The LHC machine status, calibration run and commissioning plans

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Abstract

The status of the ongoing LHC installation is reported with some attention given to the long straight sections around the experiments. An overview of the proposed commissioning schedule for 2007 and 2008 presented. This schedule includes a calibration run at the end of 2007 which aims to deliver collisions at 450 GeV beam energy. The details of this run and planned beam conditions are summarised. The full commissioning to 7 TeV will be a challenging exercise and an overview of the plans for 2008 is given.

Finally, the beam related issues associated with the LHC upgrade are briefly introduced.

I. MACHINE STATUS

At the time of writing (September 2006) LHC installation is proceeding at a very committed pace around the whole ring. The situation is summarised in table 1 [1].

Table 1: Status of LHC installation – September 2006 (c/o Sylvain Weisz)

Sector	Phase
1-2	QRL installation has now passed 90%, with all internal welds done. Pressure tests October 28th.
Point 2	Water cooled cables installation in progress in UA23, done in UA27. Air treatment and cooling units installation close to completion in UA23/27. Installation of power converters just started in UA23, done in UA27.
2-3	Cryo-magnet installation in progress, from RZ33 to Point 2 (14 dipoles and 1 SSS in place).
LSS3	Installation of power converters in UJ33 slightly delayed. Installation of control cables and refurbishing of warm cables in progress in RZ33.
3-4	Cryo-magnet transport and alignment in progress: all 154 dipoles in place, 44 (out of 45 available) arc SSS in place. Interconnection in progress.
Point 4	RF installation in progress: 4 cavities (ACS) in place, damper (ADT) and pick-up (APWL) in place in LSS4R. RF wave guides in place, connection to cavities in progress. Klystron installation in progress (7 out of 16 in place in UX45). Interconnection D4-Q5/DFBML and Q6/DFBMG about to start in LSS4R.
4-5	All available cryo-magnets are in place. Interconnection in progress, above nominal rate
Point 5	RR53 & USC55: Short circuit tests finish next week. Low-β, DFBXF, D1 (6 MBXW) in place in LSS5R. UJ56-RR57: power converters, DYPE racks, energy extraction systems (DQR/DQS) in place.
5-6	Cryo-magnet transport in progress: 153 MB and 41 SSS in place. Dump 62 - installation of vacuum pipe in progress in TD62. All elements in place, about 50% welded
Point 6	UA63: ready to start short circuit tests UA67: power converters in place, cabling (AC, DC, Control & Water cooled) in progress, MKD generators and associated control racks installation in progress
6-7	Cryo-magnet installation: Dipoles during week-ends. 26 dipoles and 22 SSS in place (06/10/2006)
LSS7	Straight section: all services completed UJ73, UJ76 & UJ77: power converters and energy extraction systems in place TZ76 gallery: control cabling completed, modification of ventilation duct in progress
7-8	DFBAN (7R) installed 25/09, Q6.R7 installed 29/09, DFBMH installed 02/10. All cold elements in place. Interconnections in progress.
LSS8L	Cold parts: Interconnection DFBAO-HCM/LCM in progress. Interconnections done for low-β/DFBX, Q4-D2/DFBMA, Q5/DFBMC. Warm parts: All components in place (except large beam pipe between D1-D2)
LSS8R	Cold part: DFBMB, DFBMI & DFBMJ in place, interconnection in progress (Low-β, D2-Q4, Q5, Q6). Warm part: MKI & MSI installed, power cabling of MKI in place
8-1	All cryo-magnets in place, interconnections in progress. DFBAA-HCM ready and transported.
LSS1L	Interconnection of low-β/DFBX, D2-Q4/QRL in progress.

As can be seen from table 1, the installation of the cryogenic distribution line has almost finished, with the last sector (1-2) due for completion in October 2006. Magnet installation is progressing well with over 1000 out of the total 1728 superconducting magnets having been installed on 5th September 2006. Installation of the last magnets is foreseen for March 2006.

One class of critical components are the feed boxes which couple the room temperature cables into the cold mass. There are four types: DFBAs for the arcs; DFBMs for the stand alone quadrupoles; DFBXs for the inner triplets and the DFBLs for the superconducting links. Planned delivery and installation over the coming months put some of these items on the critical path; in particular the DFBAs which have to be in place before a sector cool-down can proceed.

The critical job of interconnecting the dipoles and short straight sections is ongoing. Around 1700 interconnects have to be made with four teams working in parallel around the ring. This is huge, painstaking, industrialised job which involves: vacuum plus leak checks, bellows, RF contacts, cryogenics, thermal shield, heat exchanger, as well as around

10,000 bus bar superconducting splices using induction welding and around 50,000 corrector circuit splices using ultrasonic welding.

The latest schedule for 2007 is available [2] and it clearly represents a huge challenge with the express goal of finishing the job of interconnections, the cool-down and at least partial hardware commissioning of all sectors.

II. 450 GeV Commissioning

The 2007 schedule also foresees a calibration run at the end of the year. It is envisaged that 4 sectors of the LHC will be hardware commissioned to a reduced level allowing powering of the main circuits to a 1.1 TeV equivalent level. As a prelude to the six weeks beam time, the schedule for the end of the year includes ring wide access tests and a ring wide machine checkout phase.

The beam time will be made up of 3 weeks beam commissioning with single beam, at low intensity for the most part, followed by 3 weeks collisions. Initial collisions will be with a single bunch on a single bunch followed by a staged increase to 156 bunches of 4 x 10^{10} protons per bunch or possibly higher. Luminosities should range from 1.3 10^{28} to 2.6 10^{29} $cm^{-2}s^{-1}$. The potential performance of this phase is summarised in table 2.

Table 2: Potential performance at 450 GeV

Number of bunches	43	43	156	156
Bunch current [10^{10}]	2	4	4	10
Intensity per beam	8.6 10^{11}	1.7 10^{12}	6.2 10^{12}	1.6 10^{13}
Beam energy [MJ]	0.06	0.12	0.45	1.1
Beta* [m]	11	11	11	11
Luminosity [$cm^{-2}s^{-1}$]	10^{28}	7.2 10^{28}	2.6 10^{29}	1.6 10^{30}
Event rate [kHz]	0.4	2.8	10.3	6.4

The collisions phase will be interleafed with low intensity single beam machine development; in particular we would hope to perform initial ramping tests to 1.1 TeV.

The commissioning run at 450 GeV is potentially very useful operationally. It allows critical checks of the whole machine with beam – principally aperture and polarities – with increased lead time for problem resolution following the run. Although reduced hardware commissioning is planned, it's clear that the machine has to be in safe state for 450 GeV operations. It will be necessary to cycle the main circuits to around 20% of nominal; quenches, with or without beam, are still possible and the Quench Protection System shall be operational, Power Interlock Controllers etc. must be qualified to the necessary level.

A. 450 GeV Machine configuration

1) Optics:

The plan is to use a partially squeezed optics with:

- β*= 11 m in IR 1 & 5
- β*= 10 m in IR 2 & 8

The squeeze is essentially limited by triplet aperture [3]. To keep things simple and to gain experience with a machine setup close to the nominal, no further squeezing is planned.

2) Crossing angles & Separation bumps

The crossing angle bumps will be off allowing 1, 12, 43, 156 bunches per beam. 156 represents the maximum number of bunches that can be injected without parasitic encounters in the interaction regions. The separation bumps will be brought on for two beam operation.

3) LHCb

The displaced IP at LHCb will necessitate the shifting of a certain number of bunches to provide collisions at point 8. It is foreseen to shift 4 out of 43 bunches, or 24 bunches out of 156. In these configurations the other experiments will experience parasitic collisions 75/2 ns away from their nominal collision point.

4) Solenoids & Exp. Dipoles etc.

It is envisioned that the experiments' solenoids and the dipole magnets in LHCb and Alice will be off to start with. Bringing then on will be scheduled in the single beam phase before collisions are established.

B. Phases

The main phases of 450 GeV beam commissioning are shown in table 3.

Table 3: Outline of 450 GeV commissioning phases

	Phase	Main Objectives
1	First turn	Commission end TI2, TI8, injection region, BPMs, BLMs, thread first turn, polarity checks.
2	Circulating beam	Closed orbit, chromaticity, energy matching, tune, RF capture.
3	Initial commissioning	RF, control & correction, transverse diagnostics, linear optics checks, beam dump, machine protection.
4a	Measurements	Beta beating, aperture, field quality checks, transfer functions, BLMs.
4b	System commissioning	RF, transverse feedback, BLMs to machine protection, tune PLL, collimators and absorbers.
5a	Two beam operations	Parallel injection, separation bumps, instrumentation and control.
5b	Establish collisions	Establish collisions, luminosity monitors, collimation, solenoids.
5c	Increase intensity	Collimators, longitudinal feedback, multi-batch injection.

For beam commissioning the basic probe beam will the pilot: a single bunch of 5 - 10 x 10^9 protons with possibly reduced emittance. For more precise measurements, the intensity is increased to a super pilot: a single bunch of around 3 to 4 x 10^{10} protons.

Given appropriate system commissioning and control of the key beam parameters the number of bunches will be increased gradually to 4, 12 bunches etc. pushing towards 43, 156 bunches of 3 to 4 x 10^{10} protons per bunch.

156 x 4 x 10^{10} represents 2% of the nominal beam intensity. This can clearly quench and/or damage a magnet at 450 GeV and it is imperative that the machine protection system be commissioned appropriately.

The estimated beam time required for commissioning two beam operation at 450 GeV is shown in table 4.

Table 4: Estimated time required for commissioning two beam operation at 450 GeV

	Phase	Time [days]	Beam
1	First turn	4	1 x pilot
2	circulating beam	3	1 x pilot
3	Initial commissioning	3	1 x pilot++
4a	Measurements	1-2	1 x pilot++
4b	System commissioning	2-3	1 x pilot++
5a	Two beam operations	1	2 x pilot++
5b	Collisions	1-2	2 x 1 x 10^{11}
		16 days	

Given an operational efficiency of 60%, the estimated time to establish first collisions gives an elapsed time of about 26 days with the obvious caveat that machine availability might well be lower during this period. There are some opportunities for parallel development and parasitic studies and one might hope gain some time here. Full details are available at [5].

C. Machine Issues

1) Luminosity measurement

The low luminosity will be straining the bounds of machine luminosity monitors installed at points 1 & 5 (ionization chambers produced by LBL, these are known as the BRAN). There will be low rates of high energy neutrons in the BRAN, with potentially high background, and a low signal/noise ratio. Initial collisions with single bunch 1.0 x 10^{11} are planned to give the BRAN something to bite on. Complementary signals from the experiments would clearly be advantageous.

Other ideas being pursued machine side to get a handle on the luminosity at this stage include the use of the beam-beam coupling signal from high sensitivity BPMs, the use of Schottky monitors and the possibility of installing dedicated scintillators.

2) Background

Background in the experiments' insertions will come from beam gas interactions and beam halo. There are four main contributing factors:

- residual gas within the experiments. The experiments themselves should be baked out and this contribution should be low;
- residual gas in the long straight sections (LSS);
- elastic scattering from gas in the adjacent cold sectors (the gas pressures here could be relatively high at start-up);
- the cleaning inefficiency of the collimator systems in IR7 & IR3.

The 450 GeV run will represent stage 0 for the vacuum system. There will have been no beam conditioning, minimal pump-down time in some sectors. The conditions will be given by the static vacuum. Potentially some LSSs could be un-baked and consequently no NEG activation. The experiments' LSS are, however, the priority and should be baked. The vacuum life time shall be greater than 35 hours and 50 hours for 2007 and 2008 respectively compared with the 100 hours nominal. For a detailed analysis, see [5].

3) Halo

Beam halo generation in the LHC will arise from: RF noise; intra beam scattering (IBS); optics mismatch; beam-gas etc. In addition, poor parameter control (tune, chromaticity) will lead to poor lifetime and stream particles to aperture limit. Nominally the halo is cleaned by the collimation system with the resulting tertiary halo potentially finding its way to the experiments insertion and the tertiary collimators installed there.

However, firstly, at 450 GeV the aperture limit is very much the arcs and the dispersion suppressors, and secondly a minimal collimator scheme is foreseen at this stage of commissioning. With low beam intensity only primaries and the TCDQ (downstream dump absorbers) will be used. At higher intensity the primary and secondary collimators will be closed to protect the arcs, however, the tertiary collimators and absorbers are not planned to be used. Un-squeezed with the tertiary collimators out and the aperture limit in the arcs one will expect low halo losses in interaction regions.

III. COMMISSIONING 2008

A staged approach is clearly going to be useful to tackling the complexity of the LHC. It is envisaged to stage the commissioning of the machine with beam as follows:

- a possible sector test [6,7] which would provide an invaluable milestone;
- 450 GeV commissioning run [4];
- Stage 1 - physics 43 x 43 with moderate intensities;
- Stage 2 - move to 75 ns with the aim of moving to intensities around 3 - 4 10^{10} protons per bunch;
- Stage 3 - move to 25 ns with the aim of moving to intensities around 3 - 4 10^{10} protons per bunch. This will need to be followed by long shutdown for installation of phase 2 collimation and additional beam dump dilutors;

- nominal 25 ns running pushing towards design intensity and full squeeze.

This staged approach will allow phased commissioning of the key sub-systems with increasing intensity. Thus initial commissioning can be performed without having to face the dangers of high beam intensity and the full rigours of the final machine protection system.

The phases of full commissioning are shown in table 5. The shaded phases are those that will possibly be addressed during the calibration run. It can be seen that the run should enable considerable progress to be made on the full commissioning plan. Although there will obviously be hand-over costs in breaking the commissioning into two stages, these costs are probably equaled by the benefits that an extended period of consolidation after the calibration run would provide.

Table 5: 7 TeV Beam commissioning phases

Phase	Main goals
Transfer and Injection	Pilot on axis through to TDI
First turn	Pilot threaded – single turn
Circulating beam	Multiple turns, RF capture.
450 GeV: initial commissioning	Q, Q', coupling. Polarities and apertures checked; basic optics checks.
450 GeV: consolidation	Well adjusted beam parameters, key instrumentation operational, machine protection as required for ramp.
450 GeV: two beam operation	Two beams, well adjusted beam parameters.
Snapback: single beam	Single beam, good transmission through snapback, requisite measurements.
Ramp: single beam	Single beam to top energy, beam dump commissioned in ramp, PC tracking checked
Single beam to physics energy	Stable beam at top energy, measurements, beam parameter adjustment.
Two beams to physics energy	Separation bumps on. Commission ramp with two beams
Physics: un-squeezed	establish collisions
Partial squeeze: single beam	single beam in steps through squeeze, parameter control
Physics: partial squeeze	Two beam through squeeze - collide

Briefly, 2008 will see the completion of the hardware commissioning to the 7 TeV level. This will be followed by a one month machine checkout and test phase, leading to the beam commissioning outlined in table 5. Given the experience gained during the calibration run, this is estimated that it will take around 2 months elapsed time to establish collisions at 7 TeV. Thus an optimistic schedule would see collisions at or near full energy around mid-2008.

IV. LHC UPGRADE - BASICS

The motivation for an LHC upgrade is essentially statistics driven: if the LHC achieves design luminosity within, say, four years, the statistical halving time will exceed 5 years within a further four years, some what more if the push to ultimate intensity and luminosity can be achieved. Thus given the present schedule and these assumptions it is reasonable to plan a phase 1 upgrade before around 2014 [8].

The upgrade options are many and varied, and only a brief attempt is made here to introduce the issues by way of motivation for discussions on this subject later in the workshop.

A. Basics Issues

Some of the main issues that must be addressed when considering an upgrade are:

- head-on beam-beam tune shift;
- long-range beam-beam in the interaction regions;
- the effect of the crossing angle: firstly via the geometrical luminosity reduction factor (F), the larger the crossing angle the larger the reduction in luminosity; and secondly the larger the crossing angle, the larger the required aperture in the insertion quadrupoles;
- β^* and beam size at IP: the smaller the β^*, the larger the beam size in the triplets and larger the required aperture;
- radiation deposition in the insertion region.

B. Options

There are many ways of playing on these various factors.

- More and shorter bunches. This could be achieved by either increasing the bunch intensity or by increasing the number of bunches by reducing bunch spacing with major implications on the RF systems of the injectors depending on the spacing chosen. The positives are a large luminosity gain with minimal event pile up.
- Increase bunch intensity via injector upgrade such as a 1 TeV superconducting SPS.
- Fewer and longer bunches give a large luminosity gain with no e-cloud, lower total beam current, easier collimation & machine protection
- The idea of super bunches has been abandoned because the event pile up becomes intolerable.
- Increase F by reducing the crossing angle and fighting long range with beam-beam compensation schemes.
- Decrease the effect of the crossing angle by using crab cavities.
- Redesign the insertions and reduce beta*, this implies new stronger quadrupoles with larger apertures. Variations include: placing a dipole first near IP to allow small crossing angle; dipole first and large crossing angle and long bunches or crab cavities. Dipoles first plus quad triplets or quad doublets. Dipoles inside the detector. Quadrupoles first, pushed in closer to IP.

Space precludes detailing these options. For more details see any of the many summary talks on the subject at, for example, [8,9,10].

C. Summary

Several LHC IR upgrade options are currently being explored. The baseline scenario includes variations on: a reduction of β* to 0.25 m, an increased crossing angle and a new bunch-shortening RF system. The corresponding peak luminosity with ultimate beam intensity is 4.6 x 10^{34} $cm^{-2}s^{-1}$ at the two interaction points. Electron cloud effects and/or cryogenic heat loads may exclude the possibility to double the number of bunches.

There is considerable amount of research and development ongoing. This research includes magnets, crab cavities, long range beam-beam compensation. A major conference devoted to the LHC upgrade was held Valencia in October 2006 under the auspices of CARE – HHH [10].

V. References

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