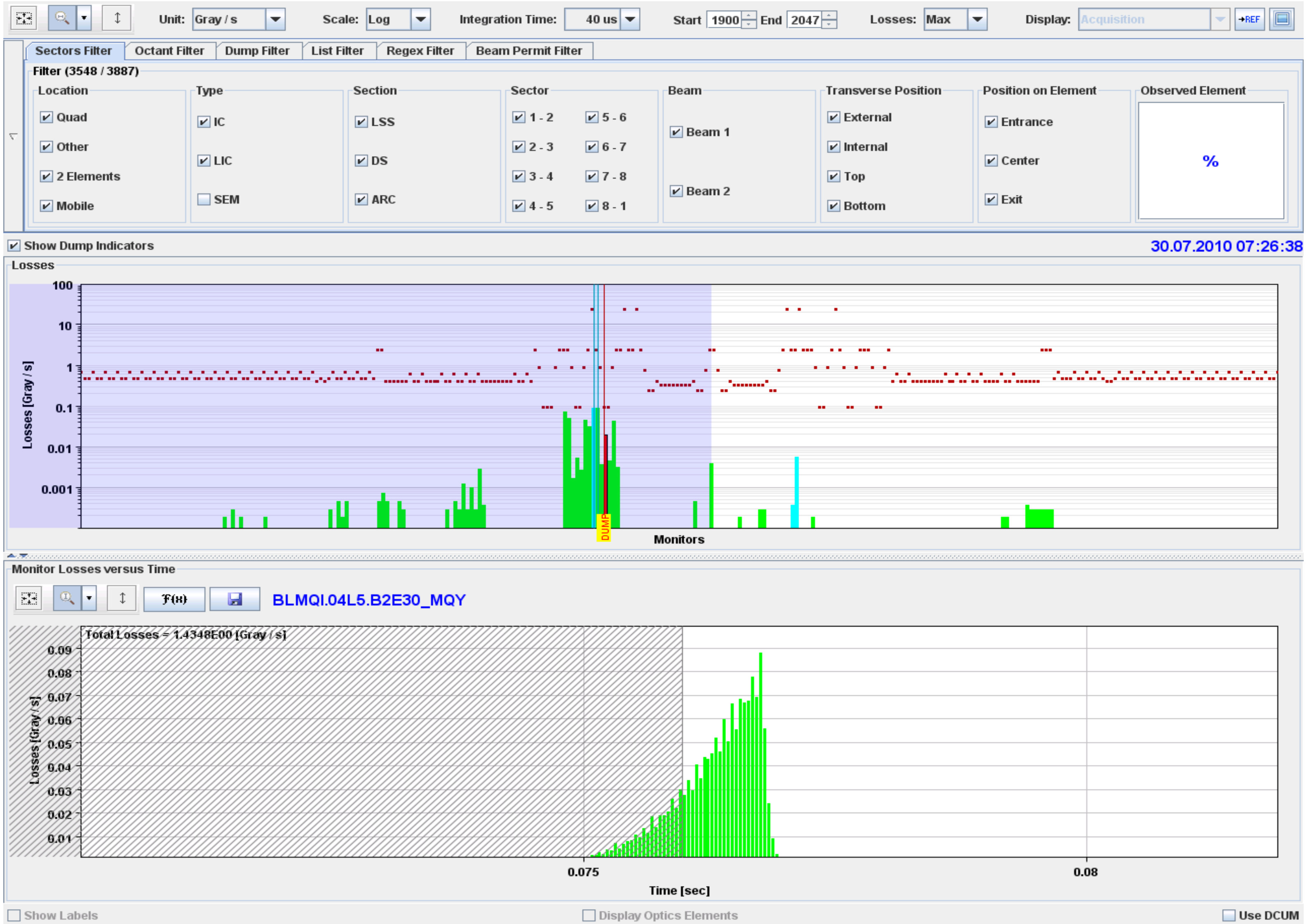
Date	Location	S (m)	Sector	Beam	Plane	Beta (m)	Max RS01 (G/s)	Risetime (ms)	Fill	No bunches	Intensity	Length (h)
07-07-2010 20:22:19	MBB.8L7**	21380	67	2	V	120	0.08	2.3	120x	9	8.4E+11	0
30-07-2010 07:26:38	Q4.R5	15160	56	2	H	274	0.08	1.25	1253	25	1.9E+12	13.15
07-08-2010 02:14:38	Q11.L4	11224	34	1	H	179	0.09	1.2	1264	25	2.1E+12	0.53
08-08-2010 01:10:46	Q15.L5	14342	45	1	V	184	0.07	1.25	1266	25	2.1E+12	1.97
14-08-2010 19:13:36	Q6.R5*	15222	56	1	V	211	0.092	0.8	1284	25	2.3E+12	3.48
23-08-2010 13:50:28	Q22.R3	9354	34	2	H	180	0.082	0.75	1298	48	3.7E+12	12.97
26-08-2010 17:25:56	Q25.R5	16179	56	1	H	180	0.125	0.8	1303	48	4.5E+12	13.08

Mechanism for the losses in not understood, but all events show a similar signature, finally dumping beams in 2.5ms running sum of BLM (increasing losses until the beam dump, non exponential increase, suggesting a maximum and possible decay in case of > BLM threshold)

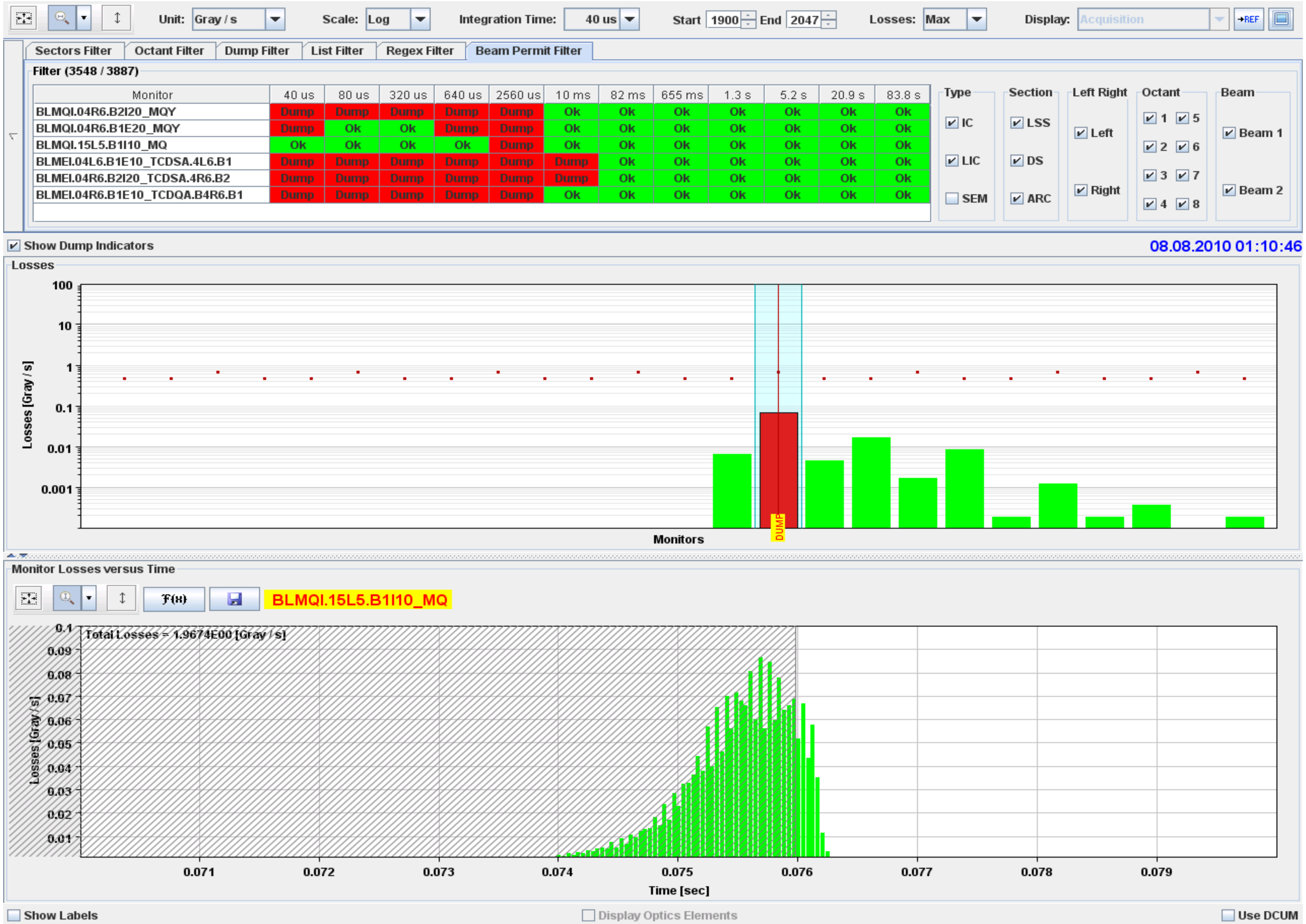
Losses seen at all aperture limits (IR3/IR7, LSS6), confirming real beam loss and at the same time nicely demonstrating BLM redundancy

*Roman pot event ** 5 pre-cursors / in squeeze

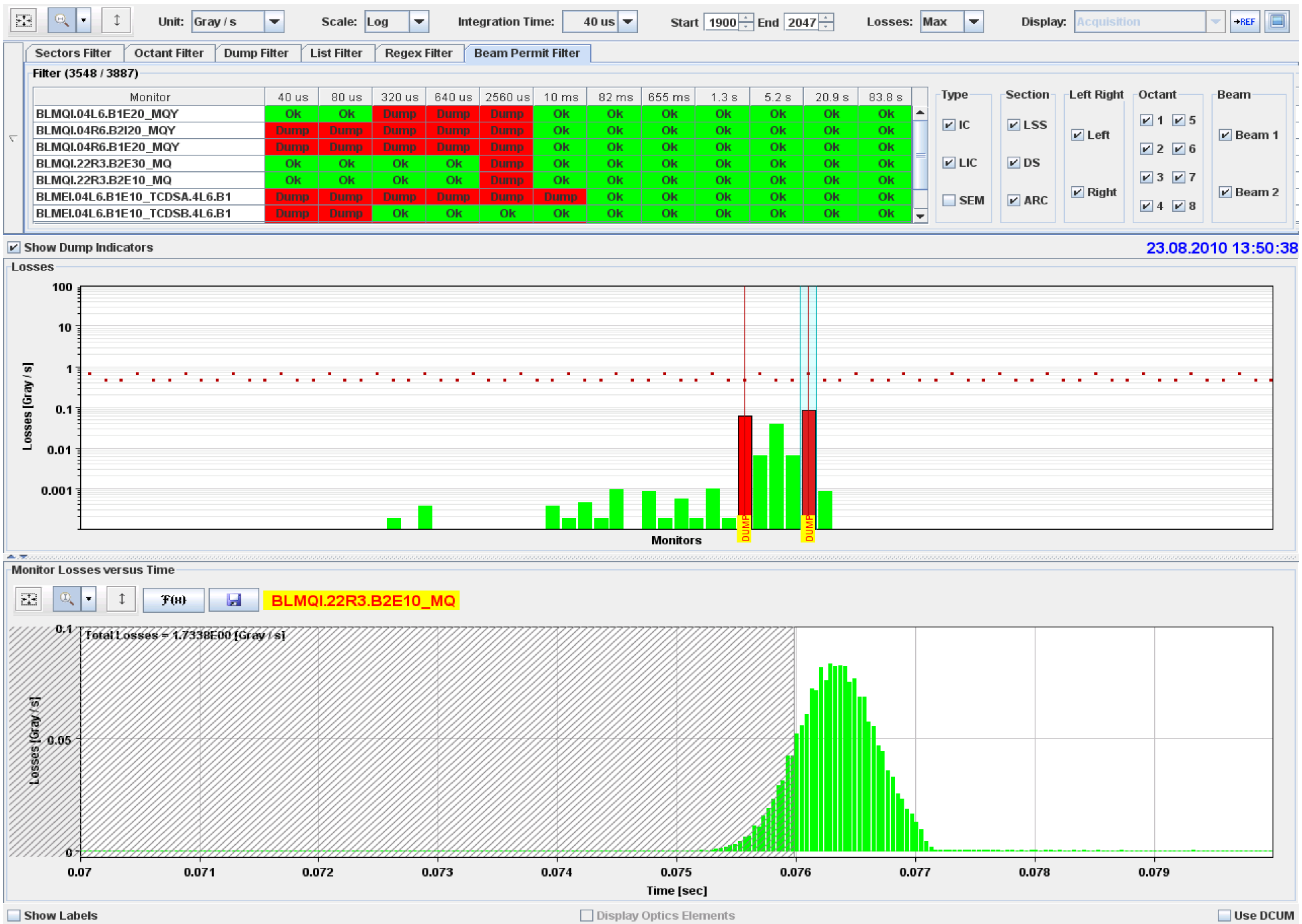
Event 30th July 2010, 07:26:38, Q4.R5



Event 8th August 2010, Q15.L5



Event 23.08.2010 13:50:38, on MQ22.R3



Event 23.08.2010 13:50:38, on MQ22.R3

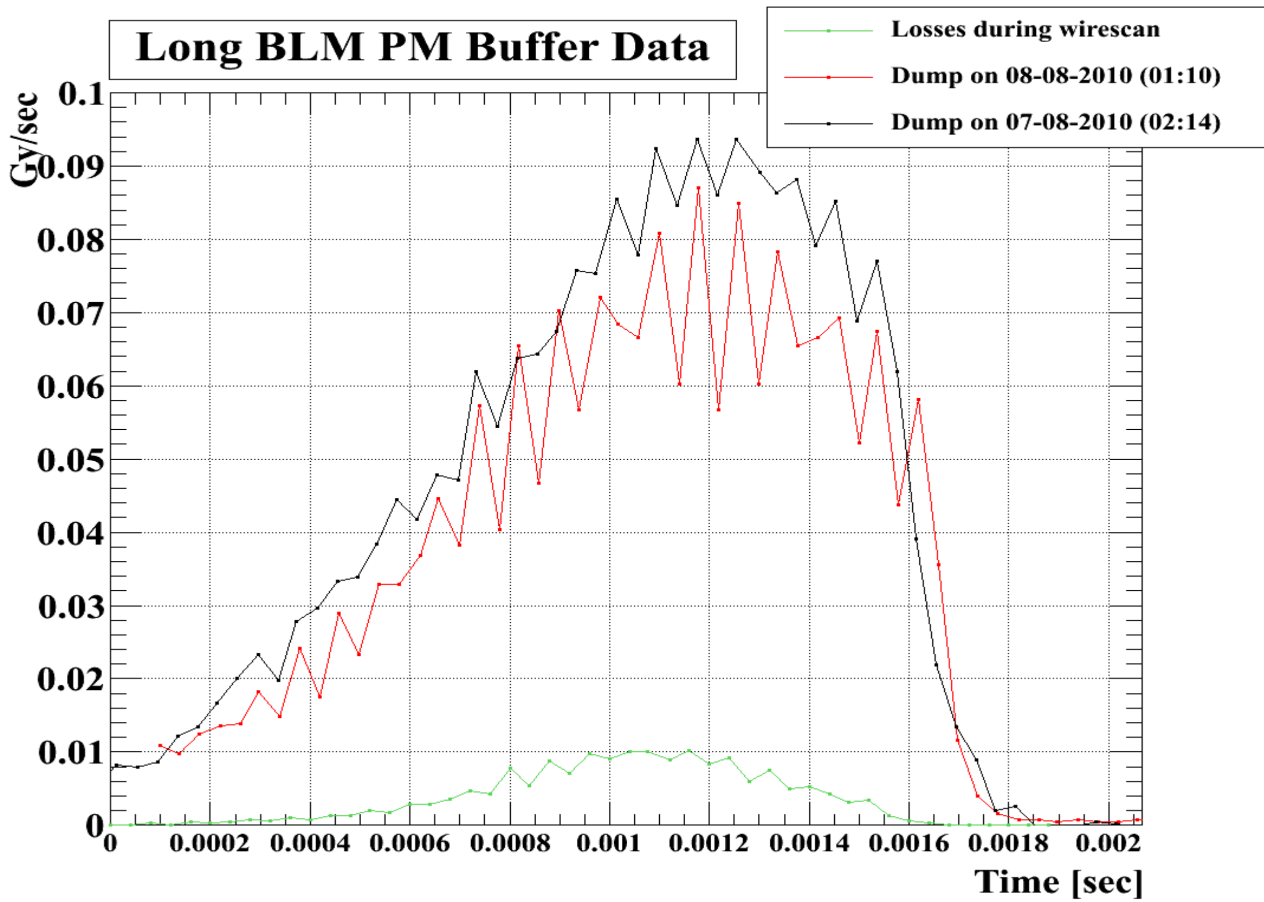
Same signal seen in cleaning insertion IR7

Fast Beam Losses – UFOs?

Current hypothesis of (dust) particles / UFOs falling through the beam

Comparison with loss patterns during a wire scan confirms similarity of shape and timescales

Additional installation of diamond detectors in IR7 done during last technical stop (PM triggered) to get bunch to bunch resolution of losses



Current proposal:

In case of two additional events, increase BLM thresholds on cold MQs by a factor of 2

Quench(ino)s

So far no real quench with circulating beam, but (very) few beam induced magnet quenches at injection

All cases would have recovered without firing of quench heaters

Example of Quench(ino) event from 18/4/2010 @ 22:33:

- Happened at injection energy, when injecting beam 1
- Injected bunch had 8E9 protons (transfer line BCT)
- Defocusing quadrupole magnets in sector 12 were mistakenly at 350A instead of injection current (760A)
- Beam loss over first turn
- PM indicates BPM.Q19R1 at =6mm, same for Q21.R1
- Losses starting in cell 18R1

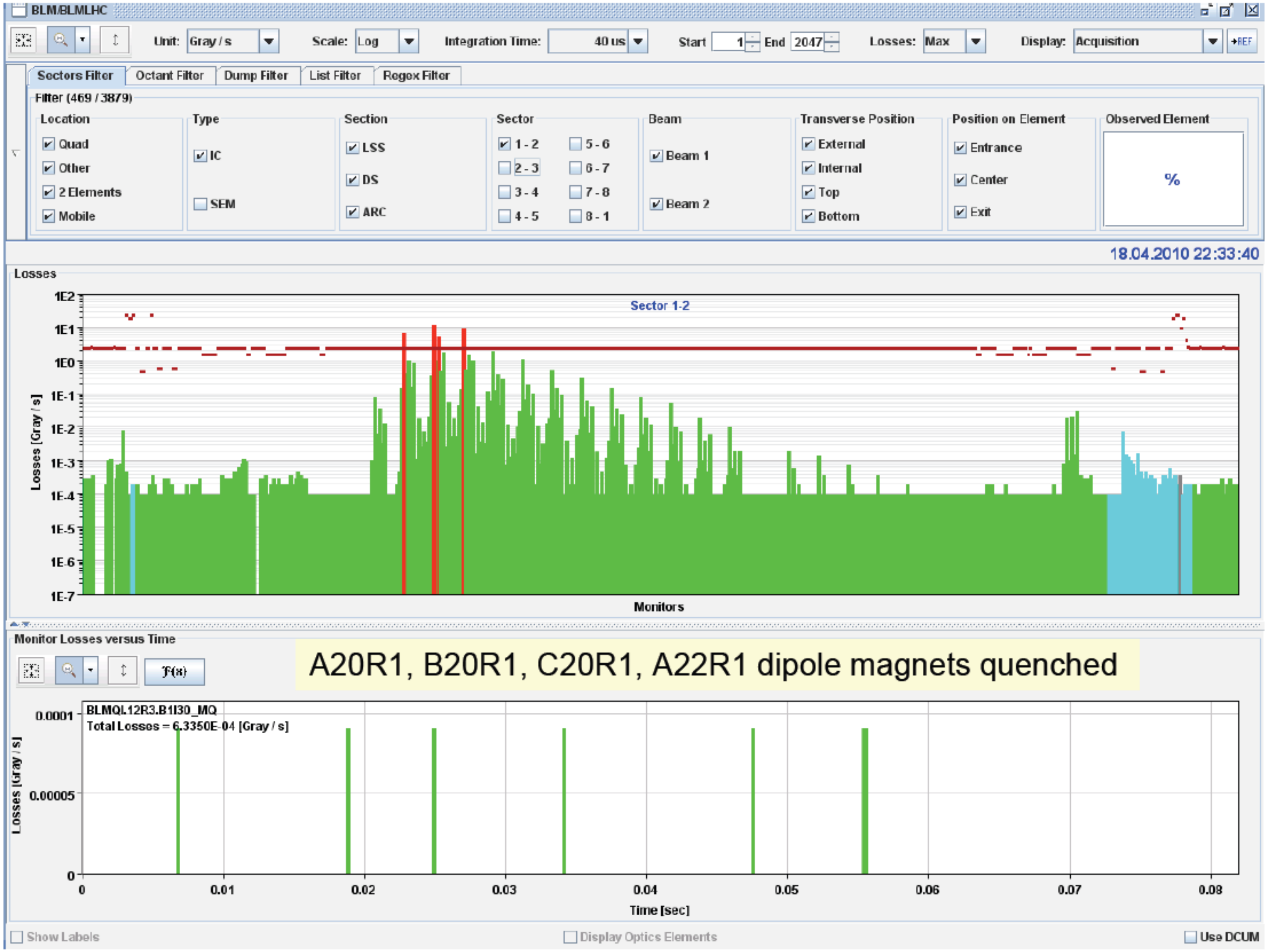
Quench(ino) event from 18/4/2010 @ 22:33

Beam 1

Courtesy of R.Appleby

Quench(ino) event from 18/4/2010 @ 22:33

Beam 1



Courtesy of R.Appleby

Event sequence for event on 18/4/2010

- Beam dump request as expected from BLM in IR1
- 20 ms later (time to develop and detect the quenchino), 2nd trigger by powering interlocks/QPS

BIC/EVENT_SEQ

HEADER

System	BIC
Class	EVENT_SEQ
Source	ISA
Event stamp	22:33:40.281 18/04/10
Version	0.4.3
Encoding	BIC/EVENT_SEQ
Qualifier	
Analysis flags	[NORMAL]

SUMMARY

pmAnalysisModuleVersion	0.4.3
Analysis result description	First USR_PERMIT change: Ch 4-BLM_UNM: A T -> F on CIB.US15.L1.B2
Triggered BIC inputs	Ch 4-BLM_UNM(L1.B2), Ch 4-BLM_UNM(L1.B1), Ch 5-PIC_UNM(L2.B2), Ch 12-PIC_MSK(L2.B2), Ch 5-PI...
Beam 1 propagation delay to LBDS	63000 ns
Beam 2 propagation delay to LBDS	63000 ns
OVERALL	38 BICs triggered valid PM data

EVENT OVERVIEW

Index	Loc.Permit A/B	Time	Delta(uSec)	Description	BIC name
525		22:33:40+281136	0	USER_PERMIT: Ch 4-BLM_UNM: A T -> F	CIB.US15.L1.B2
526		22:33:40+281136	0	USER_PERMIT: Ch 4-BLM_UNM: B T -> F	CIB.US15.L1.B2
527		22:33:40+281136	0	USER_PERMIT: Ch 4-BLM_UNM: A T -> F	CIB.US15.L1.B1
528		22:33:40+281136	0	USER_PERMIT: Ch 4-BLM_UNM: B T -> F	CIB.US15.L1.B1
1596		22:33:40+302019	20883	USER_PERMIT: Ch 5-PIC_UNM: A T -> F	CIB.UA23.L2.B2
1597		22:33:40+302019	20883	USER_PERMIT: Ch 5-PIC_UNM: B T -> F	CIB.UA23.L2.B2
1598		22:33:40+302020	20884	USER_PERMIT: Ch 12-PIC_MSK: A T -> F	CIB.UA23.L2.B2
1599		22:33:40+302020	20884	USER_PERMIT: Ch 12-PIC_MSK: B T -> F	CIB.UA23.L2.B2
1600		22:33:40+302020	20884	USER_PERMIT: Ch 5-PIC_UNM: A T -> F	CIB.UA23.L2.B1
1601		22:33:40+302020	20884	USER_PERMIT: Ch 5-PIC_UNM: B T -> F	CIB.UA23.L2.B1
1602		22:33:40+302021	20885	USER_PERMIT: Ch 12-PIC_MSK: A T -> F	CIB.UA23.L2.B1
1603		22:33:40+302021	20885	USER_PERMIT: Ch 12-PIC_MSK: B T -> F	CIB.UA23.L2.B1
1608		22:33:40+302082	20946	USER_PERMIT: Ch 5-PIC_UNM: A T -> F	CIB.UA27.R2.B2
1609		22:33:40+302082	20946	USER_PERMIT: Ch 5-PIC_UNM: B T -> F	CIB.UA27.R2.B2
1610		22:33:40+302082	20946	USER_PERMIT: Ch 5-PIC_UNM: A T -> F	CIB.UA27.R2.B1
1611		22:33:40+302082	20946	USER_PERMIT: Ch 5-PIC_UNM: B T -> F	CIB.UA27.R2.B1
1612		22:33:40+302083	20947	USER_PERMIT: Ch 12-PIC_MSK: A T -> F	CIB.UA27.R2.B2
1613		22:33:40+302083	20947	USER_PERMIT: Ch 12-PIC_MSK: A T -> F	CIB.UA27.R2.B1
1614		22:33:40+302084	20948	USER_PERMIT: Ch 12-PIC_MSK: B T -> F	CIB.UA27.R2.B2
1615		22:33:40+302084	20948	USER_PERMIT: Ch 12-PIC_MSK: B T -> F	CIB.UA27.R2.B1
1620		22:33:40+303098	21962	USER_PERMIT: Ch 5-PIC_UNM: B T -> F	CIB.US15.R1.B2
1621		22:33:40+303098	21962	USER_PERMIT: Ch 5-PIC_UNM: B T -> F	CIB.US15.R1.B1
1622		22:33:40+303098	21962	USER_PERMIT: Ch 5-PIC_UNM: A T -> F	CIB.US15.R1.B1
1623		22:33:40+303099	21963	USER_PERMIT: Ch 5-PIC_UNM: A T -> F	CIB.US15.R1.B2
1624		22:33:40+303099	21963	USER_PERMIT: Ch 12-PIC_MSK: A T -> F	CIB.US15.R1.B2
1625		22:33:40+303099	21963	USER_PERMIT: Ch 12-PIC_MSK: B T -> F	CIB.US15.R1.B2
1626		22:33:40+303099	21963	USER_PERMIT: Ch 12-PIC_MSK: A T -> F	CIB.US15.R1.B1

SOURCE OVERVIEW

Index	Source Name	Data Valid
1	CIB.UJ56.R5.B1	true
2	CIB.UA83.L8.B2	true
3	CIB.UA83.L8.B1	true
4	CIB.UJ56.R5.B2	true
5	CIB.US15.L1.B1	true
6	CIB.US15.L1.B2	true
7	CIB.SR7.S7.B1	true
8	CIB.SR7.S7.B2	true
9	CIB.USC55.L5....	true
10	CIB.UA87.R8.B1	true
11	CIB.UA87.R8.B2	true
12	CIB.USC55.L5....	true
13	CIB.US15.R1.B1	true
14	CIB.US15.R1.B2	true
15	CIB.UJ33.U3.B2	true
16	CIB.UJ33.U3.B1	true
17	CIB.UA63.L6.B2	true
18	CIB.UA63.L6.B1	true
19	CIB.SR3.S3.B2	true
20	CIB.SR8.INJ2.1	true
21	CIB.SR3.S3.B1	true
22	CIB.SR2.INJ1.1	true
23	CIB.UA67.R6.B2	true
24	CIB.SR2.INJ1.2	true
25	CIB.UA67.R6.B1	true
26	CIB.CCR.LHC....	true
27	CIB.UA47.R4.B1	true
28	CIB.UA23.L2.B2	true
29	CIB.CCR.LHC....	true
30	CIB.UA47.R4.B2	true
31	CIB.UA23.L2.B1	true
32	CIB.UA43.L4.B2	true
33	CIB.UA43.L4.B1	true
34	CIB.TZ76.U7.B2	true
35	CIB.TZ76.U7.B1	true
36	CIB.SR8.INJ2.2	true

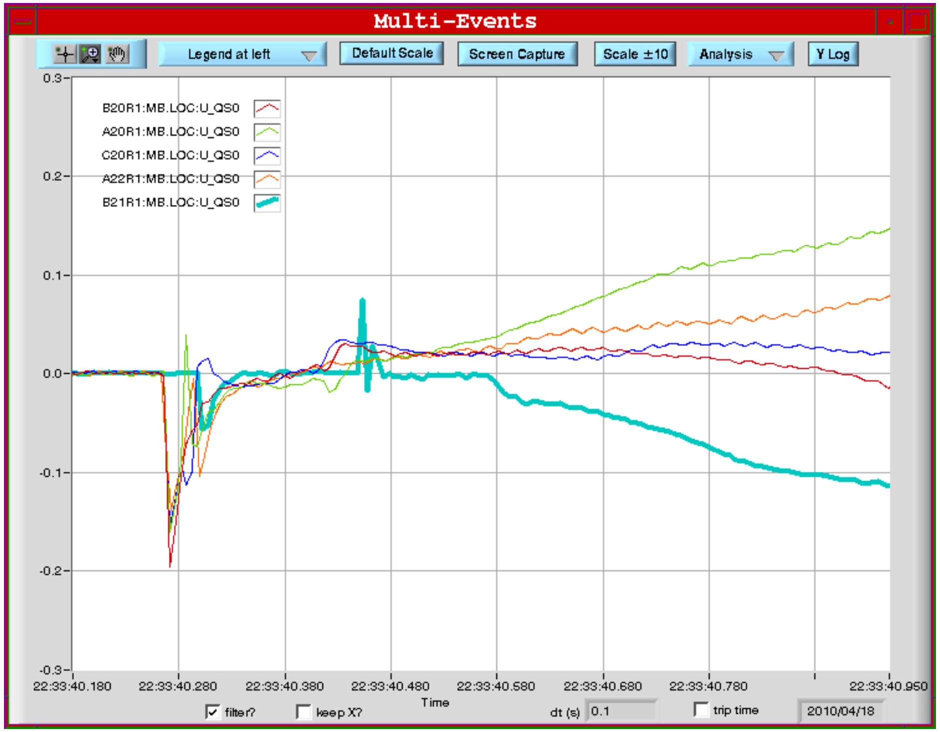
FILTER

☐ Beam_Permit_Loop ☐ Beam_Permit ☐ Local_Permit ☑ User_Permit ☐ User_Permit_Glitch ☑ Software ☐ Mask ☑ Masked_Permit

☐ Disabled_Permit ☐ Channel_Enable ☐ Test ☐ Power ☐ Self_Test ☐ Time ☐ Safe_Beam_Flag ☐ Marker ☐ Injection BICs

☑ Channel A ☑ Channel B ☑ Beam 1 ☑ Beam 2 ☐ Generator

Quench limit vs BLM thresholds



QPS signals on quenching magnets showing threshold crossing of 100mV before recovering (until heater firing becomes effective)

Few quenchinos and current experience shows that BLM thresholds are well set (even too conservative?)

Few 'quench' tests will be performed to determine 'real' quench limit vs current BLM thresholds

- Some of the tests will not quench a magnet, but just measure the voltage below the QPS threshold. Proposed tests:
  - Single turn test at injection in cell 14R2 (special QPS diagnostics installed)
  - Closed orbit bumps (cell 14R2) at injection and at 3.5TeV (intensities for the 3.5 TeV test tbd after 450GeV test)
  - Wire scan at 3.5TeV (probing the time scales of ~1 ms)
  - Quench test from collimators (losses in the cleaning insertion)
  - Quench test of Q4 in IR6 (important to define the abort gap population limits)

Summary

So far the LHC Machine Protection Systems have been working extremely well

Most failures are captured before effects on beam are seen, No quenches with circulating beam (with > 3MJ per beam and 10mJ for quenching a magnet)

Experiments are well protected, no issue with background so far

Most beam dumps are understood (except fast losses)

No evidence of possible loopholes or uncovered risks

MPS systems nicely captured even rare / 'unexpected' events, e.g.

- Fast beam losses (seen at all aperture limits, confirming BLM redundancy)
- Controls problems resulting in wrong transmission of beam energy (captured by RF interlock and eventually Collimators) -> implicit protection
- End of fill test by scraping with primary collimator in IR7 the beam 2 tails. Moving it into the beam with 10 micron step every 4 seconds (see collimation talks)
- Thunderstorms (correlated failures of > equipment systems)

Acknowlegements

Thanks a lot for your attention

Many thanks to a number of colleagues for their contributions to the talk (R.Schmidt, M.Ferro-Luzzi, R.Appelby,…)