LHC COMMISSIONING PLANS

R. Alemany Fernández, CERN, Geneva, Switzerland

Abstract

Operating the Large Hadron Collider (LHC) at design performance is not going to be easy. The machine is complex and with nominal beams has the capacity to destroy itself. Consequently, a staged approach has been developed, in which the complexity and the destructive power of the LHC beams are both increased incrementally. The overall approach is described, with particular emphasis on the commissioning to first high energy collisions.

INTRODUCTION

The LHC [1] is an accelerator with unprecedented complexity and energy stored in the magnets and the beams. At nominal values, the energy stored per LHC beam is 362 MJ, enough to melt 500 kg of copper; and the energy stored in the magnets is 11 GJ. Recalling other accelerators, it can be seen that, for example, the beam energy in LEP2 was 20 kJ and in Tevatron it is around 2 MJ. Therefore, LHC beam energies exceed other accelerators by one to two orders of magnitude.

Another challenging activity will be to keep more than 30000 tones of material at 1.9 K during several months; an operation never done before that also needs careful commissioning of the cryogenic system.

Furthermore LHC will have almost 3000 bunches per beam with $1.15 \cdot 10^{11}$ protons per bunch, colliding at 40 MHz. This will have consequences on the unwanted beam-beam interactions, that will have to be very well mastered, and on the number of pile-up events in the experiments, amongst other things.

Another challenging aspect when operating LHC is the emittance budget, which is very small already at injection and, therefore, a limiting factor for the luminosity. Consequently, the emittance will have to be kept constant along the ramp and squeeze phases of the operation.

The goal of a collider is to provide as high a luminosity as possible to the detectors it hosts. In the case of LHC, it has to satisfy the very different requirements of several experiments (different physics programs, different types of beams, etc), adapting, consequently, its operation mode, which definitively adds another degree of complexity to the operation of the machine.

On the other hand, the experiments will have to learn how to stand running at nominal values, which is also a complex enterprise for them.

It is clear that this complexity is not going to be tackled all at the same time but, in the case of LHC, three steps are foreseen. The first step is the Hardware Commissioning of the different machine systems and equipment. The second step will cover the integration into operations of the different systems and equipment, as they become hardware commissioned, and the first cold checkout of the accelerator. Finally, the third step will be the commissioning of the machine with beam. Within each step, the commissioning of the machine is further factorized to approach, sequentially, higher levels of complexity and risk.

The staged commissioning approach agreed for LHC will be presented in this paper, but giving particular importance to first high energy collisions with protons.

The paper is organized as follows. After the Introduction, there is a Section that presents the overall commissioning strategy. The main goals, the documentation and the human resources needed to perform the Hardware Commissioning, Machine Checkout and Proton Beam Commissioning are summarized in the three following Sections, respectively. Finally, the last one is devoted to the conclusions.

OVERALL STRATEGY

The overall LHC commissioning [2] is organized in three well defined steps, each one of crucial importance:

1. Hardware Commissioning: a thorough commissioning of technical systems and services without beam.
2. Machine cold checkout, which also includes a first integration into the operation group of the sectors as they are hardware commissioned. Testing all subsystems as thoroughly as possible without beam during this step, allows the resolution of many problems that would have otherwise dogged commissioning with beam.
3. Beam commissioning, which will be carried out in four stages. The staged directive will allow phased commissioning of the key-systems with increasing intensity. Thus, the initial commissioning can be performed without having to face the dangers of high intensity beams and the full rigour of the final machine protection system, which will be introduced in steps as the commissioning successfully proceeds.

In the following, steps one and two will be summarized, while step three will be covered with more detail.

HARDWARE COMMISSIONING

The goals of the Hardware Commissioning [3] are to test, qualify and validate for future operation the individual systems: magnets, vacuum, cryogenics, power converters, quench detection system, energy extraction system, Radio Frequency system, all the beam instrumentation equipment, kickers, septa, beam dump system, collimators, absorbers, etc; and the associated services: AC distribution, water-cooling, ventilation, access control and safety systems. The commissioning is done in two stages. First, the systems are commissioned individually following the procedures specific for each of them; then they are commissioned as a whole, with the granularity of a sector in most of the cases, following the procedures that take into account the relationship between systems.

In order to do so, a team composed of specialist and owners of the different equipments was mandated to work out a commissioning strategy, evaluate the resources needed and build the necessary environment, i.e., prepare the procedures, test folders, analysis tools, logbooks, collaborative tools, web pages, logging data, databases, etc.

Documentation

The main outcome of the previous preparation activity was the elaboration and documentation of the different test procedures, with detailed steps describing the commissioning of simple and complex systems (made of several sub-systems). The procedures are divided in three main parts:

- Entry conditions: conditions required to start the test.
- Test procedures and conditions required to perform them.
- Exit conditions: those which define that the test is complete.

The conditions range from availability of utilities, status of equipment, access conditions, safety measurements, signalling, etc.

The documentation can be found in the Hardware Commissioning Web pages [4] in the form of Engineering Data Management Service (EDMS) documents and Equipment Management Folder (MTF) database, as persistent storage media. Web pages and Microsoft Office documents are used for fast update of the procedures when needed, and fast communication among people.

The second main outcome, but not least important, is the definition and description of the data to be recorded during the test and to configure the MTF that is receiving these data. Each equipment owner automatically uploads to MTF the test results upon completion of the commissioning activity. Subsequently, up-to-date reports are generated and made available to the community on the Hardware Commissioning Web pages.

Human Resources

The LHC Hardware Commissioning is currently taking place. The people carrying out this step are composed of:

- System experts.
- Field engineers, who have a global understanding of the individual systems of a particular sector and the interplay amongst them. They coordinate the activities within the sector.
- Hardware commissioning coordinators, who plan the commissioning of the full machine.
- LHC machine operators and engineers in charge (EIC) from the operation group.

Another goal of the Hardware Commissioning step is to train operation staff for later efficient machine operation. Therefore, during this period it has to be ensured an optimal exchange of information from the hardware commissioning team to the LHC operation crew. The way this issue has been tackled in LHC consists of giving to the EICs the responsibility of the smooth running of the tests during the shift assisted by the LHC operators. In cooperation with the Field Engineers, the EIC coordinates the work with the system experts, defines the set of circuits to be tested, is responsible for the detailed reporting in the e-logbook of all what happens during the shift, ensures the proper logging into the database, the post-mortem system and the MTF of the relevant data, reports to the coordination meetings, and last but not least is responsible for the safety.

MACHINE CHECKOUT

Following the end of Hardware Commissioning, a Machine Checkout [5,6] period is foreseen, to be performed by the operation group. The objectives of this activity are:

- Drive all the relevant systems in a synchronize way through the standard operational sequence.
- Check the functionality of the control system from the CCC high-level software applications.
- Check the beam instrumentation acquisition chain.
- Check the timing synchronization.
- Check all equipment control functionality.
- Check machine protection and interlock system.

The Machine Checkout will be planned in a modular way such that it can be done on individual systems, multi-systems and on sectors, as they become hardware commissioned. The Machine Checkout is organized in three stages:

1. Individual system test using the high-level software applications. This stage can be considered as the first integration into the operation group of the equipment and systems. The timing, the acquisition chain, the control, etc in agreement with the relevant equipment group will be checked.
2. Multi-system test as for example Machine Protection, where the interplay between Beam Loss Monitors (BLM), Beam Interlock System (BIS) and LHC Beam Dump System (LBDS) will be validated.
3. Dry run driving the whole machine through the nominal sequence from the LHC Sequencer [7]. At this point, all the high-level software application functionality will be checked with realistic test cases. After this stage the LHC will be ready for Beam Commissioning.

Stages one and two will be performed in parallel with the Hardware Commissioning; stage three will have two parts. During the first part, the dry run will be done in the sectors that have successfully gone through the hardware commissioning. The second and last part will be a dry run of the whole machine, which implies that the Hardware Commissioning phase is over.

Documentation

The Machine Checkout procedure is currently under preparation and will follow the same structure as the hardware commissioning activities: entry conditions, procedures and exit conditions. It is obvious that a perfect matching between the exit conditions of the Hardware Commissioning phase and the entry conditions of the Machine Checkout is essential, and therefore, the experience and knowledge acquired by the operation group during the Hardware Commissioning step will be of great help.

The preparation of the procedures is done in the form of web pages [5] for fast communication and easy input from the actors. Then an EDMS document will be prepared and will have to be approved by the operation team. This document will constitute the reference for the activity; however, updates on the procedure will always be done in the web pages. Updated EDMS documentation will be done when major releases will be needed.

Human Resources

The machine checkout will be coordinated by the Operation group with the support of equipment specialist and the Hardware Commissioning team. In particular, the responsibility of the successful machine checkout will fall on the LHC Machine Coordinators and the EICs assisted by the operators.

The activities will be performed from the CCC.

BEAM COMMISSIONING WITH PROTONS

Even after LHC Hardware Commissioning and Machine Checkout, operating the accelerator with the nominal parameters [1], remains a challenging enterprise for both the machine and the experiments. Therefore, a staged beam commissioning approach is essential, aimed at finding a balance between robust operations (machine protection) and satisfying the experiments (luminosity and event pile-up).

The LHC Beam Commissioning [8,9] will be carried out in four stages that will be explained in the following subsections, pointing out, in particular, when the Machine Protection commissioning with beam [10] takes place along the phases.

Stage A: Pilot physics run

This stage comprises from the first beam injection into the machine, to the top energy collisions. The type of beam will be, first, pilot beam (1x1 bunches with 5.0 - $10.0 \cdot 10^9$ p+ per bunch), and then 43x43 bunches, with a maximum of 156x156. The number of protons per bunch at this stage is limited to $9.0 \cdot 10^{10}$, colliding at top energy without crossing angle. The benchmark energy is 7 TeV per beam, although it may be lower for reasons of overall machine reliability, as dictated by the magnets performance at high field with beam. The initial physics will be with the injection optics. Once this has been achieved, the squeeze will be partially commissioned. Table 1 summarizes the beam characteristics and performance levels at CMS and ATLAS detectors for stage A. In this table two set of values are quoted, the target or benchmark, and the limit that can be obtained by pushing the parameters as far as possible without comprising the safety of the machine and experiments.

Stage A is further divided into eleven phases:

Phase A.1 – Injection and first turn. Objectives:

1. Commissioning of the last 100 m of the transfer line and the injection.
2. First commissioning of key beam instrumentation.
3. Commissioning of the trajectory acquisition and correction.
4. Threading the beam around the two rings (first turn).
5. Closing the orbit to be ready for phase A.2 (establishing circulating beam).

The entry conditions of Phase A.1 in what concerns machine protection assume that during Hardware Commissioning and/or Machine Checkout:

- The Beam Interlock System has been fully commissioned without beam to the state “ready for pilot injection”.
- The Beam Dump System, in terms of equipment and instrumentation, has been fully installed and commissioned, and that its functionality has been checked.
- Collimators are out since the beam intensities used here are not yet an issue for machine protection.

The exit conditions of Phase A.1 in what concerns machine protection require that:

- Measurements of quench limits and BLMs response are done.
- The BIS is operational with all beam and injection permits.
- The LHC Safe Beam Parameters for beam injection permits are tested and validated.
- The Software Interlock System (SIS) is operational with all beam permits.
- Commissioning with beam of the Beam Position Monitors (BPM).
- Full acquisition chain of BLMs and BPMs are tested.

Phase A.2 - Circulating pilot and RF capture. Objectives:

1. Establish closed orbit.
2. Commissioning of additional instrumentation: BPM intensity acquisition.
3. Preliminary orbit, tune, coupling and chromaticity adjustments.

4. Obtaining circulating beam (few hundred turns at least).
5. SPS-LHC energy matching.
6. Commissioning of RF capture.

The machine protection requirements are the same as in phase A.1.

Phase A.3 - 450 GeV initial commissioning. Objectives:

1. Commissioning of beam instrumentation.
2. Improving lifetime.
3. First optics checks.
4. First commissioning of the Dump System.

In what concerns machine protection, the requirements are the same ones as in previous phases, but during this one the collimators and protection devices will be commissioned with beam to be ready for limited higher stored energies (ramp or higher intensities at 450 GeV). Further more, dedicated beam loss studies will be carried out to make a preliminary estimate of the cleaning inefficiency of the collimator system, and beam loss maps.

Phase A.5 – 450 GeV, Increasing intensity. This phase marks a clear inflection point in the commissioning strategy because machine protection becomes a critical part since we start dealing with unsafe beams. The idea is to commission the machine with beam intensities above the damage level assumed to be ~ $1.0\cdot10^{12}$ p+. The objectives are the following:

1. Safe machine operation with up to $1.4\cdot10^{13}$ p^+ at 450 GeV.
2. Multi-bunch injection commissioned up to 16 x $9\cdot10^{10}$ p^+ and well tuned, including cleaning and protection.
3. LHC BIS fully commissioned.
4. Commissioning of the Beam Dump System up to $1.4\cdot10^{13}$ p^+ at injection energy.
5. Collimators set-up for operation up to $1.4\cdot10^{13}$ p^+ at injection energy, in particular, BLM loss pattern established.
6. Improved definition of thresholds for the BLMs.
7. Beam instrumentation operational with up to 156 bunches and total intensity of up to $1.4\cdot10^{13}$ p^+.
8. RF adjusted for injection and circulating multi bunch operation.

The approach will be sequential in terms of beam intensity. First increase the number of bunches up to 43

Table 1: Beam characteristics and performance levels in points 1 (ATLAS) and 5 (CMS) for the different commissioning stages. The grey line between Stage C and D indicates the installation of phase II collimators and beam diluters.

Machine Parameters	Stage A		Stage B		Stage C			Stage D
	Target	Limit	Target	Limit	Target	Limit		Nominal
$N_{bunches}$	43	156	936	936	2808	2808		2808
p+/bunch	$4\cdot10^{10}$	$9\cdot10^{10}$	$4\cdot10^{10}$	$9\cdot10^{10}$	$5\cdot10^{10}$	$5\cdot10^{10}$		$1.15\cdot10^{11}$
Bunch spacing (ns)	2021	566	75	75	25	25		25
Xangle (µrad)	0	0	250	250	285	285		285
β* (m)	2	2	2	1	1	0.55		0.55
£ ($cm^{-2}s^{-1}$)	$6.12\cdot10^{30}$	$1.12\cdot10^{32}$	$1.28\cdot10^{32}$	$1.24\cdot10^{33}$	$1.13\cdot10^{33}$	$1.91\cdot10^{33}$		$1.01\cdot10^{34}$
Evt rate/crossing	0.76	3.85	0.73	7.09	2.14	3.63		19.18
p+/beam	$1.72\cdot10^{12}$	$1.40\cdot10^{13}$	$3.74\cdot10^{13}$	$8.42\cdot10^{13}$	$1.40\cdot10^{14}$	$1.40\cdot10^{14}$		$3.23\cdot10^{14}$
I_{beam}(mA)	3.09	25.3	67.4	152	253	253		581
E_{beam} (MJ)	1.93	15.7	41.9	94.3	157	157		362
σ_{beam} (µm)	31.7	31.7	31.7	22.4	22.4	16.6		16.6

The first commissioning of the Dump System with beam takes place at this phase with, first, a pilot beam and then with $3.0\cdot10^{10}$ p+ per bunch. The system is commissioned with circulated beam and with extracted beam.

During this phase the BLM system can be further commissioned parasitically adjusting thresholds on "accidental quench & learn basis". Another possibility, although with very low priority at this stage, is the BLM calibration with lose/quench on purpose.

Phase A.4 – 450 GeV optics. The main goals of this phase are:

1. The measurement and correction of closed orbit, linear and non-linear optics.
2. The measurement and correction of the aperture and momentum aperture.
3. Full commissioning of the RF.
4. Commissioning of the non-linear correctors and insertion region (IR) bumps.
5. Detailed injection matching.

with $1.0 \cdot 10^{10}$ p+ per bunch, and then increase the intensity per bunch up to $4.0 \cdot 10^{10}$ p+. Second, increase the number of bunches up to 156 with $1.0 \cdot 10^{10}$ p+ per bunch, and then, if the experiments can stand the event rate, the bunch intensity could be pushed up to $4.0 \cdot 10^{10}$ p+ per bunch.

Phase A.6 – 450 GeV, two beam operation. Objectives:

1. Establish two safely circulating (unsafe) beams with a lifetime of 5 to 10 hours. The differences between the two beams in terms of emittance and intensity should be < 40 % and < 20 %, respectively. The settings and measurements will constitute a reference for correctors in SIS, collimation, BLMs, etc.
2. Separation bumps fully commissioned.
3. Aperture in triplet and IR verified for both beams.
4. Two beam collimation commissioned.
5. Interleaved injections working.

Phase A.7 – 450 GeV collisions. This phase covers the collision at injection energy of two (unsafe) beams. The goals are, first bring the beams into collisions, and later optimize luminosity in the experiments. The procedure is the same as in phase A.10.

Phase A.8 – Snap-back and ramp. This phase deals with machine protection issues from a new point of view, the increase of energy. Initial ramp attempts would be to a much reduced maximum energy (~ 1 TeV) enabling us to factor out the problems of machine protection that come with the move to higher energies. The key steps would then be:

1. Single beam through snap-back, checking the key instrumentation and control of the key beam parameters: orbit, tune, coupling, chromaticity.
2. Stopping in ramp and then pushing on in steps (ΔE ~ 1 TeV) would allow one to commission beam dump and machine protection along the ramp. Beam based checks would also be possible at these intermediate energies.
3. Culminating in a single beam to 7 TeV.
4. Repeat the process for the other beam.
5. Repeat the process with both beams at the same time.

Phase A.9 – Top energy checks. Objectives:

1. Measure and correct the optics at 7 TeV before colliding/squeezing beams: orbit, tunes, coupling, chromaticity and beta beat.
2. Transition from injection optics to un-squeezed collision optics.
3. Aperture measurements at 7 TeV.
4. Disentangling of triplet alignment errors and D1/D2 transfer function errors; set good conditions for squeeze.
5. Optimization of the Beam Dump System before we start collisions or squeeze, and before we increase intensity.
6. Optimization of beam lifetime.

Machine sensitivity to losses is extreme at 7 TeV, therefore a critical point in this phase is the need of defining safe beam excitation means and collimation settings for optics measurements.

Phase A.10 – Top energy collisions. Objectives:

1. Get beams into collisions at top energy.
2. Optimize integrated luminosity with relative luminosity as the main performance parameter.
3. Keep background low and stable without spikes.
4. Provide a rough knowledge of the absolute luminosity from beam parameters (beam intensities and sizes).

For unsqueezed optics the procedures loops over increasing intensity; for squeezed optics it loops over decreasing β*.

Phase A.11 – Top energy squeeze. Objectives:

1. Commission the squeeze without crossing in IP1 and IP5 at 7 TeV. Goal for this phase is β*=2m.
2. Squeeze of IP8 for LHCb operation with reduced beam intensities (β*=2m).
3. Setup of the required protection, in particular, commissioning of the tertiary collimators, i.e., collimators to protect the experiments.

In terms of machine protection there are no special requirements in this phase with respect to the previous phase, the only difference is that at this point the tertiary collimators are commissioned for the first time.

Figure 1 shows the possible commissioning paths that can be followed. This diagram gives an idea of the advantage of having a factorized beam commissioning allowing us to adapt the commissioning activities according to the needs or circumstances at a particular moment.

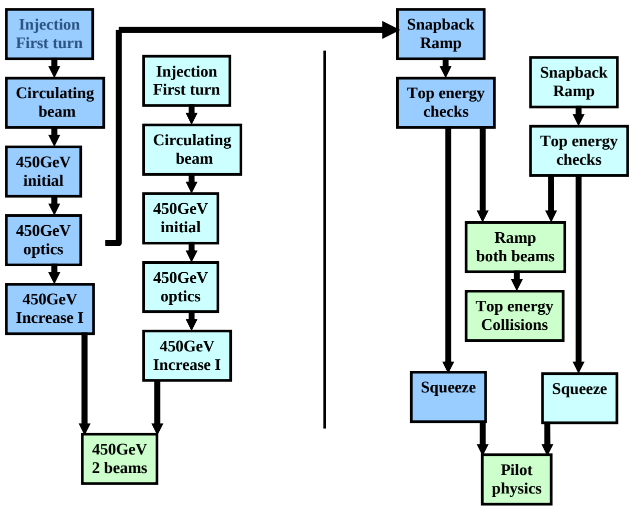

Figure 1: Stage A commissioning phases activity diagram. The arrows indicate the possible variants to the commissioning plan.

Stage B: Intermediate physics run

This stage is also called 75 ns operation because the bunch spacing is set at 75 ns. There are several advantages to this [11]:

- The reduced number of parasitic beam-beam encounters allows a relaxed crossing angle allowing the commissioning of the collisions with crossing angle to be done in steps.
- Electron cloud is not expected to be a problem.
- Total beam intensities and power are managed in an incremental way, letting the machine protection systems to be gradually commissioned.

Initial operation at 75 ns would be with the β* achieved in the pilot physics run (β*=2m), and a crossing angle of 250 μrad. In this mode, the beta squeeze will be pushed as far as possible. A typical performance expected is given in Table 1.

Stage C: 25 ns operation I

This stage aims at commissioning the machine with 2808 bunches and up to $5.0 \cdot 10^{10}$ p^+ per bunch, i.e. with a 40% of the nominal intensity. At this point, beam scrubbing may be needed to reduce the effects of electron cloud. Table 1 shows the performance level that can be reached for target and limit values, resulting from the staging of collimators and beam dump.

Luminosity at ATLAS and CMS will be of the order of 10^{33} $cm^{-2}s^{-1}$. For LHCb and with the injection optics, the luminosity is reasonably optimal. In ALICE, however, detuning and transverse beam separation will be required.

Stage D: 25 ns operation II

Once the performance levels for Stage C have been achieved, a period for the installation of phase II of the collimation system and the full complement of beam dump dilution kickers will be scheduled.

Following this, the last stage of the beam commissioning will take place, during which bunch intensities will be progressively increased toward nominal values. Performance values can be seen in Table 1.

Documentation

As in the case of the Hardware Commissioning and Machine Checkout, detailed procedures for each phases of each stage are being elaborated. They are organized in entry conditions, procedures and exit conditions. Whenever possible, potential problems and unresolved questions are included in each phase, together with priorities for the different steps (1 meaning compulsory, 2 meaning optional). The body to carry out the step is also indicated, e.g., shift crew, expert teams, etc. In order to be as dynamic as possible and to speed up the communication among the people, the procedures are elaborated and kept in the form of web pages [12]. Once the procedures are agreed on, an EDMS document per phase is written and circulated again through the teams participating in the beam commissioning for final approval. The documents remain the reference, but updates on the procedures are done in the web pages. After major revision, the EDMS documentation will be modified accordingly.

Human Resources

The beam commissioning activities will be coordinated by the Operation group. There will be a central team of people composed of Machine Coordinators, Commissioners in Charge (CIC), Engineers in Charge and operators.

The Machine Coordinator takes overall responsibility for the LHC machine for a period of one week. The CICs have the role of executing the LHC commissioning program during a shift period. The EICs responsibility is to run the LHC machine during the shift assisted by the LHC operator.

CONCLUSIONS

Effective commissioning of the LHC with beam will demand very good planning. All concerned subsystems will need to be well prepared and thoroughly tested before the first beam, during the Hardware Commissioning and Machine Checkout phases. The hand over from Hardware Commissioning to Machine Checkout must be well defined and the later planned and executed with care, otherwise, unresolved problems encountered during this step will, certainly, dog commissioning with beam.

Following Machine Checkout, a staged approach to commission LHC with beam will take place in order to tackle the complexity and potential risk of the accelerator in steps. The stages cover from the first physics pilot run (very low intensities and relaxed beam parameters), to nominal machine operation. Every stage is, at the same time, divided in phases that range from the first injection into LHC to the top energy collisions.

Among the many critical issues associated with the commissioning activity, finding the best way to document and keep the documentation is one of them. For LHC so far the practice consists of writing very detailed commissioning procedures that are kept in the form of Web pages for fast communication between the actors, and in the form of EDMS documents that compile major releases of the procedures.

ACKNOWLEDGEMENTS

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REFERENCES

[1] “LHC Design Report”, CERN-2004-003, 4 June 2004.

[2] M. Lamont et al.; “A Staged Approach to LHC Commissioning”; LHC Project Report 949, EPAC’06 Edinburgh, 2006.

[3] R. Saban et al.; “The Commissioning of the LHC Technical Systems”; PAC’07 Albuquerque, New Mexico, 2007.

[4] Hardware Commissioning Coordination Web Site: http://hcc.web.cern.ch/hcc/
[5] http://wikis/display/LHCOP/Home under the item LHC Machine Checkout (access restricted inside CERN).
[6] J. Uythoven; "Machine Checkout"; proceedings of the LHC Project Workshop 2005, CERN-AB-2005-014.
[7] R. Alemany et al.; "LHC Sequencer, Operational Functionality, Interfaces and Requirements "; LHC-CQ-ES-0001 ver. 0.6.
[8] R. Bailey; "Summary of Overall Commissioning Strategy for Protons"; LHC Project Workshop - Chamonix VX proceedings.
[9] R. Bailey; "The Minimum Workable LHC – Plans and Requirements for Beam Commissioning in Years 1 and 2"; LHC Project Workshop - Chamonix VX proceedings.
[10] J. Uythoven; "Commissioning and Early Operation – View from Machine Protection"; LHC Project Workshop - Chamonix VX proceedings.
[11] O. Bruning, "Parameter evolution for the first luminosity runs", Chamonix XII proceedings, p. 268.
[12] LHC Beam Commissioning Procedures http://lhccwg.web.cern.ch/lhccwg/overview_index.htm