Near and medium term LHC machine prospects

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2010-01/8

The challenges facing the LHC machine as it nears the end of its initial commissioning period are recalled. With these in mind projections are made for the coming two years' operation. The foreseen shutdowns for the following years are briefly outlined and estimates for the potential luminosity and integrated luminosity cautiously presented.

1 Introduction

The LHC is drawing to the close of a successful initial commissioning period. The machine has proven to be magnetically and optically well understood and there is excellent agreement with model and machine. It is magnetically reproducible; this is important because it means optics and thus set-up remains valid from fill to fill. The aperture is clear and as expected. There has been excellent performance from instrumentation and controls, and key subsystems are performing well, namely: injection; the beam dump systems; collimation and machine protection.

The ramp and squeeze are, in general, under control and the LHC routinely injects, ramps and squeezes multiple bunches and brings them into stable beams conditions allowing data taking by the experiments. It has also proved possible to keep these conditions for extended periods of time. The maximum fill length is a remarkable 30 hours - impressive for a machine at this stage of commissioning. Nominal bunch intensities have been injected, successfully ramped and brought into collisions at 3.5 TeV.

This progress has been made in the face of the daily challenge of operating an immensely complex machine with the omnipresent concern for machine safety. Operations is dependent on some huge supporting systems, for example: cryogenics, quench protection systems, powering, access, and vacuum and also dependent on a large number of critical sub-systems: RF, synchronization, timing, transverse feedback, orbit and tune feedback, beam instrumentation with huge distributed systems, controls infrastructure, software, databases. Most of these are performing well but there are clearly some features left to iron out and commissioning to finish.

The problems posed by the above systems eat into machine availability and some of them give pause when considering machine safety. The scale of the dangers that the machine faces has been well documented. The 11 GJ of energy stored in the magnets at 7 TeV are sufficient to heat and melt around 15 tons of Copper. The 360 MJ stored in the nominal beam correspond to around 80 kg of TNT. The damage potential of a mere 2 to 3 MJ beam has already been amply demonstrated in extraction tests of the LHC beam from the SPS.

Two points are to be made here: firstly, the LHC has a way to go before it is ready to handle the dangers of beams with stored energies of tens of mega-Joules or higher; secondly it will always be faced with an enormously complex infrastructure and the attendant problems. Even a cursory glance at the evolution of accelerators like HERA, the Tevatron, and LEP show that ramping up luminosity production takes time. LHC has started well, and to be credible in face of expectations, it had to.

2 Machine protection issues

A brief reminder of the main machine protection issues is given below. Full mastery of these dictates the ability of the ramp up in peak luminosity and motivates the cautious, staged increase in total beam current outlined later.

- **The Beam Interlock System (BIS)** of the LHC uses 16 beam interlock controllers (BIC) distributed around the ring to gather about 140 user permits [1]. All systems for protection during beam operation have an interface with the BIS, for example: beam dumping system, collimators, beam dilutors, beam monitors, powering interlock systems, RF system, vacuum system, access safety system, and the LHC experiments. The LHC BIS provides a beam permit signal based on the status of the above inputs, and also on the status of the mask settings and the LHC setup beam flag. When the LHC beam permit signal changes from true to false, injection into the LHC is inhibited, and the LHC beam dump system is triggered within 3 turns to remove safely any circulating beam.
- **The LHC beam dump system (LBDS)** is designed to perform fast extraction of beam from the LHC in a loss free way [2]. For each beam a system of 15 horizontal kicker magnets (MKD), 15 vertically deflecting magnetic septa (MSD) and 10 diluter magnets (MKB) is installed. After the kickers the beam sees an additional deflection when traversing the Q4 quadrupole. The MSD deflect the beam vertically before it is further swept in the horizontal and vertical planes in a spiral shape by the MKB kickers. After several 100 m. of beam dump line the beam is absorbed by the dump block (TDE). To protect the septa from mis-kicked beams a special fixed 8 m long graphite protection device (TCDS) is placed just in front of the MSD.
- For nominal operations the MKD rise time should always be accurately synchronised with the 3 μs **abort gap**, so that no beam is swept across the aperture. However some failures can occur which lead to an asynchronous dump. In addition stray particles may also be present in the abort gap. To protect the LHC aperture from these eventualities, a movable single-jawed 6 m long graphite protection device (TCDQ) is installed upstream of Q4, supplemented by a two-jaw 1 m long graphite secondary collimator (TCSG) and a 2 m long fixed iron mask (TCDQM).
- The primary purpose of **the LHC collimation system** is beam halo cleaning [3]. During LHC operation, proton losses must be kept under control in order to avoid quenches of the superconducting magnets. Almost 100 collimators and absorbers with alignment tolerances of less than 0.1 mm ensure that over 99.99% of stray protons are intercepted. The primary and secondary collimators are made of reinforced graphite and are regarded as robust; the tertiary collimators are made of tungsten are regarded as non-robust.

The hierarchy that exists between primary, secondary, tertiary collimators and the protection devices must be respected. It is thus imperative that the collimators and protection devices are in the correct position at all times. The collimators and protection devices are positioned with respect to the closed orbit and therefore the closed orbit must be in tolerance at all times. This includes the ramp and squeeze and orbit feedback becomes mandatory during these phases. Failure to enforce these strictures will exposed the machine to damage; it will take some time to ensure this categorically.

3 Looking ahead

3.1 Operational schedule

In future it is planned to operate the accelerator complex on a two year basis. Within a two years running period there will be regular six weekly technical stops to solve non-conformities and perform preventive maintenance. There will be a short mid-period Christmas break to perform essential maintenance activities in both the LHC and the injectors.

An operational year within the two year period will include:

- 4 days technical stop and recovery every 6 weeks;
- at least 2 days machine development per month;
- 4-5 week ions run per year;
- other experiment requests for special running conditions e.g. Totem.

The machine availability will, optimistically, be in the order of 50 to 60% during the time dedicated to physics production. Any integrated luminosity estimates should of course take into account the impact of the above on time available to the delivery of luminosity. The two-yearly cycle will be punctuated by relatively long shutdowns, the drivers for which are enumerated below.

3.2 Foreseen long shutdowns

The main drivers for the upcoming major shutdowns [4] are summarized in table 1. From a machine perspective the three major tasks foreseen are:

- **Splice consolidation:** to be 100% sure that the LHC can go safely to 7 TeV per beam, full eradication of the well documented splice issues requires a complete warm-up and long shutdown (2012) during which all interconnect splices will be equipped with mechanical clamping and electrical shunts [5].
- **Collimation phase II** represents the necessary upgrades of the collimation system to allow operation with nominal and ultimate intensities. The upgrades target limitations in efficiency, impedance and other issues. They will consist of two main phases: the warm leg which foresees additional secondary collimators and scrapers into IR3 and IR7 warm regions; and the cold leg which sees installation of collimators in the super-conducting dispersion suppressors in IR7, IR3 and IR2. The latter upgrade is a huge exercise involving moving superconducting magnets. The aim is to do the first part of the exercise (IR3) in the 2012 shutdown [7].

Table 1: Main LHC shutdown activities foreseen in the next 10 years.

Year	Main driver	Secondary activities
2012	Splice consolidation	Collimation phase 2 IR3
15 months		Helium relief valves
		LHC experiments - consolidation
		Radiation to electronics
2016	LINAC4	Booster upgrade
12 months	Collimation phase 2	RF cryogenics upgrade
	LHC experiments consolidation	Radiation to electronics
		Possible crab cavity installation
2020	Preparation for LHC high luminosity	
	Experiments upgrades	

- **LINAC4** represents stage one of the LHC Luminosity upgrade program. The existing proton LINAC - LINAC2 - presents serious reliability and sustainability worries with persistent vacuum problems and an obsolete RF tube design. Instead of an intensive consolidation program the decision has been made to replace it with a new LINAC using modern technologies for better injection and reduced losses (H- injection). LINAC4 will require 7 months to link up with the booster and commission during which time no protons will be available to the accelerator complex.

4 Looking ahead - luminosity

4.1 2010

The clear priority in 2010 is to lay the foundations for 2011 and the eventual delivery of 1 fb^{-1} by the end of 2010/2011. By July 2010 the remaining main objectives of the LHC commissioning with beam program were:

- finish commissioning of some critical sub-systems such as abort gap monitoring, abort gap cleaning, and the transverse damper;
- consolidation and routine physics at stored beam energy of over 1 MJ for an extended period with machine development periods as required;
- gain solid operational experience of faultlessly injecting, ramping, squeezing and establishing stable beams;
- perform a safe, phased increase in intensity with validation and a running period at each step.

Machine protection is clearly hypercritical once the safe beam limit is passed, as is fault free operations and operational procedures. The pre-requisites and detailed planning for increasing intensity are in place and will essentially cover: a full verification of aperture, orbit and optics; full verification of beam dump, protection devices, collimation, injection protection; guaranteed beam quality from injectors; a fully tested beam interlock system including transmission of safe

Table 2: Projected intensity increases and associated performance in 2010 with around nominal bunch intensity (1.1×10^{11}). All numbers approximate.

N_b	N_c	I_{tot}	Energy per beam [MJ]	Peak Luminosity [$cm^{-2}s^{-1}$]	Days	Int. Lumi [pb^{-1}]	Approx. date
3	1	3×10^{11}	0.2	2.5×10^{29}	5	0.03	W4 June
4	2	4×10^{11}	0.2	5.1×10^{29}	5	0.07	W1 July
8	4	8×10^{11}	0.4	1.0×10^{30}	5	0.13	W2 July
20	10	2×10^{12}	1.1	2.5×10^{30}	10	0.6	W3/4 July
24	16	2.4×10^{12}	1.5	4.9×10^{30}	20	1.7	August
48	32	4.8×10^{12}	3.0	9.8×10^{30}	10	1.7	September
96	96	9.6×10^{12}	5.9	2.9×10^{31}	10	5.1	September
144	144	1.4×10^{13}	8.9	4.4×10^{31}	10	7.6	October
192	192	1.9×10^{13}	11.8	5.9×10^{31}	10	10.1	October
240	240	2.4×10^{13}	14.8	7.3×10^{31}	10	12.7	November

machine parameters; fully tested hardware interlock systems; and all required feedback systems operational and appropriate interlocks fully tested.

This list is not exhaustive. Resolution of all procedural, operation, controls, machine protection system, instrumentation, and hardware issues must all have been addressed. It is clear that above will not happen overnight and that a full and careful program of tests and checks is required. An extended operational running period with all prerequisites in place should be pursued. This will allow confirmation that all operational procedures, controls, and instrumentation are fully functional.

Near nominal bunch intensities have been pushed into physics successfully and the resulting outline of the planned increase in beam intensity in 2010 is shown in table 2. The key issue here is the staged increase to and above 1 MJ which is seen as as the damage threshold. An extended running period over summer at around 1.4 MJ is foreseen. This will allow thorough testing of the operations' procedures, and extended verification of the full gamut of machine protection issues before moving on.

4.2 2010 - heavy ion run

A five week lead ion run is scheduled for 2010 with ion set-up starting in the LHC at the beginning of November. It is hoped to leverage the experience gained with protons to rapidly push through the ion commissioning program - the magnetic machine will be near-identical to that used for protons. Ions in the injector chain will have been commissioned in the weeks before they are brought to the LHC.

The early ion parameters that will be applicable to the 2010 run are shown in table 3 and quoted directly from [8]. The initial interaction rate will be around 100 Hz of which 10 Hz will be central collisions with an impact parameter between 0 and 5 fm. In month one might hope to see around 10^8 interactions.

4.3 2011

The present schedule sees a restart of the LHC on 4th February 2011 after a two month technical stop spanning the Christmas period and January. The year foresees 9 months of proton running

Table 3: Parameter list for early (2010/2011) and nominal ion running.

Parameter	units	Early	Nominal
$\sqrt{s}$ per nucleon	TeV	2.76	5.5
Initial luminosity	$cm^{-2}s^{-1}$	1.25×10^{25}	1×10^{27}
Number of bunches		62	592
Bunch spacing	ns	1350	99.8
β^*	m	2	0.5
Pb ions per bunch		7×10^{7}	7×10^{7}
Transverse norm. emittance	μm	1.5	1.5
Luminosity half life (1,2,3 expts.)	hours	$3< \tau_{IBS} <70$	8, 4.5, 3

Table 4: Possible 2011 ball-park scenarios with 1.1×10^{11} protons per bunch.

N_b	β^* [m]	Energy per beam [MJ]	Peak Luminosity [$cm^{-2}s^{-1}$]	Int. Lumi per month [pb^{-1}]
432	3.5	27	1.3×10^{32}	61
432	2.5	27	1.8×10^{32}	85
796	3.5	49	2.4×10^{32}	113
796	2.5	49	3.4×10^{32}	157

and a 4 weeks lead ion run. The clear aim during the physics running period is to run flat out above 1×10^{32} $cm^{-2}s^{-1}$ and accumulate an integrated luminosity of 1 fb^{-1} .

The exact parameters for the run will be established given the experience gained in 2010 but ballpark scenarios are shown in table 4. Assuming nominal bunch intensity and nominal transverse emittance, the key parameters in play become β^* and the number of bunches.

- The limit for β^* at 3.5 TeV with the crossing angle on is taken to be 2.5 m. [9].
- Constraints from the collimation system limit the total intensity to around 20% of nominal [3].
- The 796 nominal bunches option shown in table 4 represents about 25% of the nominal intensity and represents an optimistic upper limit for operations in 2011.
- A Hübner factor of 0.2 is assumed for a 27 day month.

4.4 2013 to 2015

4.4.1 Constraints

The beam energy of the LHC will be limited to 3.5 TeV until after splice consolidation in 2012. The consolidation should open the way to 6.5 and eventually 7 TeV. Here it is assumed that it will take around 2 years at 6.5 TeV before the necessary training of the dipoles to 7 TeV is completed [6].

At higher energy, estimates of the limits from collimation phase 1 state that the maximum acceptable intensity is 40% of nominal into a perfect machine [3]. This number drops if imperfections are taken into account. To go beyond this limit the collimation system must include

Table 5: Possible 2013 -2015 beam parameters and associated integrated luminosity

Year	Months	Energy [TeV]	$\beta*$ [m]	N_b	Peak Luminosity [$cm^{-2}s^{-1}$]	Int. Lumi per month [fb^{-1}]
2013	6 (+1)	6.5	1.0	720	1.4×10^{33}	0.7
2014	9	6.5	1.0	1404	2.8×10^{33}	1.3
2015	8	7.0	0.55	2808	1×10^{34}	4.7

collimators, at minimum, in the dispersion suppressors down stream of IR3 and appropriate repartitioning of the existing cleaning configuration [7]. The successful completion of stage one of the collimator upgrade - the installation of collimators in the dispersion suppressors of IR3 in the 2012 shutdown - would open the way towards nominal intensity; the full scheme should allow nominal and ultimate intensities.

4.4.2 Performance

In exploiting 6.5 TeV there will be a move up another learning curve and a stepped increase in total intensity and a possible squeeze to a conservative β^* of 1 m. and finally to 0.55 m. At least a month should be allowed for recommissioning after the long shutdown. The resultant peak luminosities and integrated total per month and per year are shown in table 5. A nominal bunch intensity of 1.15×10^{11} protons is assumed. The β^* and number of bunches will of course be tuned given operational experience and it must be noted that the table show illustrative, ball-park figures. With the usual provisos one might hope to hit nominal energy and luminosity in 2015.

4.5 2017 and beyond

Coming back from a long 2016 shutdown one would hope that:

- the booster, the PS at increased injection energy together with LINAC4 are good to deliver the ultimate bunch intensity (after a suitable commissioning period) to the SPS;
- following an upgrade program, the ultimate intensity can be handled by the SPS;
- the LHC by this stage can handle the ultimate intensity.

The ultimate intensity is very challenging for the LHC. Many systems will be at their technological limits with little or no margin [10]. Given this, the way to 2020 would be steering the LHC between two options: running at or around nominal intensity delivering something like 40 - 50 fb^{-1} in a 9 month year; pushing over one or two years towards ultimate intensity which could eventually deliver around 100 fb^{-1} in a 9 month operational year.

5 Conclusions

The LHC has seen impressive initial commissioning. Further increases in total beam intensity must be accompanied by careful validation of all aspects of machine protection. Short and medium term luminosity estimates are presented. In the short term the objectives are clear and realistic i.e. 1 fb^{-1} by the end of 2011. After a long shutdown for splice consolidation, three years running at 6.5/7 TeV are envisaged. Installation of stage 1 of the phase 2 collimation system in 2012 should open the way for a push to nominal intensity in the years 2013 - 2015. Progress after a long shutdown in 2016 will be dependent on what is learnt in the previous years and could include: running steady at a nominal production rate; or pushing intensities towards ultimate.

The luminosity estimates presented here are biased towards the optimistic and assume that the LHC can achieve 21st century Hübner factors. The errors bars are big and numbers should be treated with a modicum of circumspection, particularly after 2012.

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