450 GEV

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Abstract

The objectives of this phase are enumerated together with the key prerequisites for establishing circulating beam. The basic procedures involved are outlined. Given circulating beam, the necessary checks, measurements and associated procedures are clearly established. Finally the exit conditions of the phase are noted.

INTRODUCTION

Beam commissioning in the LHC at 450 GeV is planned to take place in several stages during four main phases:

- A sector test with beam through sector 7-8 several months before completion of installation and hardware commissioning of the whole machine
- Preliminary commissioning of the machine at 450GeV using a special machine cycle with low dynamic effects and a different working point.
- Passage to a 'normal' acceleration cycle in preparation for commissioning the ramp.
- Detailed study of the machine at 450GeV interleaved with ramp commissioning.

This paper will concentrate on the second and fourth phase above. However, the first part is also valid for the sector test. The first sections are described as if there is a single beam. Of course each of these stages will have to be repeated – first for beam 2, then for beam 1.

PREREQUISITES

Magnetic Cycles and Optics

At the very beginning of machine commissioning the knowledge of the machine parameters will be rather poor. In order to ease the initial commissioning it has been decided to perform the first stages of commissioning on a special cycle [1]. This cycle has two important, independent features:

- A 'degauss blip' [2] which essentially suppresses the dynamic effects coming from the decay of persistent currents.
- A relaxed working point having well separated tunes of Q_h=64.285, Q_v=59.385.

The first feature eases the understanding of the machine at injection energy since the stability and reproducibility of the machine is increased. A similar effect could be achieved by waiting before injecting onto the nominal cycle. It should be noted that the effect of the degauss blip has only been tested on the dipoles so far. A similar cycle needs to be defined for all other magnetic elements.

The relaxed working point has been designed to ease early operation when the coupling is not well corrected. The uncorrected coupling in the LHC is estimated to be around $|c_-| = 0.1$. With the proposed working point, separating the two tunes should be possible even with only partial compensation of the coupling using the skew quadrupoles.

Even with the use of a 'degauss cycle' a clear field cycle has to be defined for all magnetic elements. This will be used on a regular basis to reset the machine after many hours of corrections. It can also be used to begin to establish reproducible behaviour. For the main circuits and insertion region magnets this cycle will probably involve a ramp to the field equivalent to around 1 TeV. For the corrector circuits a repetitive max-min hysteresis cycle will probably be needed to reset the field to a known value.

Non-Powered Circuits

For the start of commissioning certain powering circuits will not be needed. Some of these will be brought on fairly rapidly once circulating beam is established. Others will only be powered much later in the commissioning phase. The following elements are probably not initially required:

• Spool Piece Octupoles and Decapoles	32
• Lattice Octupoles	32
• Lattice Skew Sextupoles	16
• Non-linear inner triplet correctors	48
• Experimental magnets and compensators	8
• SR Undulator	2

This gives a total of 138 powering circuits that can be left off. Of these, the lattice octupoles and the non-linear inner triplet correctors will remain off for a considerable time. The remainder will be commissioned fairly rapidly.

Settings Generation

For 450 GeV commissioning only the injection optics is needed. This must be prepared for a flat machine – ie with no crossing angle, no separation scheme and no experimental magnets. The MAD file will be used for the main circuits and insertion region magnets. The b_3 spool piece magnets and skew quadrupoles will be powered based on information from magnetic measurements. For the first turn the lattice sextupoles will be switched off. Finally, all orbit correctors must be cycled and set to zero current.

Other Prerequisites

Many other things must be tested and ready before beam commissioning starts. The list includes:

- Beam instrumentation. The BPM's should be in auto-triggering mode and give both position and intensity for a single beam.
- BLM, BCT & radiation monitors checked and ready.
- Collimation and protection elements completely retracted. All other mobile devices out.
- Screens in the injection region and in IR4 tested and put into the aperture as needed.
- Beam interlock system checked and tested to the minimum level to match our minimum situation.
- RF system off, but low-level controls for synchronisation tested and available.
- Transfer lines and injection system commissioned with beam.
- Application software and software interlock system tested and ready.

In addition the basic output from the machine checkout should be present: cold, powered magnets, a working access safety system, controls and technical services.

FIRST TURN

At this stage it is desirable to have an extraction interlock in the SPS preventing beam above the pilot intensity. In addition a system of 'Beam on Demand' would be very useful. Instead of beam automatically coming each supercycle from the SPS a single shot request could be made by the LHC each time beam is required. This would avoid unnecessary activation of components in the LHC during the 1st turn threading.

It is expected that the beam will, on average, go around 4-5 ½-cells before being lost. This contrasts with LEP where the beam would normally go through a whole octant. It is likely that initial threading will be done manually although an automated procedure could be useful. Such procedures are rather prone to perturbation by BPM's with large unphysical offsets as well as calibration or cabling errors. In addition large non-linear fields in the LHC mean that the beam is usually lost rather quickly and correction over a small range of BPM's is better than correcting the whole trajectory.

LHC has some special features that complicate the threading process these include:

- The 8 main powering sectors. Each will have to be matched to the beam energy. Final tracking between the 8 sectors can only be done with beam.
- The separation and recombination dipoles, together with the dogleg magnets will act like very strong correctors during the threading. Any errors in their transfer functions will have to be corrected at this early stage.
- Normally the higher order magnets, b_3 and above, are cut to avoid generating problems due to non-linear fields and feed-down. However, in the LHC these fields are present anyway. The b_3 spool pieces will therefore be powered for the first turn. The situation for the b_4 and b_5 spool pieces remains to be clarified.

Even at this early stage the first checks of the BPM's can be made. This is best done using difference trajectories with a series of single kicks. This technique should be good enough to find non-responding, polarity reversed or plane swapped pickups.

GETTING CLOSURE

Once the beam passes all the way around the machine continued trajectory corrections can be used to try and increase the number of turns. However, decoherence of the beam signal will limit the number of turns that can be observed. Tab. 1 shows the expected chromaticity with the degauss cycle settings and various sextupole corrections. The second line corresponds to the situation likely at the end of threading the 1st turn. A chromaticity of ~100 leads to a decoherence time of just 6 turns. In this case the lattice sextupoles should be switched on and the chromatic correction used as a knob with the number of turns the observable to tune on.

Table 1: Expected Chromaticity for the degauss cycle

	Q'_h	Q'_v
No Correction	+83	-263
80% Dipole Correction Only using spool piece correctors	-75	-105
Natural Q' Only corrected using lattice sextupoles	+176	-176
Both Corrections	+18	-18

Establishing more than a few turns also requires control over the betatron tunes. A reasonable measurement and correction of the tunes should be possible with around 10 turns measured [3]. This method assumes that the coupling is reasonably well corrected and therefore requires that the skew quadrupoles are powered based on magnet measurement data.

As more turns are achieved, the average of these turns can be used to generate a closed orbit measurement. Correcting this iteratively with tune and chromaticity adjustments can be used to increase the number of turns to around 100. At this point RF capture can be attempted.

RF CAPTURE

Many of the details for commissioning the LHC RF system and capturing the beam have already been presented [4]. Here only the basic process and methods are outlined.

RF Capture falls into 3 basic steps: Initial energy correction, First capture and Energy matching. These are outlined below:

Initial Energy Correction

The energy of the beam injected from the SPS must match closely the energy defined by the main dipole magnets of the LHC. For clean capture an energy error of around $1x10^{-4}$ can be tolerated. For initial capture this tolerance can be relaxed significantly. The easiest way to correct the energy is to observe the horizontal offset of the beam in the arcs on the first turn. A 1mm position offset corresponds to $7x10^{-4}$ in dB/B. Adjusting the dipole field or the SPS energy can bring the trajectory offset down to ~0.5-1.0 mm.

A wall current monitor is next used to observe the beam over several turns. The phase slip between an RF reference and the beam indicates the energy error. The phase slip can be minimized either by fine tuning the main field of the dipoles, or changing the RF frequency reference, f_{lhc}.

First Capture

At this stage the RF power can be switched on and the phase adjusted to capture the beam. Once captured, the beam will be accelerated by the RF system onto a new orbit to match the energy defined by the RF system.

Energy Matching

This process is used to match the LHC machine to the beam energy given by the SPS. Firstly, either the dipole field, or the RF frequency f_{lhc} should be fixed. In the SPS this is the frequency that is fixed, however in the LHC fixing the dipole field may be more logical.

Using the first turn trajectory the energy in the SPS can be tuned to centre the beam in the arcs of the LHC. Once capture by the RF system the orbit can also be centred by changing the RF frequency. This process often requires iteration.

PRELIMINARY COMMISSIONING

With a captured pilot bunch a large programme of checks and measurements can be started, together with the initial commissioning of several hardware systems. This section can be broken down into four stages that are described here sequentially although in reality the activities from all four stages are likely to be mixed.

Get a Reasonable Lifetime

This stage principally involves roughly tuning the basic machine parameters – tunes, orbits, coupling and chromaticity. In order to do this several beam instrumentation systems must be commissioned and operational. This includes the Q-meter (based on single kick measurements) and the beam loss monitors. At this stage it is worth while to commission the beam synchronised timing for the instrumentation – which has been relying on auto-triggering up to now. First commissioning of a transverse profile monitor would also be useful.

Beam Dump Commissioning

The very first commissioning of the beam dump may take place even before the beam is captured by the RF system. However, a more systematic check and testing of the system will be needed at this stage. By now a stable closed orbit has been defined and hence the trajectory of the extracted beam is reproducible. Once the timing is adjusted the screens can be used to correct the MKD and MSD strength. At this stage, with a single pilot bunch, it is not clear if the dilution kickers will be commissioned. In any case the dilution sweep of the MKB can only be observed by changing the relative timing of the MKB to the beam.

Once commissioned the beam dump can be hooked into the machine protection system and the various hardware interfaces tested. Beam position interlocks and the orbit feedback system in IR6 can be tested and put into operation if desired.

Collimation and Protection Elements

The precision of the beam instrumentation increases as the intensity increases. For this reason it is desirable to be able to inject bunches in excess of the pilot intensity. Since this will be above the quench threshold for the cold machine some protection will be needed from the collimation and protection system. Before the collimators can be used with beam their jaw positions must be accurately calibrated using a ‘find beam’ technique controlled using local beam loss monitors.

The primary collimators in the betatron collimation region (IR7) can then be moved in to provide a single stage cleaning system with a loose set of settings to protect the cold aperture. With these collimators in place the TDI can also be moved in. As a final step the TCDS, which protect the cold arc in case of dump misfire, can also be set into a coarse position for basic protection. With these measures in place it should be possible to inject an intensity of $1\text{-}2x10^{+10}$ safely.

Bumps with Everything

A systematic study of the whole ring should now be undertaken to detect polarity, cabling, calibration and alignment errors, together with aperture restrictions and major optical defects. Two different tools can be used: the single kick and the sliding bump.

Single kicks are an easy way to detect pickup and corrector errors. A difference orbit is measured with and without a single kick from a given corrector. The response around the whole ring can be analysed. A system to power each corrector and analyse the difference orbit can check the response of all pickups and correctors. In order to avoid possible problems with non-linear fields, amplitudes below 1-2 mm should be used.

Systematic sliding bumps can be used to extract much more informational juice. A closed 3-bump can be used to increase the beam position at a specific point. Eventually the lifetime of the beam will drop and beam losses recorded in the local BLM will increase. At the mechanical aperture the beam will be lost. This method can be used to give a measure of the mechanical aperture and report on any serous aperture restrictions. In addition it can be used to calibrate the BLM’s with known point losses. Measuring the orbits and tunes as the amplitude of the bump increases gives a measure of the quality of the optics. Local coupling can lead to transfer from the bumped plane to the other. Finally, powering the non-linear correctors within the bump can be used to check the local corrector polarity.

A software system to slide the chosen bump around the machine and analyse the data will be needed since the number of combinations of rings, planes, positions amplitudes and measurements is rather large. The same techniques can be used for the dispersion supressors, the matching sections and the inner triplet.

Two beam Operation

Extra information can be extracted by commissioning both beams in parallel. Notably this gives complimentary measurements between the two rings and can be used to compare and contrast the behaviour in each ring. For example, before requesting the re-alignment of a ring element it is useful to observe the same kick appearing in both rings.

In addition, significant sections of the machine have elements which are common to the two rings. This includes the inner triplets and separation dipoles. Corrections in these regions must be done taking the other beam into account.

The commissioning can use one beam then the other. However, two beam operation is possible even without commissioning the separation scheme. For this it is necessary to displace one beam with respect to the other such that the crossing point occurs in regions where the two beams are in separate chambers.

TUNING-UP

Once we have sufficient intensity for good quality measurements, then a new round of fine tuning and detailed system commissioning can begin. For this stage it can be assumed that a beam of ~$3 \times 10^{+10}$ protons is sufficient. Initially this will be in a single bunch. Later this could take the form of multiple bunches from the SPS, or several SPS transfers to further increase the intensity. In addition, while a single beam should be used at first, the later stages of tuning should be done with 2 beams using the standard separation scheme for each IP.

It is not clear how much of this tuning will be done on the degauss cycle. It is likely that at least part of the activities described below will be done only after the move to the nominal ramping cycle.

More System Commissioning

A list of systems to visit – or re-visit -for fine tuning is given below. Only the equipment needed for the initial pilot physics run is included in the list:

- RF system tuning
- Multiple injection synchronization and bucket selection systems
- Longitudinal feedback (may be needed for multi-bunch operation)
- Transverse feedback – only the injection damper part commissioned for the moment
- Transverse profile measurements
- Beam dump
- Refine collimation and protection systems if necessary for the increased intensity.
- Injection tuning and matching of the transfer line to the LHC.
- Beam loss monitors to revisit calibration factors and thresholds with higher intensities and multiple bunches.
- Commissioning other instruments including PLL tune history, fast BCT and SR telescopes.

Linear Optics

A reasonable knowledge of the machine optics will be required before attempting to ramp. In addition the correction of the main machine parameters to tighter tolerances will be needed. At this point the tunes should be corrected to ~0.001, the Q' to ~2 units and the $|c_-|$ to <0.01. In parallel a cleanly corrected reference orbit with an rms. below 1mm should be established. Beta-beating measurement and correction can now be attempted.

Beta-bating can be measured using the same method as used in LEP [5]. Fig 1 shows a beta-beating measurement from LEP after correction. The quality achievable with the measurement technique can be seen. What can also been seen from the data of Fig. 1 is that in the case of LEP, even after correction, the beta-beating was of the order of 20%. In the case of the LHC this represents an upper limit to what is acceptable for operation.

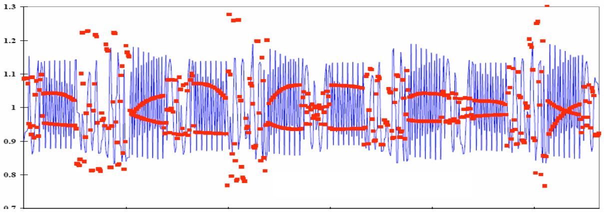

Figure 1: A Typical Beta-Beating Measurement in LEP. Red Dots Vertical Plane, Blue line Horizontal plane.

Tools for analysis and correction of the beta-beating are under development. In particular procedures for identifying and correcting transfer function errors in insertion region quadrupoles are required.

In addition to beta-beating, phase advance and β^* measurements can be made. Where K-modulation hardware exists, the pickup offsets can be measured and used in the orbit correction package.

Two Beam Operation

Getting two beam operations with the nominal separation scheme in the four experimental regions should have a high priority. The bumps must be put on in each case and closure checked. With the separation scheme in place the machine parameters may require further optimization and the effect of the bumps on parameters such as dispersion and beta-beating can be accessed. With both beams in the machine the first check of crosstalk in the beam instrumentation of the long straight sections can be addressed. Notably the beam loss monitors around the experimental insertions and the collimation regions should be studied.

At the same time as two beam operation is established, the experimental magnet powering and compensation must be checked and added to the operational cycle. Closure of the compensation schemes and coupling correction will require study.

Other Steps

The remaining parts of the tuning might be left until initial commissioning of the ramp is complete. Many aspects have already been discussed [6], especially the non-linear optics measurements and corrections. Studies during this period will include tune scans, spool piece powering correction, non-linear chromatic effects and off-momentum studies.

THE END GAME

The exit conditions of the 450 GeV commissioning and optimization phase are the following:

- Two separated beams in the machine each with a total intensity of ~$3x10^{+10}$.
- Multiple injections with bunch rotation tested and operational.
- Well adjusted beam parameters including Q to ~0.001 and Q’ ~2 units.
- Polarity and cabling errors checked for all pickups and magnets.
- Alignment of the main machine components checked and corrected as necessary. Physics aperture of the two rings known.
- Good understanding of the static field errors in the machine at injection optics checked and corrected to bring the static beta-beating below 20%.
- Spool piece powering checked for b_3 and hopefully b_4 and b_5.
- Fully functioning beam instrumentation – at least at injection energy and modest intensity.
- BLM calibration and thresholds established at least for critical detectors.
- Machine protection system in place and tested. Operation of the system sufficiently good to allow ramping.
- Single stage collimator settings established to protect the cold aperture.
- Protection element positions established complimentary to the collimator settings.
- Orbit feedback operation established – at least in the beam dump and collimation regions.
- Application software checked, tested and working.

The above description leaves several issues open for later study this notable includes:

- Any issues concerning the dynamic effects present with the nominal ramping cycle. This is considered more properly to belong to the ramp commissioning phase
- Anything to do with 25ns, or 75ns operation.
- Anything not directly required for the initial pilot physics run.

Operation with bunch trains will require significant systems commissioning for the RF system, transverse feedback, beam instrumentation, beam dump and the collimation and protection systems. In addition, the crossing angle bumps will need to be put on the machine and their effect compensated. Long range beam-beam effects, abort gap cleaning and electron cloud will require study during this period.

Additional studies will be required for the alignment optics and the powering of the inner triplet correctors – this will be needed once it is planned to squeeze below ~1m.

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