How to safely reach higher energies and intensities

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Abstract

The LHC Machine Protection System has been commissioned in November and December 2009 for low intensity and low energy beam operation. During this period interlocks were activated step by step and masking of channels was used regularly to improve the commissioning efficiency. As intensity and energy are increased this flexibility will be lost as the machine has to be protected at all times. It is therefore essential that all protection functionality must be commissioned at low intensity. Intensity and energy must be increased progressively, and every new step in energy or optics must be performed at low intensity. The steps that must be performed at the various stages will be outlined. The issues related to masking of interlock channels will be discussed.

INTRODUCTION

During the second half of 2009, and in particular in November and December 2009, a large majority of interlocks were tested and activated. Despite the presence of close to 20'000 interlocks capable of stopping the beams, the LHC could be operated without significant problems due to the Machine Protection System (MPS) [1]. No magnet was quenched with circulating beam thanks to an excellent collimation setup, with cleaning efficiencies well above 99%. The frequently predicted "with so many interlocks it will never work" scenario did not occur thanks to the excellent preparation, see Fig. 2 for an overview of all systems feeding into the LHC Beam Interlock System (BIS).

It must however be noted that the beams were modest compared to design: the maximum stored energy was 30 kJ see Fig. 1, a factor 10000 to go, and no beam made it above the Setup Beam Flag (SBF) limit [2].

The 2010 plans for the LHC imply World record stored energies, approximately 10 times larger than TEVATRON, to be reached on the time scale of a few months !

MPS IN 2009

MPS tests without beam were almost entirely completed (some test were not required for low intensities). Following the stop in January and February 2010, some tests must be repeated (equipment changes or upgrades, in particular for the LBDS). Concerning MPS tests with beam, approximately 2/3 of individual system beam tests were completed. Global setup and tests were performed for injection energy. Collimators and absorbers were set up (for injection only a partial setup was made). Global setup and tests must be repeated at all energies and β^* values. A major item missing in 2009 was the abort gap cleaning; it was tested, but was not made operational (for beam 1 the undulator was not commissioned) and not interlocked. This will become critical at high(er) intensity and smaller β^* (aperture limited by triplet, quenches of Q4 in case of excessive gap population).

A few issues have been uncovered during the 2009 operation of the LHC MPS.

- Safe Machine Parameters (SMP) System: reliability issues on the Safe Energy were observed before startup with beam. This resulted in the transmitted beam energy being set to 7.86 TeV. It must be noted that this value is the SAFE state. This issues affects the machine availability (false dumps), but not the machine safety. The Setup Beam Flag (SBF) and Beam Presence Flag (BPF) had reliability issues related to the data transmission from the LHC BCTs. Solutions will be in place in 2010 to address the safety issues: the energy value and transmission will be surveyed with the Software Interlock System (SIS [3]), the SBF will be forced FALSE if needed. The SMP system specification and design will be reviewed in 2010.

- BLM signal cross-talk and saturation was observed mostly in the injection region (TDI and TCDI colli-

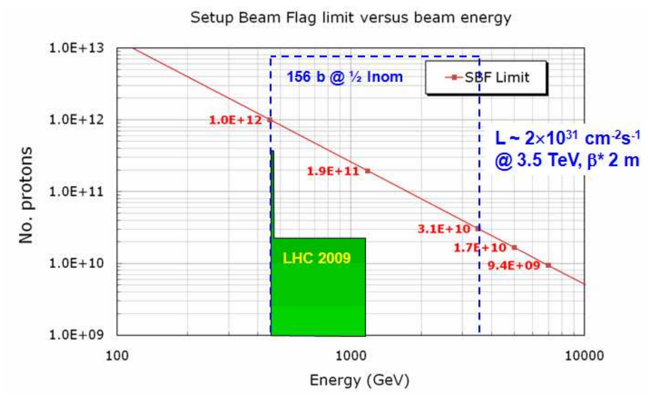

Figure 1: Setup Beam Flag limit as a function of beam energy. The green area indicates the region that was explored in 2009. The dashed region indicates the stored energy area for operation with 156 bunches at half-nominal bunch intensity.

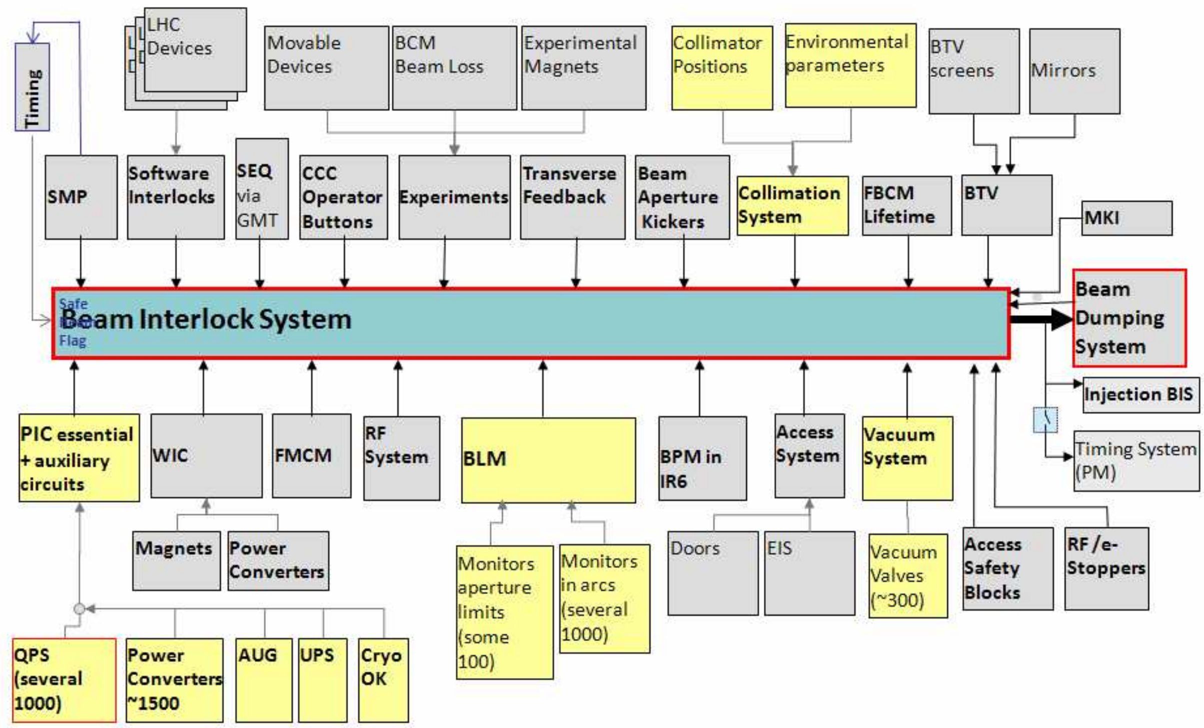

Figure 2: Schema of the LHC Machine Protection System with all its clients.

mators). BLMs on the injection dumps (TDI) were saturated for short time scales already with a single pilot bunch. Losses on the TCDI transfer line collimators induce large signals on LHC ring BLMs due to the close distance between the collimators and the BLMs that are protecting the LHC super-conducting magnets. Shielding of the BLMs from the TCDI may be a longer term solution, but simulations are required to evaluate if sufficient shielding can be installed in the crowded injection region. Due to the TCDI-ring BLM shower cross-talk, scrapping in the SPS was mandatory already for very small intensities. Injection of a pilot bunch on the IP8 TDI (required for over-injection) triggered a dump on a BLM installed on the D1 magnet to protect the triplet (Q3). Possible solutions to the problem will be evaluated. Despite those issues the performance of the BLM system proved to be remarkable and the diagnostics (1 Hz data stream) proved to be excellent, Remarkable

MOVING TOWARDS UNSAFE BEAMS

MPS operation at 3.5, 5 or 7 TeV is essentially equivalent (splices are not considered). There are differences due to the emittance, the minimum β^*, the collimator settings and the quench level. Collimators and absorbers must be set up at every energy. The quench level decreases with energy, see Fig. 3, which makes collimator more and more critical as the energy is increased.

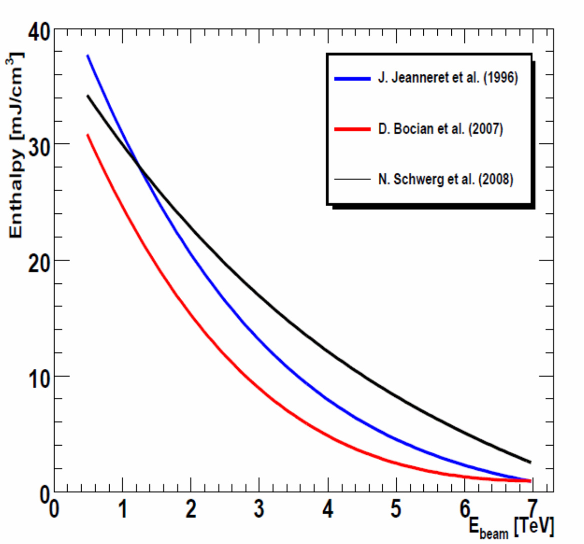

Figure 3: Estimated magnet enthalpy as a function of the energy for 3 different models (Courtesy M. Sapinski).

A certain number is conditions must be fulfilled to operate with unsafe beam:

- All MPS system test steps must be completed (with and without beam).
- Collimators and absorbers must be in place, in partic-

ular during the stable beams periods.

- Global protection tests must be completed. This includes triggering powering failures to ensure that the beam is dumped in due time, inducing low lifetimes to very the quality of the collimator positioning.
- Injection protection will only be required when unsafe beams are injected directly.
- Beam diagnostics must be working reliably, in particular the for BPMs and BLMs.
- The Post-mortem diagnostics must be adequate [4]. More and more online analysis must be developed with experience.
- The optics must be known and reproducible.
- The orbit must be reproducible at the level of at least one rms beam size.
- The 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. The safety levels of those systems are either unknown or estimated from reliability analysis. Dry operation is used to verify some reliability estimates (see for example the LBDS and BIS reliability runs). A critical point for such safety level estimates concerns common cause and correlated failures leaving the machine unprotected in some situations. For certain failure cases, protection redundancy based on a diversity of systems reduces the likelihood and impact of correlated failures, but redundancy does not exist for all cases. Careful performance monitoring of the MPS 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 unfortunately takes time!

The control system also plays a role in operating with unsafe beams. Errors due to operational mistakes or controls issues may trigger dangerous situations that could have dramatic consequences in case of a coincidence with another failures (failure coincidence).

The beam is a another complex variable in the MP game. Both beam shape and position must be well controlled. Tail populations and distributions are an issue at the LHC: the tails of a high intensity LHC beam constitute an unsafe beam. The available reaction time to certain failures depends strongly on tail properties, which can vary significantly depending on the operating conditions (beam-beam).

MD periods

During standard physics operation sequences and settings can be frozen to ensure best possible protection, even if so far only orbit correctors settings are surveyed.

Machine Development (MD) phases interleaved with standard operation are a potential threat since the experiments may involve interlock masking. Settings changes introduced during MDs can potentially break the collimator-absorber hierarchy. To provide more safety, one MD participant must be responsible to restore machine conditions. Separation of settings for MD and for regular operation is a simple means to avoid undesired settings changes. The scope of "end-of-fill" MDs (at the end of a stable beams period) will be severely limited because the beams will most likely be unsafe. Squeeze, crossing angle, etc experiments can only be performed if they have been tested previously at low intensity.

Interlock masking

Interlock and signal masking at the LHC is strongly dependent on the system.

- BIS inputs: for maskable channels the possibility to mask is conditioned by the SBF. The SBF reliability depends on the LHC BCTs, and more experience is needed to decide if the safety is sufficient. For regular physics fills the SBF will be forced to FALSE (at the start ramp). Beyond a certain intensity one might consider forcing permanently the SBF to FALSE. An expert would in that case unforce the SBF for MDs.
- SIS inputs: masking of tests is conditioned by RBAC and limited to EICs and SIS experts.
- BLMs: disabling a BLM is only possible by following an approved procedure. There are strict rules for disabling a loss monitor to avoid creating local 'holes' in the protection by disabling to many monitors of a region.
- PIC (electrical circuits/magnets): masking of circuits is only possible by the PIC expert. This is evidently also limited to uncritical circuits since the LHC cannot operate without the main elements (RB, RQ, IPQ, IPD IT). Depending on the circuit it may be more efficient to repair than to perform a low intensity ramp to check ramp ing a circuit may be more efficient that rechecking ramp and squeeze. Faulty orbit correctors could become an (efficiency) issue. MCBX

Post-mortem

The Post-mortem (PM) system holds all the essential information to diagnose beam dumps (programmed or emergency). A careful analysis of the data must be performed to validate the performance of the MPS, and to detect anomalies that could lead to severe incidents before it may be too late.

A PM analysis team must check all the beam dumps, and develop automated tools to perform as much diagnostics as possible online. In 2010 the EICs will have to acknowledge every beam dump, and SIS will inhibit injection as long

Phase	k_b^{inj}	k_b	N_b (10^{10} p)	E_{stored} (kJ)	Step	$\mathcal{L}$ (Hz cm^{-}2)	Comment
1	1	4	0.5	11.2		4.2 $\times 10^{27}$	pilot collisions
2	1	4	2	44.8	4	6.8 $\times 10^{28}$	$\approx$3 times above SBF limits
3	1	4	5	112	2.5	4.2 $\times 10^{29}$	
4	1	8	5	224	2	8.4 $\times 10^{29}$	
5	4	16	5	448	2	1.7 $\times 10^{30}$	Injection of 4 bunches
6	4	32	5	896	2	3.4 $\times 10^{30}$	
7	4	43	5	1204	1.3	4.6 $\times 10^{30}$	Standard 43$\times$43
8	6/12	48	5	1344	1.1	5.1 $\times 10^{30}$	50 ns trains of 6 or 13 bunches

Table 1: A possible scenario for the intensity increase in 2010 up to about 1 MJ. k_b is the total number of bunches, k_b^{inj} the number of injected bunches. The injected intensity remains below the SBF limit at injection up to phase 7. Train operation is started with short trains of 6 or 12 bunches.

as the last beam dump is not acknowledged. A database of beam dumps must be established for later analysis, and operation must be stopped if an abnormal event is detected.

STARTUP 2010

Initial operation will be performed with 'safe' beams (intensity below SBF limit). At 3.5 Tev 4 pilot bunches beam are just are just at the SBF limit (3E10 p) and the risk is very limited. The first commissioning steps:

1. Establish stable beams at 3.5 TeV with β^* of 11 m.
2. Establish stable beams at 3.5 TeV with β^* of 2-3 m.

The commissioning of the β^* squeeze should be done in parallel to operating for physics with β^* 11 m. There will be no intensity increase in this period. Quiet beams periods will be banned in 2010.

Increasing intensity

Decisions to increase the beam intensity will be based on the performance of the MPS and on operational stability. For the MPS, the decision will involve beam losses (all machine phases), analysis of the Post-mortem system. Green light for an intensity increase will be given by MPP for machine protection performance and MP3 for magnet performance (quenches). The intensity steps should not be larger than a factor f = 2-4, with f a decreasing function of intensity. The ratio luminosity to stored energy should be maximized through the bunch charge: increase bunch intensity first, then increase number of bunches. A long(er) stable running period should be planned for a stored energy of 1 MJ which corresponds to present state of the art. This is also the stored energy where by experience vacuum chambers and magnet coils are damaged by uncontrolled beam loss. A possible progression of stored energy and luminosity is indicated in Table 1 up to a stored energy of 1 MJ. The progression above 1 MJ is difficult to predict, as it depends on many factors, some of them not necessarily related to MP (cleaning efficiency, beam-beam etc).

MPS setup and global MP tests must be repeated when when β^* is changed, when crossing angles are switched on and when the operating energy is changed. To gain efficiency the number of MP setups should minimized. It is recommended to select 1-2 β^* values and then stick to them (as much as possible). At any given time there will be a well defined operation envelope:

- Total intensity
- Maximum injected intensity
- Minimum β^*
- Crossing scheme

CONCLUSION

In 2010 the LHC will hopefully operate (highly) unsafe beam: it may be possible to reach sufficient stored energy to shutdown the LHC for some months in case of severe incident. The MPS commissioning must be finished, and some parts must be repeated (for example global tests). A careful commissioning planning will avoid repetition of MP testing. The operational cycle must be established to switch to unsafe beam, and intensity increases must be gradual. Careful analysis of losses and post-mortem data will be used to validate machine safety. Finally great care must be used during MD periods not to jeopardize safety of regular operation.

ACKNOWLEDGEMENTS

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