How to safely reach higher energies and intensities?
Settings and commissioning of MPS for 5 TeV operation

Preconditions for operating at 5 TeV in 2010

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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 did not occur!

But the beams were modest – compared to design:
- the maximum stored energy was ~30 kJ – a factor 10’000 to go…
- no beam made it above the SBF limit.

The 2010 plans imply World record stored energies ~10xTEVATRON to be reached on the time scale of a few months!

17 bunches – 30 kJ
A pilot bunch (5E9 p) is the only beam that can be used for commissioning (and for most MD) activities at ≥ 3.5 TeV!

For TCTs the limit can be lower!!

\[ L \sim 2 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1} \]

\[ @ 3.5 \text{ TeV}, \beta^* 2 \text{ m} \]
MPS tests without beam.
- Almost completed (some test were not required for low intensities).
- Only a few need to be repeated (equipment changes or upgrades).

MPS tests with beam.
- ~2/3 of individual system beam tests completed.
- Global setup and tests were performed for injection energy.
  - Setting up of collimators and absorbers (some only partially).
  - To be repeated at all energies and $\beta^*$ values.
- A major item missing in 2009 was abort gap cleaning.
  - Tested, but operational (one undulator missing !) and not interlocked.
  - Critical at high(er) intensity and small $\beta^*$ (aperture limited by triplet).
The more tricky issues from 2009

- **Safe Machine Parameters (SMP).**
  - Reliability issues on ‘Safe Energy’ before startup with beam.
  - ‘Setup Beam Flag’ and ‘Beam Presence Flag’ issues related to BCT.
  - Solutions are (will be) in place to address safety issues – to be evaluated.
  - SMP system specification and design to be reviewed in 2010.

- **BLM signal ‘cross-talk’ and saturation (see previous talk).**
  - Remarkable performance of the (very complex) BLM system.
  - BLMs at injection dumps saturated for short time scales.
  - Losses on transfer line collimators induce large signals on ring BLMs.
    - Scrapping in SPS mandatory – reliability issue (ISR scrappers !).
  - Over-injection not possible on ring2 due to similar effect from injection dump losses.
  - Solutions should be available for the startup…
For MPS operation at 3.5, 5 or 7 TeV is essentially equivalent. (splices not considered here…)

- Emittance, minimum $\beta^*$ and collimator settings are different.
  - Collimators and absorbers must be setup again at every energy.

- Quench level decreases with energy.
  - Collimator setup more critical at 5 TeV.
Moving towards unsafe beams

To operate with unsafe beam:

- All MPS system test steps must be completed (with/without beam).
- Global protection tests must be completed.
- Collimators and absorbers must be in place.
  - Injection protection only required when unsafe beams are injected directly.
- Beam diagnostics must be working.
- Post-mortem diagnostics must be adequate.
  - In place, more online analysis to be developed.
- Operational cycle must be established.
The systems that are part of the MPS monitor equipment and beam parameters and 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).

- **Critical point:** common cause and correlated failures leaving the machine unprotected in some situations!
  - **Protection redundancy** based on a diversity of systems reduces likelihood of correlated failures – but we do not always have redundancy.
  - **Careful performance monitoring during operation** may reveal issues before they are the cause of incidents.

Confidence in the safety is mostly obtained by running the system and monitoring it carefully >> this takes time !
A good and stable setup

For unsafe beams, we need a careful machine setup, a well established operational cycle, good diagnostics and a reliable control system.

- Machine must be under control.
  - Optics, orbit, aperture.
- Protection by collimators and absorbers at all times.
- Appropriate interlock settings (BLMs, PCs...).
- No (if possible!!) operational mistakes.
  - Good sequences, state machines, clear UIs…
  - Avoid dangerous failure coincidences (OP error + other failure).
The beam is a complex variable in the MP game.

- Must control and know shape and position.
- 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:
- Intensity increase
- Stable running
- Careful monitoring
The ‘safe’ part: ⇔ proposal from Evian Workshop (19-20.01)

- Initial operation with setup (‘safe’) beams ($I < SBF$ limit).
  - Up to 4 pilot bunches/beam are ~ at SBF limit ($3 \times 10^9$) – limited risk.

- Step 1: establish STABLE BEAMS @ 3.5 TeV, $\beta^* = 11$ m.

- Step 2: establish STABLE BEAMS @ 3.5 TeV, $\beta^* = 2-3$ m.
  - Commissioning of $\beta^*$ squeeze in parallel to physics with $\beta^* = 11$ m.
  - No intensity increase wrt Step 1.

- No more ‘Quiet beams’ periods.
Increasing intensity

- Monitor MPS performance and operation stability.
  - Losses (all machine phases), Post-mortem diagnostics,

- Green light for intensity increase by MPx:
  - MPP for machine protection performance.
  - MP3 for magnet performance (quenches…).

- Moderate intensity steps.
  - \( f \leq 2-4 \) max, \( f \) decreasing function of intensity).

- Maximize luminosity/stored energy.
  - Increase bunch intensity first, then increase number of bunches.

- Plan a long(er) stable running period at \(~0.5-1\) MJ stored energy – that’s when we start drilling holes in the SPS!
(Recent) SPS incidents

Uncontrolled beam loss in the SPS at 400-450 GeV leads to severe damage for stored energies $\geq 1$ MJ.

(SBF limit = 70 kJ)

TT40 transfer line quadrupole vac. chamber
2.2 MJ @ 450 GeV

SPS dipole vacuum chamber
2 MJ @ 400 GeV
Lessons from SPS incidents

- Simulate failure scenarios, design the MPS to cope with the fastest failures.
  🙁 SPS ring is not fully protected against fastest failures.
  😈 Detailed analysis at the LHC

- Stop when you have doubts, make sure you have good diagnostics.
  - TT40 MD was continued despite some warning sign.
  - Insufficient diagnostics to evaluate situation.

- Both incidents: direct impact on vacuum chamber.
  - Even imperfect dilution by collimators reduces strongly the local energy deposition and prevents damage.

  >> Respecting collimator/absorber hierarchy is essential!

A MJ-class beam in the LHC presents a much lower risk of damage than at the SPS if the collimators are properly setup!
Global protection checks with beam

Test that collimators intercept the (almost) all the beam.

- Beam moved across tune resonance to induce large losses.
- Mask BLMs for full loss of beam (low intensity).

>> very successful: >99% of the beam intercepted by collimators

![Graph showing beam losses and sectors](image-url)
MPS setup and global MP tests must be repeated when:
  - $\beta^*$ is changed.
  - Crossing angles are switched on.
  - Energy is changed.

To gain efficiency, minimize the number of MP setups.
  - Choose 1-2 $\beta^*$ values - stick to them (if possible).

At any given time there is a well defined operation envelope.
  - Total intensity
  - Injected intensity
  - Minimum $\beta^*$
  - Crossing scheme

To be respected
During standard physics operation sequences and settings can be ‘nailed down’ for MP.

- So far only orbit correctors are surveyed.

MD phases interleaved with standard OP are a potential threat.

- Interlock masking.
- Settings changes could break the collimator-absorber hierarchy.
  - One MD participant responsible to restore machine conditions.
  - Separation of settings for MD and for regular operation.

The scope of End-of-fill MDs will be severely limited because beams will be unsafe.

- no squeeze, crossing angle, etc MDs that have not been tested before at low intensity.
(Interlock) masking

- **BIS inputs**: *maskable channels are conditioned by the SBF.*
  - SBF reliability depends on BCTs – more experience needed.
  - For regular fills we will force the SBF to FALSE (start ramp).
  - Beyond a certain intensity we could consider *forcing permanently SBF to FALSE.* Unforced by expert for MDs.

- **Software Interlock System**: masking conditioned by RBAC.
  - Limited to EICs and SIS experts.

- **BLMs**: approved procedure.
  - Strict rules for disabling a loss monitor.

- **PIC/PC**: masking of circuits by expert possible.
  - Repairing a circuit may be more efficient that rechecking ramp & squeeze!
  - Faulty orbit correctors could be an (efficiency) issue – MCBX…
Improvements & upgrades

- **Setting interlocks.**
  - Protection against settings errors at injection is implicitly performed by the concept of beam presence for high intensity injection.
  - Circuits settings are only checked for RBs and orbit corrector (Software Interlock) — we may have to consider extending considerably, and performing interlocking PC currents at the level of the PC FECs.

- **Injection protection.**
  - No protection by absorbers in horizontal plane.

- **Abort gap population.**
  - Reliability and safety of synchrotron light monitor based protection.

- **Squeeze factor (= min. β*)**
  - Additional ‘Safe Parameter’ to be distributed to collimators and absorbers.

- ...
Conclusions

In 2010 we will operate (highly) unsafe beam: we may reach sufficient stored energy to shutdown the LHC for some months in case of incident.

- MPS commissioning to be finished, some part to be repeated (global tests).
  - Collimators and absorbers are critical.
- Careful commissioning planning will avoid repetition of MP testing.
- Operational cycle must be established to switch to unsafe beam.
- Intensity increase must be gradual.
  - Careful analysis of losses and post-mortem data to validate safety.
- Machine (MPP) and Magnet (MP3) Protection must work close(r) together.
  - In particular if we start to quench!
- Great care must be used during MD periods not to jeopardize safety of regular operation.