Commissioning and Operation of the LHC Machine Protection System

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HB 2010, Morschach

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1v0

Outline

Protection Functions of the LHC Machine Protection System (MPS)

Main Building blocks of the LHC MPS

Machine Protection Commissioning

Failures, beam losses and beam dumps during 3.5 TeV operation 2010

What caused the failure and what captured the failure?

What is understood, what remains to be understood?

Outlook and Summary

Protection Functions of LHC MPS

Beam Protection: Beam Energy (360 MJ) → Beam Dump

100x energy of TEVATRON

0.000005% of beam lost into a magnet = quench

0.005% beam lost into magnet = damage

Failure in protection – complete loss of LHC is possible

Powering Protection: Magnet Energy (9 GJ) → Emergency Discharge

10-20x energy per magnet of TEVATRON

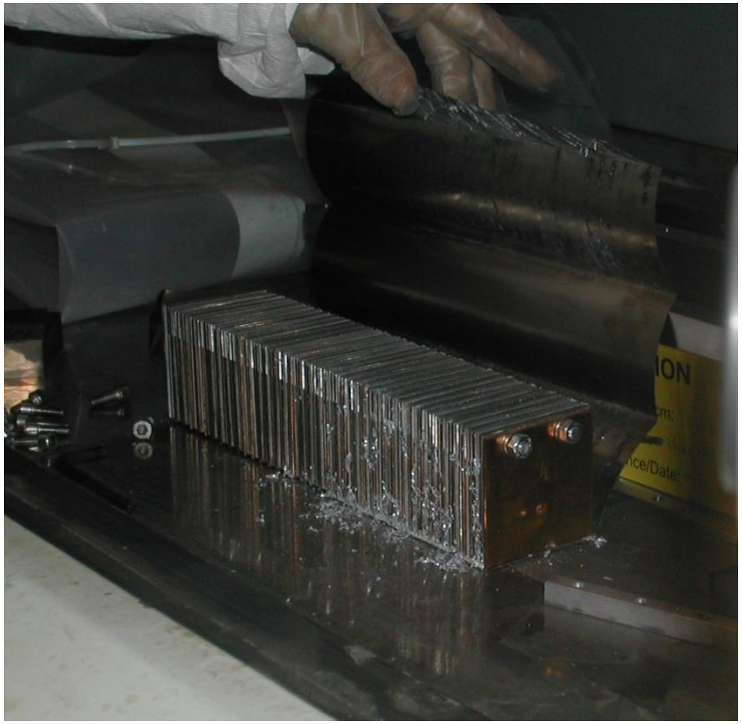
magnet quenched = hours downtime

many magnets quenched = days downtime

magnet damaged = $1 million, months downtime

many magnets damaged = many millions, many months downtime (few spares)

Controlled beam damage test in TT40 (SPS-LHC Transfer line)



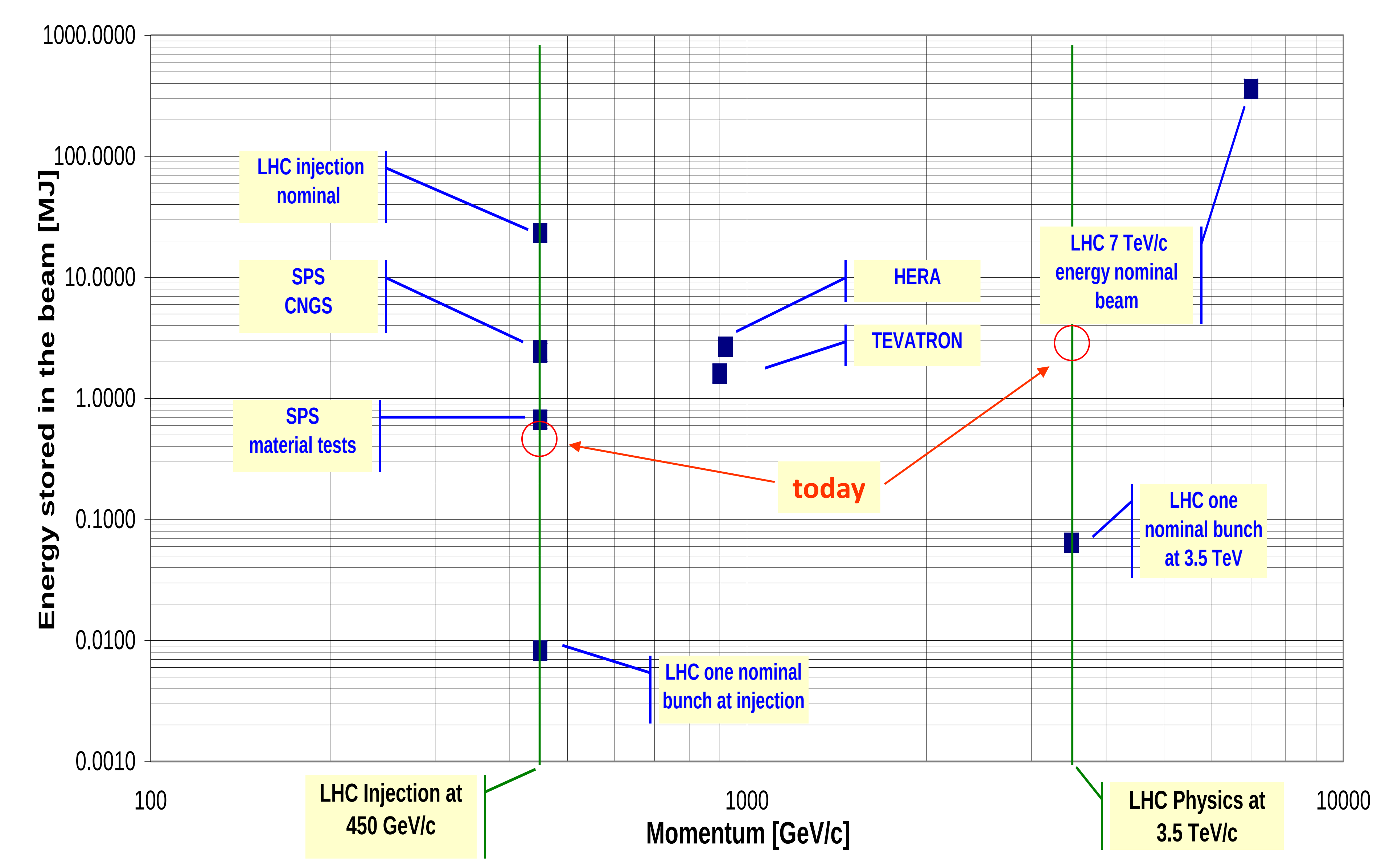
Controlled beam damage test in SPS
0.1 % of the full LHC beams

@ 450GeV
$8 \cdot 10^{12}$ protons clear damage
beam size $\sigma_{x/y}$ = 1.1mm/0.6mm
above damage limit

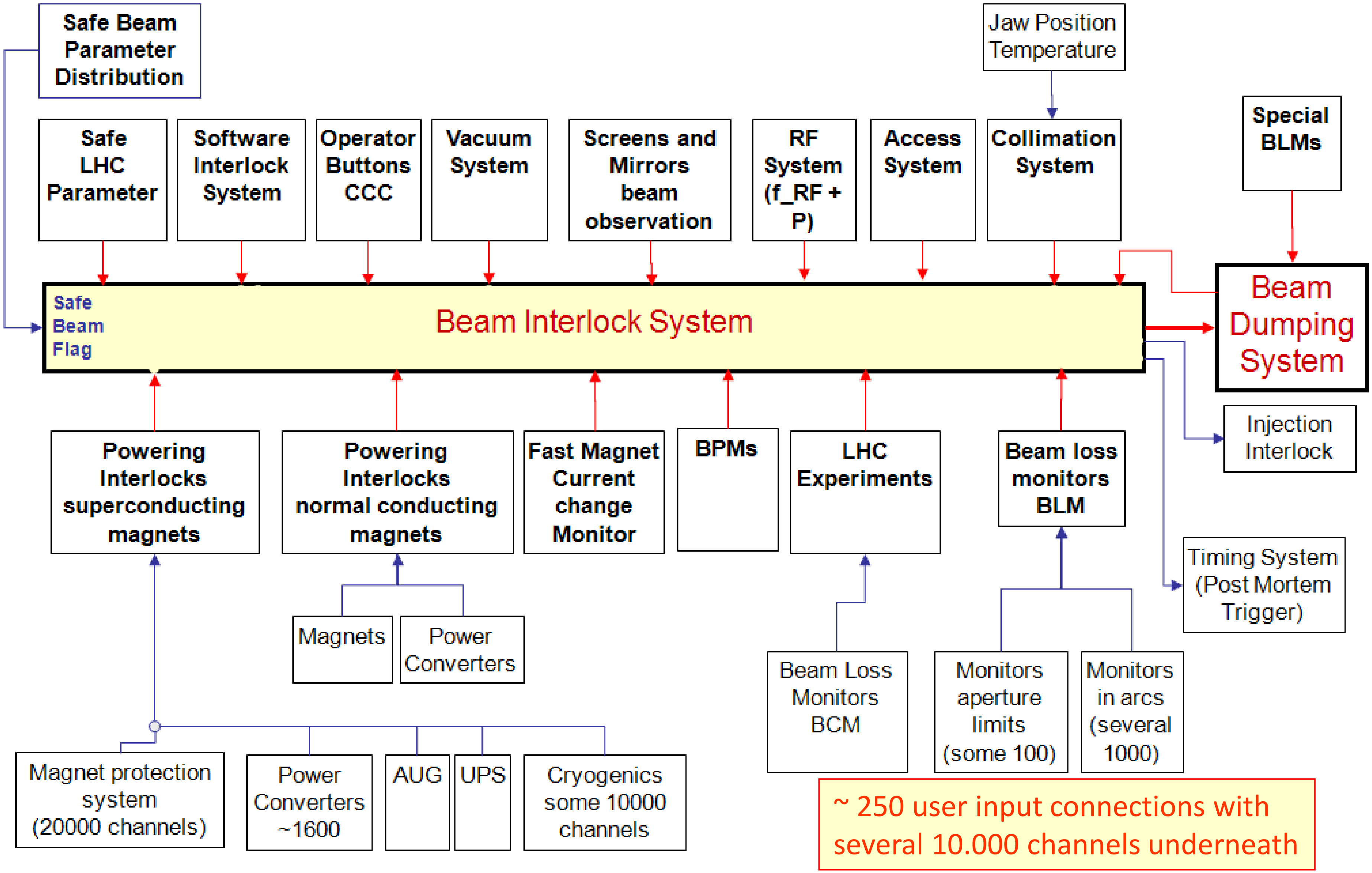
Accidental release of 600 MJoule stored in the LHC dipole magnets (one out of eight sectors, interconnect)

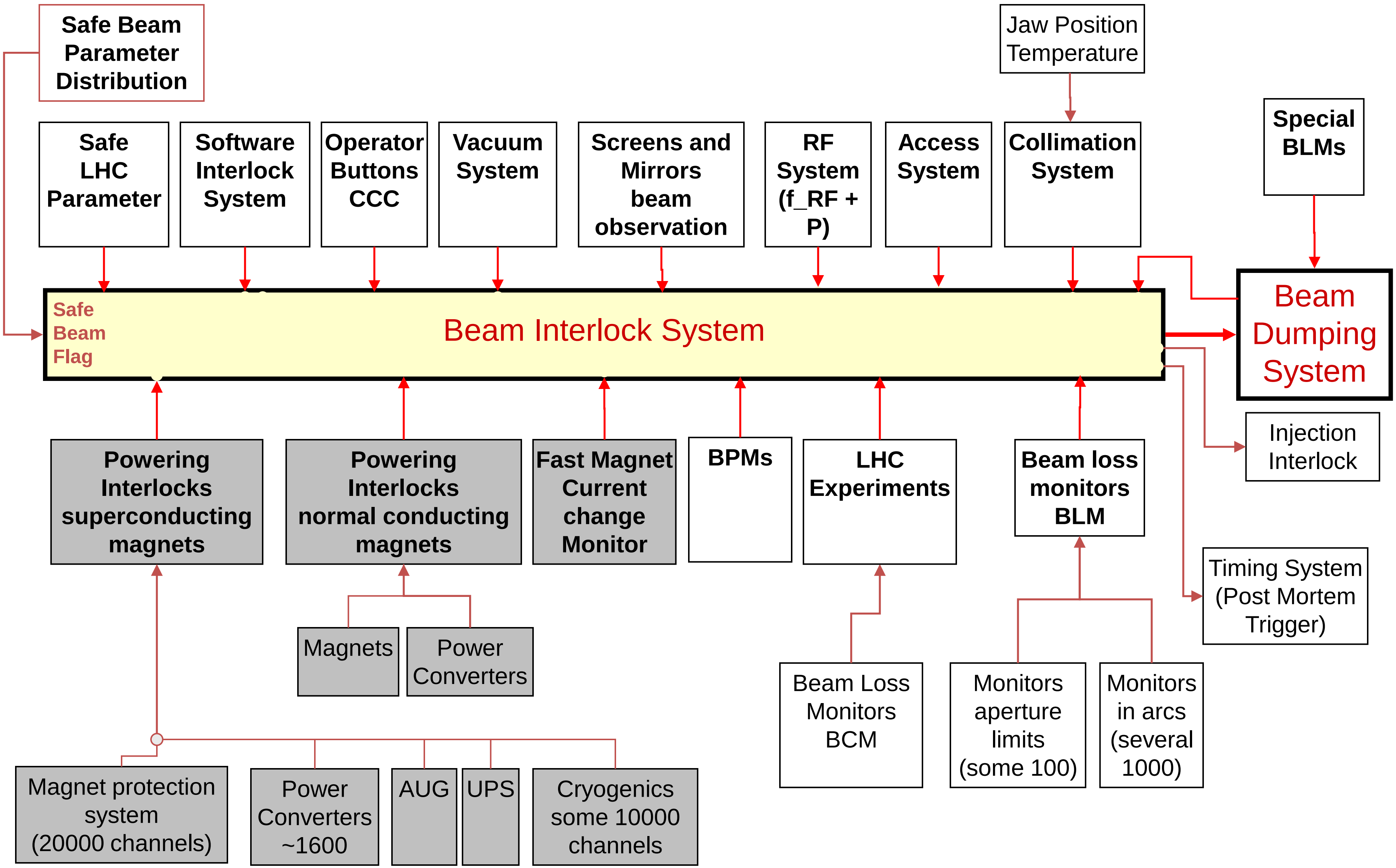
during powering tests…without beam!

Energy stored in one LHC beam and risks

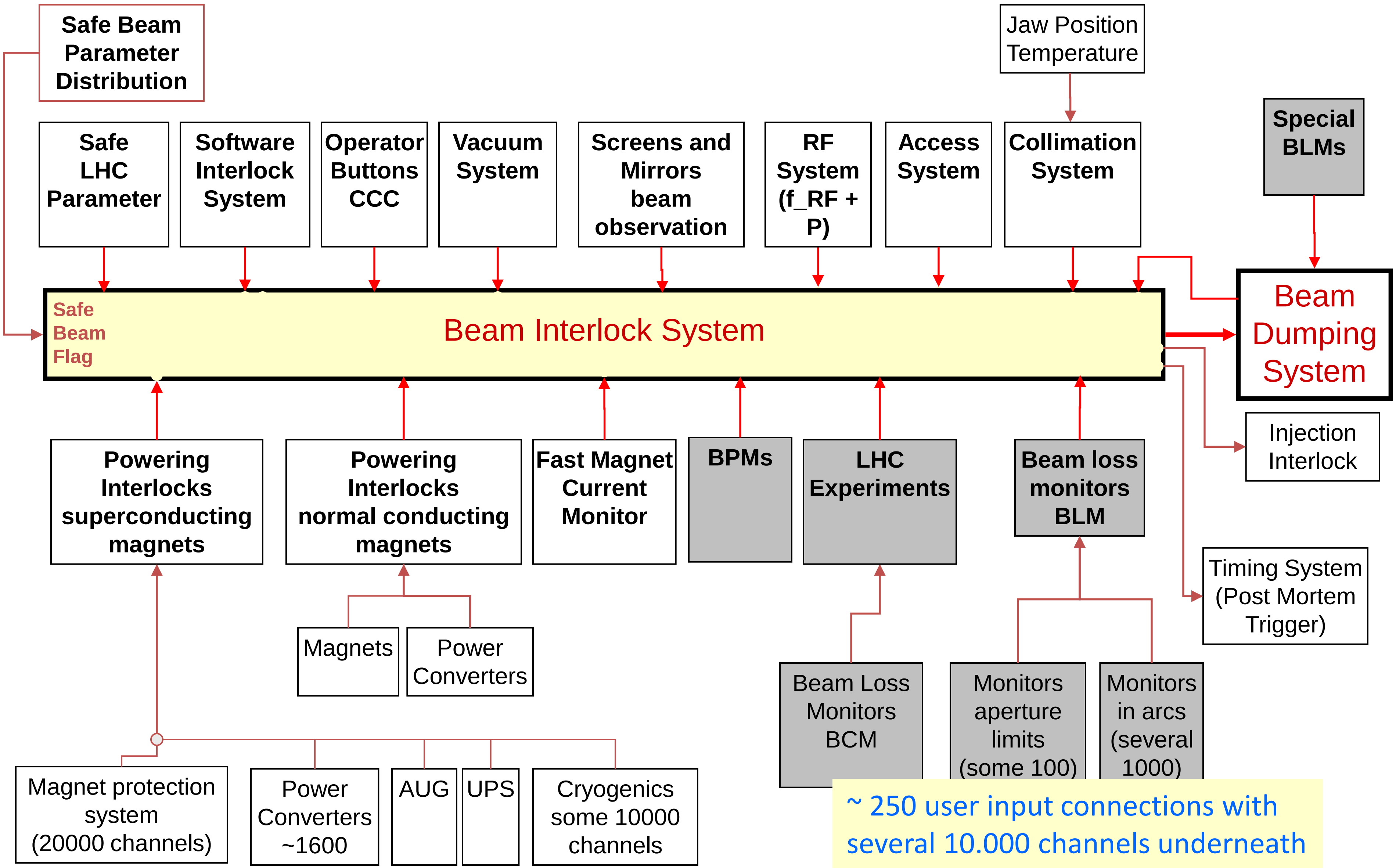


Architecture of LHC Machine Protection System



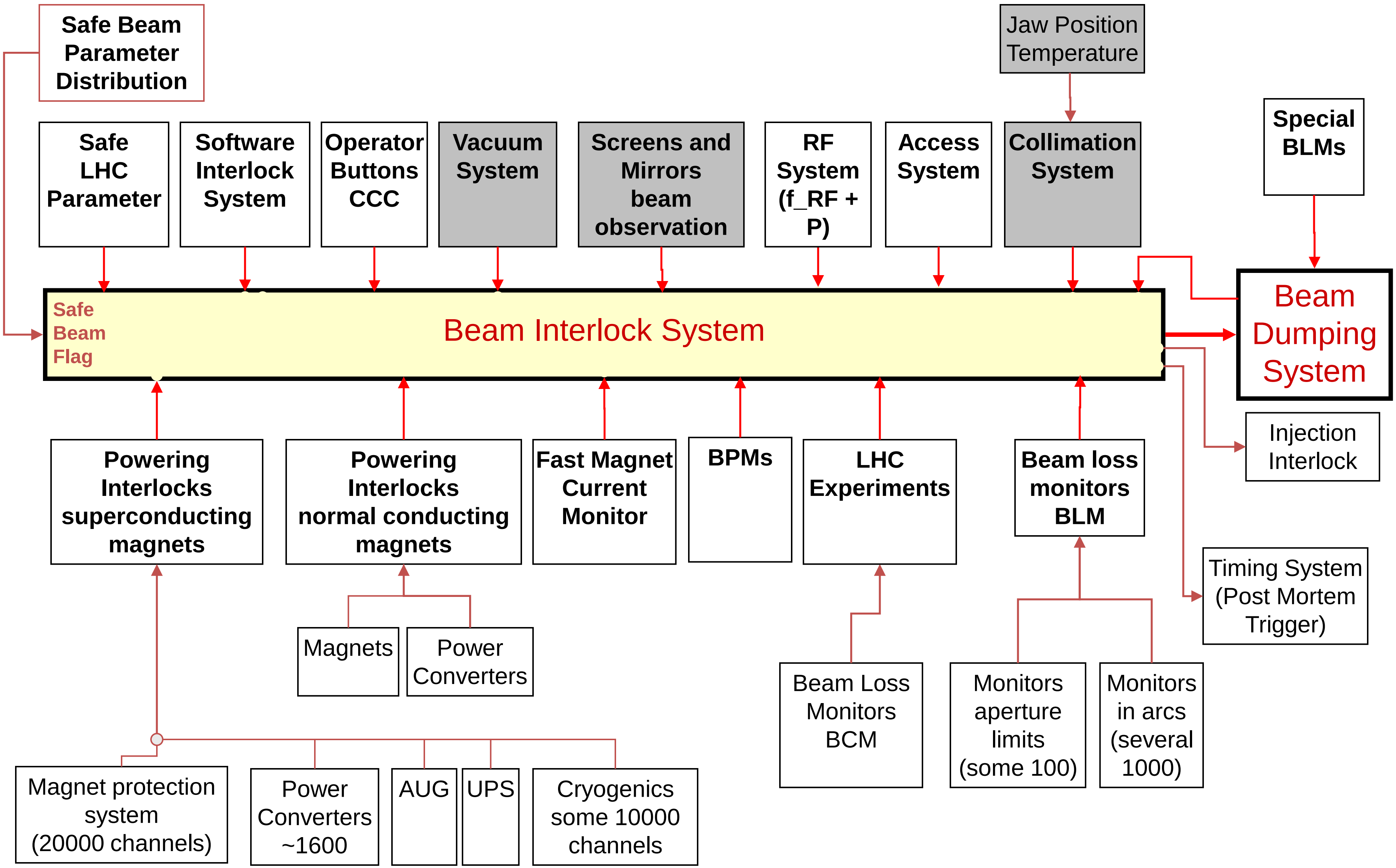

Safe Beam Parameter Distribution
Jaw Position Temperature
Safe LHC Parameter
Software Interlock System
Operator Buttons CCC
Vacuum System
Screens and Mirrors beam observation
RF System (f_RF + P)
Access System
Collimation System
Special BLMs
Safe Beam Flag
Beam Interlock System
Beam Dumping System
Injection Interlock
Powering Interlocks superconducting magnets
Powering Interlocks normal conducting magnets
Fast Magnet Current change Monitor
BPMs
LHC Experiments
Beam loss monitors BLM
Timing System (Post Mortem Trigger)
Magnets
Power Converters
Beam Loss Monitors BCM
Monitors aperture limits (some 100)
Monitors in arcs (several 1000)
Magnet protection system (20000 channels)
Power Converters ~1600
AUG
UPS
Cryogenics some 10000 channels

Interlocks from beam instrumentation

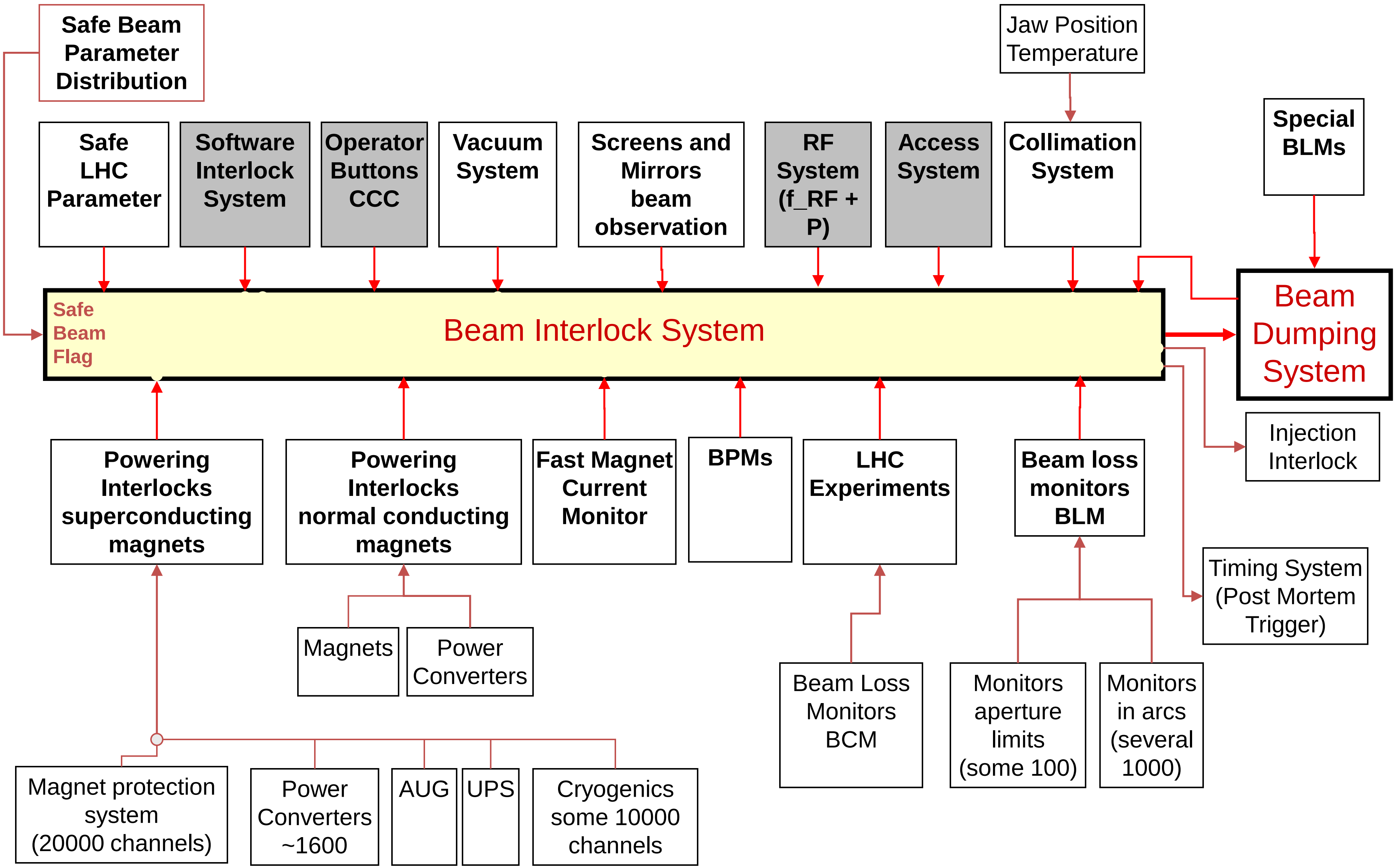


~ 250 user input connections with several 10.000 channels underneath

Interlocks from movable devices



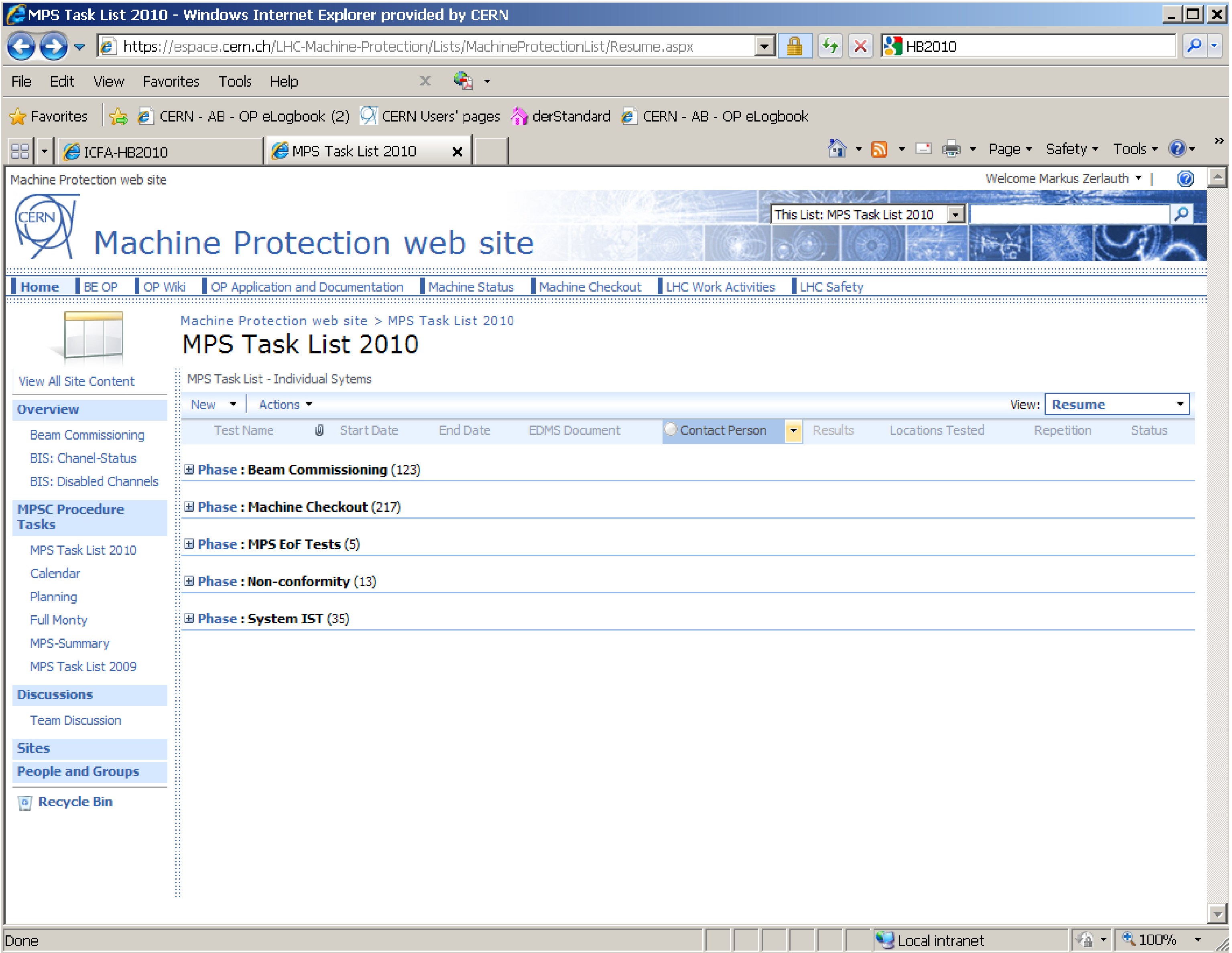
Other interlocks



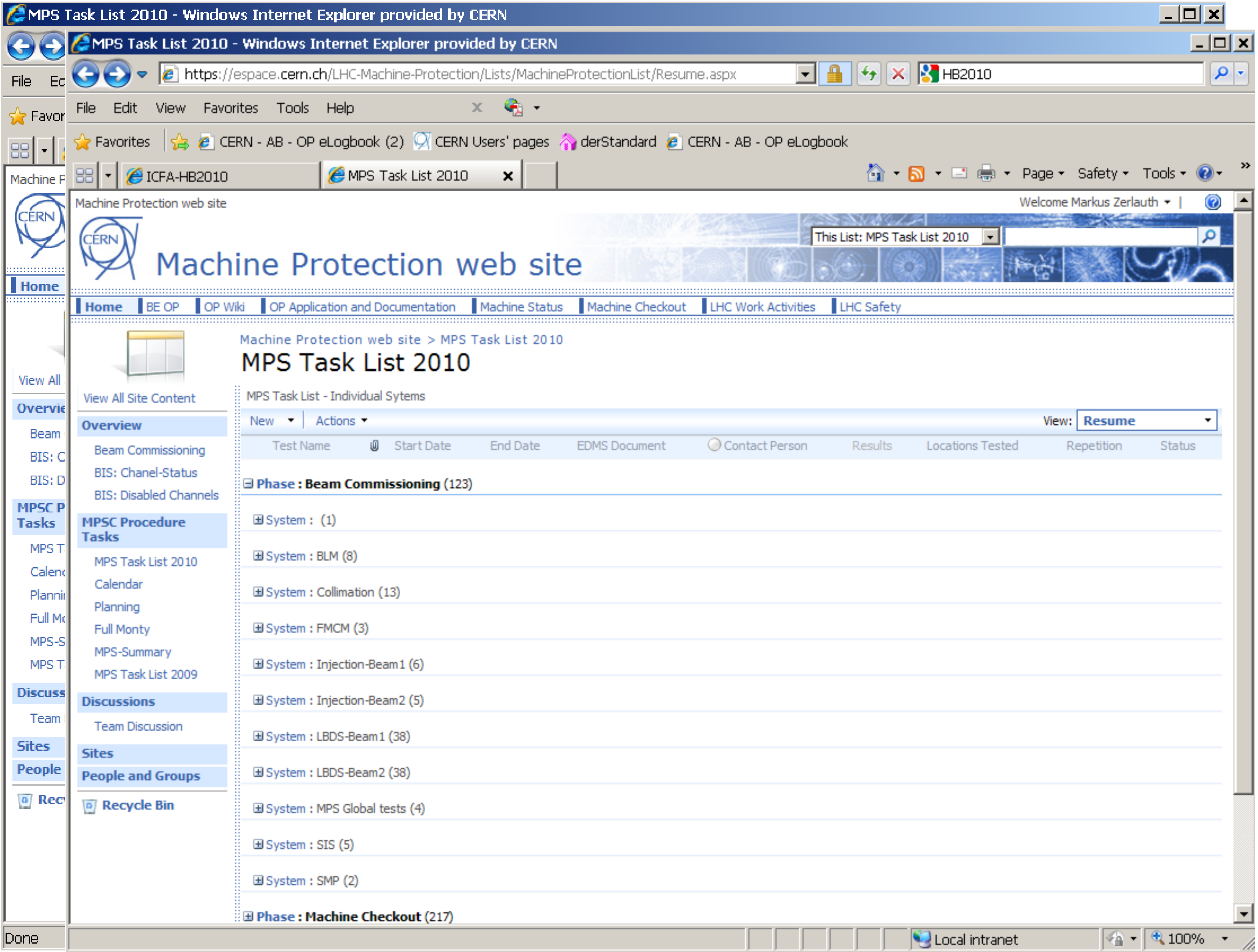
Commissioning of LHC protection systems

- Machine Protection System is reflecting the complexity of the LHC machine
- LHC Commissioning is driven to a large extend by commissioning/understanding of the machine protection system (still ongoing!)
- Main subsystems commissioned first in stand-alone and then during machine checkout phase without beam (powering interlocks, beam interlocks, injection logic, collimators, BLM setup, beam dumping system…) in ~ 260 commissioning steps
- Followed by Machine Checkout phase for validation of protection with low intensity beams (verifying protection redundancy, injection process, passive protection settings, controls…) in ~ 120 commissioning steps
- All steps documented (along with eventual non-conformities) and signed by equipment / MPS experts as pre-requirement for operation with unsafe beam.

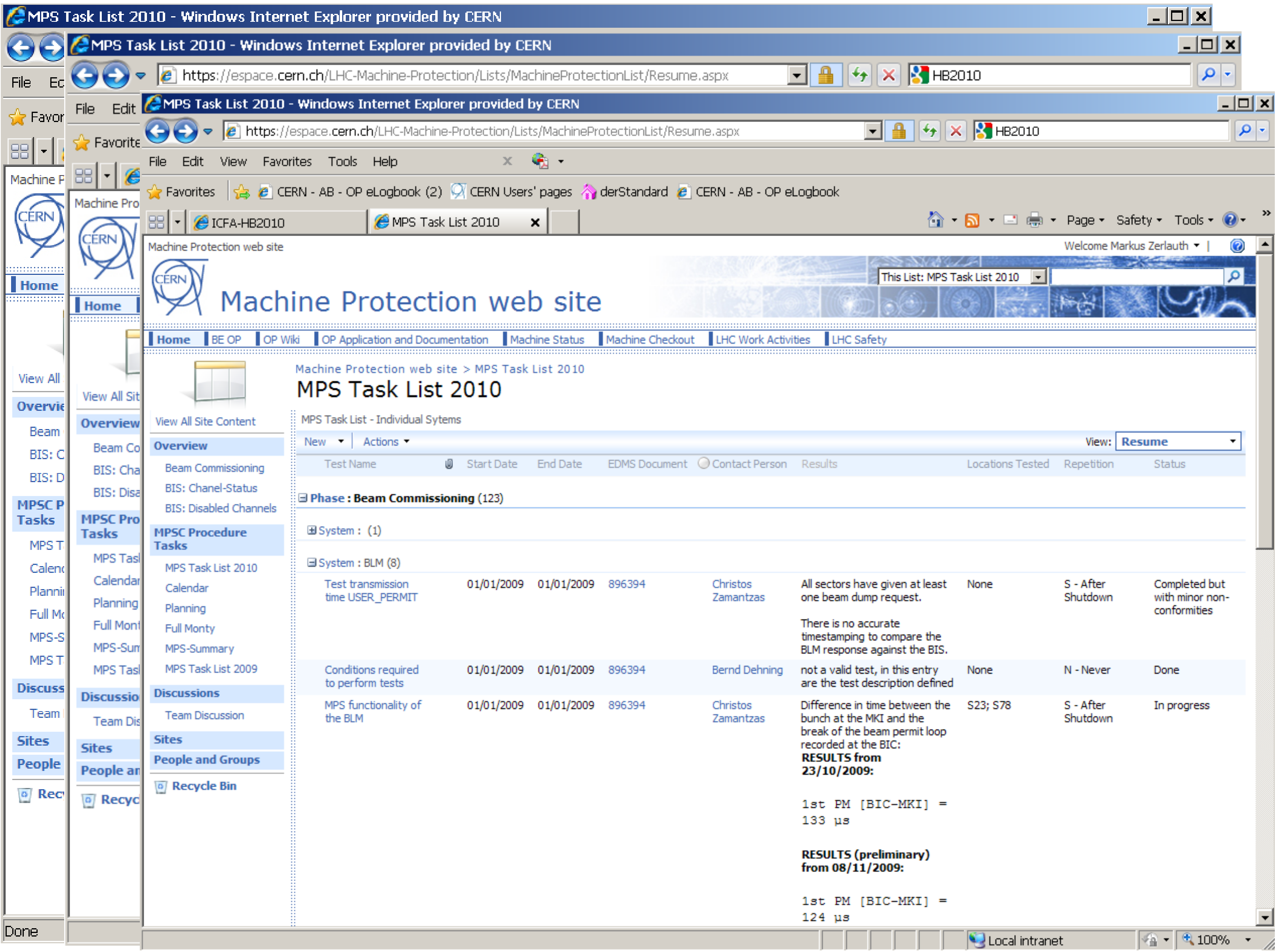
Common MPS Repository



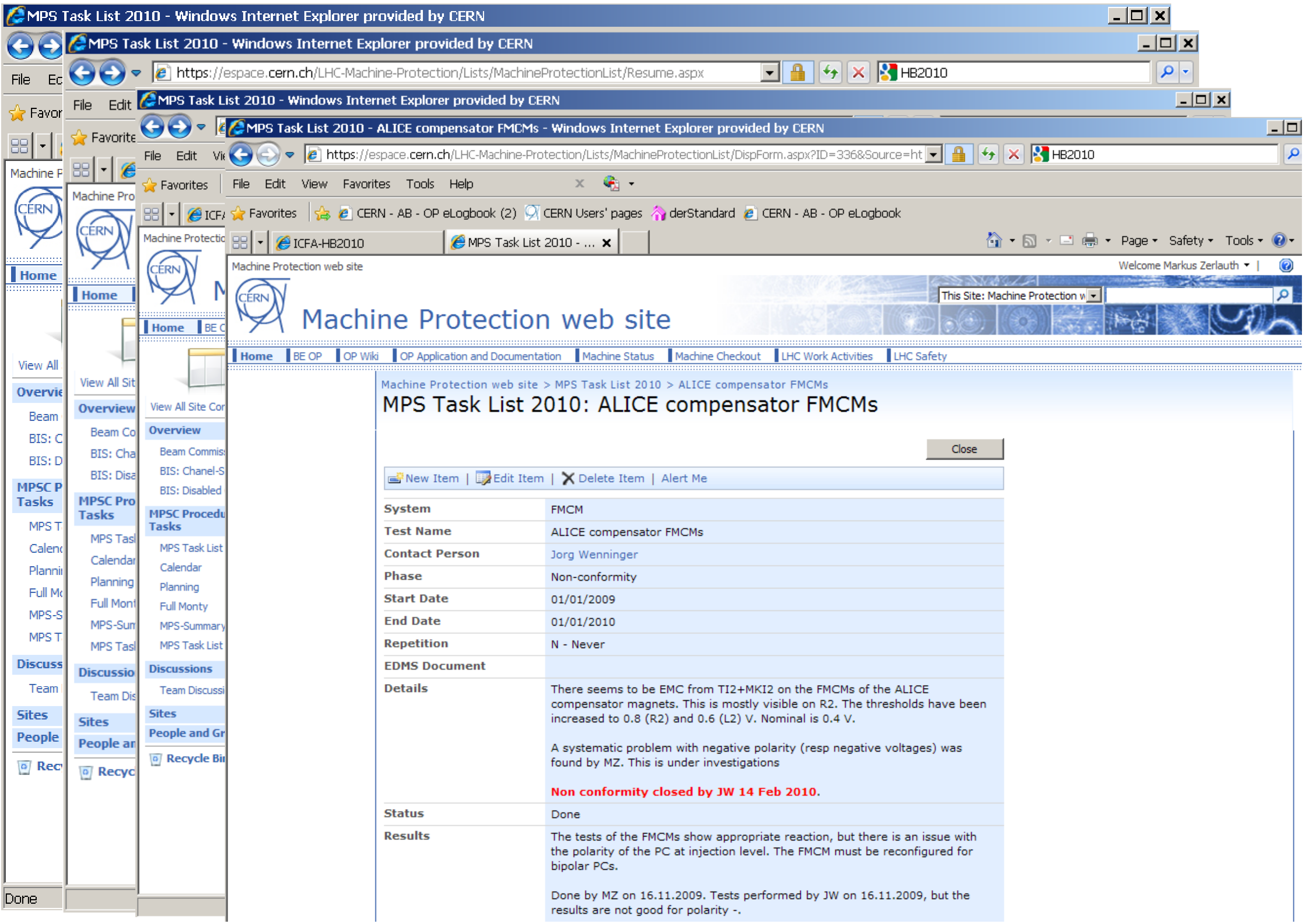
Common MPS Repository



Common MPS Repository

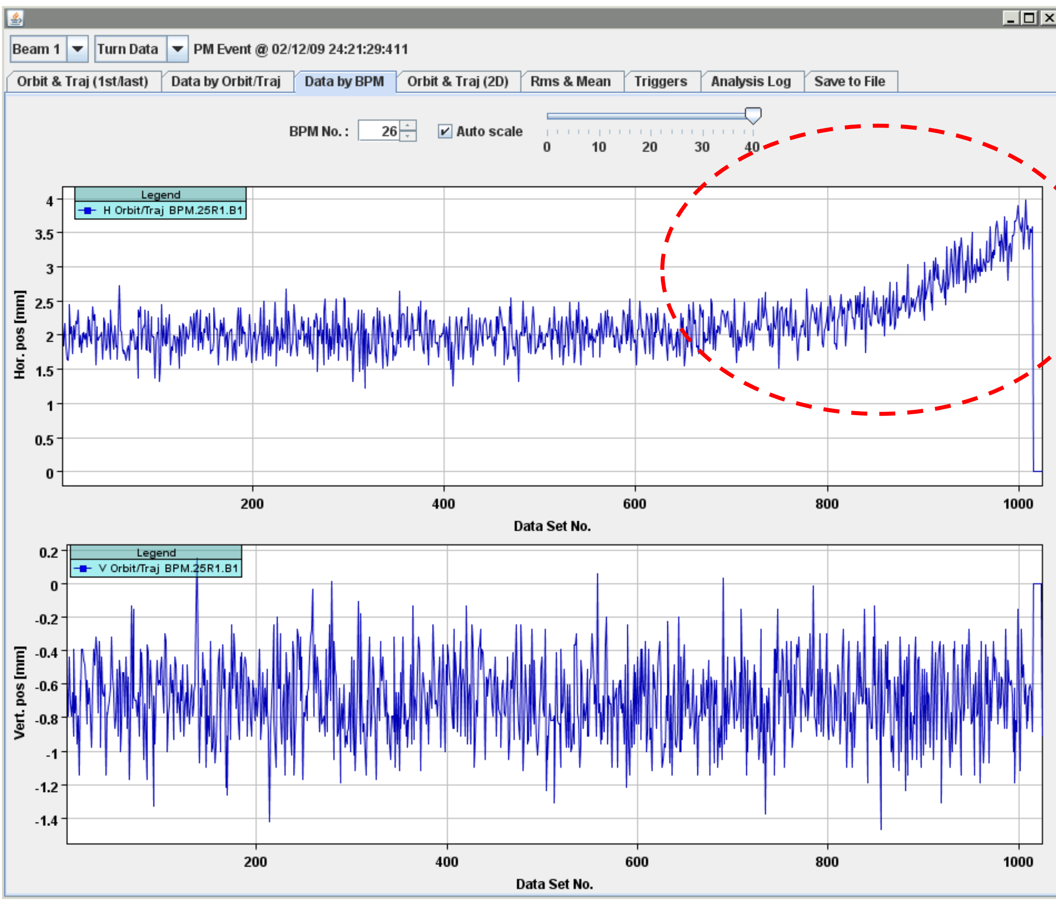


Common MPS Repository



Example of Typical MPS test with beam

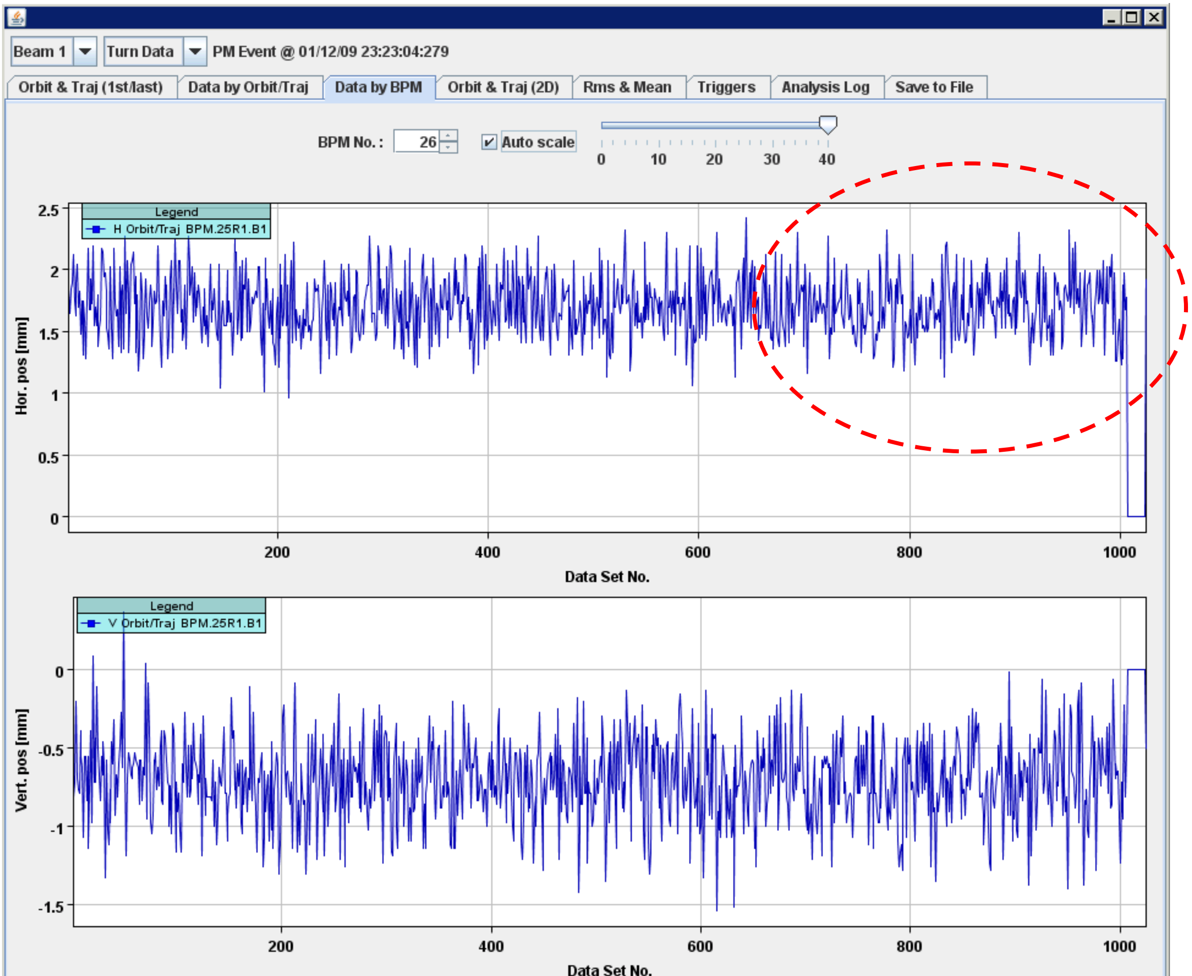
- Magnet Current Change Monitors used for detection of fast powering failures (as complement to slower converter controls and redundancy to BLMs)
- Initial setup / commissioning of FMCM is done without beam
- Confirmation of threshold with (low intensity) beam test @ injection and 3.5 TeV



- Trajectory evolution after OFF send to RD1.LR1, with FMCM masked
- Beam dumped by BLMs in IR7
- Trajectory over 1000 turns at a BPM
- Position change of ~1.5 mm over last 250 turns

Example of Typical MPS test with beam

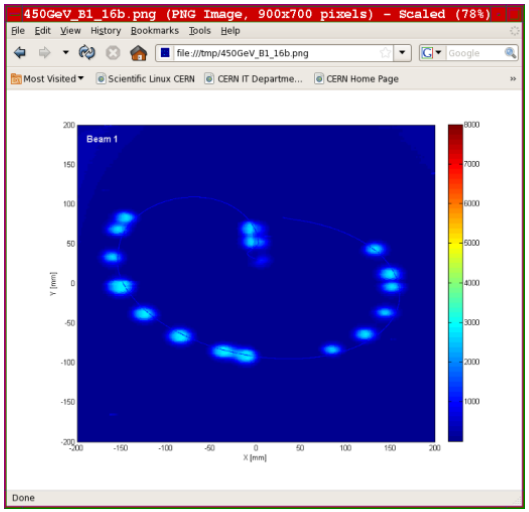
- Trajectory evolution after OFF send to RD1.LR1, with FMCM active
- Beam dumped by FMCM, no BLM triggers

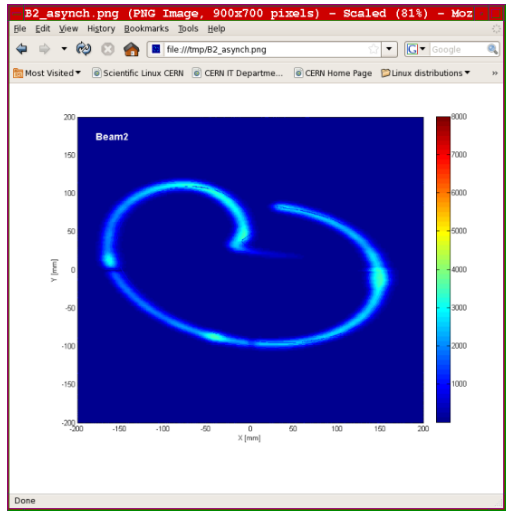


- Trajectory over 1000 turns at the same BPM
- No position change visible within resolution

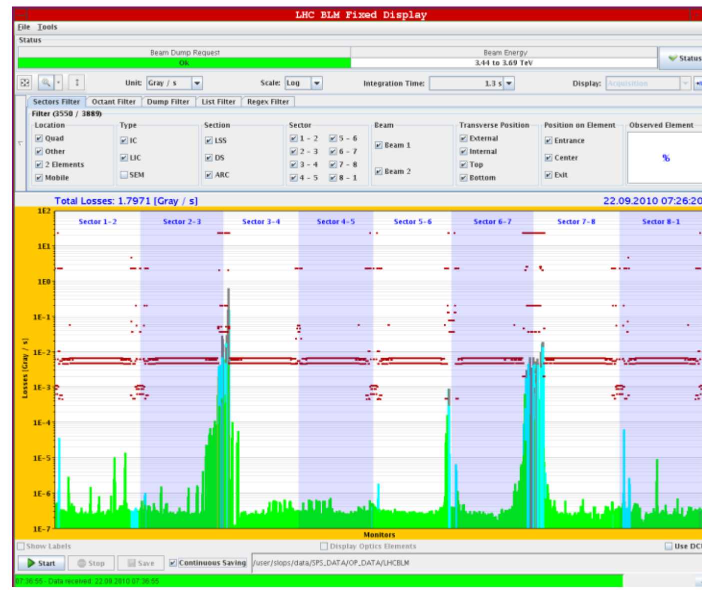
>> The redundant protection is working

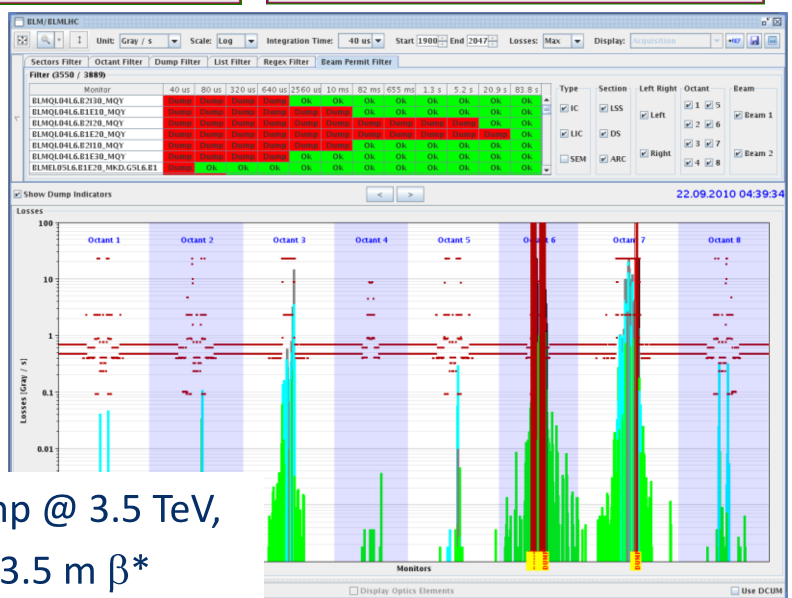
..and many many more tests…





Bunched and debunched beam 2 on the dump BTV





Asynchronous dump @ 3.5 TeV,
End of Squeeze @ 3.5 m β*
110/100 urad Xing, separated

Loss Map @ 3.5 TeV
Unsqueezed, separated
110/100 urad Xing
off momentum

Masking of Interlocks

- (Safe an controlled) masking of interlocks has greatly simplified initial commissioning of the LHC

- User inputs to Beam interlock system are divided into
  - Non-maskable User Inputs: active in all phases of operation e.g. circuit powering defining lattice, vacuum, experiments, dump system, BLMs on sc elements, ..
  - Maskable: inputs may be masked if the beam intensity is below the setup beam intensity, e.g. BLMs on collimators, collimator positions, ‘uncritical’ circuit powering, RF, …

- Setup beam flag defines the transition between a ‘safe’ beam (where masking is possible) and ‘unsafe’ beam.

  - Enforced in the BIS HW (derived from energy & intensity information).

at 450 GeV:	limit is 1E12 protons	~ 70 kJ
at 3.5 TeV:	limit is 3E10 protons	~ 17 kJ

- If beam becomes UNSAFE, all masks are automatically removed

Activation of MPS in 2010

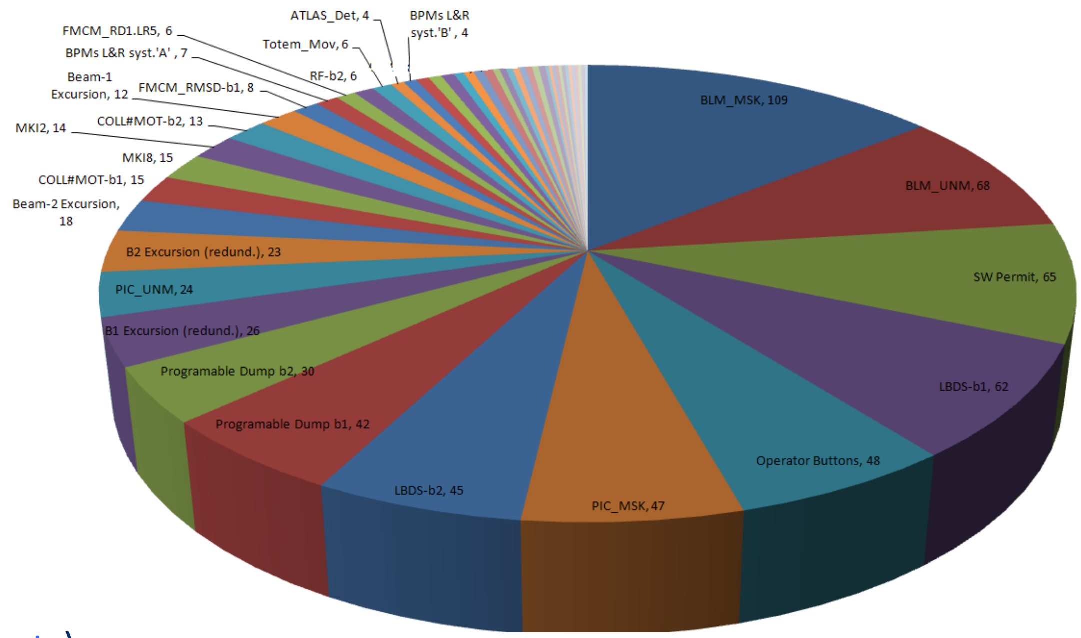
Every beam dump request exercises (parts of) the machine protection system and is being used to evaluate and improve its performance

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

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

Some 220 beam dumps happened AFTER the start of the energy ramp

Detailed analysis of beam dumps are vital for the further understanding of MPS and for unveiling possible loop holes (beware of combined or rare/unforeseen events)

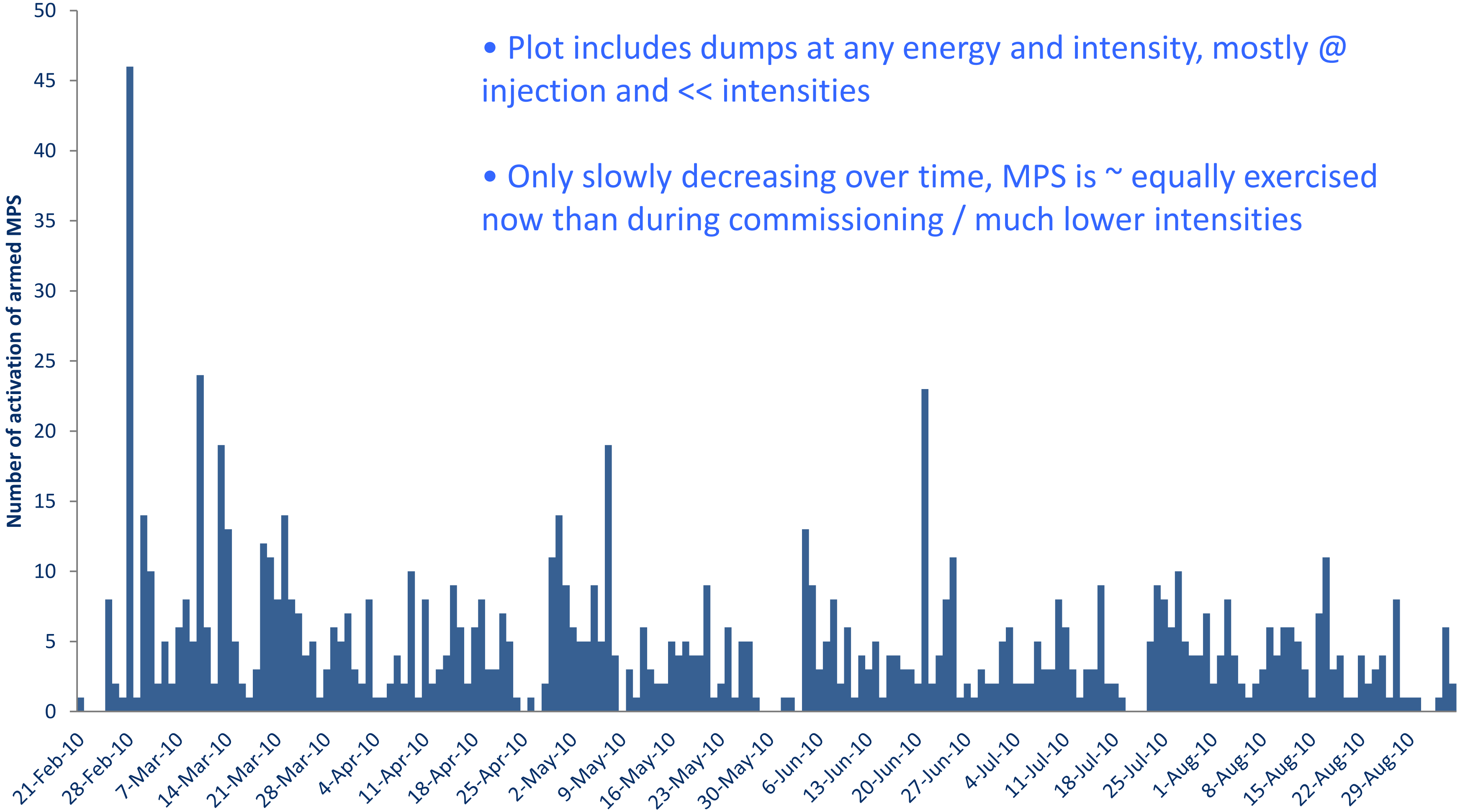


User inputs requesting a beam dump in the LHC (since Jan 2010)

MPS strategy (especially before increasing intensity): Every beam dump needs to be clean and/or understood before next injection

A bit of statistics # 1 …

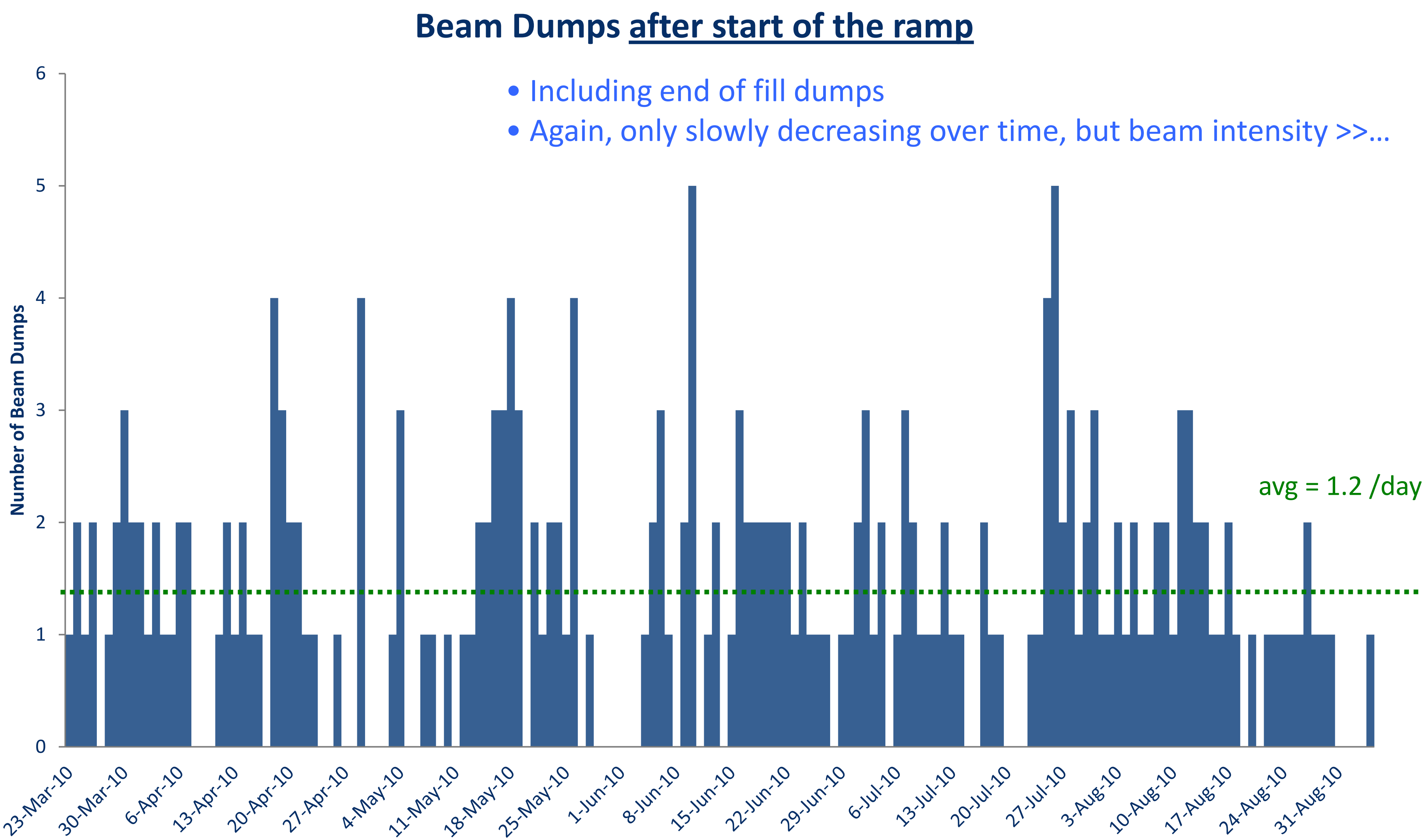
Activation of (armed) MPS for 2010



- 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…



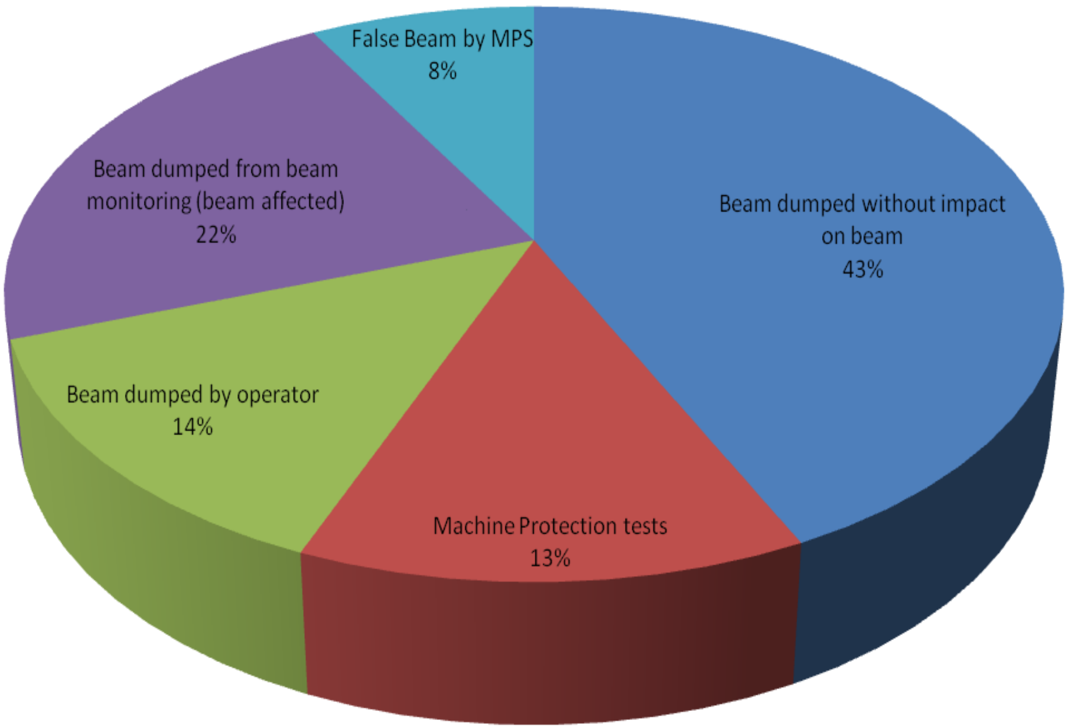
Beam dump events by Category

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

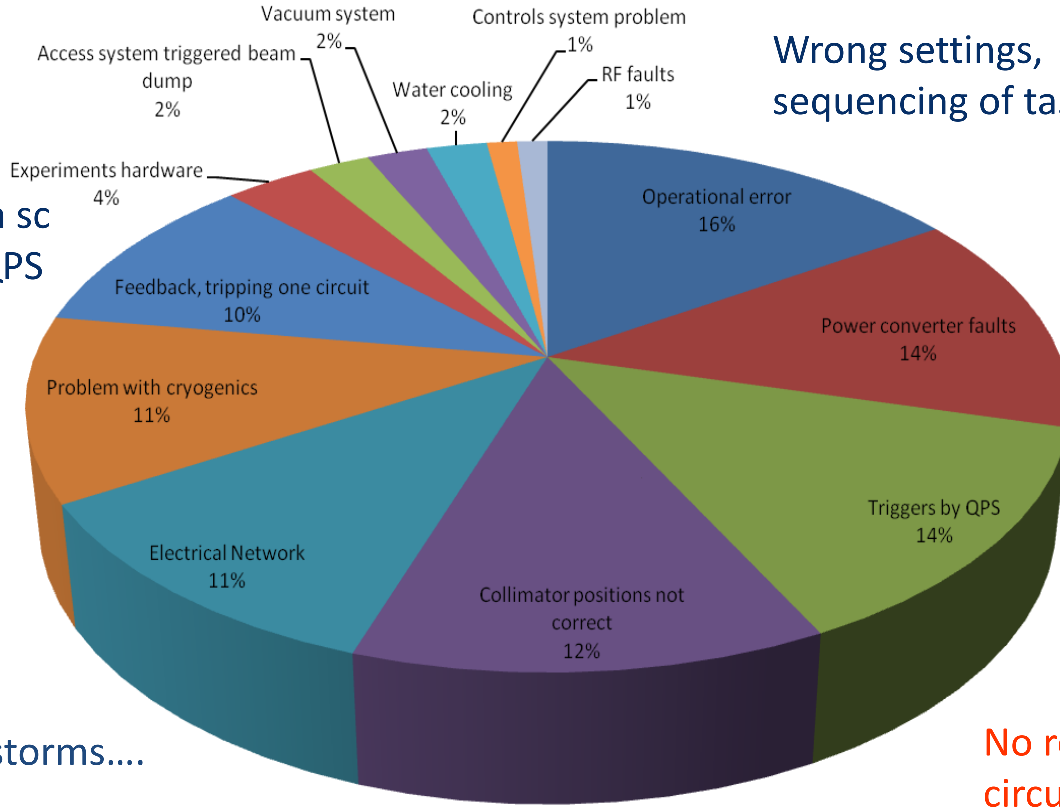
Only small fraction of programmed (end of fill) dumps by operations

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…)

Continuous improvements to mitigate failure cases with effects on beams (adding additional SW or HW interlocks)



Beam dumps NOT affecting the beam



Wrong settings, sequencing of tasks,..

Tuning to comply with sc circuit parameters / QPS

Faulty power modules / water cooling,…

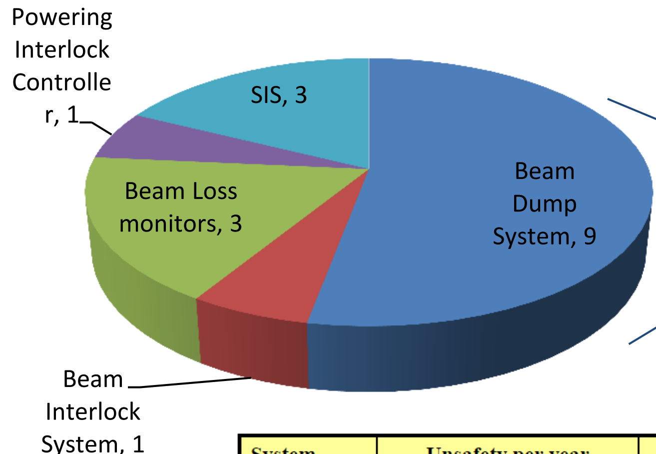
Few losses of cold compressors, often instrumentation or transient signals

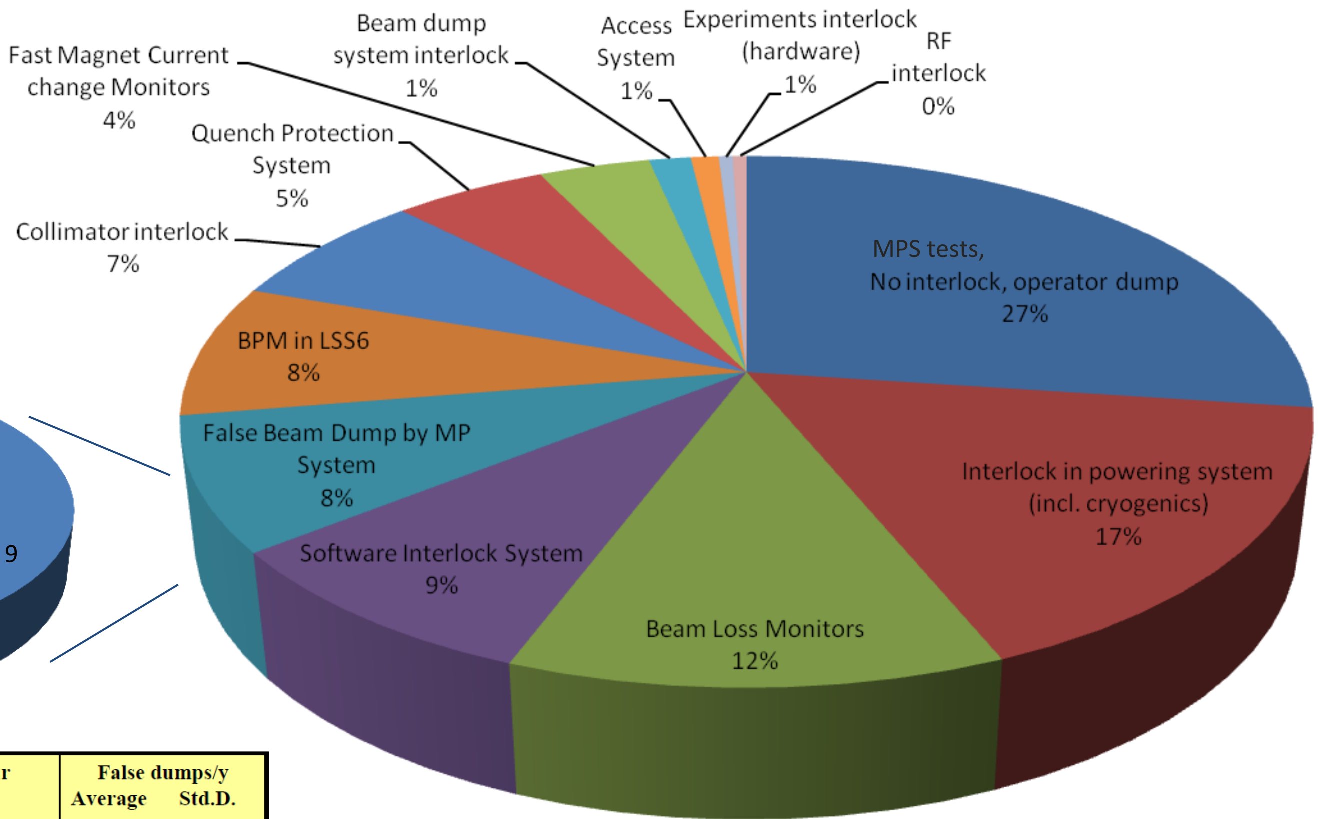
Thunderstorms….

No real quenches yet with circulating beams, but EMI, too tight thresholds, di_dt/acceleration issues,…

Mostly during initial setup / adjustment

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)

Fast Beam Losses – UFOs?

So far EVERY beam dump is understood, except….

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

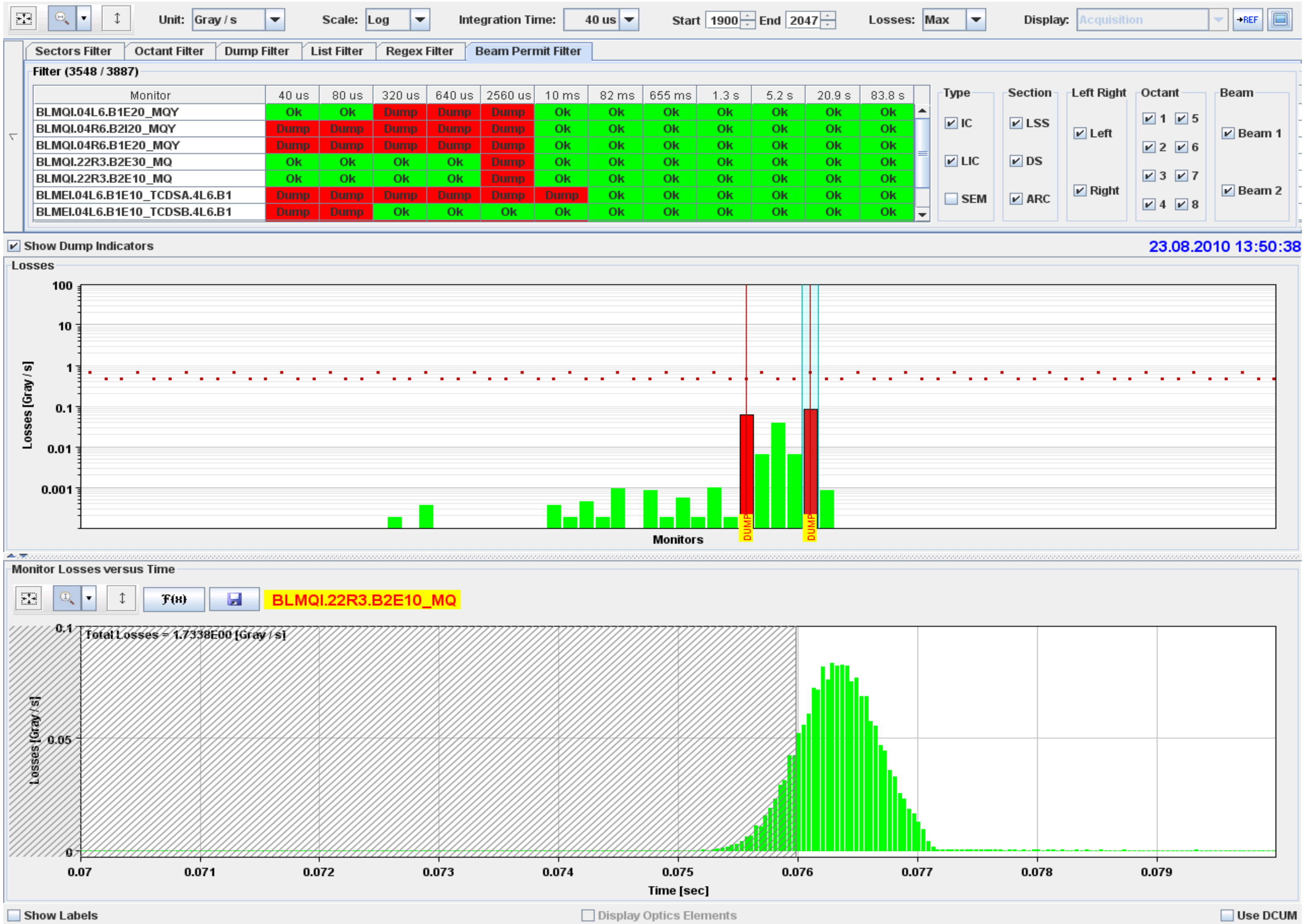
Date	Location	S (m)	Sector	Beam	Plane	Beta (m)	Max RS01 (G/s)	Risetime (ms)	Fill	No bunches	Intensity	Length (h)
07-07-2010 20:22:19	MBB.8L7**	21380	67	2	V	120	0.08	2.3	120x	9	8.4E+11	0
30-07-2010 07:26:38	Q4.R5	15160	56	2	H	274	0.08	1.25	1253	25	1.9E+12	13.15
07-08-2010 02:14:38	Q11.L4	11224	34	1	H	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
22-09-2010 12:48:05	MBB.8L7	21380	67	2	V	120	0.4	0.44	1363	24	3.26E+12	0

Mechanism for the losses in not understood, but all events show a similar signature, finally dumping beams in 2.5ms running sum of BLM

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

See tomorrows talk of E.B.Holzer for more details

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

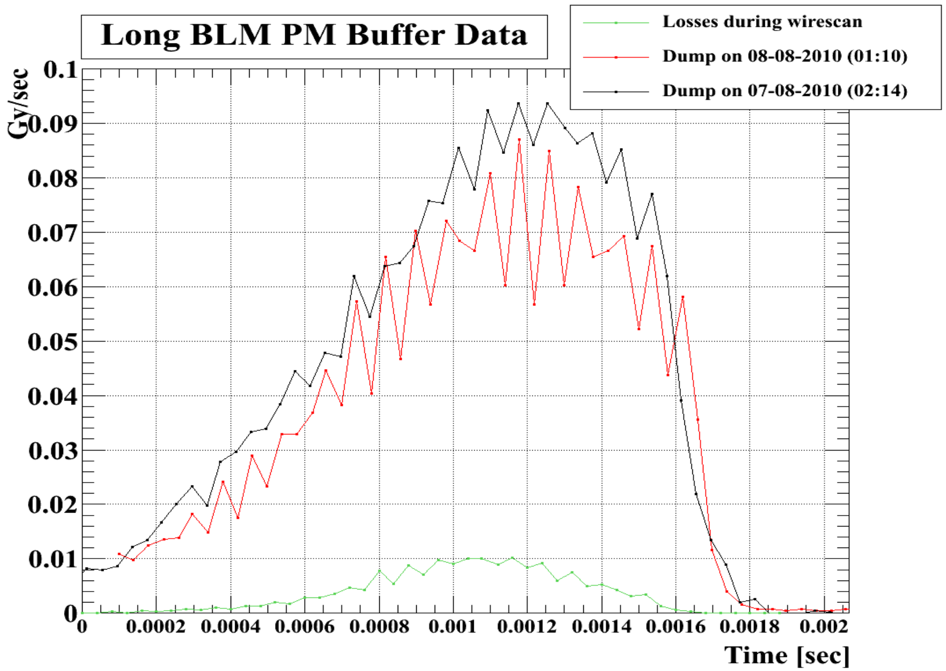


Monitor	40 us	80 us	320 us	640 us	2560 us	10 ms	82 ms	655 ms	1.3 s	5.2 s	20.9 s	83.8 s
BLMQI.04L6.B1E20_MQY	Ok	Ok	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMQI.04R6.B2I20_MQY	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMQI.04R6.B1E20_MQY	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMQI.22R3.B2E30_MQ	Ok	Ok	Ok	Ok	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMQI.22R3.B2E10_MQ	Ok	Ok	Ok	Ok	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSA.4L6.B1	Dump	Dump	Dump	Dump	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok
BLMEI.04L6.B1E10_TCDSB.4L6.B1	Dump	Dump	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok	Ok

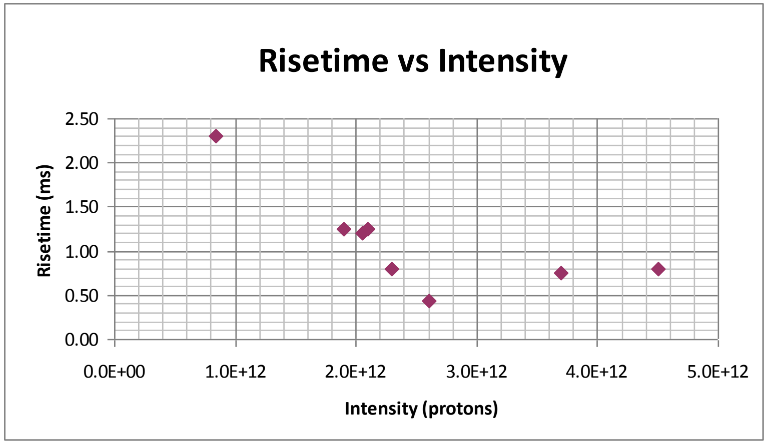
Fast Beam Losses – UFOs?

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

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



Rise time of losses decreases with energy -> could become an issue if loosing a large fraction of (high intensity) beam in few turns only



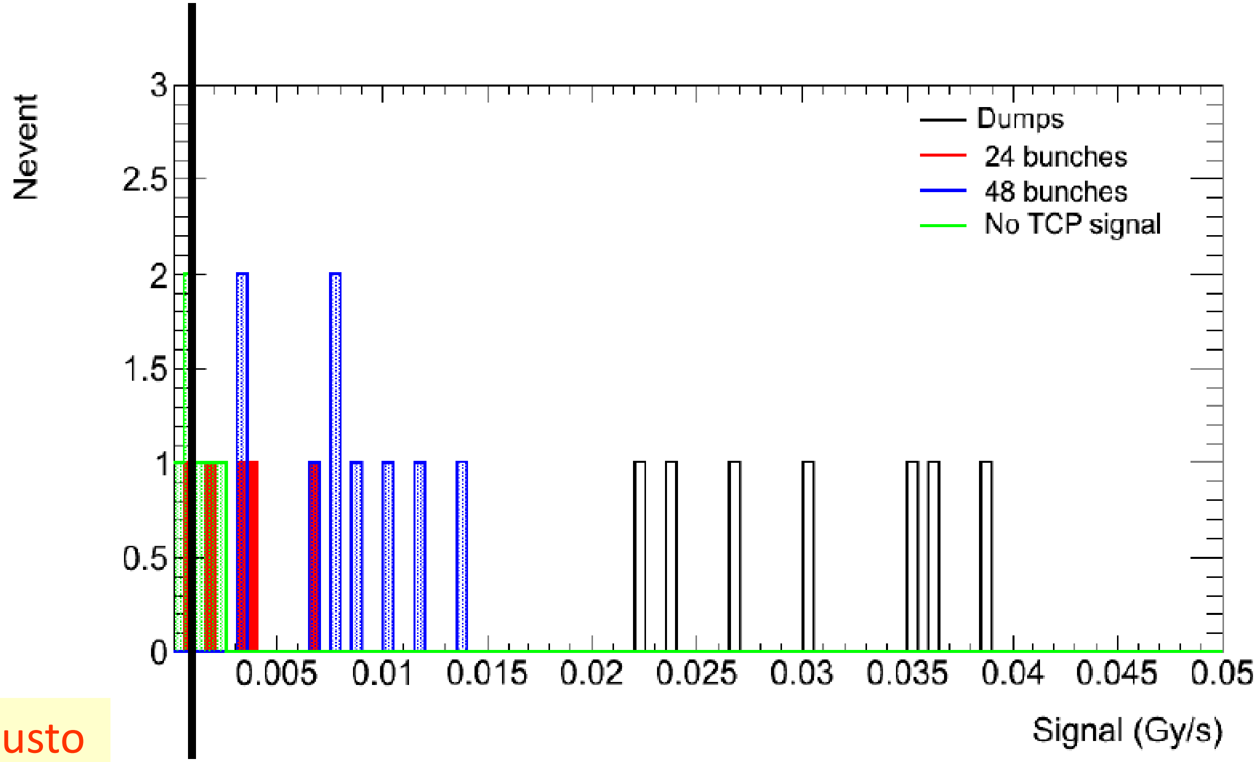
Search for Sub-threshold UFOs

Hypothesis of dust-particles and observed dependency of risetime vs intensity would suggest more events at lower intensity (with too low losses for dumping beam)

Total of 228.6 hours of stable beam have been analyzed:

141.3 hours (24 bunches) → 0.0566 evts/ hour

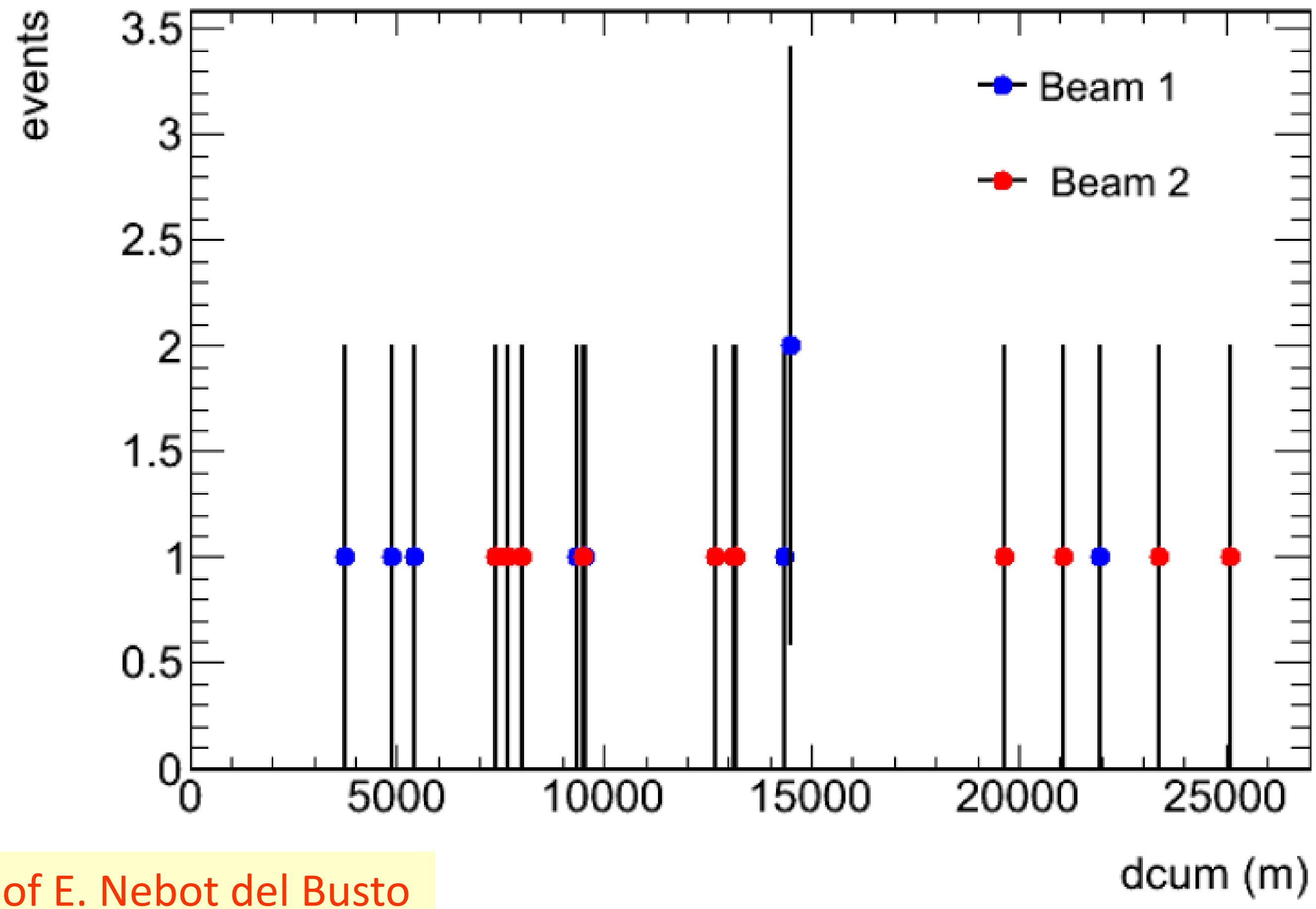
87.3 hours (48 bunches) → 0.1260 evts/hour



Courtesy of E. Nebot del Busto

UFO Distribution along the ring

While events dumping the beam for time being only observed in half the ring (ie IR3 – IR7), extended study including sub-threshold UFOs shows equal distribution around ring



Courtesy of E. Nebot del Busto

Further increasing the intensity in 2010

Strategy so far: Maximum intensity increase versus stored energy:

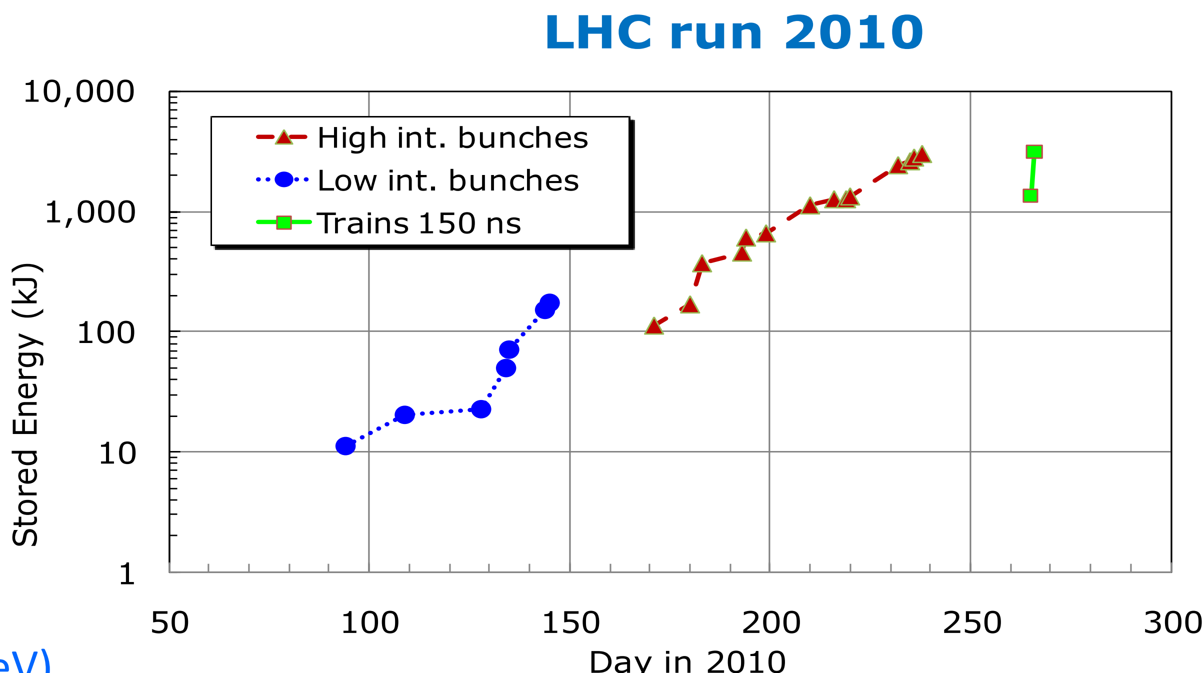
Up to 0.25 MJ	typical factor ~2, max 4
Up to 1-2 MJ	max. factor ~2
Above 1-2 MJ	≤ ~3 MJ per step

Reduced Machine Protection Panel (rMPP) to define operational envelope in accordance with MPS commissioning progress (and issues)

As of last week operating bunch trains of 150ns, with intensity steps of 48 bunches

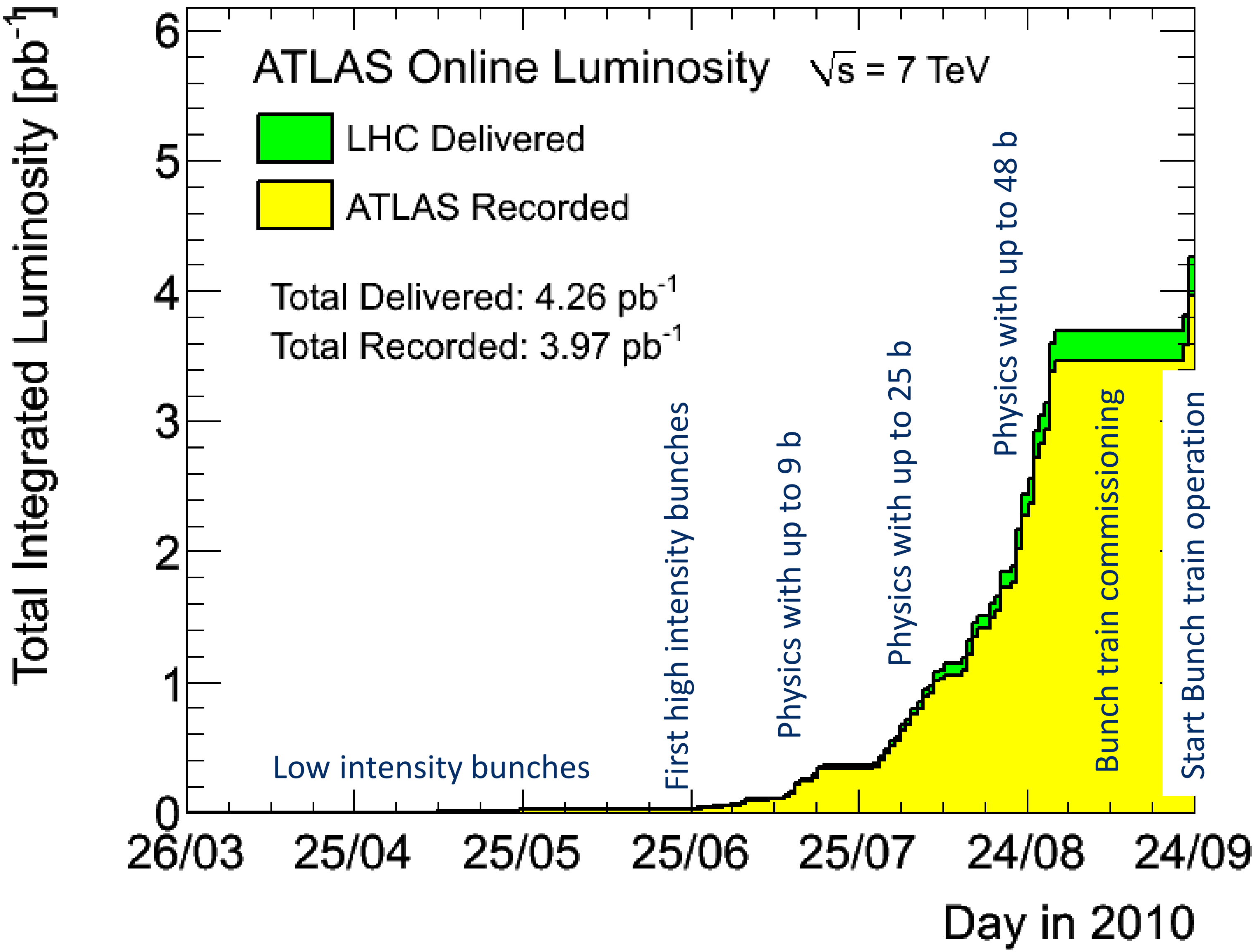
Check-list for intensity increase after ~20 hours /3 fills of stable beams at previous level

Goal to reach luminosity of 10E32 for end 2010 (ie ~400 bunches / beam @ 3.5TeV)



Courtesy of J.Wenninger

MPS commissioning vs physics



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)

Very well protected for CIRCULATING beam (Loads of redundancy), major worry are injection failures when moving to high intensity injections....

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
- 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,…)