EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 922

LHC PROGRESS AND COMMISSIONING PLANS

O. Brüning (for the LHC commissioning team)
CERN, Geneva, Switzerland

Abstract

The LHC at CERN is in its final installation phase and hardware commissioning has started in 2006. The commissioning of the machine with beam is planned for summer 2007. The paper summarizes the current status of the LHC installation, outlines the expected performance limitations for the commissioning and summarizes the main milestones and phases for the commissioning and their potential performance levels.

Presented at
EPAC'06, Edinburgh, UK,
June 26-30, 2006

CERN,
CH-1211 Geneva 23,
Switzerland
Geneva, June 2006

LHC PROGRESS AND COMMISSIONING PLANS

Oliver Brüning (for the LHC commissioning team), CERN, Geneva, Switzerland

Abstract

The LHC at CERN is in its final installation phase and hardware commissioning has started in 2006. The commissioning of the machine with beam is planned for summer 2007. The paper summarizes the current status of the LHC installation, outlines the expected performance limitations for the commissioning and summarizes the main milestones and phases for the commissioning and their potential performance levels.

LHC INSTALLATION STATUS

The LHC is entering its final installation phase and the activity at CERN is slowly shifting from installation work to the actual hardware commissioning. Almost all LHC cryo dipoles have been delivered to CERN by now and will have passed the cold test by the end of 2006. The magnets are currently delivered to CERN at a rate of 30 magnets per month and the last delivery is expected for October 2007 (including the spare magnets). Approximately 3/4 of the Main Bending (MB) magnets have been prepared for installation and assigned to a position in the LHC tunnel. This number corresponds to approximately 6 sectors of the LHC (status as of June 2006). Almost half of all LHC main dipole magnets have been installed in the tunnel and the installation of the dipole magnets is projected to progress at a rate of 20 magnets per week until the end of installation (33 weeks required for finalizing the installation of the main dipole magnets) and the rate of magnet interconnections is expected to increase from 24 to 32 per week.

Also almost all arc quadrupole assemblies have been delivered to CERN and 1/3 of the required arc quadrupole assemblies has been installed in the tunnel by now. Approximately 2/3 of all arc assemblies have already been assigned to a position in the LHC tunnel and the installation of the quadrupole magnets is projected to progress at a rate of 5 assemblies per week (minimum of 45 weeks required for finalizing the installation of the arc quadrupole assemblies).

MAIN CHALLENGES AND PERFORMANCE LIMITATIONS

The main worries and challenges for the LHC commissioning are:

- Mechanical aperture limitations.
- Polarity errors in the magnet circuits.
- Global magnetic field quality in the final machine during operation.
- Collimation efficiency during operation.
- Correction circuit powering and feedback loops.
- Beam power and machine protection.
- Collective effects and impedance limitations.
- Triplet aperture and beam-beam interaction.
- Electron cloud issues.

In the following we will discuss the main issues and foreseen actions during the installation and commissioning phases of the LHC separately for each item.

Mechanical Aperture Limitations

The mechanical acceptance of the machine limits the maximum acceptable beam emittance during injection and therefore the maximum obtainable luminosity (beam brightness) for an operation at the beam-beam limit. Furthermore, a small mechanical aperture implies small gap openings for the LHC collimation system which in turn implies small tolerances for the closed orbit and beta-beat during operation. A maximum mechanical aperture of the LHC is therefore a key prerequisite for maximising the performance reach of the LHC.

All LHC dipole assemblies are geometrically measured at CERN prior to the fiducialisation and installation in the tunnel. The LHC dipole magnets are approximately 15 m long, slightly bent objects (9mm sagitta) with 2 separate apertures for the 2 LHC beams. The geometry measurements at CERN generate a 3 dimensional map of the magnet apertures. Based on the measured aperture deviations from the ideal reference geometry, all LHC dipole magnets are grouped into three main classes [1]:

- 'Golden' magnets fulfilling tight geometry tolerances over the whole length of the magnet: central bore axis within ±0.8mm of the horizontal and ±0.5mm of the vertical reference axis.
- 'Silver' magnets satisfying slightly relaxed tolerances: central bore axis within a race track envelope with half circle radius of 0.65 mm and a straight part of 1.4 mm.
- 'Mid-cell' magnets satisfying relaxed mechanical tolerances: central bore axis within a race track envelope with half circle radius of 3 mm and a straight part of 1.4 mm.

The first 2 classes are further separated into 4 sub-classes:

- 'Silver Left' and 'Silver Right' magnets satisfying the tolerances of a 'Silver' magnet only on one side of the magnet and having relaxed tolerances for the radius of the racetrack envelope (2mm) on the other side.
- 'Golden Left' and 'Golden Right' magnets satisfying the tight tolerances of a 'Golden' magnet only on one side of the magnet and having relaxed vertical tolerances (±1.5 mm) on the other side.

The aperture requirements in the machine depend on the optical functions and therefore on the final location where the magnet is installed. The above classification allows a fast slot assignment of the measured and tested magnets while conserving a maximum mechanical acceptance for the installed machine (‘golden’ type magnets for locations with large optic functions).

Furthermore, all cold mass assemblies are inspected for potential obstacles and aperture limitations after the final measurements on ground and the final installation in the tunnel using a microwave vector network analyzer (5-9 GHz) with synthetic pulse option analyzing the reflected signals for two different waveguide modes [2]. This procedure ensures that no additional aperture limitations are introduced during the beam screen installation and the welding process in the tunnel.

Polarity Errors in the Magnet Circuits

Once the machine installation is finished, polarity errors in the magnet circuits can only be detected via beam based measurements. Such a measurement procedure, however, is only feasible if the perturbation due to the polarity error is small enough for having sufficiently long beam lifetimes in the machine. Polarity errors in the main circuits will prohibit a circulating beam in the machine and can therefore not be distinguished from beam losses due to aperture obstacles in the machine.

The polarity of all electrical circuits in the LHC is verified first for each cryo module after its assembly on the surface. The circuit polarity is verified again in the tunnel during the magnet interconnection. The measurements are done with automatic procedures that guarantee the conformity to the quality assurance standards [3].

Global Magnet Field Quality in the Machine

The global field quality in the machine determines the dynamic aperture and the maximum obtainable beam lifetime at injection energy. A high integrated luminosity requires large beam lifetimes and an efficient machine operation with small beam losses. A good field quality is therefore the prerequisite for obtaining a maximum machine performance in terms of integrated luminosity.

The magnet field quality of the LHC machine is optimized by three different strategies:

- A careful monitoring and steering of the field quality during the magnet production.
- A detailed measurement program that provides input for the powering of the correction circuits.
- A sorting strategy for the magnet installation in the tunnel.

All magnets are measured at room temperature at industry. These measurements are performed at low excitation currents and provide information on the geometric field error components. The measurement data is used for a continuous monitoring of the field quality during the production and the implementation of corrective measures in case the field quality exceeds the specified production tolerances [5] [6]. For example, the LHC main dipole magnets featured 2 cross section modifications during the early phase of the production to keep the field error components inside the production tolerances, while the main quadrupoles cross-section was changed once during production to steer the b6 component.

All main magnets are cold tested at CERN (quench behaviour and electrical integrity) but only a sub series of the magnets undergoes a field quality measurement at cryogenic temperatures [6]. These measurements are used for establishing a correlation between the measured field quality at room and cryogenic temperatures and for calibrating the magnet transfer functions. A smaller subset of magnets undergoes an additional extended measurement programme that is fully targeted to the preparation of the LHC operation. These measurements investigate the effect of the operation cycle on the dynamic effects of the magnet field errors (decay and snap back) and look at the influence of the operation cycle on the magnet reproducibility and the hysteresis function.

The LHC main dipole magnets feature systematic differences in their field quality between the three different production companies and the three different magnet cross sections that evolved during the production period. Based on the warm magnet measurements (which exist for all magnets) and the warm-cold measurement correlation the magnets are grouped in pairs of opposite deviations from the average field error component (flip-flop pairing) or equal deviations and a phase advance of 180^0 between the two magnets (π-pairing). This sorting strategy is the prerequisite for installing magnets with different cross sections in one sector and aims at a minimization of the sextupole driving terms, the beta-beat and coupling due to normal and skew quadrupole field error components [1].

All measured field quality data is used as an input for a Field Description for the LHC (FiDeL) [8] during operation which will be implemented into the LHC control system and used for automatic adjustments of the LHC correction circuits powering during the different operation stages.

Collimation Efficiency

For the operation with nominal beam parameters the LHC magnet quench levels correspond to a very small fraction of beam losses. Table 1 lists the different acceptable losses for instantaneous and transient losses at injection and top energy. The maximum acceptable continuous relative beam loss corresponds to less than 2.2 10^{-6} and 2.5 10^{-8} of the total nominal beam intensity at injection and top energy respectively. This is quite small when compared to expected losses during operation and the experience from existing superconducting proton storage rings (up to 20% to 30% beam losses during the ramp in HERA and TEVATRON). For example, looking at continuous losses and assuming further that all losses occur at one location (smallest mechanical aperture and/or largest orbit excursion and beta-beat) beam lifetimes of 128 h and 1100 h at injection and top energy respectively already exceed the magnet quench level in the LHC. In order to allow a machine operation with lifetimes smaller than the above values one needs to ensure that all particles are removed from the beam halo before they can reach the aperture of the cold magnets. An efficient collimation scheme is therefore essential during all phases of the LHC operation. The LHC employs a 2 stage collimation system plus additional dedicated absorbers and collimators at special locations in the ring with a target local cleaning inefficiency (number of protons at 10 σ at a given location in the ring / number of protons impacting on the primary collimators) of 2 $10^{-5}m^{-1}$. The design value for the global cleaning inefficiency (total number of protons above 10 σ / number of protons impacting on the primary collimators) is 10^{-3} which allows beam lifetimes down to 0.1 h at injection and 0.2 h at top energy (local cleaning inefficiency). The heat deposition for these small beam lifetimes inside the collimation amounts to 200kW and 500kW respectively.

Table 1: MB quench level expressed in beam losses [9]. The nominal LHC beam parameters feature 2808 bunches with 1.15 10^{11} protons per bunch

	Continuous	Transient	length
Units	[Protons/m/s]	[Protons/m]	[s]
Injection	7×10^8	2.5×10^{10}	5×10^{-2}
Collision	8×10^6	4×10^7	8×10^{-3}

The cleaning inefficiency depends on the collimator jaw openings and on the orbit and optics errors in the machine. The collimator positions are optimized for a given optics configuration (phase advance between neighbouring jaws and relative beam sizes). Optic and orbit errors either imply an increase in the cleaning inefficiency or require an online correction of the orbit, transient coupling and beta-beat during machine operation. For example, for vertical orbit errors above 1 mm and a transient β-beat above 20% the cleaning inefficiency increases by more than one order of magnitude [10].

One clearly recognizes the deterioration of the cleaning inefficiency for orbit errors above 0.5 mm RMS and transient beta-beat perturbations above 20%. A static beta-beat has a much smaller impact on the cleaning inefficiency provided the collimator jaw openings are empirically adjusted to the actual beam sizes in the cleaning insertion. While a transient beta-beat of 30% can increase the cleaning inefficiency to above 0.1 (a value associated with a single stage cleaning system) a static beat-beat of the same order of magnitude increases the cleaning inefficiency only by approximately 50% (provided the jaw opening is empirically adjusted to the actual beam sizes) [10]. A correction of the closed orbit and transient beta-beat perturbations are therefore required during all phases of the machine operation. Similar arguments apply to coupling errors and the required correction of the local tilt of the beam ellipsoid. This applies in particular to the early phase of beam acceleration (snap back of the persistent current field errors) and the squeeze of the injection to the collision configuration optics (sensitivity to transfer function errors due to large beta function values) where large optics and orbit perturbations are expected. However, there is no simple diagnostic tool for measuring the cleaning inefficiency of the LHC and the correction of the various error sources can not rely on the measurement of a single steering parameter. Rather, a reliable performance of the collimation system relies on a tight control of all critical beam parameters.

Correction Circuits and Feedback Loops

The field errors of a super conducting magnet system are not constant in time but vary during the machine operation (field error decay and snap back) and from fill to fill (persistent current dependence on the magnet powering history) [11]. For example, the change of the machine chromaticity related to the dynamic effects of the magnet field errors in the LHC is estimated to be of the order of 50 units which clearly exceed the operational tolerance of ±2 units. The operation of the LHC machine therefore requires dedicated correction circuits that can be adjusted during the machine operation.

The LHC features individually powered correction dipole magnets for the closed orbit correction next to each quadrupole module (total of ca 550 corrector magnets per beam) and a total of 112 additional correction circuits per beam:

- Trim quadrupole magnets for individual tune adjustments in the 2 LHC rings.
- Skew quadrupole circuits for a correction/ adjustment of the machine coupling.
- Skew sextupole circuits for a correction of field errors.
- Normal sextupole, octupole and decapole spool piece circuits (attached to the dipole magnets) for a correction of the main dipole field errors.
- Normal sextupole corrector magnets for the adjustment of the machine chromaticity.
- Octupole spool piece circuits for the correction of dipole field errors.
- Octupole correction circuits for the adjustment of transverse Landau damping by detuning.
- Decapole spool piece circuits for a correction of the dipole field errors
- Dedicated skew and normal quadrupole, sextupole and octupole and normal dodecapole correction circuits in the triplet quadrupole assemblies.

Only the closed obit corrector magnets can be empirically adjusted using non-destructive beam measurements via Beam Position Monitors (BPMs). The LHC incorporates a dedicated closed orbit feedback system that is planned to be operational from the beginning of the machine commissioning. The adjustments of the remaining correction circuits either rely on destructive beam measurements during dedicated measurement runs and the machine reproducibility from fill to fill, or on a precise and reliable functioning of the FIDEL, or on novel measurement techniques that minimize the impact on the beam quality and allow an online correction during the nominal machine operation. The LHC operation will use all three strategies during the various phases of the machine commissioning. The FIDEL system will be incorporated into the LHC control system from the beginning and drive an automatic powering of the correction circuits (feed forward). Dedicated measurement runs will be used for verifying and refining the FIDEL during the machine commissioning. Sensitive tune measurement techniques based on Phase Locked Loop (PLL) technology will be used for online measurements and potential corrections of the tune, coupling and chromaticity during luminosity operation [12]. However, the commissioning of these special feedback loops requires development time with beam and will probably not be operational during the early commissioning phase of the LHC.

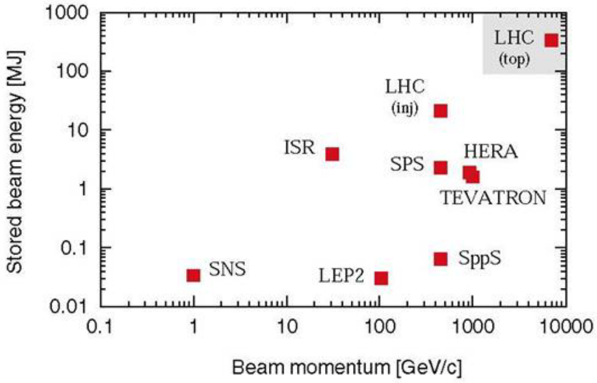

Figure 1: Total beam power versus beam energy in various past, existing and planned synchrotrons [13].

Beam Power and Machine Protection

The stored beam energy in the LHC with nominal beam parameters exceeds 350 MJ per beam and thus exceeds the beam energies in existing and past storage rings by more than 2 orders of magnitude as illustrated in Fig. 1. One MJ can melt 2 kg of Cu and the stored beam energy in the LHC therefore represents an enormous damage potential and requires a sophisticated machine protection system. The LHC features a multilevel machine protection system:

- Voltage taps at the superconducting magnets monitor the conductivity and trigger a beam abort in case a magnet looses its superconducting state during operation (magnet quench).
- Distributed Beam Loss Monitors (BLMs) monitor the beam loss pattern around the machine and initiate a beam abort in case the local losses exceed the estimated threshold values that guarantee an operation with losses below the magnet quench limits.
- Robust collimator jaw (Graphite) and absorber designs that protect the machine during an asynchronous beam abort at top energy with nominal beam parameters.
- A Beam Interlock Controller (BIC) collects the information of all key system components and initiates a beam abort in case of system failures.

The LHC features a 2 phase collimation system: Phase 1 features graphite collimator jaws that can protect the machine in case of failure modes and Phase 2 will allow a jaw closure compatible with nominal beam intensities and β^* values either via the deployment of low impedance jaws, a non-linear collimation method or a low noise feedback system. However, a genuinely safe machine operation in the LHC is only possible with strongly reduced beam intensities (1/60 and $2\ 10^{-5}$ of nominal intensities at injection and top energy respectively). At higher beam intensities the machine operation requires a precise control of all beam parameters and an accurate adjustment of all collimator jaws. In order to assure a proper setting of all machine parameters prior to the injection of a new fill, each new fill into the LHC starts first with the injection of a pilot bunch (approximately one 1/20 of a nominal bunch). Once beam based measurements with the pilot bunch have confirmed the proper functioning and adjustment of all systems (closed orbit, tune, chromaticity and collimator jaw position) the injection with nominal beam intensities can start. In this process the injection kicker system simultaneously ejects the circulating pilot beam onto a dedicated absorber and deflects the injected beam onto closed orbit of the LHC.

Collective Effects and Impedance Issues

The Phase 1 graphite collimator jaws provide robustness against machine failure modes during the commissioning period. However, their impedance exceeds the maximum acceptable values for beam stability once the jaw openings are closed to their nominal opening for the $\beta^* = 0.55$m collision optics. Operation with the Phase 1 graphite collimator jaws therefore either requires larger than nominal β^* values (-> larger than nominal collimator jaw openings) or smaller than nominal beam intensities (less than 50% of nominal beam intensities for $\beta^* = 0.55$m). The operation with nominal beam intensities and $\beta^* = 0.55$m requires the installation of an additional Phase 2 collimation system with low impedance or special operation arrangements that suppress the most dominant collective instabilities [14][15].

Triplet Aperture and Beam-Beam Interactions

The nominal operation with 2808 bunches per beam features 31 potential collision points per experimental Interaction Region (IR). In order to avoid all but one beam collision at the central Interaction Point (IP) the LHC requires for the nominal operation a crossing angle bump over the IR. Beam stability requires on average a beam separation of 9.5 σ at the unwanted collision points [16]. For $\beta^* = 0.55$ m this requires a total crossing angle of 285 μrad which brings the beams inside the triplet quadrupole magnets close to the cold bore aperture and requires a good correction of the triplet field errors and small gap openings for the collimator jaws which requires in turn a tight orbit control inside the triplet magnets and the collimation sections (better than 200 μm). The requirements on the triplet field error correction and the orbit control can only be relaxed for β* larger than 1 m, a larger bunch spacing (less long range beam-beam interactions), or reduced bunch intensities (weaker long range beam-beam interactions).

Electron Cloud Effects

The impact of secondary electrons due to the electron cloud effect [17] results in a heat deposition on the beam screen and a potential emittance growth [18]. In case the Secondary Emission Yield (SEY) of the beam screen exceeds δ_{sec} = 1.3 the resulting heat load exceeds the cooling capacities of the beam screen and limits the beam intensities to less than nominal values. In order to reach SEY of less than δ_{sec} = 1.3 the beam screen surfaces need to be carefully conditioned during the machine commissioning by slowly increasing the beam intensities towards the threshold limits of the electron cloud effect.

MAIN LHC COMMISSIONING PHASES

The various challenges for the LHC operation are tackled by deploying a staged commissioning approach [19]. This aims at addressing each operation challenge separately while the machine performance is pushed past key milestones for the experiments and machine equipment. The first stage incorporates the following major milestones:

1. Operation with low beam intensities to minimize the risk of damage, magnet quenches and electron cloud effects, a sufficiently small number of bunches that does not require crossing angle bumps at the IR's and an unsqueezed insertion optics. The key parameters are: 43 on 43 bunches, 10^{10} protons per bunch (ppb), β* = 18m (the nominal injection optics value). This operation mode features a maximum luminosity of L = 4.2 10^{28} cm^{-2} sec^{-1} with less than 1 event per bunch crossing and a total beam energy of 0.5 MJ.
2. Building on these milestones the optic functions at the IPs are squeezed to β* = 2m (requires tighter settings for the collimator jaws) and the number of protons per bunch is increased to 4 10^{10}ppb. This operation mode features a maximum luminosity of L = 6.1 10^{30} cm^{-2} sec^{-1}.
3. The number of bunches per beam is increased to 156 still requiring no crossing angle but increasing the beam energy to 7 MJ.
4. Increasing the intensity further to 9 10^{10} ppb the luminosity increases during the final phase of the first commissioning stage to L = 2.1 10^{32} cm^{-2} sec^{-1} with almost 4 events per bunch crossing and a total beam energy of 16 MJ.

The second commissioning stage introduces operation with crossing angle bumps in the IR's and features the following main milestones:

1. Operation with crossing angles is introduced for an operation with 936 bunches per beam (10 long range beam-beam interactions per IR) and starts again with the injection optics value for β* (18m) and bunch intensities of 4 10^{10} protons per bunch. The stored beam energy now increases to 42 MJ per beam while the maximum luminosity remains at L = 2.5 10^{32} cm^{-2} sec^{-1} with 1.4 events per bunch crossing.
2. The β* values are gradually reduced to β* = 1m and the bunch intensities increased to 9 10^{10} ppb. This operation mode features a maximum luminosity of L = 1.2 10^{33} cm^{-2} sec^{-1} with 7 events per bunch crossing and a total beam energy of 94 MJ.

The third commissioning stage introduces the operation with nominal beam parameters. The main milestones include:

1. Operation with 2808 bunches starts again starts again with β* = 18m and bunch intensities of 4 10^{10} to 5 10^{10} ppb.
2. The β* values are gradually reduced to β* = 0.55m providing a maximum luminosity of L = 1.9 10^{33} cm^{-2} sec^{-1} with 3.6 events per bunch crossing and a total beam energy of 157 MJ.

In a final step, the bunch intensities are increased to 1.15 10^{11} ppb providing the nominal luminosity of L = 1 10^{34} cm^{-2} sec^{-1} with 19 events per bunch crossing and a total beam energy of 362 MJ. However, this final commissioning step requires the installation of new hardware (e.g. Phase II collimators and Phase II of the dump dilution kicker system).

REFERENCES

[1] S. Fartoukh, EPAC 2004, LHC Project Report 769.
[2] Tom Kroyer et al, WEPLS141, this conference.
[3] D. Bozzini et al, WEPLS099, this conference.
[4] E. Todesco et al, 18th ICMT, Morioka Japan, 2003 and LHC-Project-Report-704 2004.
[5] S. Fartoukh and O. Brüning, LHC Project Report 501, October 2001.
[6] A. Lombardi et al, EPAC 2004, Lucern, Switzerland.
[7] L. Bottura, V. Granata, S. Fartoukh, E. Todesco, Proceedings of EPAC 2004, 2004.
[8] N. Sammut, L. Bottura, J. Micallef, Phys. Rev. Special Topics – Accel. and Beams 9,012402 (2006).
[9] J.-B. Jeanneret et al, LHC Project Report 44, 1996.
[10] C. Bracco et al, TUPLS018, this conference.
[11] N. Sammut et al, WEPLS104, this conference.
[12] P. Cameron et al, THPCH105, this conference.
[13] R. Assmann, TUODFI01, this conference.
[14] J. Resta et al, MOPCH091, this conference.
[15] A. Faus-Golfe et al, WEXFI03 this conference.
[16] W. Herr et al, http://cern.ch/lhc-beam-beam/
[17] F. Zimmermann. LHC-MAC June 2005: http://mgt-lhc-machine-advisory-committee.web.cern.ch .
[18] E. Benedetto, THPCH018, this conference.
[19] R. Bailey et al, MOPLS005, this conference