COMMISSIONING OF THE LHC WITH BEAM

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Abstract

After more than a year of repairing and preparing the Large Hadron Collider after a major technical problem, beams were injected again in November 2009. The commissioning plan for the 2009 to 2011 run was ambitious, aiming for centre-of-mass collision energies of 7 TeV and an integrated luminosity of 1 fb^{-1}. To date the LHC has not disappointed its user group or its designers. The first energy ramp to 1.2 TeV took place only 1 1/2 weeks after the start-up. A short technical break at the beginning of 2010 was followed by a series of commissioning highlights, including beams at 3.5 TeV, first collisions at 3.5 TeV, collisions with squeezed beams and injection of nominal bunch intensity. The major challenge for 2010 is to prepare the machine for higher and higher intensities to reach the target integrated luminosity by the end of 2011. This talk will give a short introduction to the LHC and its challenges and then focus mainly on the commissioning strategy, the preparation, the commissioning highlights, the status of the LHC and the plans for the coming months.

LHC NOMINAL PARAMETERS

The LHC surpasses existing accelerators in two aspects: the main dipole field is a factor 2 above other accelerators and the luminosity a factor 30.

The field of the LHC superconducting main dipoles has to be 8.3 T to keep 7 TeV protons in the vacuum chambers of the 27 km long accelerator installed in the former LEP tunnel. The design proton luminosity is 10^{34} $cm^{-2}s^{-1}$. This luminosity requires 3 x 10^{14} protons stored in the LHC which corresponds to a stored energy of about 360 MJ at 7 TeV - enough to cause serious damage in case it is lost in an uncontrolled way. One of the main accelerator systems is therefore the LHC machine protection system consisting of 100s of collimators installed around the LHC ring, 4000 Beam Loss Monitors (BLMs), absorbers in critical locations such as the beam dump region and the injection region and many other components. In total about 20’000 signals are connected to the beam abort system [1]. Figure 1 shows an overview of the LHC beam dumping system.

LHC BEAM COMMISSIONING

A short overview of the commissioning activities in 2008 and 2009 will be given. The focus will then be on the run 2010/11.

2008 and 2009

The LHC beam commissioning officially started on 10th of September 2008 with the first attempt to establish circulating beams. Preparations had been ongoing for a long time before. Long periods of hardware commissioning and dry runs were followed by transfer line tests and LHC injection tests [2].

The 2008 commissioning activities were put to a sudden hold when on 19th of September a splice of a superconducting main busbar in one of the LHC sectors suffered from a thermal runaway during a typical powering test. The lateral damage caused by the incident was significant [3] and led to more than one year of shutdown for repair, consolidation and testing.

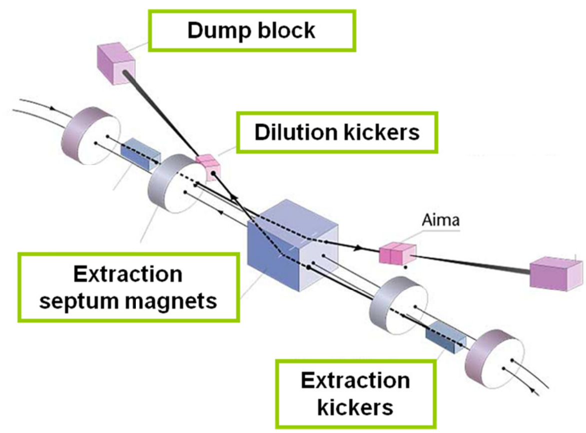

Figure 1: Overview of the LHC beam dumping system installed in the LHC point 6.

It was not until 20th of November in 2009 that the LHC could be started up again. The target energy during this period (governed by the status of the quench protection system) was 1.18 TeV. 18 days after start-up the first collisions at 1.18 TeV could be achieved.

2010/11- The Plan

The current plan for the run 2010/11 foresees protons for most of the time and ions towards the end of each year. The 2010 proton run will be finished end of October. November will be spent with ions. The current physics energy is 3.5 TeV per beam and the target β^* is 3.5 m (nominal β^* is 0.55 m).

The goal for the 2010/11 run is to collect 1 fmb^{-1} of data at 3.5 TeV per experiment. This requires a luminosity of 10^{32} $cm^{-2}s^{-1}$ and an intensity of 700 bunches with 10^{11} p^+/bunch. The stored energy at 3.5 TeV corresponding to this intensity is 30 MJ.

Obviously this ambitious goal can only be achieved with a strict, clean and reproducible machine setup and the machine protection system running at near nominal performance.

Commissioning Phases

The beam commissioning of the LHC can be roughly divided into three commissioning phases.

Phase 1: Phase 1 was the period of commissioning with single low intensity bunches with only limited risk of damage in case of beam loss. The machine protection systems were commissioned during that phase.

Phase 2: Phase 2 was the period of running in the machine protection system with already up to 50 bunches per beam. The crossing angles were still kept off at injection and the bunch spacing was large (> 1 – 2 µs). This phase lasted until end of August 2010.

Phase 3: The LHC is currently in this commissioning phase. Crossing angles have been introduced and the bunch spacing has been reduced to 150 ns. Bunch trains are injected from the SPS. The number of bunches will be increased to 400 before the end of the 2010 proton run

Commissioning Philosophy

The commissioning of the LHC is to a large extent driven by the commissioning of the machine protection systems.

New schemes are tested with very low intensity in the beginning (~ pilot intensity: 5 x 10^9 p^+). Under these conditions the LHC can be operated with a less stringent machine protection system. Flexibility is built into the system such that inputs can be "masked" with very low intensity (< setup beam intensity flag) [1], in this way they are not taken into account for the evaluation of the beam permit. They are automatically unmasked if the intensity is increased.

For each new configuration – e.g. operation with crossing angles – or significant increase in intensity a number of tests have to be carried out:

- References are established: the optics and the aperture are measured. Reference orbits are recorded.
- Protection elements are set up: the collimators and absorbers are aligned to the new orbit references and the thresholds of the interlocked BPMs are adjusted.
- The protection level is verified: loss maps are produced to verify the collimator hierarchy and asynchronous dumps are simulated to qualify the protection against this potentially dangerous failure.
- Intensity is increased: if the qualification tests are passed successfully, the intensity is increased.
- Operational validation: before the next intensity step at least 3 fills with about 20 h in physics have to be achieved to gain confidence in the new setup.

In addition continuous monitoring ensures that protection systems do not degrade with time. After every fill a post mortem analysis is carried out. Typically the beam loss levels and the collimation hierarchy are verified. Automatic post operational checks are launched after each injection and each beam dump.

COMMISSIONING STEPS 2010

Currently the LHC is running with 104 × 104 bunches and 150 ns spacing – the result of several months of beam commissioning. The stored energy is about 6 MJ, more than any other collider before, see Fig. 2. Table 1 shows an overview of the main achievements in 2010.

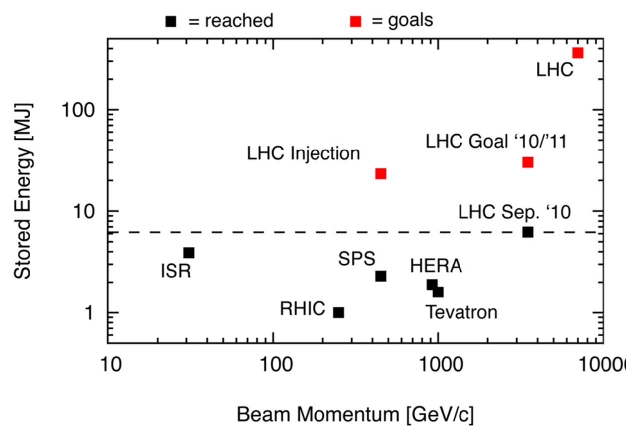

Figure 2: The LHC is currently running with 104 on 104 bunches. The corresponding stored energy is already higher than in any other machine. *Courtesy R. Assmann.*

Table 1: Achievements in 2010

Start-up	28th of Feb.
Ramp to 3.5 TeV commissioning	March
First collisions @ 3.5 TeV	30th of March
Squeeze to 2 m commissioning	mid April
13 x 13 bunches, 2 m β*	until mid May
nominal bunches (10^{11}/bunch), 3.5 m β*	June
Increase number of bunches to 50	July, August
Crossing angle commissioning	September

PERFORMANCE

In August the LHC ran with 50 on 50 bunches. Peak luminosities of 10^{31} $cm^{-2}s^{-1}$ were recorded. A lot of commissioning was still ongoing, but nevertheless 40 % of the time was spent in physics with the experiments taking data, see Fig. 3. Until 27th of September 7 pb^{-1} of data had been integrated (Fig. 4). The maximum availability per week so far is 85 %. The new LHC record peak luminosity with 104 on 104 bunches is 3.5 10^{31} cm^2s^{-1} (Fig. 5).

The beta beating and dispersion beating are within tolerance (20 %) throughout all phases of the LHC and very reproducible. A comparative measurement of the beta beating in May and in August at injection energy is shown in Fig. 6. Optics reproducibility is essential for increasing intensity, in particular for collimators.

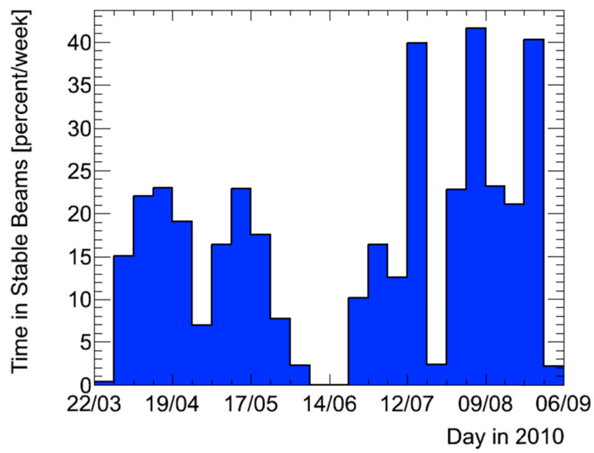

Figure 3: Time in stable beams in 2010. *Courtesy ATLAS.*

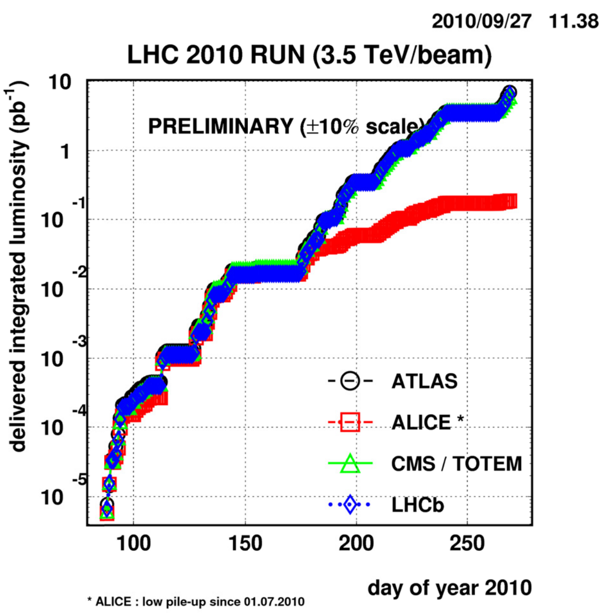

Figure 4: Integrated luminosity in 2010 until 27th of September. *Courtesy M. Ferro-Luzzi.*

Only 14 % of all the beam aborts above injection energy were so-called “programmed dumps” executed by the operations crew. The remainder was issued by the machine protection system through interlocking equipment.

At 3.5 TeV a local loss of 10^7 p^+/s can lead to a quench. The hierarchy of the collimators therefore has to be respected at all phases [4]. The collimation hierarchy is regularly verified through loss maps by resonance crossing or large frequency trims. The typical result of a loss map is shown in Fig. 7. Due to the excellent performance of the collimation system and the fast reaction time of the LHC Beam Loss Monitor system, no quench has occurred so far at 3.5 TeV.

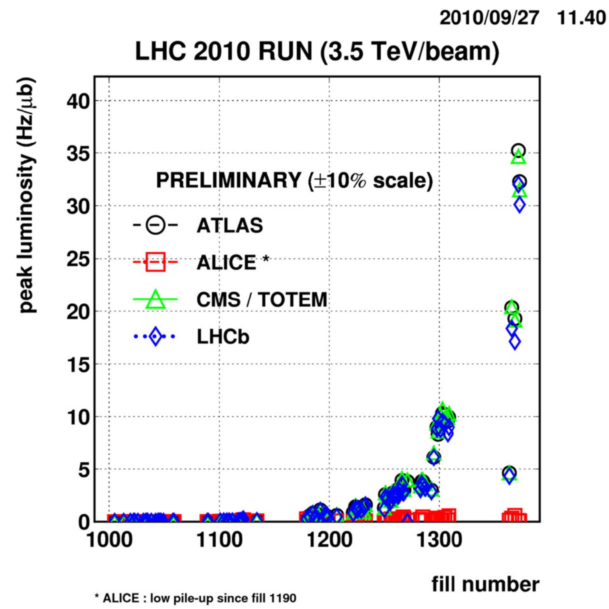

Figure 5: Peak luminosity for fills in 2010 until 27th of September. *Courtesy M. Ferro-Luzzi.*

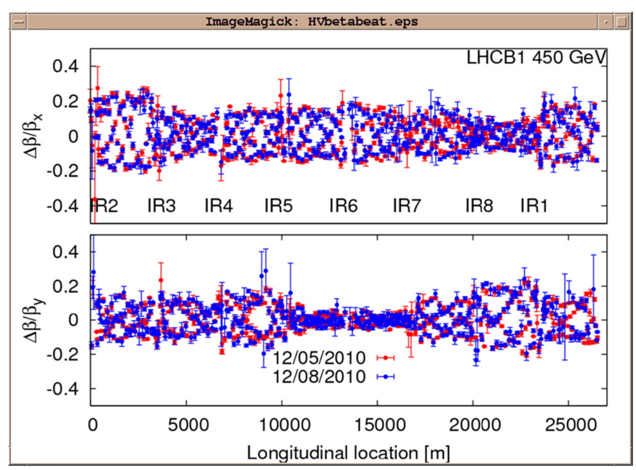

Figure 6: Beta beating at 450 GeV for beam 1 measured middle of May (red) and middle of August (blue). The beating structure and amplitude is unchanged. *Courtesy R. Tomas.*

The performance of the LHC relies to a considerable extent on feedbacks. Many feedback systems are used: tune feedbacks, orbit feedbacks, radial loop and transverse feedback. The tune feedback was introduced already at the third ramp trial, the orbit feedback is part of regular operation since May and the transverse feedback is used since June. The achieved orbit stability with the feedback on during the ramp is shown in Fig. 8.

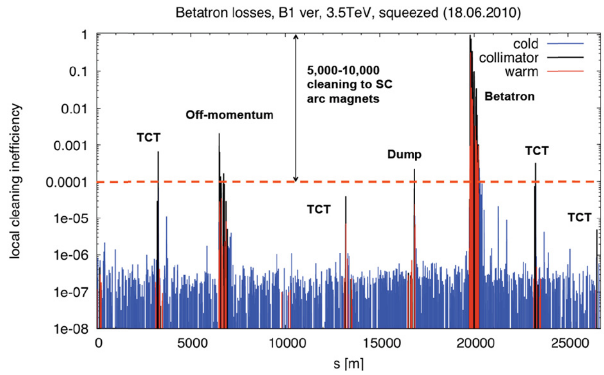

Figure 7: Loss map after crossing resonance for beam 1 at 3.5 TeV, squeezed beams. All the losses occur in collimator regions and the required loss hierarchy from primary to tertiary collimators and dump protection is well respected. *Courtesy R. Assmann.*

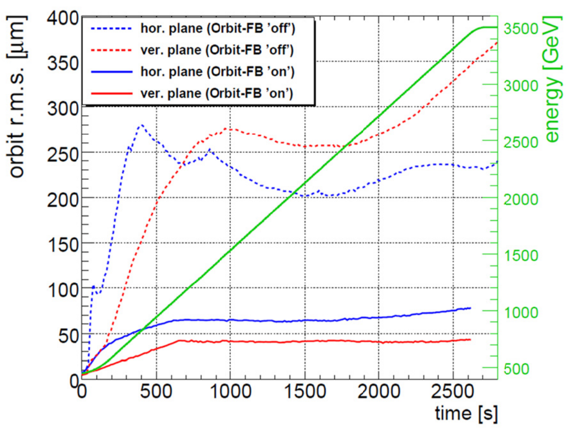

Figure 8: Orbit stability during with and without feedback. With feedback a stability of < 80 μm R.M.S. can be achieved. *Courtesy R. Steinhagen.*

CURRENT CHALLENGES

The "Hump"

The emittance of the nominal bunches injected into the LHC is consistently around 2 μm - smaller than nominal (nominal: 3.5 μm), which is very good news for the luminosity performance. However, frequently the beams are excited by an unknown source, called the "hump", of varying frequency, especially affecting beam 2 in the vertical plane. If the frequency coincides with the beam tunes, emittance blow-up of up to a factor 2 has been observed. The source of the "hump" could not be revealed yet. Several tests have been performed. The transverse damper, the AC dipole, the transfer line power converters, the experimental magnets, the GSM and fire brigade radio network in the tunnel, the triplet beam screen cooling and several other possible sources could all be excluded.

Beam-beam

During the first physics fills with nominal bunches coherent beam-beam instabilities led to sudden strong losses on only a few bunches (those with three collisions), see Fig. 9. The exact source for these instabilities is not understood yet.

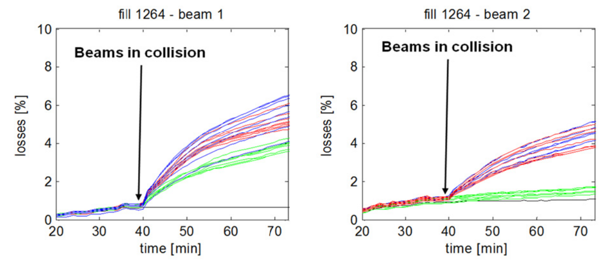

Figure 9: Bunch-by-bunch losses during collisions. The red and blue lines show the data for bunches with three collisions, the green ones with two collisions and the black line correspond to the losses of a witness bunch without any collisions.

Since the transverse damper was introduced during collisions, losses due to these instabilities have not occurred anymore. The luminosity lifetime is between 20 – 30 h, the beam life time during collisions is typically around 100 h after a dip in life time down to a few hours when bringing the beams into collision.

Sudden Local Losses

When intensities were increased during the summer period 2010, beam dumps at top energy due to sudden local losses were observed, sometimes in the middle of the arc. The risetimes were found to be in the ms range, partially even below 1 ms (~ 10 LHC turns). These losses did not provoke any quenches, but preventive dumps. The reason for these sudden losses is unclear. A potential explanation could be dust particles falling into the beam and creating scatter losses. More on that subject can be found in [5].

Injections with "Unsafe" Beam

Currently (for 104 on 104 bunch operation) only maximum 8 bunches are injected per injection. This can still be considered as safe. For the next intensity step, injections of 16 bunches will have to become part of the game. The injection protection system and associated procedures will have to be fully operational by then.

High intensity injections are delicate. Longitudinal and transverse beam parameters in the injectors must be very well under control not to create losses on the transfer line collimators in the injection line, a part of the passive injection protection system. The transfer line collimators are very close to the LHC superconducting magnets, see Fig. 10. Any losses on the collimators are seen by the beam loss monitors located on the LHC magnets. The setting of the collimators is 4.5 σ. With the current injection losses only a factor 10 is left to the LHC beam loss monitor dump thresholds.

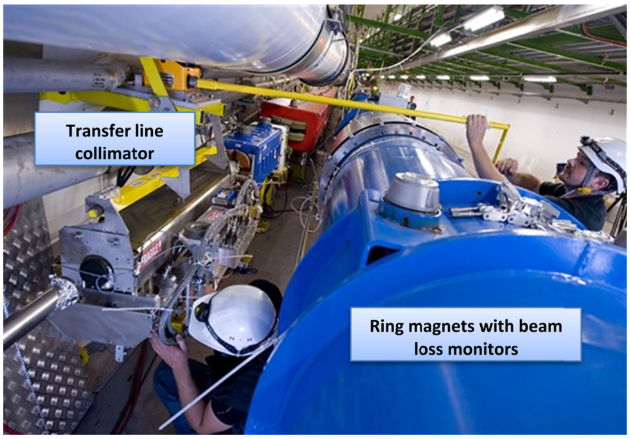

Figure 10: The transfer line collimators are very close to the superconducting LHC ring magnets. Any losses on the collimators are seen by the beam loss monitors mounted on the LHC magnets.

SUMMARY

The LHC is commissioned in steps of energy and intensity. Machine protection is crucial and qualification tests are performed at every change of configuration or increase of intensity. Despite the complexity of the machine and the immaturity, about 40 % of the time in physics could be achieved during the month of August, a month dedicated to stable running. Higher intensities will bring new challenges. Single Event Upsets might be come and issue and sudden local losses might occur more frequently. With the progress achieved so far the goals for the LHC run 2010/11 seem feasible: 30 MJ of stored energy and a luminosity of 10^{32} $cm^{-2}s^{-1}$.

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