COMPARISON OF INTEGRATED LUMINOSITIES

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Abstract

Luminosity estimates are presented for the LHC in the short and medium term.

INTRODUCTION

The standard luminosity formula for instantaneous luminosity is deceptively simple. However, it extrapolation over time to give a realistic integrated luminosity is notoriously difficult. Such estimates necessarily rely on assumptions of machine availability, machine performance, turn-around times etc. For the LHC at its present stage of commissioning it is particularly difficult. There is no experience of beam behaviour during high energy collisions.

The motivations for making estimates of the potential of the machine are clear. In the short term the immediate discovery potential needs to be evaluated by the experiments. In the medium term, scheduling of interventions on the machine need to be planned taking in account the experiments' requirements, and in the long term any potential upgrades have to scheduled at appropriate times in the luminosity evolution of the LHC.

This paper aims to provide ranges of potential luminosity evolution, with the most optimistic providing an upper limit on the potential luminosity delivery of the LHC in the medium term. Large error bars are to be assumed.

INTEGRATED LUMINOSITY ESTIMATION

The estimates presented here calculate the peak luminosity given the usual inputs: bunch current, number of bunches, emittance, β^*, crossing angle, bunch length etc. The luminosity lifetime is estimated taking into account the luminosity, the total cross-section, the beam-gas lifetime, and intra-beam scattering growth rates. Single beam losses to diffusion process are assumed to be balance by damping from synchrotron radiation around 7 TeV.

Given an assumed turnaround time, it is then possible to optimize the fill length for a given luminosity lifetime. Given the fill length and luminosity lifetime it is straightforward to the calculated integrated luminosity per fill. For a given running period and machine availability a figure for the integrated luminosity is obtained.

ASSUMPTIONS

Turn around time

A breakdown of the foreseen LHC turn around time is shown in table 1. The main components are the ramp-down from top energy; the injection of beam from the SPS; the ramp to high energy; and the squeeze. The ramp-down, the ramp, and the squeeze duration are given by the current rate limitations of the power converters. Of note is the 10 A/s limit up and down for the main bends; and the need to respect the natural decay constants of the main quadrupoles, the individually power quadruples and the triplets during the ramp-down and the squeeze. The latter are powered by single quadrant power converters and take a considerable time to descend.

Table 1: LHC turn around time

Phase	Time [mins.]
Ramp down/pre-cycle	60
Pre-injection checks and preparation	15
Checks with set-up beam: orbit, tunes, injection oscillations, injection losses, lifetime etc.	15
Nominal injection sequence	20
Ramp preparation	5
Ramp	25
Squeeze	30
Adjust/collisions	10
Total	**180**

From table 1, one can see that realistically a three hour minimum turn around time might be assumed. In the long term some second order optimization might be possible (a combined ramp and squeeze for example). Herein four hours is assumed; this could be regarded as optimistic given the enormous complexity of the LHC and the clear potential fro problems during the turn around sequence).

The ramp-down/precycle stage represents the presently adopted operational strategy for coming down from high energy: the main bends, quadrupoles, independently powered quadrupoles, inner triplets etc. are ramped down to their pre-injection levels, while the other circuits are put through their normal pre-cycle which puts them on their right hysteresis branch at injection.

Operational month & year

The following assumptions are made for an average operational month:

- 30 days per month;
- 3 days per month technical stop and recovery;
- around 2 days machine development which is absorbed into unavailability for this exercise;
- 60% machine availability during which operations is dedicated to trying to do physics.

The operational year, will in the medium term, be dependent on shutdown requirements for splice consolidation, collimator upgrades etc. One should take into account the following:

- 4 weeks of ion running per year (plus a few days setup);
- other requests for dedicated running e.g. Totem.

An estimate of the available time for dedicated protons physics over the coming years is shown in table 2.

Table 2: proton physics – months per year

Year	Comment	Months protons
2010	Commissioning, 3.5 TeV	8
2011	3.5 TeV	9
2012	Shutdown for splice consolidation	0
2013	Recommissioning, 6.5 TeV	5
2014	6.5 TeV	9
2015	Collimation phase 2, 7 TeV	4
2016	7 TeV, nominal luminosity	7
2017-20	Production running	7

Clearly, it is too early to claim much exactitude for the above numbers but they are assumed here as the basis for the figures shown below. Some optimization is possible; in particular a two year operational cycle is presently under consideration. This could certainly help shutdown efficiency but won't increase the number of months in a year.

Beam parameters

The nominal beam parameters assumed in the calculation of the luminosity and the luminosity lifetime are shown in table 3.

Table 3: Nominal beam parameters

Transverse normalized emittance	3.75 μm rad
Crossing angle - nominal	285 μrad
Crossing angle - ultimate	315 μrad
RMS bunch length	7.55 cm
Beam-gas lifetime	100 hours
Total cross section at 7 TeV	110 mb^{-1}
Horizontal emittance growth time	80 hours

The Hübner factor

A standard method for integrated luminosity estimates takes product of the scheduled physics time (minus MD, scheduled stops etc.) and the peak luminosity. It multiplies the result by the so-called Hübner factor to given an estimated integrate luminosity for said period.

The Hübner factor is an approximation that implicitly takes into account luminosity lifetime, turnaround, unplanned interventions etc. During the LEP era it was usually taken to be around 0.2

Here the luminosity lifetime and optimal fill length have been explicitly calculated. The equivalent Hübner factor is around 0.3. This higher value comes from long luminosity lifetime, longer fills, the assumed 4 hour turn around and 60% machine availability. To perform at all the LHC has to be good, here the assumption is made that it will be so.

ESTIMATE FOR 2010

A proposed staged increase in intensity to a single beam energy of 2 MJ has recently been approved [1]. The resultant luminosity and estimates for the integrated luminosity are shown in table 2. Here a simple Hübner factor of 0.25 has been assumed to give some indication of expected performance. The machine will still be in a commissioning phase and operations will be treading carefully as experience is gained with potential dangerous beams.

Table 4 covers the first five months or so with a final luminosity of 10^{31} $cm^{-2}s^{-1}$ being a useful and encouraging first phase deliverable. The potential of another factor of two in beam energy is shown in the final line of the table.

The potential steps towards a luminosity of around 10^{32} $cm^{-2}s^{-1}$ are shown in table 5 [2]. Given the above steps to 2 MJ and a conservative approach to intensity increase it is clear that the final steps shown in the table will probably not be realized in 2010 and represent target for well optimized, well tested machine that one should see in 2011.

ESTIMATE FOR 2011

Hopefully in 2011 the progress made in 2010 can be used for production running combined with a gentle probing of the foreseen intensity limits [3]. The integrated target for 2010/2011 is around 1 fb^{-1}. To deliver this, the LHC will have to be pushing 10^{32} $cm^{-2}s^{-1}$. Illustrative numbers are shown in table 6. The monthly integrated luminosity total should range between X and Y. As noted above this represent the final steps of table 5.

2012 - 2014

Constraints

The beam energy of the LHC will be limited to 3.5 TeV until after the splice consolidation in 2012. The consolidation should open the way to 6.5/7 TeV and here it is assumed that if will take around 2 years at 6.5 TeV before the necessary training of the dipoles to 7 TeV is completed [4].

There are beam intensity limits from collimation phase one [3]. Briefly these state that the maximum acceptable is 40% of nominal intensity maximum into a perfect machine. This number drops if imperfections are taken into account. To go beyond this limit the collimation system must include collimators in the dispersion suppressors (DS) down stream of IR3 and IR7 and the full phase two implementation [3]. The DS collimators would open the way to nominal intensity; the full scheme should allow nominal and ultimate intensities.

The DS collimators require a movement of magnets in the dispersion suppressors and this is viewed as distinctly non-trivial exercise. Planning has yet to be established.

Here we assume the 40% limit on total intensity holds until the circa 2015 shutdown. This still represents a formidable amount of beam and should not be considered a showstopper.

Performance

In exploiting 6.5 TeV there will be a learning curve. This will see a stepped increase in total intensity and a squeeze to a conservative 1 m. and finally to 0.55 m. Bearing in mind the collimator limitations highlighted above we assume 24% nominal intensity for 2013 and 27% for 2014. The resultant peak luminosities and integrated total per month and per year are shown in table 7.

2015 – 2016

Given the installation of collimation phase 2 and the DS collimators the way is opened for nominal, and ultimate, intensity from a collimator perspective.

Following a short run in 2015 and 4 years cumulative experience, and assuming there are no fundamental limits found during those 4 years one might optimistically hope to reach nominal performance in 2016. With the assumptions outlined above this should result in an integrated luminosity of around 50 fb^{-1} for a 7 month proton run.

The performance of the LHC might well not reach nominal quite as quickly. There is also the possibility that peak luminosity gets pinned at a lower level by intensity related effects. Less optimistic scenarios are shown in figure 1.

BEYOND 2016

Prediction of progress beyond 2016 is difficult. Experience must be gained of running the LHC at high energy to evaluate its potential. A number of possible scenarios might be considered.

- Achieving and holding steady luminosity production at nominal between 2016 and 2020.
- Pushing intensity towards ultimate in the face of a number of challenges [5]. This assumes that something like ultimate intensities are deliverable from the injectors. Illustrated below in figure 1 is a staged increase in intensity between 2017 and 2020 reaching ultimate luminosity in 2020 and annual integrated luminosity of around 100 pb^{-1}.
- A phase 1 like upgrade after 2-3 years peak production rate. This might make sense if nominal performance proves difficult to achieve.

Nominal performance

If the delivery of integrated luminosity is at a near constant yearly value, consideration of the statistical error halving time shows that a naïve 3 extra years at given rate is required to halve the statistical error. The message here is that a constant rate of luminosity production soon becomes uninteresting. However, it should be noted that by 2016, if things are going well, the peak luminosity will have just reached nominal and delivery rate of luminosity will not have flattened out. It is clear that another major shutdown would not be optimal at this stage.

Increased intensity

If one were to contemplate increasing intensity above nominal one would have to make the following assumptions:

- The PS is operation at increased injection energy, which together with LINAC4 would enable it to delivery around ultimate intensities to the SPS (This after a suitable commissioning period following the required upgrades).
- ~1.7 x 10^{11} can be swallowed by the SPS. Detailed requirements for this and planning to be established.
- The LHC can handle ultimate intensity. The issues here were nicely summarized in Chamonix 2010 [5]. "Ultimate intensity is challenging for the LHC. Many systems at technological limits with little or no margin."

If one assumes that the limitations can be lifted by 2017 one could imagine pushing beyond nominal intensity over a period of years arriving at full ultimate intensity in 2019/2020 if things go well. This scenario represents the most optimistic presented here.

CONCLUSIONS

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 2 years running at 6.5 TeV are envisaged with the total intensity limited by phase 1 collimation. Installation of phase 2 collimation in or around 2015 would allow nominal performance to be achieved in 2016 if things go well. Progress thereafter is dependent on what is learnt in the previous years and could include: running steady at a nominal production rate; pushing intensities towards ultimate; or a possible upgrade in or around 2018 if conditions dictate.

The estimated 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 2016. It will important to gain some operational experience.

REFERENCES

[1] J. Wenninger, Strategy for intensity increase 2010, Minutes LHC Machine Committee meeting No. 44, February 2010.

[2] M. Giovannozzi et al, LHC BEAM PARAMETERS FOR THE PHYSICS RUN AT 3.5 TEV, LHC-OP-ES-0020 rev 3, January 2010.

[3] R. Assmann, Intensity limits from phase-1 collimation, Minutes LHC Machine Committee meeting No. 6, March 2009.

[4] E. Todesco, Dipoles retraining for 7 TeV, these proceedings.

[5] R. Assmann, Implications of higher intensities in the LHC, these proceedings

Table 4: potential luminosity development during the first 6 months of LHC operation. The last row shows the potential of a further doubling in number of bunches.

	Bunch intensity	Number of bunches	Energy per beam [MJ]	Peak luminosity [$cm^{-2}s^{-1}$]	Days	Integrated luminosity per month [pb^{-1}]
4 bunches	5 e9	4	0.01	4.5 e27	14	0.001
4 bunches	2 e10	4	0.05	7.1 e28	14	0.002
4 bunches	5 e10	4	0.11	4.5 e29	14	0.13
8 bunches	5 e10	8	0.22	8.9 e29	14	0.27
4 x 4 bunches	5 e10	16	0.45	1.7 e30	14	0.55
8 x 4 bunches	5 e10	32	0.9	3.6 e30	30	2.3
43 x 43 bunches	5 e10	43	1.2	4.8 e30	14	1.5
8 trains of 6 bunches	8 e10	48	2.2	1.3 e31	14	4.0
					128	
50 ns trains	8 e10	96	4.3	2.7 e31	30	17.2

Table 5: potential stages of luminosity development during first year of LHC operation. Steps 9 to 11 are most likely to be realized in 2011.

Step	Phase	E [TeV]	N	Fill scheme	I/I^{nom} [%]	E_{beam} [MJ]	β* [m] IP1/2/5/8	L (IP1/5) [$cm^{-2}s^{-1}$]	Run time (indicative)
1	**Beam** commissioning, safe beam limit	0.45	$5x10^{10}$	2x2	0.03	0.0072	11/10/11/10	$2.6x10^{27}$	Days
2		3.5	$2x10^{10}$	2x2	0.01	0.02	11/10/11/10	$7x10^{27}$	
3	Beam commissioning, safe beam limit, squeeze		$2x10^{10}$	2x2*	0.01	0.02	2/10/2/2	$3.6x10^{28}$	
4	Bunch trains from SPS		$3x10^{10}$	43x43	0.4	0.7	2/10/2/2	$1.7x10^{30}$	Months
5	**Increase intensity**		$5x10^{10}$	43x43	0.7	1.2	2/10/2/2	$4.8x10^{30}$	
6			$5x10^{10}$	156x156	2.4	4.4	2/10/2/2	$1.7x10^{31}$	
7			$7x10^{10}$	156x156	3.3	6.1	2/10/2/2	$3.4x10^{31}$	Months
8	Bring on crossing angle , truncated 50 ns.		$7x10^{10}$	50ns - 144	3.1	5.7	2/3/2/3	$3.1x10^{31}$	
9	Increase intensity		$5x10^{10}$	50ns - 288	4.4	8.1	2/3/2/3	$3.3x10^{31}$	
10			$7x10^{10}$	50ns - 432	9.3	17	2/3/2/3	$9.4x10^{31}$	
11			$7x10^{10}$	796	17.1	31.2	2/3/2/3	$1.8x10^{32}$	

Table 6: Potential 2011 luminosity production scenarios. ß* of 2 m assumed.

	Number of bunches	Bunch intensity	Total intensity	Energy per beam [MJ]	Peak luminosity [$cm^{-2}s^{-1}$]	Integrated luminosity per month [pb^{-1}]
50 ns	432	7 e10	3 e13	17	9.2 e31	78
50 ns	796	7 e10	5.1 e13	31	1.7 e32	145

Table 7: 2010 to 2016 luminosity estimates – optimistic scenario

Year	Number of months	Energy [TeV]	ß* [m]	Number of bunches	Intensity per bunch	Total beam intensity	Total beam energy [MJ]	Peak luminosity [$cm^{-2}s^{-1}$]	Integrated luminosity per month [fb^{-1}]	Integrated per year [fb^{-1}]	Cumulative integrated luminosity [fb^{-1}]
2010	8	3.5	2	96	8 e10	7.7 e12	4.3	2.7 e31	0.02	-	~0.1
2011	9	3.5	2	796	7 e10	5.6 e13	31	1.7 e32	0.14	~1	~1
2013	6	6.5	1	720	1.1 e11	7.9 e13	82	1.3 e33	1	6	7
2014	7	6.5	0.55	796	1.1 e11	8.8 e13	91	2.9 e33	2	14	21
2015	4	7	0.55	1404	1.1 e11	1.6 e14	160	4.6 e33	3.3	13	34
2016	7	7	0.55	2808	1.15 e11	3.2 e14	362	1 e34	7.5	53	87

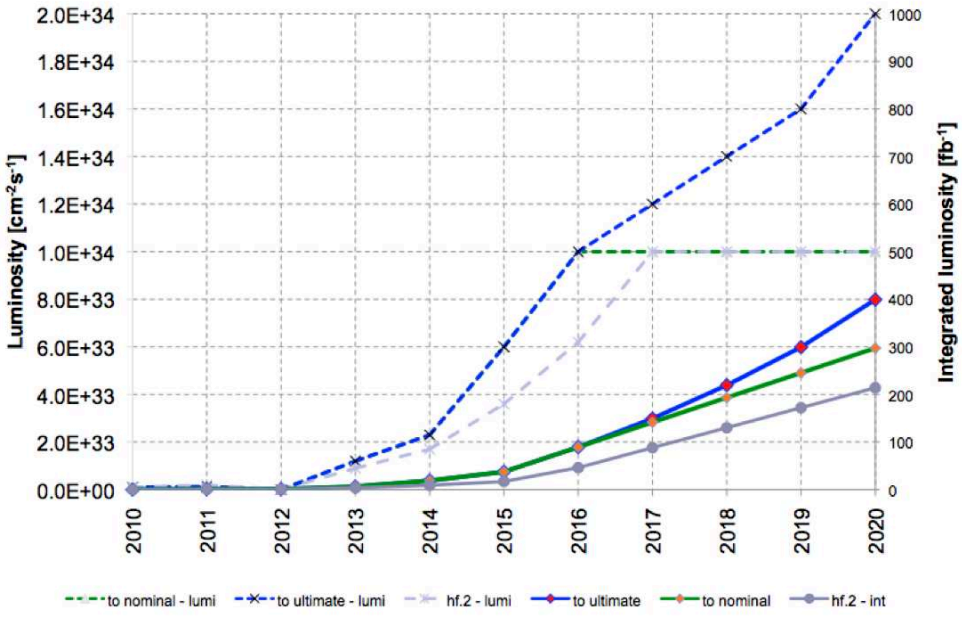

Figure 1: Luminosity estimates - summary plot. 3 scenarios shown: running at around nominal after 2016; pushing to ultimate after 2016; hitting nominal in 2107 with a Hübner factor of 0.2.