INTENSITY RAMP-UP

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Abstract

In 2010 the LHC operated with destructive stored beam energies. The main phases of operations and the intensity ramp up strategy are recalled along with a look at the outcome of machine protection and operations reviews that took place during the year. With the experience gained in 2010 in mind a possible strategy for progress in 2011 is presented.

PREAMBLE

LHC is pushing into dangerous territory. The LHC represents a huge capital investment for CERN and the consequences of getting it wrong with beam are enormous. The maximum stored beam energy in 2010 was around 28 MJ, this is enough energy to cause serious damage. It is planned to at least double this figure in 2011. Damage to a superconducting magnet and leak of helium into the beam vacuum would require a stop of several months and cause severe delay to the physics program.

2010 - OVERVIEW

The main milestones of the 2010 commissioning are outlined in table 1.

Table 1: main commissioning milestones 2010

Date	Milestone
March	Initial commissioning leading to first collisions
April	Squeeze commissioning
May	Physics 13 on 13 with 2e10 ppb
June	Commissioning of nominal bunch intensity
July	Physics 25 on 25 with 9e10 ppb
August	3 weeks running at 1 – 2 MJ
September	Bunch train commissioning
Oct - Nov	Phased increase in total beam intensity

The intensity ramp-up following the bunch train commissioning in August is shown in table 2.

Table 2: intensity ramp-up and associated performance

Date	Bunches	Colliding pairs	Luminosity
29th August	50	35	1×10^{31}
1 – 22nd Sept.	Bunch train commissioning		
22nd Sept.	24	16	4.5×10^{30}
23rd Sept.	56	47	2×10^{31}
25th Sept.	104	93	3.5×10^{31}
29th Sept.	152	140	5×10^{31}
4th Oct.	204	186	7×10^{31}
8th Oct.	248	233	8.8×10^{31}
14th Oct.	248	233	1×10^{32}
16th Oct.	312	295	1.35×10^{32}
25th Oct.	368	348	2.07×10^{32}
4th Nov.	Switch to heavy ions		
9th Nov.	17	16	3.5×10^{24}
15th Nov.	121	114	2.88×10^{25}

REVIEWS

Operations review

An operations review was held in June 2010. It asked the question: are operations ready to deal with the destructive potential of 0.5 to 1 MJ stored beam energy?

Issues were identified with: preparation for beam and operational procedures; injection; collimator settings control; reliability of feedbacks; the sequencer; controls; software and settings management; the post operational checks of the beam dump system (XPOC); post mortem; and orbit stability and control through the nominal cycle.

The answer to the question posed above was a simple "no". At the time of the review it was clear that operations was not yet ready to deal with fully unsafe beams. The machine protection systems were working well but the potential to put the machine into an unsafe state was still possible and had been demonstrated on occasions. There was still a lot of room for human error.

Following the workshop a lot of effort went into resolving the issues identified and reducing the number of manual actions required when driving the machine through the nominal cycle. Improvements to the sequencer and sequences were rigorously pursued.

Internal Machine Protection Review

An internal machine protection review took place on the 17th and 18th June 2010 [1]. The following systems were considered and again a number of issues were identified.

- Beam Interlock System
- Safe machine parameters
- PIC, WIC and FMCM
- LBDS
- Collimation
- Transfer and injection
- Dump protection
- BPM system
- Orbit feedback
- RF frequency and power interlocks
- BLM system
- Software interlock
- Post Mortem system

Some of the issues raised are listed in table 3 []. They are listed more to illustrated the nature of the problems rather than highlight the problems themselves. It can be seen that, among other things, they concern intervention tracking, redundancy of signals, reliability of beam instrumentation, control issues etc.

Table 3: some issues arising from internal MPS review

System	Issue
BIS	Automated connection tests with users required.
BIS	Beginning of the ramp – operations – Safe Beam Flag to FALSE and unmask all inputs (sequencer)
SMP	Energy distribution must be checked, since there is no redundancy
SMP	Intensity for SBF – no redundant readings
SMP	SBF limit – MPS commissioning/availability
SBF	Now uses the FBCT - too complex for providing a safe system
PIC	After technical stops and interventions the traceability of changes and required testing must be documented. Sloppy if compared to HWC.
PIC	PIC configuration: automated tests of configuration and BIC connection to be performed more regularly.
XPOC	Reliability of some beam instrumentation data not good enough
LDBS	Technical stop modifications not properly tracked.
LBDS	Interlocked beam position monitors - safety – threshold and algorithms needs to be addressed
COL	Machine stability important, some worries
COL	Steady state losses are different from failure transients – careful with extrapolations
BPM	BPM sensitivity settings: automated and reliable sensitivity switching required
Dump protection	Abort gap monitoring and cleaning not operational
BPM	BPM readings dependence on intensity. Need a long-term approach for critical location (IR3, IR7, TCT-IR regions).
BPM	Orbit correction strategy not clear
BLM	Threshold management – critical. Must be managed properly.
BLM	Data from "direct dump" BLM
SIS	Most conditions are maskable (independent of SBF)

EXTERNAL REVIEW

An external machine protection review took place 6th to 8th September 2010. The review panel came to the following conclusions.

Clear criteria should be established by which steps and under which conditions the beam intensity will be increased. This includes, among other points:

- *establishing the necessary operational discipline associated with the potential risks in the new regime of stored energy which to a large extent was promoted during the LHC engineering and construction phase,e*
- *the understanding of the mechanisms populating the abort gap and their scaling as a function of beam intensity,*
- *consolidation of the beam position monitoring system,*
- *the improvement of a detailed and comprehensive post-mortem analysis, and*
- *establishing a robust and rigid set of operating procedures and sequences.*

In summary, the Committee felt that the LHC was ready to go beyond 3 MJ. It saw no objection to a relatively fast but successive increase in stored energy. This conclusion was based on what was presented on the machine protection system and its performance. It assumes

- *that the improvements are implemented which have been presented by the LHC project team themselves, including the priorities made by the Committee in addition to further recommendations,*
- *that the machine performance is all the time understood as the stored energy increases and that confidence is gained in all the operational phases,*
- *and that it is verified that there is no onset of new phenomena affecting the reliability of the machine protection system.*

PUSH TO 1-2 MJ

There was a halting push through nominal intensity commissioning to a total stored beam energy of around 1-2 MJ. The LHC was held at or around this range for around 3 weeks. There was much discussion about the need for the hiatus, which saw the LHC running with 25 bunches per beam (1.6 MJ) until 17th August and 48 bunches until 1st September (3.1 MJ).

The question of whether or not we could we have gone to 1 to 2 MJ earlier was naturally enough asked many times. The answer from an operational and machine protection standpoint was a categorical "no". One must read between the lines of the above summaries of the reviews and realize that the LHC was still very much in a commissioning phase during these months. It simply was not in a state to accept the risks and the consequences of getting it wrong with a multi-mega Joule beams.

BUNCH TRAIN COMMISSIONING

The period of steady running at in August was followed by a timeout for bunch train commissioning that lasted around 3 weeks. The importance of this period should be stressed. Besides getting the machine ready for bunch trains this commissioning period saw a lot of ramps and squeezes for the required loss maps. These provided an opportunity to consolidate and really marked: the transition to a more rigorous, dependable sequence; the reduction of manual actions in the nominal sequence; and some sense that routine operation was under control. Operations had eventually nailed down the sequence, procedures, orbit, and settings to a state that pushing high stored energy beams through the cycle could be more or less be done with some confidence that the safety of the machine would not be compromised.

Interestingly enough, once the procedures had been established at the start of the intensity ramp-up, very little was changed thereafter. There was a clear reluctance to fiddle with a proven modus operandi. It was only when the switch to lead was made that significant modifications were made.

MOVING ABOVE 2 MJ

The key features of the procedure use to control the steps up in intensity follow.

- Maximum step size: 50 nominal bunches (~ 3.2 MJ)
- 3 physics fills required at each step
- 20 hours of stable beams required at each step. There was always some debate. The critical phases are those before stable beams and it was argued that even if the fill was lost a short time after going into physics (e.g. UFO) the necessary tick had been made. Some latitude was asked for and some given.
- Dump BPM test had to be performed for each new bunch configuration.
- The checklist had to be signed off before moving up in intensity (see below).
- A meeting of rMPP took place where practicable. Lively debate was common.
- Some step-ups took place at night, and at weekends. Essentially the operations crew were given the go ahead to increase the number of bunches and were then responsible of pushing the increased intensity into physics.

Criteria for passage – the checklist

The criteria in the intensity increase checklist are tabulated below. See discussion below.

Magnet powering
No unexplained IPOC failure in Post Mortem for FMCM and PIC
No magnet quench after beam dump in RQ4.R/L6
No unexplained quench of a magnet
No unexplained abort of the 3 previous fills by magnet powering system
No problems with loss of QPS_OK for main circuits following injection process
Beam interlocks
No unexplained IPOC failure in Post Mortem for BIC
No unexplained false beam dump from beam interlock system
No failure of BIS pre-operational check
BLM
Internal test (sanity checks) results must be true
Rise time (10 to 90%) of fast losses must be larger then 200 us
No unexplained BLM check failures
Expected losses for the to be injected beam must be 30 % below threshold level
BLM system modification (ECRs) have to be agreed on, EDMS: notified persons signature is needed
No nonconformities in the energy transmission to the BLM crates
Collimation
Betatron loss map
Off-momentum loss map
No observed violation of cleaning hierarchy
Post-mortem
Loss leakage to TCTs below 0.5% during beam dump
UFO occurrences
No unexplained PM event above 450 GeV
Orbit
Global orbit in tolerance in stable beams (< 0.2 mm rms)
Orbit IR3/IR7 collimators within ± 0.2 mm in stable beams
Check that orbit is correctly measured
BPM IP6 (interlock BPM) test at start of first beam with higher intensity and different bunch pattern
Orbit at TCTs in tolerance in stable beams (≤ 1 sigma)
Feedbacks & operation
OFB operational status / no anomalies
QFB operational status / no anomalies
Beam dump
Asynchronous dumps understood? Protection worked correctly?
Parasitic asynchronous dump data show no loss of protection
No positioning errors on TCSG/TCDQ
No settings or thresholds mistakes/wrong sequences/unexplained faults on TCSG/TCDQ
No unexplained MKD, MKB kicker, TSU or BETS faults
No potentially dangerous XPOC or IPOC failure on MKD or MKB
No unexplained synchronization problem with TSU
Pressure and temperature rise in TDE block within tolerances
Requalification passed OK at 450 GeV and 3.5 TeV with pilot in case of any important component exchange
Injection
Injection oscillations within tolerance for all injections
No unexplained large beam loss on TCDIs
No issues in injection procedure, settings or tolerances
Orbit in injection region in tolerance wrt reference (tolerance <0.5 mm)
Resetting of TL trajectories and TCDIs done when needed
No increased rate of MKI flashovers
No increased rate of MKI switch erratics or missings
No unexplained MKI vacuum or temperature activity
No machine-protection related injection system failures

Could we have gone faster?

Could we have gone faster? There are really two questions here: could we have started the ramp-up in intensity sooner; and could be have performed the ramp up faster. The answer to the first question is given above.

The ramp-up was already very fast: ~6 MJ per week. As Ralph Assmann notes, we passed beyond Tevatron and HERA record stored energy in as little as 6 months. We added 3 record Tevatron or HERA beams every week. It was safely done with not even a single quench. (Although we should be careful not to confuse safety with luck.)

The collective awareness of the dangers and the collective experience of operating the LHC provided a natural brake on over exuberance. The length of time spent on the intensity increase seems appropriate, if not pushing the limits of haste.

Discussion and observations

- **Checklist** The circulation to the rMPP seems appropriate. There was good representation of concerned parties in the membership, although it might be noted that there was a limited number of initials against the items. There was fast turnover that sometimes took place at nights and at weekends. This might lead one to question the rigor with which full and comprehensive sign-off was pursued. What was probably happening that there was a perceived sense among the community that things were OK, and only a nod was made towards to the checklist.

- **MPS coverage**. Is it assured? The checklist should certainly be reviewed. If we agree that it is a useful device then it must be taken seriously.
- No special considerations were invoked when coming out of **technical stops**. (Although test dumps are routinely performed.)
- **Operational non-conformities** were observed during the ramp-up. These included tune feedback not working in ramp and squeeze. Others affected the orbit (particularly experiments' IRs). These did not prevent increases in intensity. The acknowledged assumption was that the beam interlock system would catch problems arising. Whether this is the right attitude is a debatable point. It wasn't all plain sailing and we indeed topped out at 368 bunches because of unexplained issues with 424 bunches.

The strategy was useful in providing a framework for a phased intensity increase. It thus prevented the need for protracted wrangling at each step.

It provided a braking mechanism and gave us the chance to address issues that did arise with increasing intensity. The eventual result would seem perfectly acceptable. This should be remembered when considering 2011.

2011

Re-commissioning in 2011 foresees:

- 3 to 4 weeks re-commissioning with a virgin set-up, new ramp, new squeeze, new beta*s, orbit, modified parameter space… it will be different.
- Full collimator set-up and full validation (loss maps, asynchronous dumps etc.)
- One would foresee a ramp backup to around 200 bunches in 50 bunch steps (with 75 ns. bunch spacing). In 2010 it took around 4 days (minimum) per 50 bunch step with most time lost to machine availability and lost fills (UFOs…). Thus it is reasonable to anticipate around 2 weeks to get back to 200 bunches
- After a 10 day scrubbing run, larger steps of 100 bunches is foreseen driving through from 200 to a maximum of 900 bunches (for 75 ns.). This should take around 3 to 4 weeks.

It is important that a revised checklist and regular meetings of the rMPP are used to sign off each step up intensity. Regular beam-based checks should also be performed.

Open Issues

- Do we need another review?
- Does the procedure need to be modified or extended? Does it need to be more formal?
- Should there be more extended MPS unit testing? This might be particularly applicable when coming back from extended stops.
- Checks should be made that all issues arising from the reviews outlined above have been satisfactorily resolved.

REFERENCES

[1] Internal review of the LHC Machine Protection System, http://indico.cern.ch/conferenceDisplay.py?confId=97349

[2] External review of the LHC Machine Protection System, https://lhc-mp-review.web.cern.ch/lhc-mp-review