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LHC – Initial Commissioning

DRAFT

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Abstract

The prerequisites for beam commissioning are enumerated. The key commissioning phases required to establish circulating beam in the LHC are detailed with time estimates given. The total time required for the initial commissioning of the LHC to first colliding beam is discussed. An outline of the commissioning stages, and the potential impact, of a 450 GeV calibration run in 2007 are examined.

1. Introduction

It's clear that the pressure will be on beam commissioning to establish colliding beams and to progress with the planned pilot physics run as fast as possible. At the same it is critical that the destructive power of the beam be bourn in mind from the start and that adequate time is taken to establish a good understanding of the machine and to properly commission the safety systems, and the instrumentation on which these depends.

1.1. Stage 1 - Objectives

The aim of this first stage is to take two moderate intensity multi-bunch beams to high energy and collide them. More specifically we would aim to take 43 on 43 with 3 to 4 x 10^{10} protons per bunch into collisions at 7 TeV. This beam simplifies things because:

- There are no parasitic encounters and hence no crossing angle required, and no long range beam.
- Larger aperture in the insertions
- Instrumentation has to deal with widely spaced bunches
- Good beam for RF [5]
- Relatively easy for Vacuum [6]
- Lower energy densities: reduced demands on beam dump system, collimation and machine protection.

The luminosity will, of course, be only moderate with around 10^{30} cm^{-2}s^{-1} at 18 m. and 2 x 10^{31} cm^{-2}s^{-1} at 1 m. However, it will mark an important milestone and it should be possible to move rapidly on to a higher number of bunches via 156 x 156 and 75 ns.

2. Prerequisites

2.1. Installation

The commissioning plan presented below assumes, of course, there are no major problems that prevent establishing circulating beam. Most technical issues should have been sorted out during hardware commissioning. However, there remain two main possibilities that could cause problems and that will only be revealed by beam:

- Aperture limitations
- Polarity errors

Depending on the problem, diagnosis and subsequent resolution can clearly shatter any planning. By way of illustration of the dangers, the problems faced by another superconducting collider, RHIC, are briefly summarised in Appendix 1.

2.2. Hardware Commissioning

Without going into detail, it is clear that comprehensive and thoroughly hardware commissioning is vital to smooth commissioning with beam. Sector by sector, sub-system by sub-system, hardware commissioning should have commissioned all of the accelerator hardware and the tested the LHC's technical infrastructure. Systems implicated include:

- Beam Vacuum [warm & cold]. Here there are clear implications for beam commissioning – pressure bumps, bake-out, NEG activation etc.
- QRL Vacuum
- Insulation Vacuum
- Cooling and Ventilation
- Cryogenics Plant
- Cryostat Instrumentation
- QRL Instrumentation

- Electrical Network
- Powering Interlocks
- Quench Protection and energy extraction
- Software Interlock System
- Access
- Survey/Alignment

More directly beam related hardware will also have gone through appropriate commissioning including:

- All magnet circuits [warm & cold]
- All power converters
- Kickers, Septa
- Collimators, Absorbers
- Beam dumps
- RF including power systems, low level, cavities, transverse feedback etc.
- Beam Instrumentation
- Machine protection system
- Controls

A breakdown of the detailed planning for the hardware commissioning is available [see, for example, 2]. Exit conditions for the hardware commissioning phase of the beam related hardware are being established.

At the end of the hardware commissioning phase we must anticipate the above systems moving into the global operational mode with appropriate facilities in the CCC. These facilities would include: monitoring, logging, displays, post mortem, diagnostics; the appropriate control applications, definition and implementation of appropriate coupling between systems. Recovery procedures from CCC must be clearly defined and tested.

2.3. Hardware tests

Following initial hardware commissioning, some systems will enter an extended phase of hardware tests to be performed by the system experts. The RF system, for example, needs time for conditioning of the cavities along with detailed low-level tests. Such tests would continue in parallel with the main thrust of he hardware commissioning. Again a well-defined hand over point to operations and the machine checkout should be established

2.4. Machine checkout

The machine checkout will be coordinated by the Operations group, with the support of equipment specialists, HWC team etc. and will be performed from the CCC. The objectives of this phase is to pull together the disparate components and subsystems of the accelerator and drive all relevant systems in a synchronized way through the complete operational sequence, anticipating the actual operation of the machine. <u>This phase is estimated to take around 4 - 6 weeks.</u> The checkout can be performed partially in parallel with the hardware commissioning and one would anticipate complete powering sub-sectors and sub-systems being signed over to operations as available. Tests will include thorough verification of the topics covered in table 1.

System	**To do - full ring**
Access	Commission full ring, EIS tests, Acceptance tests, operation. Debug its numerous sub-systems and test all the operational procedures.
Beam Hardware	
Kickers	Interlocks, timing, controls, diagnostics, reliability tests
Septa	Interlocks, timing, controls, diagnostics, reliability tests
Power Converters	Cycling. Full machine ramp & squeeze, trims, real time control. Timing. Tracking

Magnets	Transfer functions, harmonics, cycling etc.
RF	Cavity conditioning, Interlocks, Controls, synchronisation with injectors, pre-pulses, low level control [cavity control, synchro, beam control, longitudinal damper], transverse damper, power systems and diagnostics
RF - TFB	Pre-commissioning, timing, acquisition tests, interface to control system
RF - LFB	Pre-commissioning, timing, acquisition tests, interface to control system
TCLI	Interlocks, control, monitoring.
TCDQ	Interlocks, ramp & squeeze, control, monitoring.
TDI	Interlocks, control, monitoring.
Collimators	Monitoring control, synchronized movement, ramp & squeeze, tests
Beam Dump	Tests of timing, post-mortem system, inject and dump mode, energy meter. XPOC, interlocks. Reliability tests.
Machine protection	
Beam Interlock Controller, WIC.	Equipment interfaces, links, logic, controls. Client interfaces [Vacuum, access, PIC, Dump, BLMs, FMCM, Experiments, Injection systems etc.]. In and out of test mode. Fill blown system wide tests.
Safe Beam Flags. Safe beam parameters	Distribution. Tests.
Beam Energy Meter	Interface, tests.
Software Interlocks	Acquisition. Logic. Reliability. Tests.
Controls	Signal acquisition Logging Post Mortem Fixed Displays Equipment control Settings generation and download Alarm system Slow timing, fast timing, synchronisation Alarms, logging, post mortem, fixed displays Equipment control & access Analogue acquisition Software: measurements, trajectory acquisition and correction, ramping etc. Sequencer, injection management Procedures for sliding bumps etc. etc.
Controls infrastructure	Networks, front-ends, timing, FIP, servers, databases etc.
Instrumentation	
Beam Loss Monitors	Interlocks, critical settings, acquisition, concentration, interface to BIS.
Beam Current Transformers	Pre-commissioning, timing, acquisition tests, interface to control system.
Beam Position Monitors	Concentration, timing, RT
Wire Scanners	Pre-commissioning, timing, acquisition tests, interface to control system.
Synchrotron Light Monitor	Pre-commissioning, timing, acquisition tests, interface to control system.
Screens	Pre-commissioning, timing, acquisition tests, interface to control system.
Tune measurement	Pre-commissioning, timing, acquisition tests, interface to control system.
Chromaticity measurement	
Abort gap monitor	
Radiation monitors	Acquisition, concentration, logging.
Residual gas monitors	Pre-commissioning, timing, acquisition tests, interface to control system.

Accelerator systems	
Beam Vacuum	Monitoring, instrumentation, valve control, interlock tests.
Cooling and Ventilation	Monitoring.
Cryogenics Plant	Recovery, communications.
Cryostat Instrumentation	Monitoring, logging, post mortem, analysis.
Electrical Network	Monitoring.
Insulation Vacuum	Monitoring, logging.
Powering Interlock	Ring wide tests. Parallel failure.
QRL Instrumentation	Monitoring, logging, interlocks, recovery.
QRL Vacuum	Monitoring, logging, interlocks
Quench Protection	QPS, Energy extraction: displays, diagnostics, post-mortem, recovery.
Miscellaneous	
Radiation Monitors	Monitoring, logging, interlocks
Radiation protection	
Experiments	Data interchange, Beam aborts, injection inhibits

Table 1: Key objectives of machine checkout

2.4.1. Commission essential operational procedures

The machine checkout will also provide the opportunity for development and testing of operational procedures. Hands-on experience of control from the CCC will clearly be a very useful pre-cursor for full commissioning. This will include commissioning of the Sequencer, Injection sequencing and cycling the complete machine through the nominal operational phases.

2.5. Transfer Lines

Here the SPS LHC cycle should have all requisite LHC beams available with the desired beam quality ready to be delivered when required [4]. TI8 & TI2 should have been commissioned and have delivered fully qualified LHC pilot beams to final TED.

3. Phases

The overall breakdown of the phases required to meet the stage 1 goal is shown in table 2 and figure 1.

	Phase	
1	First turn	Ring 2; Ring1. Commission injection, thread beam around first turn, commission relevant beam instrumentation.
2	Circulating beam	Ring2; Ring 1. Capture, adjustment of key beam parameters
3	450 GeV - Preliminary system commissioning	
4	450 GeV - Detailed measurement program	Increase current, commission machine protection, transverse damper, measure aperture, optics. Increased Intensity Machine Protection
5	450 GeV - two beams	Pilots → higher intensity. Separation bumps, BLMs, crosstalk
6	Snapback – single beam,	Ring 2, ring 1
7	Ramp - single beams	Single beam, ring 2; ring1. Stop in ramp. Commission beam dump, machine protection in ramp, ring 2. Single beam at physics energy
8	Two beams to physics energy	
9	Prepare 7 TeV physics	Collide pilots. Un-squeezed.
10	Physics. Un-squeezed.	Experiments on. Increase to 43 on 43
11	Commission squeeze	Single beam partially through squeeze, etc.

12	Physics with partially squeezed beams. No crossing angle	
13	Pilot physics run	Intertwined physics and further commissioning of squeeze, raising bunch intensity, increasing the number of bunches

Table 2: Commissioning phases – stage 1

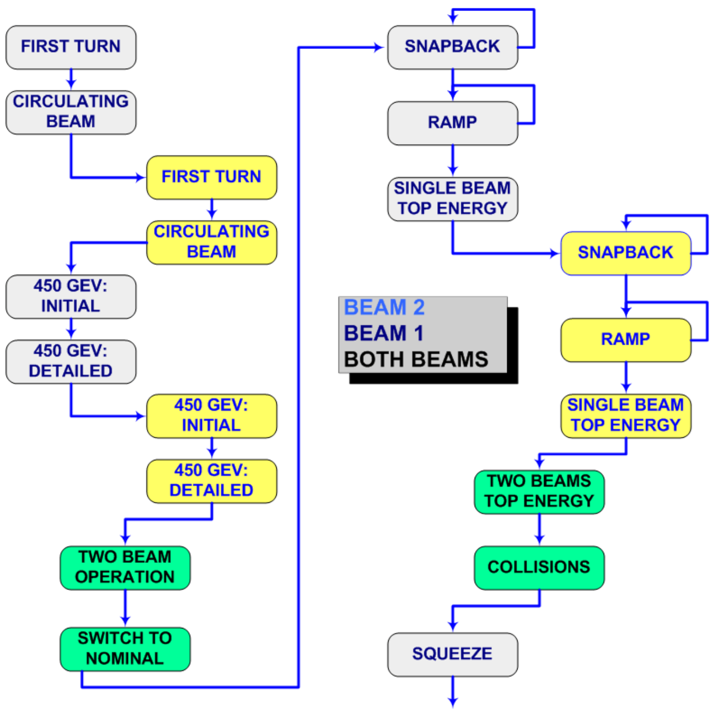

Figure 1: Phase switching between rings

3.1. Phase 1 – first turn

Assumptions: The clear assumption here is that both apertures are clear and that there are no major polarity errors. Either of these problems could seriously hamper establishing a first turn and necessitate a crash program of measurements to try and find the location of the problem.

Prerequisites: machine configuration as specified. Full machine checkout performed. Kicker pre-pulses, timing events.

Exit: pilot around one turn with trajectory corrected to better than x mm., beam on first turn screen

Team	Sub-phase	Total Time both rings	Priority	450 GeV Collisions
BT/OP	Commission TI8 & TI2 end transfer line. Commission injection region: kickers, septa, check aperture, instrumentation, beam to TDI.	24	1	Essential
OP/BI	Commission trajectory acquisition and correction, thread beam - first turn, energy matching	48	1	Essential
BI	Commission Beam Loss Monitor system - phase 1	12	1	Parasitic
OP/AP	Optics measurements, kicks, trajectory, BPM and corrector polarity checks	24	1	Essential
OP	Initial aperture checks	16	1	Leave
OP	Momentum aperture	6	1	Do
COL	Setting up of injection machine protection	12	2	Leave
		6 days		4 days

Table 3: Injection and first turn

3.2. Phase 2: Circulating beam

Prerequisites: first turn, lattice sextupoles, first cut b3 compensation, RF, BPM system

Exit: Circulating low intensity beam - both rings.

	Sub-phase	Total Time both rings	Priority	450 GeV Collisions
OP/AP	Adjust chromaticity, close trajectory, establish multiple turns, obtain closed orbit	24	1	Essential
OP/RF	Energy matching and correction, B-sps, f-lhc, B-lhc - both rings, RF capture	32	1	Essential
OP/AP	Measure integer tunes, fractional tunes, phase advance per turn	16	1	Essential
		3 days		3 days

Table 4: Establish circulating beam

3.3. Phase 3: 450 GeV – initial commissioning

Aim: Get the machine in a good enough shape that we can sensibly start performing detailed adjustment and measurements and checks. There is no point in details if we're not sure the basic optics is not correct and the beam instrumentation isn't working properly. This is also required if we are to safely increase the number of bunches plus intensity.

Prerequisites: reasonable lifetime, circulating pilot, roughly adjusted tunes, chromaticity, orbit and coupling

Exit:

- Polarities and aperture checked.
- Basic optics checks performed.
- First pass commissioning of BI performed.
- Phase 1 of machine protection system commissioning performed.

Team	Sub-phase	Total Time both rings	Priority	450 GeV Collisions
RF	Beam control loops (Phase, Synchro, Radial). Tuner loop, RF Feedback loop. Synchronisation	24	1	Essential
OP/AP	**Test control and correction (**corrector polarities, cabling, control system, software, procedures …). Measure & correct orbit.	24	1	Essential
OP/BI	**Commission transverse diagnostics - tune measurement [FFT]. Measure and adjust** tunes, chromaticity, and coupling.	24	1	Essential
OP/AP	**Linear optics checks:** check orbit versus kick, phase advance, BPM and corrector polarity.	24	1	Essential
BI	**Commission beam loss monitors** - acquisition, display etc. No connection to BIC for the moment.	12	1	Parasitic
BT	**Commission beam dump** - phase 1	24	1	Essential
BI	Commission BCTs: lifetime measurement	-	1	Parasitic
MPS	**Commission beam interlock system** with beam - phase 1. BIC to dump with beam. Check.	8	1	Essential
		5 days		3 days

Table 5: 450 GeV – initial systems commissioning

3.4. Phase 4: 450 GeV – consolidation

Aim: Well-adjusted machine, beam instrumentation and machine protection working well enough for first, safe excursions into the ramp. Machine protection system allows increase intensity/number of bunches [beam dump operational, BIC, BLMs, collimators to coarse].

Exit: Well-adjusted beam parameters, aperture, fully functioning beam instrumentation. RF - beam control loops operational and adjusted. Ability to increase number of bunches/intensity. Commissioned multi-bunch and/or multi-batch injection, synchronisation, BI acquisition.

Machine protection good enough to allow attempts to ramp intensities somewhat greater than pilot

3.4.1. Measurement program

Team	Sub-phase	Total Time both rings	Priority	450 GeV Collisions
BT	Matching between TI8/TI2 and ring. Pilots.	8	2	Leave
AP/OP	Measure beta beating. Identify and correct local sources of phase advance errors.	16	1	Do
MA/OP	Check key transfer functions (separation dipoles etc.)	24	1	Later [MD]
AP/OP	**(Re)visit mechanical aperture checks.** Bumps - check the aperture in the cold machine is free and has the expected size	16	1	Essential
OP/MA	**Field quality checks.** Check design fields, field harmonics, fields due to offsets between beam and magnet	16	1	$\leq$ b3
OP	**Momentum aperture**	8	2	Do
OP	IR bumps, check aperture in IRs	8	1	Leave
OP/AP	Reproducibility after cycling machine. Effect of magnetic cycle, reproducibility, field model	16	1	Leave
BI/AP	Quench levels and BLM response	24	2	Leave
		5 days		1-2 days

Table 6: 450 GeV consolidation – measurements

3.4.2. System commissioning

Team	Sub-phase	Total Time both rings	Priority	450 GeV Collisions
RF	Loop adjustment	8	1	Do
RF	Transverse damper	8	2	Do later
RF	Longitudinal feedback	8	1	Do
BI	Transverse profile monitors	8	2	Parasitic
BI	**Commission beam loss monitors** - phase 2, calibration, thresholds. Commission the BLM's around the collimators. Link to BIC	16	1	Do
BI	Tune - PLL	16	1	Do
OP	Closed orbit feedback	16	1	Do
COL	**Adjustment of collimators**, orbit stabilization, test positioning procedures, beam loss monitors. Positioning of jaws with respect to closed orbit. Looking a minimum set of primaries in first instance. This for basic protection up the ramp.	36	1	Essential for intensity increase
BT	**TDI.** Position, angle, interlocks	8	1	Essential
BT	**TCDQ** orbit at 6, position, angle, interlocks	16	1	Essential
MPS	FMCM	4	1	Do
MPS	Test Safe LHC Parameters: Safe Beam Flag, Beam Presence Flag, Safe LHC mode, Safe Energy, Safe Squeezing Factor	8	1	Essential (some parasitic)
		7 days		2-3 days

Table 7: 450 GeV consolidation – system commissioning

3.5. Phase 5a: 450 GeV - two beam operation

Prerequisites: Both beams separately with well-adjusted parameters. All requisite beam instrumentation must be available. TI8 & TI2 injecting in interleafed mode.

Exit: Circulating beams, well adjust beam parameters, simultaneous orbit stabilization, well adjusted separation bumps, BDI - simultaneous acquisition from both rings.

Team	Sub-phase	Total Time	Priority	450 GeV Collisions
OP	SPS - switch rings - TI8/TI2 in parallel	8	1	Parasitic
OP/BT	Commission separation bumps. Closure of bumps. Check aperture. Check injection region.	16	1	Essential
OP/AP	Effect of bumps - dispersion, non-closure	8	2	Leave
BI	Beam parameters: Q split, Q' split, coupling, Beam instrumentation: BLMs, BPMs cross talk etc.	8	1	Do
OP	Control system: real-time feedback, orbit correction, orthogonality etc., energy matching - 2 rings	8	1	Partial
		2 days		1 day

Table 8: 450 GeV – establish two beam operations

3.6. Phase 5b: 450 GeV – colliding beams

Prerequisites:

- Clearly establish beam life times, stable loss pattern, stable closed orbit both beams
- TCDQ and collimators providing adequate single stage protection
- Beam size measurement operational
- Data exchange mechanism operational
- Separation bump reduction knob plus collision point steering

Exit:

- Colliding beams – all four experiments
- First pass luminosity monitors commissioning (at very low data rates)

Team	Sub-phase	Total Time	Priority
OP	Separation bump reduction, check interaction with orbit feedback: points 1,2,5 & 8. Establish collisions	4*8	Essential
BI	Commission luminosity monitors (v. low interaction rates)	8	Parasitic
COL	Collimation setup	-	Optimisation
OP	Commission spectrometer compensation (check situation at 450 GeV). Bring solenoids on.	2*8	Essential
		2 days	1-2 days

Table 12: Establish 450 GeV collisions – low intensity

3.7. Phase 5c: 450 GeV – increase intensity

Team	Sub-phase	Total Time	Priority
COL	n1 = 6, n3= 30, N_{TCDQ} = 10 moving towards n1 = 5.7 n2= 6.7 na = 10.0 n3 = 30	3*8	1

TDI	Move towards $N_{TDI} = 6.8$	2*8	1
OP	Multi-batch injection	16	1
RF	Longitudinal feedback	8	1
		3 days	Spread

3.8. Phase 6: snapback

Prerequisites: Stable pilot at injection, nominal cycle, predictions from FiDeL, control system for parameter control during ramp in reasonable state.

Exit: Reasonable transmission of pilot through first 2 minutes of ramp. [26 GeV ~ 100 s.]

Foresee ramp setup to 1 TeV in the first instance. Key thing is to get key BI acquisition working and ramp-to-ramp stability and explore need to feed forward corrections.

Team	Sub-phase	Total Time both rings	Priority
OP/MA	Incorporate FiDeL predictions, ramp mechanics: RF, Power Converters	48	1
BI	Commission beam instrumentation acquisition in ramp: orbit, tune, chromaticity, coupling	16	1
OP	Orbit feedback	8	2
PO	Tracking between sectors	16	1
		4 days	

Table 9: Snapback

3.9. Phase 7: ramp - single beam - both rings

Prerequisites:

- Pilot++ (allowing some loss along the way)
- Ability to stop ramp at pre-defined energy.
- Magnets/FiDeL: Transfer functions, harmonics, decay and snapback, coupling currents.
- Settings generation: nominal ramp, design optics
- Timing system

Exit: Single super pilot at 7 TeV

After snapback and the first 100 GeV we expect things to quiet down considerably. The ramp dependent coupling currents are expected to be reproducible, small and thus to be taken care of in corrector functions. In the ramp some orbit corrections will be necessary; tune measurement plus some operator control will be necessary.

Team	Sub-phase	Total Time both rings	Priority
OP/MA	Incorporate FiDeL predictions, mechanics. Load RF, power converters	24	1
BI	Commission beam instrumentation acquisition in ramp: orbit, tune-PLL, chromaticity, coupling	16	1
OP	Orbit feedback	8	2
PO	Tracking between sectors	24	1
BT	Commission beam dump in ramp	48	1
BI	Commission BLMs - energy tracking of thresholds	8	1
RF	Commission RF: frequency, voltage, dampers. Measure: capture loss, continuous measurements of frequency response loops, bunch length - emittance growth/RF noise. Feedforward of measured frequency offset for eventual switch to synchro-loop operation	16	1

OP	Measurements at intermediate energy	16	2
OP/AP	Measurements at 7 TeV	24	1
		8 days	

Table 10: Ramp single beam

3.10. Phase 8: ramp - both beams

Prerequisites: pilots to 7 TeV in both rings separately, separation bumps through the ramp, orbit feedback commissioned with 2 simultaneously. RF, collimators, beam dump commissioned with 2 beams.

Exit: 2 counter rotating pilots with potential collisions in point 1 & 5.

Team	Sub-phase	Total Time	Priority
OP	Incorporate FiDeL predictions, ramp mechanics. Load RF, power converters.	8	1
OP	Commission separation bumps in ramp	8	1
OP	Orbit feedback	8	2
PO	Tracking between sectors	8	1
BT	Commission beam dumps in ramp - multiple ramps	24	1
OP/RF/BI	Check RF, BLMs, instrumentation, correction strategies	with above	1
OP/AP	Measurements with 2 beam at 7 TeV	24	1
		3 days	

Table 11: Ramp two beams

3.11. Phase 8: 7 TeV set-up for physics

Prerequisites:

- Clearly establish beam life times, stable loss pattern, stable closed orbit both beams
- TCDQ and collimators providing adequate single stage protection
- Beam size measurement operational
- Data exchange mechanism operational
- Separation bump reduction knob plus collision point steering

Exit:

- Colliding beams
- First pass luminosity monitors commissioning (at very low data rates)

Team	Sub-phase	Total Time	Priority
COLL	Collimation setup	24	1
OP	Separation bump reduction, check interaction with orbit feedback: points 1 & 5	16	1
BI	Commission luminosity monitors	8	1
OP	Establish collisions	8	1
		2 days	

Table 12: Establish collisions

3.12. Total time to establish 7 TeV collisions

Given the breakdown above, the time for the individual phases, and the resultant total is shown in table 13.

	Phase	Ring factor	Total Time [days] both rings
1	Injection and first turn	2	6

2	Circulating beam	2	3
3	450 GeV - initial	2	5
4	450 GeV – system comm & meas	2	12
5	450 GeV - two beams	1	2
6	Snapback - single beam	2	4
7	Ramp - single beam	2	8
8	Ramp - both beams	1	3
9	7 TeV - setup for physics	1	2
10	Physics un-squeezed	1	-
	TOTAL to first collisions		**45**
11	Commission squeeze	2	6
12	Increase Intensity	2	6
13	Set-up physics - partially squeezed.	1	2
14	Pilot physics run		

Table 13: Full 7 TeV commissioning breakdown. Shaded items are those that would be addressed in a 450 GeV calibration run.

4. Discussion

4.1. Machine availability & operational efficiency

Machine availability during the commissioning phase cannot be expected to be very high. We will be working in the post-machine checkout phase and there will be ongoing debugging of various systems. A figure of 60% machine availability for beam is taken.

Operational efficiency during the first month will also be lower. Standard operations such a cycling the complete machine, giving access, quench recovery will require debugging and optimisation. An attempt is made to factor this into the times quoted above.

4.2. Time to establish colliding beams

The total time allocated to the phases above totals around 45 days. The allocation is made in terms of a quantum of an eight hour shift. The total represents a fairly complete commissioning of all required systems for the planned pilot physics phase. Further commissioning to raise the intensity and to squeeze will be required.

A priority of 2 in the tables above implies that the tasks concerned could be skipped in the first pass through to colliding beams. This would bring the total down to around 40 days. Further reduction might be possible through judicious use of parallel commissioning. This is discussed below.

Caveat: saving time in not commissioning the non-essential but very useful can cost time in the longer run. This has been clearly established many times before (examples here might include PLL and orbit feedback.)

<u>40 days taken with a machine availability of 60% gives an elapsed time of around 2 months to establish circulating beams.</u> This is under what RHIC took at their second attempt (see Appendix 1).

4.3. Opportunities for parallelism, parasitic development

- Injection region of beam 1 with ongoing commissioning of ring 2.
- Parasitic beam instrumentation commissioning: transverse beam profiles, beam loss monitors, orbit acquisition, BCT lifetime.
- Collimators: ring 2/ring 1, momentum/betatron cleaning.
- RF: ring 1/ring 2. Could imagine RF working on beam 2, BI on ring 1 etc.
- Orthogonal scans etc.

The caveat is that it can be disadvantageous to try and do too much at any one time, and we will have limited expertise. A full exploration of the possibilities is to be performed.

4.4. Sector Test

A sector test is a standard procedure for all large accelerators. Performed thoroughly it has the potential to reveal potentially major problem (see LEP, RHIC etc). If we don't do it for the LHC we will be the first to skip it. If things are OK, so well and good, but if there are problems, the test gives us appreciable lead time. In this sense the test clearly implies risk minimisation. It provides, among a lot of other things, the opportunity to check for aperture and polarity problems.

4.5. Commissioning run at 450 GeV

The commissioning run at 450 GeV is potentially useful, with many of the same arguments used for the sector test. It allows critical checks of the whole machine – principally aperture and polarities – with increased lead time for problem resolution. Although reduced hardware commissioning is possible, 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 and Energy Extraction systems, Power Interlock Controllers etc. must be qualified to the necessary level.

4.5.1. OBJECTIVES

The principal aims of the exercise are to:

- establish the fastest safe path to low intensity collisions;
- commission essential safety systems;
- commission essential beam instrumentation;
- commission essential hardware systems;
- perform measurements to check: polarities, aperture & field characteristics.

One would aim to skip non-essential procedures and also take advantage of the run to push in interleafed MD: the first part of ramp (to 1.1 TeV); reproducibility etc. We could also parasitically commission beam instrumentation (PLL etc.) and other systems.

The overall breakdown of the phases required to establish collisions at 450 GeV, and estimate of the time required, is shown in table 14. A full breakdown of the phases is available [5].

4.5.2. Machine availability & operational efficiency

Machine availability during the commissioning phase cannot be expected to be very high. We will be working in the post-machine checkout phase and there will be ongoing debugging of various systems. A figure of 60% machine availability for beam is taken.

Operational efficiency during the first month will also be lower. Standard operations such a cycling the complete machine, giving access, quench recovery will require debugging and optimisation. An attempt is made to factor this into the times quoted above.

4.5.3. Total time to first collisions at 450 GeV

	Phase	Beam time [days]

1	First turn	4
2	Establish circulating beam	3
3	450 GeV – initial	3
4a	450 GeV - consolidation	1-2
4b	450 GeV – system commissioning	2-3
5a	2 beam operations	1
5b	Collisions	1-2
		~16 days

Table 14: Phase breakdown for 450 GeV calibration run

The total beam time required for a reasonably systematic commissioning of two beam operation and the establishing of collisions at 450 GeV is estimated to be 16 days (see table 14). Given an operational efficiency of 60%, the estimated elapsed time to establish collisions at 450 GeV is around 26 days. This could be reduced if full advantage is taken of the opportunities for parallelism.

4.5.4. Impact of 450 GeV run on full commissioning to 7 TeV

The phases of full commissioning are shown in table 13. The shaded phases are those that could possibly be addressed during the calibration run. It can be seen that the run enables considerable progress to be made on the full commissioning plan. However, there will obviously be hand-over costs in breaking the commissioning into two stages, machine check-out will need to be partially re-performed, the phases implicated will have to be re-done to a certain extent. These costs are probably equalled by the benefits that an extended period of consolidation after the calibration run would provide.

It's clear that full commissioning to top energy will proceed faster with the experienced gained in the 450 GeV run. The proviso being that we will need systematically fill in the blanks and re-commission where necessary. One might expect the total beam time required to establish circulating beam to be reduced from around 45 days to around 30 days. With an operational efficiency of 60% this reduces the time to first collisions to around 7 weeks. Again this should be compared with RHIC's two and a half months to establish colliding beams following what turned out to be an engineering run in the previous year (details below).

(Even with the experience gained at 450 GeV, it would be difficult to offer less than a month to first collisions. A lot still remains to be done to get two beams safely to 7 TeV.)

5. Conclusions

5.1. With 450 GeV run

Run		
450 GeV - 2007	Machine checkout	2 weeks
450 GeV - 2007	Colliding beams – beam time	16 days
450 GeV - 2007	Colliding beam – elapsed time 60% op efficiency	26 days
7 TeV - 2007	Machine checkout	4 weeks
7 TeV - 2007	Colliding beams – beam time	30 days
7 TeV - 2007	Colliding beams – elapsed time 60% op efficiency	7 weeks

Experience and post-commissioning work following the 450 GeV will lead to increased efficiency in the subsequent post first collisions commissioning. The 4 weeks machine checkout could possibly be reduced if operations have clear access to already hardware commissioned sectors and subsystems.

5.2. Without 450 GeV run

Run		

7 TeV - 2007	Machine checkout	4 – 6 weeks
7 TeV - 2007	Colliding beams – beam time	40 days
7 TeV - 2007	Colliding beams – elapsed time 60% op efficiency	2 months

6. References

[1] See http://cern.ch/LHC-HCWG/
[2] T. Linnecar, "RF Capture and Synchronisation", LHC Performance Workshop – Chamonix XII, CERN-AB-2003-008 ADM.
[3] V. Baglin, "Running In – Commissioning with Beam", LHC Performance Workshop – Chamonix XII, CERN-AB-2003-008 ADM.
[4] M. Lamont, "LHC Sector Test", LHC Performance Workshop – Chamonix XIII.
[5] M. Lamont et al, LHC Commissioning, http://cern.ch/lhc-commissioning/

7. Appendix A - RHIC commissioning

7.1. Commissioning run: June-September 1999

0600 Monday August 16: The first RHIC Beam Commissioning run finished this morning. Beam is next expected to be seen in RHIC in December 1999. A brief summary of progress so far in BLUE and YELLOW rings is as follows:

BLUE Beam has been efficiently injected, captured, and stored in the BLUE ring, with lifetimes as long as 45 minutes. Acceleration by a modest amount - about 1 GeV per nucleon - has been demonstrated at a slow ramp rate. The biggest challenge in commissioning the BLUE ring was the need to manoeuvre the closed orbit around a small number of apparent obstacles in the beam pipe. These obstacles will be investigated - and removed - when the ring is warmed up in September.

YELLOW Thousands of turns of beam were briefly seen in the YELLOW ring, allowing successful RF capture. Long lifetimes have not yet been established, nor has acceleration been performed. No apparent obstacles have been found in YELLOW, in a positive contrast to BLUE. On the other hand, steering and second turn closure in the injection region were found to be more difficult than in BLUE, as also was steering through the YELLOW dump area. The situation will be greatly ameliorated in the next beam commissioning run, when we will be able to use the nominal injection optics with a beta function value of beta* = 10.0 meters at all 6 interaction points. The optics used so far had beta* = 2.9 meters, much closer to the nominal luminosity optics with beta* = 2.0 than to the injection optics.

"Abstracts for EPAC 2000 - no RHIC papers are being presented. A discussion of the RHIC commissioning indicated the problems associated with shortcuts taken due to reduced funding."

7.2. First Physics - 2000

- First beam April 3rd
- First successful ramp: June 1st
- First collisions June 12th

After meeting successive milestones such as the first sextant test in February 1997, the completion of magnet production in September 1998, and the assembly of the RHIC collider ring in January 1999, almost on schedule, the initial test to verify functionality of the collider system took place in June-September 1999. The actual commissioning with colliding beams, the commissioning of detectors, and the initial physics run took place during the late spring to summer of 2000.

For the operation in the year 2000, the cool-down of the collider ring began on March 10. After reaching the stable operating temperature of 4.6K, the Au beam was introduced into one of two rings (Blue Ring) on April 3 and to the other ring (Yellow Ring) on May 6. On May 20 the beam in the Blue Ring was accelerated through transition to approximately 60 GeV/u. Acceleration and storage of beams in the Blue Ring took place on June 1, and that in the Yellow Ring on June 6. These led to the achievement of collisions in the STAR and PHOBOS detectors on June 12 at the beam energy of 28 GeV/u (or the total collision energy 56×A GeV). Collisions in the PHENIX and BRAHMS detectors were observed 3 days later. Shortly thereafter, the beam energy was increased to 65 GeV/u, realizing the center of mass collision energy of heavy ions some seven times higher than that achieved at the CERN SPS Pb beam operation.

The target luminosity for the year 2000 run (10% of the design luminosity) was reached at this energy on August 20, two weeks before the end of the heavy ion runs on September 5.