#### Commissioning and Operation of the LHC Machine Protection System

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HB 2010, Morschach

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Acknowledgements: J.Wenninger, R.Schmidt and the whole Machine Protection team



- 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**



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



@ 450GeV  $8.10^{12}$  protons clear damage beam size  $\sigma_{x/y} = 1.1$ mm/0.6mm above damage limit

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



# 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



#### Powering interlocks







## Interlocks from beam instrumentation



### Interlocks from movable devices



#### Other interlocks







□ 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.



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				Status	Done						
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#### HB2010, Morschach, 28<sup>th</sup> September 2010

## 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

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#### ...and many many more tests...



#### Bunched and debunched beam 2 on the dump BTV



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

110/100 urad Xing, separated



### 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)



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

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#### 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





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#### A bit of statistics # 2...

#### Beam Dumps after start of the ramp

- Including end of fill dumps
- Again, only slowly decreasing over time, but beam intensity >>...





### 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



# What saved us (who dumped the beam)?





#### 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	н	274	0.08	1.25	1253	25	1.9E+12	13.15
07-08-2010 02:14:38	Q11.L4	11224	34	1	н	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	н	180	0.082	0.75	1298	48	3.7E+12	12.97
26-08-2010 17:25:56	Q25.R5	16179	56	1	н	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

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#### HB2010, Morschach, 28<sup>th</sup> September 2010



### 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





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)





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





### 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 10 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

LHC run 2010



### MPS commissioning vs physics

Total Integrated Luminosity [pb<sup>-1</sup>]







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)





#### 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,...)