

MP overview: experience and scaling to 2010

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Inspired by the discussions, commissioning shifts, email fights, coffees and other activities in and around the CCC with my MPP, OP, BI colleagues.

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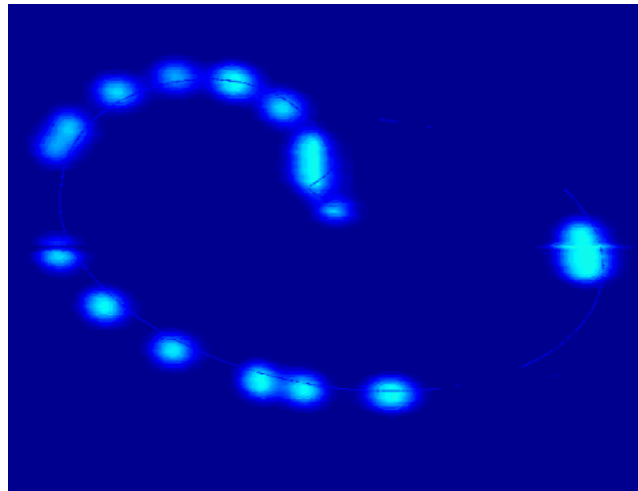
Global MP tests

LHC MP number: 276 Megaseconds

The time span from 9th March 2001...

when Rudiger kicked off the first meeting of the LHC Machine Protection WG

... to the first dump of a 17 bunches beam (30 kJ)



We have ~1000 days left to dump 360 MJ after 360 Ms !

2009 Achievements

- The large majority of interlocks were tested and ACTIVATED !
 - and we could still operate the LHC !
 - and we did not quench with circulating beam – thank you collimation !
 - the '*with so many interlocks it will never work*' scenario has been avoided !

Thanks to all of you for the excellent work !

(and a little bit also to the maskable BIS inputs)

- Let us not be too euphoric:
 - we operated with a maximum stored energy of ~30 kJ – a factor 10'000 to go...
 - no beam made it above the SBF limit.

2009 Performance

- From the previous presentations it is clear that we have uncovered a variety of more or less critical issues (see also later).
 - But we also successfully commissioned an impressive number of interlocks.
 - And we performed a large number of MP tests in a record time.

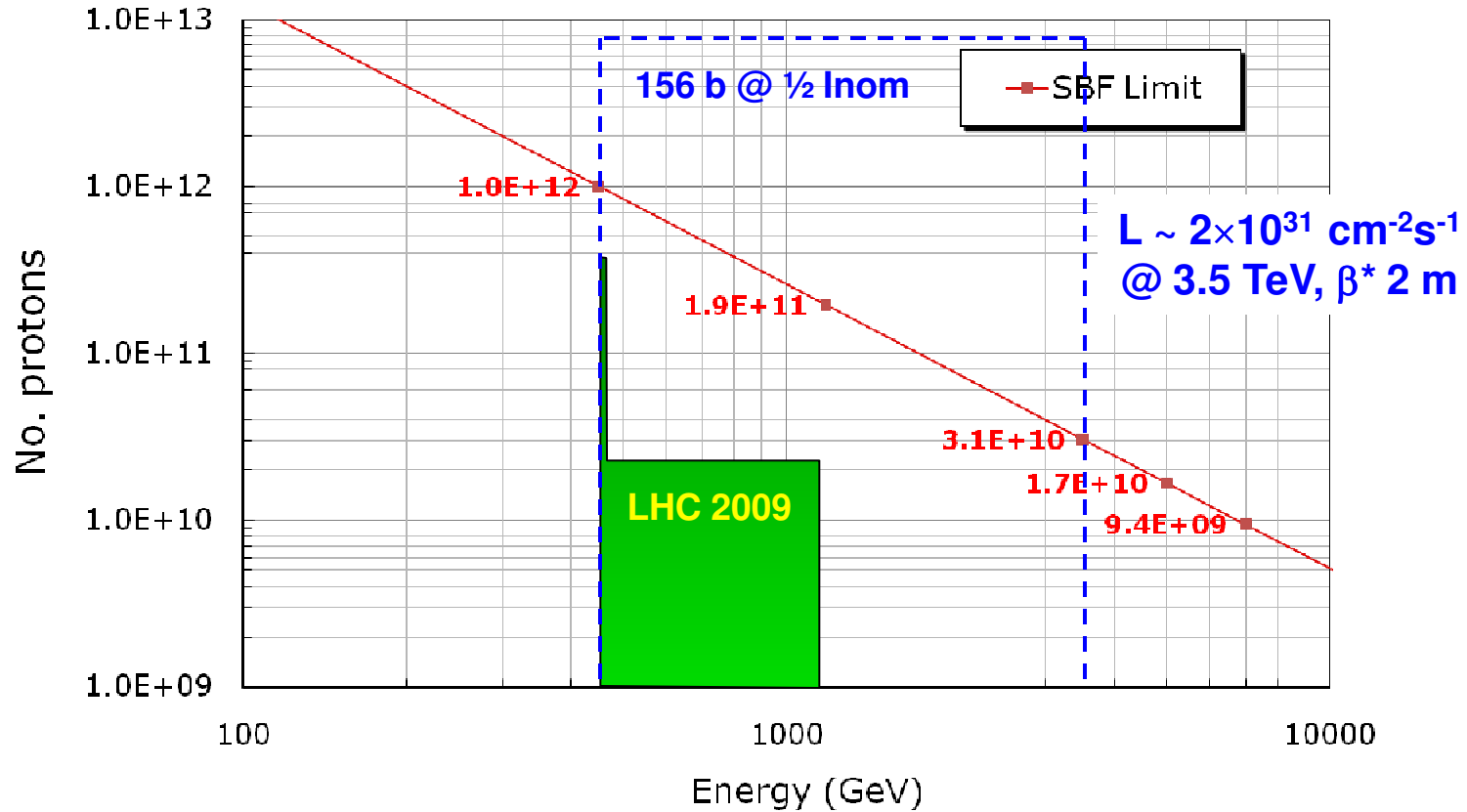
- Seen from the SPS perspective
 - The SPS operates beams with 100 times more stored energy (2 MJ) than the LHC.
 - The LHC has a MP system that is 10-100 times safer/better than the SPS MPS.

Provocative claim : we were 1000-10'000 times safer than at the SPS!
(does not take into consideration repair times...)

MP Footprint

For TCTs the limit can be lower !!

Setup Beam Flag limit versus beam energy



A pilot bunch is the only beam that can be used for commissioning (and for most MD) activities at $\geq 3.5 \text{ TeV}$!

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Fundamental MP Question

Let us assume that

1. ALL MP tests have been successfully performed with setup beam,
2. Beam instrumentation works for all beams and intensities,
3. Beam cleaning is adequate,

What is preventing us then from running with nominal beams (180 MJ @ 3.5 TeV) ?

MP @ LHC is... (1)

- A collection of systems monitoring equipment and beams with the aim to safely extract the stored energy in case of failure.
 - Safety levels are either unknown or estimated from reliability analysis.
 - 'Dry' operation to verify reliability estimates (LBDS and BIS reliability runs).
 - MP protection expert's nightmare: **common cause and/or correlated failures leaving the machine unprotected in some situations!**
 - Protection redundancy based on a diversity of systems reduces likelihood of correlated failures.
 - Operate (safely) and monitor carefully.

Confidence in the safety is mostly obtained by running the system and monitoring it carefully (IQC, XPOC, PM...) >> takes time !

MP @ LHC is... (2)

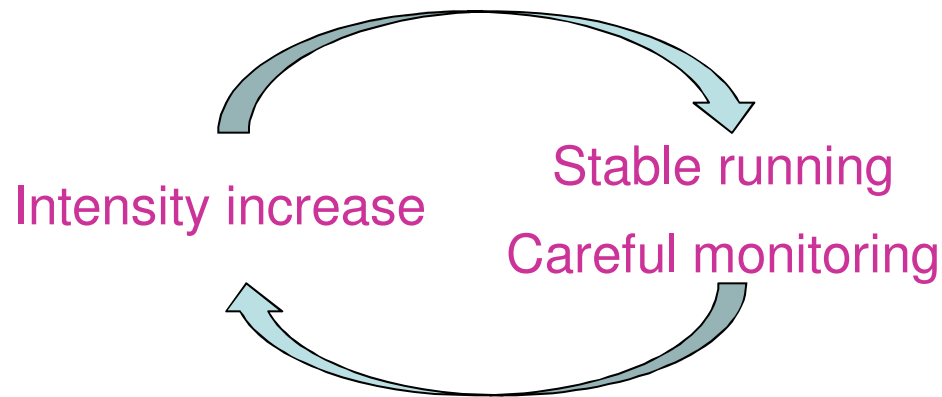
- A careful and safe machine setup, and a well established operational cycle:
 - Aperture protection by collimators and absorbers at all times.
 - Must be maintained over many months !
 - Appropriate interlock settings (BLMs, PCs...).
 - Minimum number of operational mistakes.
 - Good sequences, state machines, good UIs...
 - **Avoid dangerous failure coincidences** (OP + other failure).

We have progressed in that direction in 2009, but there is lot's of room for improvements.

And finally there is the beam!

- The beam is a complex variable in the MP game.
 - Must control and know shape and position (transverse & longitudinal)
 - Tail populations and distributions are an issue.
 - The tails of a high intensity LHC beam constitute an unsafe beam.
 - Available reaction time to certain failures depends strongly on tail properties. And tails can vary a lot (beam-beam...).

We must build up experience step by step:



Proposal for 2010

- Establish STABLE BEAMS @ 3.5 TeV with 4 pilots ‘**asap**’.
 - ‘Quiet beams’ periods must be banned.
 - 4 ‘fat’ pilots are ~ at SBF limit (3E10) – limited risk.
- Interleave STABLE BEAMS with further MPS commissioning (as appropriate).
 - Moderate intensity steps ($f \leq 2-4$ max, f decreasing function of intensity).
 - *Increase bunch intensity first to $\sim 4-5e10$ (< BPM sensitivity change), then increase number of bunches* (higher lumi/stored energy).
 - Monitor carefully before increasing – **approved by ?**
 - Plan for a long(er) stable running period at $\sim 0.5-1$ MJ stored energy (20-40 bunches of 4E10) – that ‘s where we start drilling holes in the SPS !

Unfortunately we have no equations to tell us how safe we are
– we can only observe that everything works as planned.

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Some 2009 issues and follow up (1)

□ SMP– Ben’s talk:

- SMP reliability.
- Counter-measures to enhance safety (SIS, forcing of SBF).

□ FMCMs:

- FMCMs did not work for PCs with polarity switch – will be fixed.

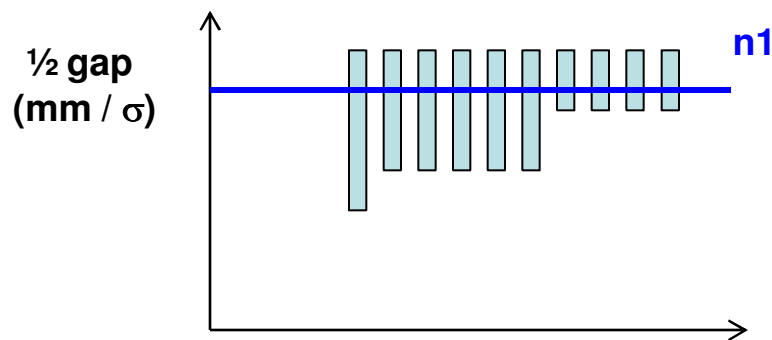
□ BLMs – Christos’ and Wolfgang’s talk:

- BLMs around TDI – thresholds (~done) + shielding (?). We must make over-injection work in 2010.
- BLMs affected by TCDI collimator losses – shielding (?) + scraping in the SPS. Sensitivity to small losses is worrying.
- BLMs at all cold elements should become un-maskable (LSS BLMs missing in 2009).
- BLMs at collimators: maskable? maskable for the first 1-2 months?

Some 2009 issues and follow up (2)

□ Collimators & absorbers:

- Energy-dependent gap interlock must be activated. Essential settings protection.
- TCDQ interlocking with beam must be activated (SIS) .
- Abort gap monitoring, cleaning and interlocking must become operational.
- Squeeze-factor (= min. β^* in machine) functions could be tested – under discussion (squeeze factor generated by SIS).
- More than nice to have: online display of all collimator gaps (in mm and sigma) – already in the pipeline.



Some 2009 issues and follow up (3)

□ LBDS:

- Injection protection in case of LBDS internal dump trigger (up to 10 ms unprotected time interval) – solution being evaluated.
- RF frequency mixing b1-b2 – solution being evaluated.

□ PIC/powering:

- Configurations changes to remove faulty MCBX or other orbit correctors will not work in the future (separation bumps, orbit...) – probably need intervention.

□ RF:

- No protection when RF switched off. So far we have to rely on abort gap cleaning (!!) and interlocking – weak protection from that side?

Sequencer and state machines

□ Sequencer and MP:

- Once a standard sequence is established, the sequencer is useful for MP since it avoids (or reduced the number of) mistakes.
- But using the sequencer to force integrity checks etc should be avoided.
 - I do not believe in the safety of 'unskippable' tasks and similar tricks.

□ Servers implementing *state machines* should be used to enforce periodic checks, task order etc

- Equipment access through state machine server (enforced by RBAC), for example for BICs, BLMs, LBDS.
- State machine can block untimely commands, refuse rearm/reset without execution of operational check...

CO should invest into a state machine framework !

PM and Event Analysis

- Acknowledging the PM (by EIC) will become mandatory to allow injection (SIS interlock – similar to ICQ/XPOC).
 - Basic check that the cause is understood.
 - Request by the experiments to be informed via page1.
 - Progressively backed by better/more automated analysis.

- An analysis team will have to check the performance of the MPS.
 - Build the team !
 - Establish PM event DB.
 - Provide more and more analysis tools (on- and offline).
 - Evaluate performance of MPS, look for signs of non-conformities.
 - One person responsible for checking, classification and early detection of 'suspicious' events on a weekly basis. [Hotline for EIC?](#)
 - Proliferation of 'strange' events or highly abnormal dump : reduce intensity – STOP.

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LHC Machine Protection System intercepts record beam intensity !

On 1 April 2010 the LHC machine protection system safety intercepted a record beam intensity of $3.14159 \cdot 10^{14}$ protons at 7 TeV/c following a provoked critical circuit failure.



People involved with the tests in the refurbished GCG after the successful test



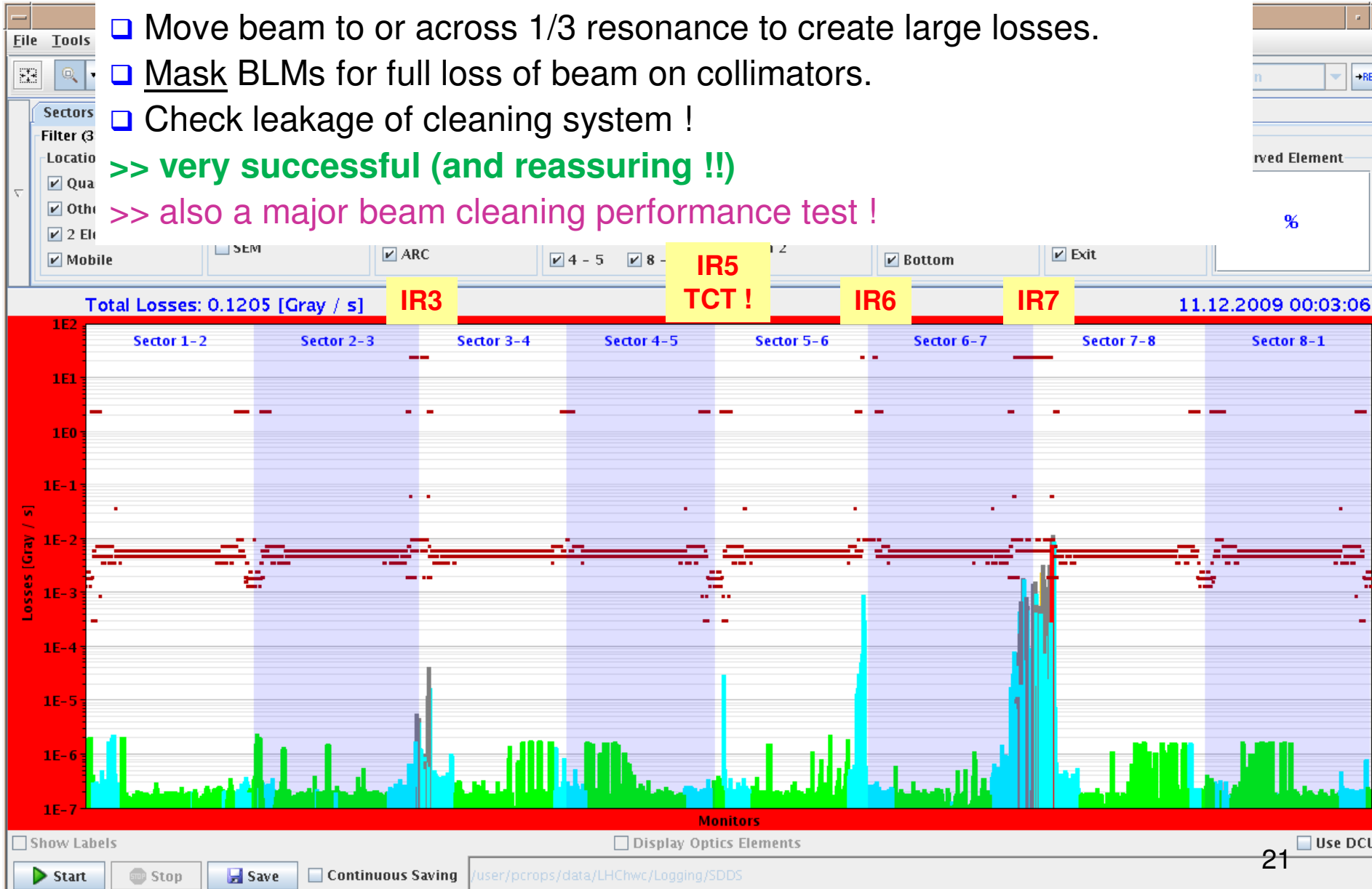
The beam spot on the control screen in front of the beam dump.

Global protection checks with beam – 2009 style

- Move beam to or across 1/3 resonance to create large losses.
- Mask BLMs for full loss of beam on collimators.
- Check leakage of cleaning system !

>> very successful (and reassuring !!)

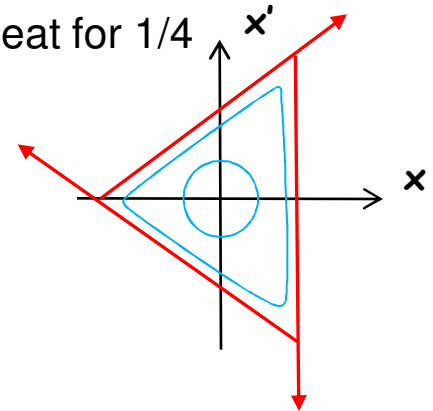
>> also a major beam cleaning performance test !



Global MP checks in 2010

- We want to be protected for every β^* and at all energies:
 - Checking every β^* step is possible, but will be very time consuming.
 - How to handle β -beat changes in the ramp? Program such tests to happen on the fly?

- *Extension* of tests to **higher energy** and to **unsafe(r) beams**.
 - If BLMs dump the test may be biased (towards most 'lossy' phase).
 - Resonance crossing itself may not be bias free !
 - 1/3 resonance expels particles over separatrix... Repeat for 1/4 resonance, 1/5 resonance?



Strategy?

Proposal for global MP checks in 2010 (1)

- Maintain the global checks of protection devices/cleaning with low intensity beams (\leq SBF limit ?):
 - For **injection** + any **STABLE BEAMS** configuration (energy & β^*):
 - Q to resonance or equivalent (with IR3/7 BLMs masked).
 - Phase scan with orbit correctors could be an alternative to Q resonance – need appropriate SW to control beam loss and speed up testing.
 - De-bunched beam dump (TCDQ).
 - Beam intensity must provide sufficient sensitivity. To be evaluated.
 - Requirement to perform tests at intermediate β^* and energy could be estimated from:
 - Evolution of β -beat.
 - Orbit and aperture information.

Proposal for global MP checks in 2010 (2)

□ Maintain safe condition over time.

- Maintain stable orbit & optics (corrector and possible orbit interlocks).
- Follow evolution of loss patterns in cold sections and at absorbers (all phases).
- Check PM & XPOC data of all beam dumps. Trends !

□ Maintain safe condition with increasing intensity.

- Same as above – but taking into account that more beam = more losses...
- Quenches should be exceptional.
 - Frequent quenches : step back intensity – cleaning check...

□ Periodic repetition of global checks?

- Triggered by suspicious signals/losses (PM, XPOC).
- Triggered by repetition of quenches.
- ...

MDs

- During standard physics operation sequences and settings can be nailed down (at least to some extent) for MP.
- MD phases interleaved with standard OP are a potential threat:
 - BIS interlock masking (AC dipole, BPM interlocks...).
 - SIS interlock masking (corrector settings, orbit interlocks ...).
 - Settings changes could break the collimator-absorber protection hierarchy.
 - **One MD participant has the responsibility to restore machine conditions** ('undo').
 - EIC cannot always track everything (shift change...).
 - ❖ **We should consider defining a mandatory protocol/checklist for each MD.**
- ***The scope of End-of-fill MDs will be severely limited*** because beams will be unsafe.
 - no squeeze, Xing angle, etc MDs that have not been tested before at low intensity.

Masking

- ❑ BIS inputs: conditioned by the SBF – depends on BCT reliability.
 - For regular fills we will force the SBF to FALSE (start ramp).
 - Beyond a certain intensity we should consider **forcing permanently**. Unforced by expert for approved MDs.
- ❑ SIS: conditioned by RBAC.
 - Roles (all interlocks) for 2010 reduced to LHC-EIC & MCS-SIS (SIS expert).
 - Finer grained masking ~ March/April 2010 (interlock basis) .
- ❑ BLMs: strict procedure available.
- ❑ PIC: masking by expert possible.
 - Not always possible take out a corrector because it's faulty – depends on usage (Xing, separation) and kick strength !

Outlook

- ❑ This will be THE year for MP: unsafe beam in the LHC !
- ❑ We did a lot and we learned a lot in 2009, but the most delicate phases are ahead of us:
 - increasing intensity into MJ-land,
 - and **how to decide that we can go there!**
- ❑ We need an established, reproducible machine cycle to run with very unsafe beams.
- ❑ In 2009 we had a terrific commissioning pace: we will not be able to sustain that pace over many months.
 - We need breaks (= stable physics periods) to breathe and to observe !