PROPOSED TESTS WITH BEAM

B.Goddard, CERN, Geneva, Switzerland.

Abstract

An overview of the proposed tests is presented, with time and beam load estimates. The necessary instrumentation and associated requirements on controls are discussed. The tests will include optics checks, aperture scans, instrumentation performance, magnet checks, injection protection, stability and quenches. For each test the methods are outlined, with the requirements on instrumentation, equipment and controls highlighted.

THE LHC INJECTION TEST

The LHC injection test [1] will provide an important milestone to the overall LHC project. The test requires an extensive and almost representative cross-section of the LHC machine sub-systems to be operational [2,3] and fully integrated into the control system, with associated application software and cycle management [4]. The beam tests allow a huge amount of progress to be made. It will be possible to validate magnet circuit polarities [5], aperture, and alignment, and to begin the detailed commissioning of critical equipment systems like the BPMs, BLMs and machine protection devices [6]. The reproducibility and decay of the persistent current effects can be measured and compared to the magnetic model [7], and the linear optics can be determined, together with some of the more important higher order effects. The quench limits of the LHC magnets can be studied [8] and correlated with the observed beam loss patterns.

OBJECTIVES AND CONSTRAINTS

Main objectives of beam tests

The main objective of the beam test is to transport the pilot beam to the IR7 TED and to perform the measurements to demonstrate that fundamental aspects of the LHC design function correctly when these are integrated into the installed machine and control system. The objectives are broken down into the following parts:

1. Commission end of TI 8 and injection with beam
2. Commission trajectory acquisition and correction
3. Linear optics measurements
4. Commission Beam Loss Monitor system
5. Aperture checks
6. Quench limits and BLM response
7. Commission nominal cycle
8. Stability and reproducibility tests
9. Field quality checks
10. Commission machine protection subsystems
11. Commission crossing and separation bump

Priorities

The beam time will be limited and obviously should be minimised to limit the impact on the remaining LHC installation and commissioning; for this reason the tests will be prioritised. Although all the tests are important and are considered necessary, items 1-5 are highest priority, 6-9 medium priority and 10-11 lowest priority.

Radiological constraints

With regard to the beam tests, the possible radiological consequences [9] and the requirements for subsequent activity in the machine areas impose two constraints:

- The LHC machine should be reclassified to a non-radiologically designated area
- There should be no radiological consequences for LHCb

This means that particular care must be taken to minimise beam losses, by using the beam sparingly and knowing at all times where the beam is actually going. This will be done by starting the tests with zero separation/crossing angle in LHCb to maximise the local aperture, and quantifying the losses in the experiment, probably with BPM intensity signals. The beam used for the tests will be pilot intensity (5×10^9 p+ in one bunch) where possible, which is below the quench limit and about a factor of 100 below the damage threshold. There will be tests which need $1\text{-}3\times10^{10}$ for improved BPM resolution, and the quench test where up to 1×10^{11} p+ may be required in one bunch. The LHCb spectrometer and compensation magnets will be locked off.

BREAKDOWN OF TEST PHASES

1. Commission end of TI 8 and injection

24 hours foreseen

Estimate 500 shots with 5×10^9 p+

The last 200 m of TI 8 and the injection systems must be commissioned, threading the beam through the line onto the TDI diluter, Fig. 1. The kickers must be timed in and their performance checked.

The key hardware systems are the TI 8 elements, the injection elements MSI, MKI and TDI, the LHC magnets Q5, Q4, D2 and correctors to the right of IP8, the beam instrumentation BTVs, BPMs and BLMs, and timing, radiation monitoring and control system.

In addition to the generic control requirements, dedicated or expert application software will be needed for injection steering, injection post-mortem, TCDI/TDI setup, injection fixed displays, equipment expert applications and possibly online aperture display and re-matching routines.

Remaining issues or areas for study include the tight vertical aperture at the MSI septum, Fig. 2, which may require a specific local correction strategy, the synchronisation of the shot-by-shot logging for each injection (not "Post-Mortem"), and the controls across the TI 8/LHC interface, in particular for injection steering.

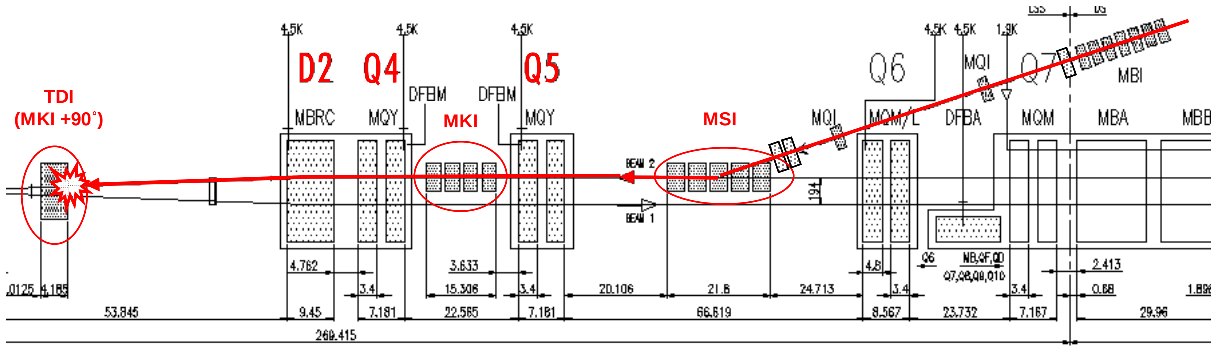

Figure 1. Last part of TI 8 and IR8 injection region, showing injection elements MSI and MKI.

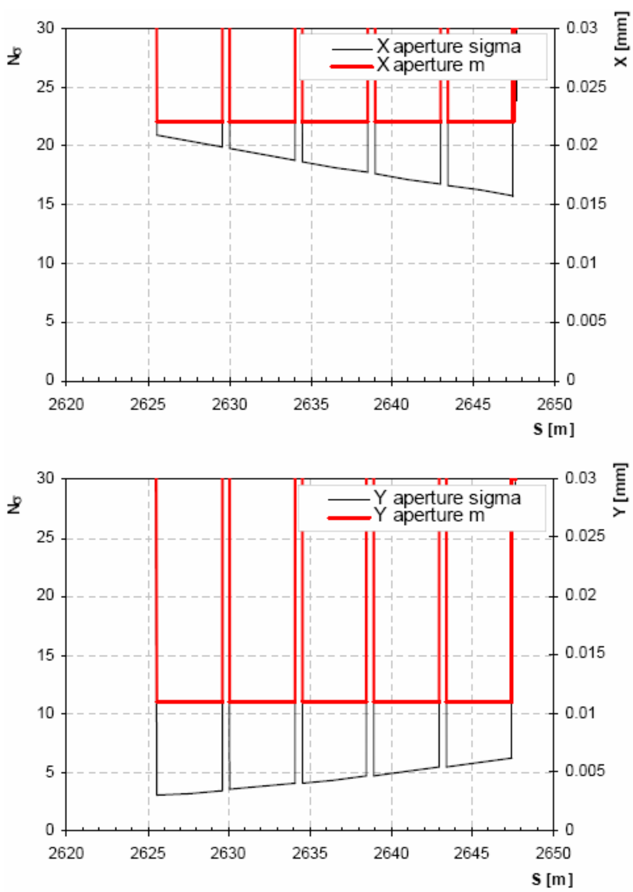

Figure 2. Aperture at MSI septum, in horizontal (top) and vertical planes.

2. Threading to IR7 dump

24 hours foreseen

Estimate 500 shots of 5×10^9 p+

Threading has been analysed and simulated [10], with few problems expected for a single LHC sector. It seems that the optimal approach is the pragmatic 'LEP' strategy, which is essentially manual using iterative measurement and correction over a small range of the machine, with manual BPM rejection. During this phase the trajectory acquisition and correction must be commissioned in parallel, with attention paid to the transfer functions of the separation/recombination dipoles.

The method for threading has been checked by coupling MAD-X to the YASP steering program [11], via a filter for aperture and added BPM noise The results were promising (in the absence of big problems, e.g. quadrupole polarity reversals), with 13 iterations required for the full LHC first-turn. 1-4 iterations are expected to thread the beam to the IR7 TED. The method was shown to be fairly insensitive to errors, such as isolated bad BPMs with large (>10 mm) offsets.

The key hardware systems (aside from the obvious infrastructure, services and machine elements of the LHC itself) are the BPMs and orbit correctors. The BLM system should be ready for beam operation, and a number of mobile BLMs ready for fault-finding.

The dedicated or expert application software required includes the orbit application (YASP) and the BPM intensity signal display, together with online radiation and loss monitoring. It will also be an advantage to have the TI 8 plus LHC beam 2 MAD-X sequence available in the control system, with the full aperture model.

Remaining issues or areas for study are to extend the present threading simulations back upstream to the TI 8 TED87765, and to to check sensitivity to injection errors, quadrupole polarity errors, BPM sign errors, BPM H/V plane crossover, BPM calibration errors with energy offsets, mega-offsets and noise. The effect of the separation/recombination dipole transfer functions should be checked, and finally, if it is still judged useful, to test an automatic threader. For this the prototype must still be developed.

3. Linear optics measurements

12 hours foreseen

Estimate 400 shots of 1×10^{10} p+

Many important linear optics measurements will be made using BPMs and orbit correctors, supplemented by momentum adjustment from the SPS. The analysis of the measured response matrix allows determination of many key optics functions, Fig. 3. The method has been tested using the prototype tools with the LHC control system, in the 2004 TI 8 tests [12]. Higher intensity will be used for most of these shots, to improve the BPM response.

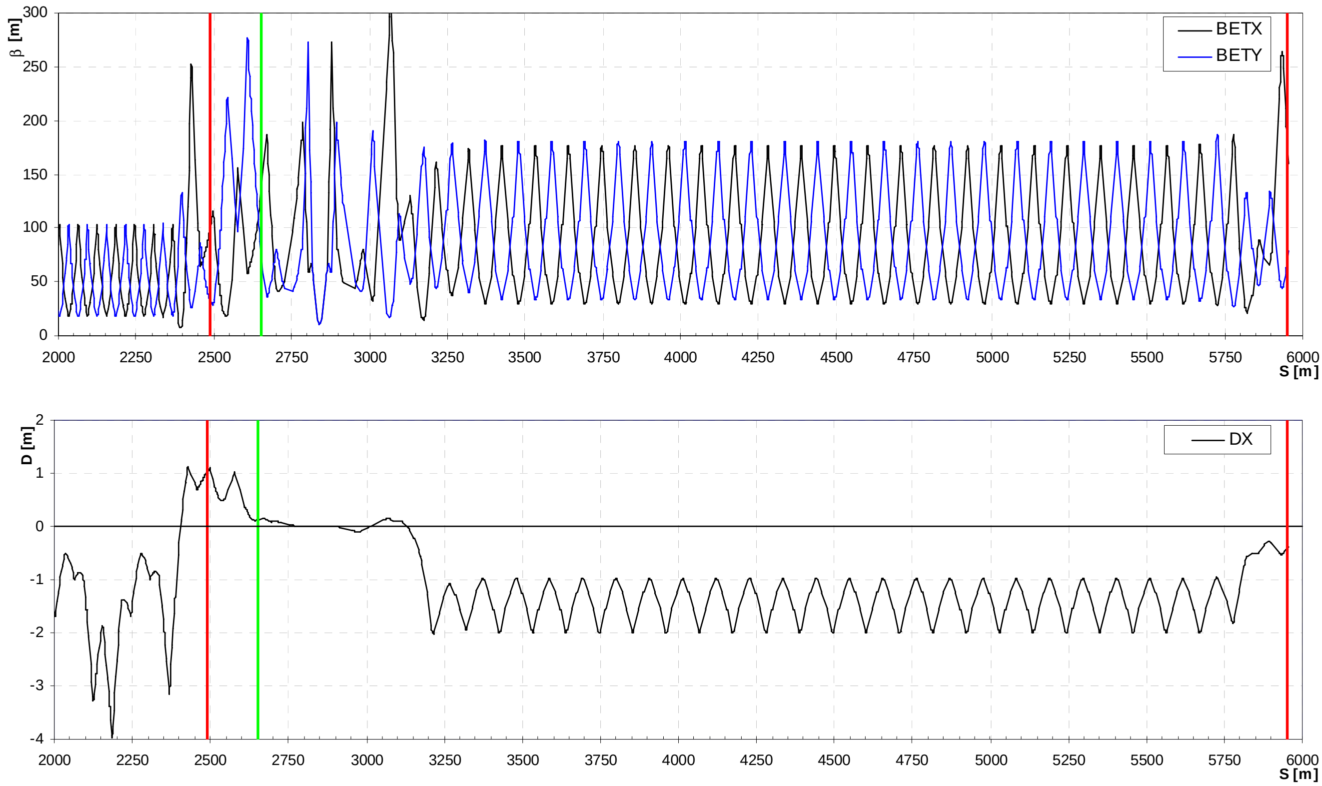

Figure 3. Beta functions (top) and horizontal dispersion function at the end of TI 8 and through LHC sector 8-7.

The possible measurements include:

- Adjustment of dipole current to beam momentum
- Phase advance
- Coupling
- BPM + corrector polarity and calibration
- Beta functions
- Dispersion functions
- Betatron matching factor (using BTVs)
- Chromaticity (momentum-dependent phase advance)

Of interest here are the errors which can be determined and expected measurement accuracy for the different parameters. During the TI 8 test results included:

- Found 20% error in 2 matching quads (due to I_{max} error in database)
- Found 11% BPM scale error (not yet understood)
- Found about 10% of the BPMs with polarity errors
- Found one corrector which did not work
- Measured 1% vertical phase shift (not yet understood)
- Measured coupling of maximum 2-3%
- Measured betatron mismatch factor λ of ~1.1
- Measured dispersion function to ±0.2 m, Fig. 4

The key hardware systems are again the BPMs and orbit correctors (which should be well-calibrated by this stage), together with the BTVs.

Dedicated or expert application software includes automatic kick-response measurement and logging, BTV image processing, online rematching tools, and possibly online (or efficient offline) analysis tools.

Remaining issues or areas for study include an estimate of the expected measurement accuracy, development if tools for online analysis and rematching, and the detailed test programme for the TI 8 beam tests in Oct/Nov 2006, which will serve as an opportunity for deployment and tests of the upgraded measurement tools.

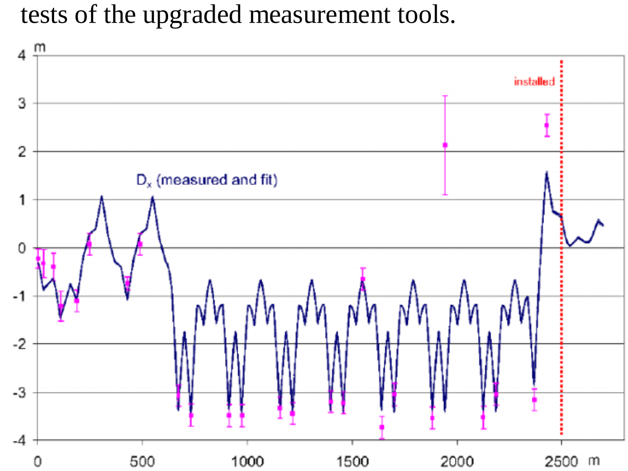

Figure 4. Measured horizontal dispersion function in TI 8 [12].

4. Commission Beam Loss Monitor system

6 hours foreseen

Estimate 500 shots of 5×10^9 p+

In addition to the BPMs, the other key distributed instrumentation system are the BLMs. These must be commissioned with beam, such that the system is up and running and recording losses. It is expected that there will be a lot of parasitic opportunity for commissioning the system during threading and first optics tests - prior calibration with a source means that many bugs will have been found, and that reasonable loss numbers can be expected quickly. During this commissioning, the acquisition and display of beam losses for as many monitors as possible is clearly required. Some crosstalk studies, Fig. 5, are also possible, as (in principle) the ‘beam 1’ monitors will be available. This BLM commissioning phase could probably be organised in parallel or in an interleaved fashion with the aperture measurements, since the requirements overlap to some extent.

The dedicated or expert application software required will be an effective BLM display program. The MCS utility [13] may also be required to adjust thresholds. The detailed general and local aperture models should be available.

Remaining issues or areas for study are to finalise the data exchange within the control system (for display, logging, PM, and threshold adjustment), how to make a meaningful BLM display (and whether this should be a prototype for the final LHC version, or a single-use application), and triggering for single-shot logging.

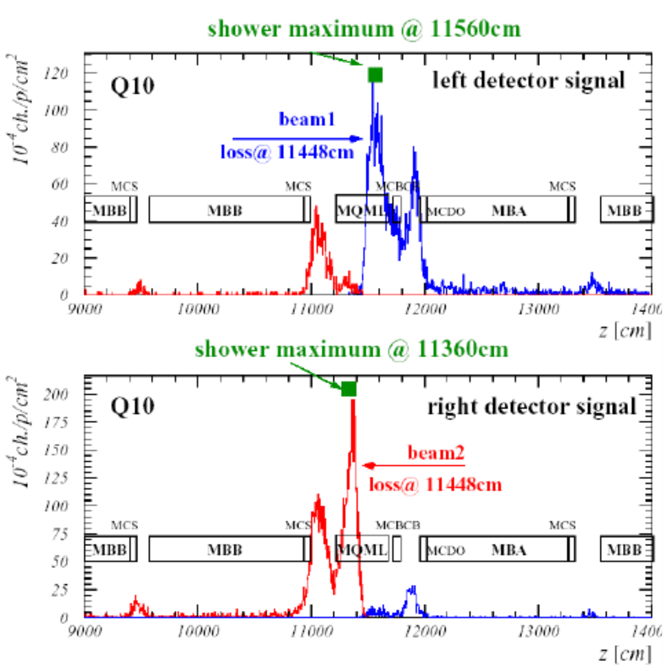

Figure 5. Simulated BLM response for LHC beam 1 and 2.

5. Aperture checks

24 hours foreseen

Estimate 1100 shots of 5×10^9 p+ with 1 μm ε_n

Although any major problems with the aperture will already have come to light by this stage, this measurement is aimed at a verification that the detailed physical aperture is as expected, particularly for known bottlenecks like the MSI, and also for the LHC arc. In a first iteration, it is planned to sequentially excite 2 correctors at approximately 90º phase difference to generate unclosed betatron oscillations, and to scan systematically over all phases, for both horizontal and vertical planes. The beam transmission will be measured and this will give a generic aperture envelope with little information about the local aperture. In a second iteration, π bumps will be produced to scan the aperture at well-defined locations, to check any local anomalies and to measure in specific regions. Clearly the region around LHCb must be treated with caution to avoid irradiation.

The momentum aperture of the LHC sector can be checked by measuring the transmission as a function of momentum offset, obtained by changing the SPS RF frequency. This will be limited by the TI 8 arc (which has a max |Dx| ≈ 4 m, compared to 2 m in LHC), where the momentum aperture has been measured at ±0.003 [12], Fig. 6, about 50% of what is expected for the LHC arc. Measurement of the momentum aperture will therefore require rematching of TI 8 to accept such a large δp.

Fig. 7 illustrates the nomalised aperture at the end of TI 8 and in the LHC sector 7-8.

The key hardware systems are correctly functioning and calibrated correctors and BPMs. A subset at least of the latter should be equipped to provide beam intensity information. The BCTs at the end of TI 8 and in IR7 will be required. BLMs will be needed, especially in the event off a local problem to be investigated, where mobile BLMs could be useful.

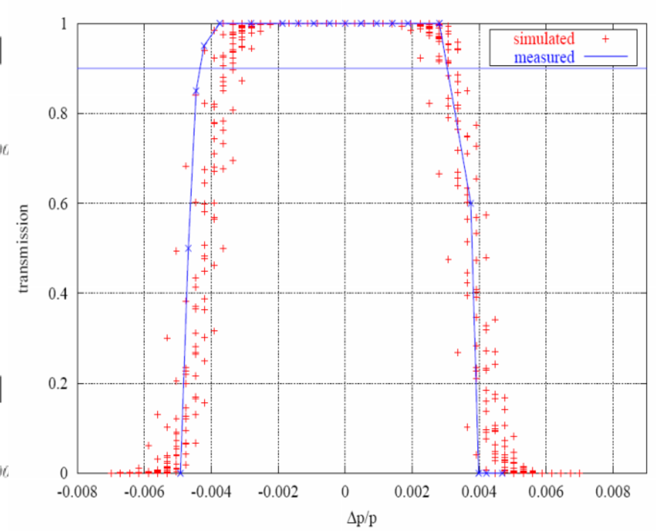

Figure 6. Simulated and measured momentum acceptance for TI 8 [14].

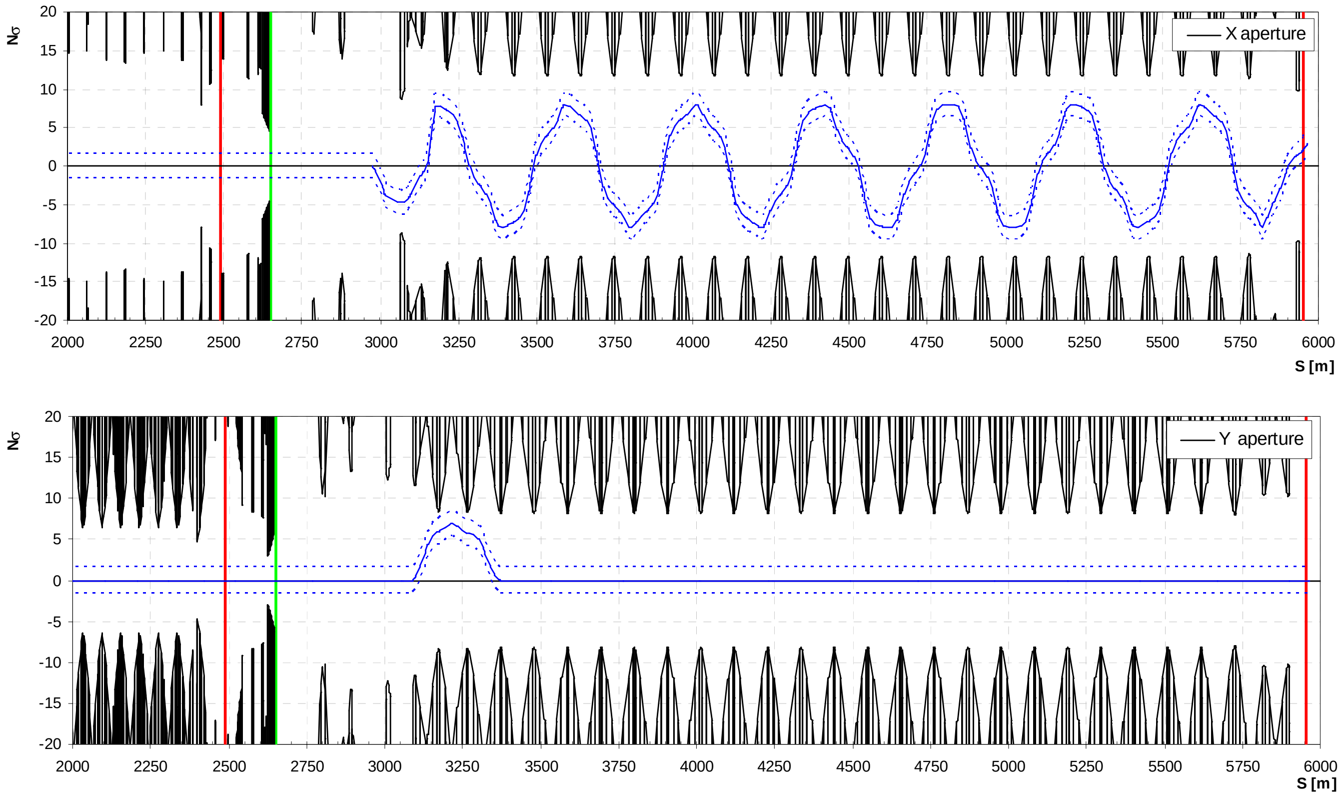

Figure 7. Unclosed horizontal oscillation (top) and closed vertical oscillation for aperture measurement. The available aperture is shown, as calculated with the transfer-line formalism described in [14].

The dedicated or expert application software required includes automatic kick-scan and transmission/loss measurement applications, for the free oscillations (where sampling ~5 amplitudes, ~12 phases, 2 planes and ~2 starting locations gives approximately 240 separate measurements), and for the sliding bumps (where ~45 correctors, ~5 amplitudes, 2 planes gives about 450 measurements). In addition, an online version of the detailed aperture model from TI 8 to the IR7 dump is necessary.

The remaining issues or areas for study are simulations of the method of how to measure the LHC momentum acceptance, rematching TI 8 to a large δp offset, and preparation of the required bumps.

6. Quench limits and BLM response

36 hours foreseen

Estimate 20 shots of 1×10^{11} p+

The injection test provides the possibility to expose the superconducting LHC magnets to beam, to verify the estimated quench levels at injection and, equally importantly, to provide a cross-check of the measured loss patterns at the BLMs, at the quench level.

For these tests, described fully in [8], the injected intensity will probably need to be increased above the pilot level, with a maximum suggested of 1×10^{11} p+, corresponding to 5% of the estimated damage level for nominal ε_n. 10 cycles with this intensity are the maximum which could be envisaged. Higher intensity is not foreseen, since this would require multi-bunch injection to be commissioned, and also reduces the safety margin with respect to the calculated damage limit.

Outstanding issues or areas for study are the detailed energy deposition model for the proposed beam trajectories and BLM disposition, checking whether the damage level of the SC coils is as presently assumed, and checking whether producing and measuring a beam with lower than pilot intensity is possible, should this be required.

7. Commission nominal cycle

24 hours foreseen

Estimate 300 shots of 5×10^{9} p+

The tests 1-6 described above are planned on the 'de-Gauss' cycle [15], in order to maximise the stability of the LHC and to eliminate the problem of persistent currents during the initial beam commissioning. However, the magnetic behaviour is expected to be better known for the nominal cycle. The stability and persistent current effects are important effects to study, Tab. 1, since understanding and control of these effects are fundamental to the operation of the full LHC. In this context it is clearly an advantage to be able to commission the real 'nominal' cycle, with the main bend current cycled to 100% of the 7 TeV value, since cycling to a reduced level (as could be imposed by a reduced hardware commissioning [5]) will reduce the level of knowledge of the magnet cycle and also reduce proportionately the magnitude of the persistent current decay.

With the nominal cycle in place, the first series of injections and measurements should take place after waiting ~30 minutes, for full decay of persistent currents. Once this has been commissioned (i.e. beam injected, threaded and the trajectory corrected) and the first series of measurements made, the injection can be made immediately after recycling, to start to address the issues associated with persistent current decay.

Table 1. Effect of different cycles on persistent current effects (values quoted in units of 10^{-4}).

Error	Systematic	Random	Decay syst.	Decay rand
b1	0.0	±8.0	0.8	±0.7
a1	0.0	±8.0	0.0	±0.0
b2	-1.1	±0.6	0.0	±0.1
a2	-0.4	±1.2	0.0	±0.2
b3	-3.7	±1.4	1.7	±0.4
	Nominal cycle			
	Waiting 30’			
	De-Gauss			

8. Reproducibility and energy offset tests

36 hours foreseen

Estimate 300 shots of 5×10^9 p+, 100 shots of 3×10^{10} p+

The reproducibility of the LHC at injection for the ‘nominal’ cycle is an important input into the operational strategy, especially for injection, machine protection and collimation. With the single-pass techniques available, the measurements are expected to be able to resolve between 0.5-1 units of b1 and about 1 unit of b3, by trajectory response and measurement of the dispersion trajectory. The b1 is expected to decay by 1.5-2 units for the nominal cycle (but only by 0.7 units for a cycle which goes to 30% of the 7 TeV level). The random error given in Tab. 1 should not be affected by cycling to lower than the 7 TeV level. These measurements will be made initially after waiting 30’ for the persistent currents to decay, and then directly after recycling. The 24 hours foreseen will not allow very many LHC cycles – from this point of view it is clearly crucial to have the measurement and data-taking tools well prepared and usable from the start.

For some part of the measurements it may be necessary to use 2-3×10^{10} p+ per bunch, for improved BPM resolution.

9. Detailed field errors – high statistics

12 hours foreseen

Estimate 200 shots of 1×10^{10} p+

The kick-response and trajectory analysis using LOCO [16] allows determination of the average a2, b2 and b3 field errors of the main bends, as shown in simulation in Fig. 8, and the b2 errors of the main focussing quadrupoles. The technique can also be extended to check multipole corrector polarity, by strong excitation of these circuits. This measurement requires the machine to be well understood regarding the linear optics, and good stability – it also needs the rms of the BPM noise and of the injection errors to be below 200 µm (corresponding to ~0.2 σ). This appears feasible based on the BPM responses from the TI 8 tests [12], from the measured 0.1 σ rms stability of the TI 8 line [17] and the expected random error of below 0.1 σ rms from the LHC injection system [18].

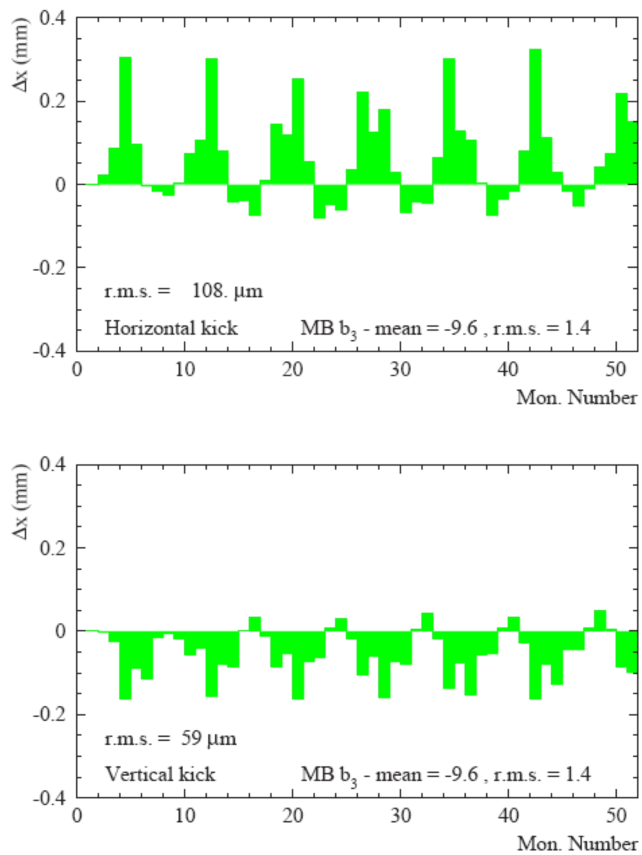

Figure 8. Effect on horizontal trajectory of b3 field errors of the main dipoles for 40 µrad horizontal (top) and vertical (bottom) kicks [16].

10. Commission machine protection subsystems

12 hours foreseen

Estimate 1600 shots of 5×10^9 p+

The machine protection at injection into the LHC relies on active and passive elements [6], including mobile collimators which must be set very accurately according to the beam axis and envelope. Setting up procedures rely on beam based alignment, and first ideas have already been tested for a single pass [19]. This technique may also be of interest for setting up the LHC machine collimators in inject and dump mode.

In the injection test, the beam-based alignment of the TCDI and TDI jaws using a transmission measurement with a single pass will be tested, using 5×10^9 p+ to limit the integrated losses given the high number of shots which will be required. Some shots of 3×10^{10} p+ may also be needed to measure accurately the beam axis. The LHC sequencer can also be tested, since the equipment must have an associated 'operational state' which is a function of the previous beam commissioning steps.

Clearly for these tests the collimator control system must be operational, and a high level applications to drive the elements through the setting up procedures.

11. Commission separation & crossing bumps

6 hours foreseen

Estimate 100 shots of 5×10^9 p+

Although the beam tests will start with the crossing and separation bumps switched off, it will be of interest to commission these in order to study the bump closure, induced dispersion, the aperture and possibly the measurement accuracy of the crossing angle. The bump amplitude can if required be limited to well below nominal, in order to avoid irradiation of this region – in any case, the LHCb spectrometer and compensation will remain switched off. Injecting onto the vertical separation bump will mean an adjustment of the trajectory at the injection point by about 0.2 mm and 3.5 μrad – it is also possible to inject onto an opposite polarity bump [20].

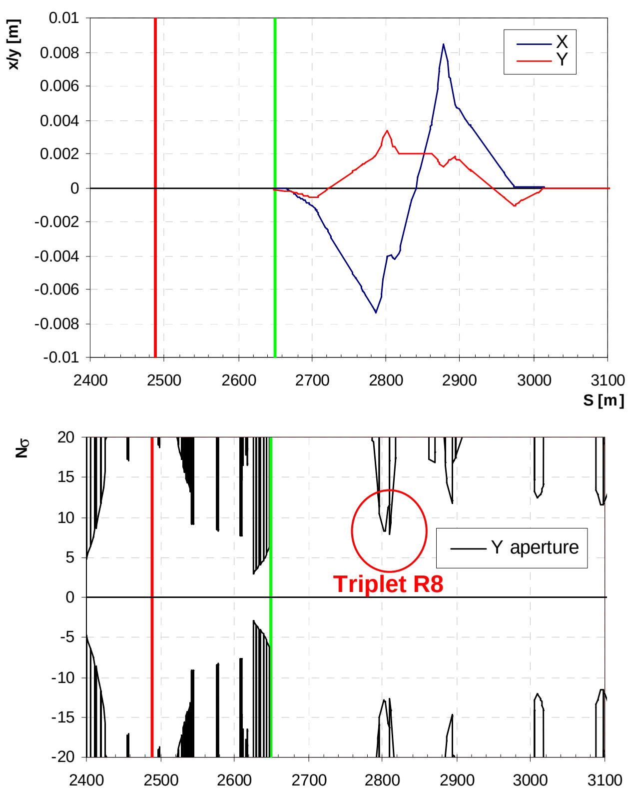

Figure 9. Crossing and separation bump in IR8 (top), together with the normalised aperture available in the vertical plane for nominal bump amplitude.

SUMMARY OF REQUIREMENTS, ISSUES AND TESTS

Requirements

The injection test obviously relies on the installation and hardware commissioning of a major part of the LHC equipment in the sectors 7-8 and 8-1, representing a large subset of the LHC accelerator systems. There are over 20 superconducting magnet types and around 120 circuits, with the injection elements and machine protection subsystems. The instrumentation essentials are the basic BDI systems, comprising the distributed BPM and BLM systems, together with individual BTVs and BCTs.

Regarding controls and software, an almost fully representative set of functionalities must be available. The minimum generic requirements for equipment control must be in place, together with data logging and diagnostics, plus some specific applications as detailed above. The magnet settings generation will need to be fully operational, with FiDeL interfaced to the LHC control system. Other requirements include the sequencer, single-shot injection logging, and online tools for matching and analysis.

Issues

Many issues still remain to be solved, or fully worked out after further study. These include the following aspects:

- The 'nominal' cycle definition – whether this can be to the 7 TeV current for the main bends or not, and the implications for the different proposed measurements.
- The expected accuracy of the magnetic model with the de-Gauss cycle.
- The LHC sequencer : whether this can be made as a full prototype, including injection sequencing from the SPS.
- Rollback for the controls system, to aid recovery from the different measurements and commissioning steps.
- The readiness of the collimator controls.
- Emittance control for the tests – whether ε_n of 1 μm is acceptable for all measurements, or needs to be larger e.g. for the quench tests.
- Verification of the damage levels of the superconducting coils.
- Intensity readback from some BPMS – which locations need to be instrumented in this way.
- Triggering and synchronisation of the single-shot logging
- Scope and feasibility of online matching and analysis tools.
- Whether multi-bunch injection should be commissioned.

Tests

A summary table of the proposed tests is given in Tab. 2. This will be updated periodically [21].

Table 2. Breakdown of the proposed tests, with priority, time estimate, intensity and cycle [21].

		Priority	Time	I	Shots	$\int I$	Cycle	Comments
			h	p+		p+		
1	End TI8, Injection Steering, commission BDI, timing	1	24	5E+09	500	2.5E+12	de-Gauss	TDI in, protecting LHCb
2	Trajectory acquisition commissioning, trajectory correction, threading, energy matching	1	24	5E+09	500	2.5E+12	de-Gauss	To IR7 beam dump
3	Linear Optics from kick/trajectory, coupling, BPM polarity checks, corrector polarity checks	1	12	1E+10	400	4.0E+12	de-Gauss	
4	Commission BLM system	1	6	5E+09	100	5.0E+11	de-Gauss	First to TDI, then to IR7 dump
5	Aperture limits, acceptance	1	18	5E+09	1000	5.0E+12	de-Gauss	Oscillations, π bumps, BLMs, BCT
	Momentum aperture	1	6	5E+09	100	5.0E+11	de-Gauss	Move energy of SPS beam
	Commission multi-bunch injection ?	*2*	*6*	*6E+10*	*50*	*3.0E+12*	*de-Gauss*	*BDI acquisition, MKI*
6	Determination of quench level - calibrate BLMs	2	36	1E+11	20	2.0E+12	de-Gauss	Start with pilot and work slowly up
7	Commission normal cycle - recheck dispersion, optics, aperture	2	24	5E+09	300	1.5E+12	Nominal	Cycle & wait
8	Effects of magnetic cycle, variations during decay, reproducibility	2	24	1E+10	300	3.0E+12	Nominal	10 cycles
	Energy offset versus time on FB	3	12	2E+10	100	2.0E+12	Nominal	Cycle & repeat
9	Field errors (high statistics)	3	12	2E+10	200	4.0E+12	Nominal	Collect data, off-line analysis
10	Transfer line collimation studies - TCDI	3	6	5E+09	800	4.0E+12	Nominal	TDI in - mainly on to TCDI
	Injection protection studies - TDI	4	6	5E+09	800	4.0E+12	Nominal	On to TDI and IR7 dump
11	IR bumps, aperture, separation, crossing angle bumps [LHCb?]	4	6	5E+09	100	5.0E+11	Nominal	Careful in LHCb

TOTAL		222		5270	2.9E+13		On to TED
DAYS		9.3			6.5E+12		On to TDI
					4.0E+12		On to TCDI

CONCLUSION

The injection beam test will be a major step towards an operational LHC. The test will verify the proper functioning of the fundamental BDI systems, with checks of the BPM resolution, cabling, polarity and offsets, BLM response and resolution, and BTV resolution. The tests will verify with certitude that the aperture is as expected in the critical injection region and also in the arc and around IP8. In addition to the BDI, other hardware will be commissioned with beam, including the main magnets, injection system, orbit correctors, timing and machine protection. The beam will sample all magnetic fields over 1/8 of the machine, which gives direct information about many aspects, including polarities, optics, key field errors to 1 unit, misalignments and corrector cabling. The test allows the deployment of control and correction procedures, via the beam threading, trajectory correction and bumps, and allows the magnetic model accuracy to be checked, providing data about the reproducibility of LHC cycle at injection and confirmation of the expected performance. The test also provides an opportunity to determine magnet quench levels and BLM response.

ACKNOWLEDGEMENT

The direct and indirect contributions from many colleagues are gratefully acknowledged, in particular from L.Bottura, B.Dehning, B.Jeanneret, L.Jensen, V.Kain, M.Lamont, V.Merten, R.Steinhagen and J.Wenninger.

REFERENCES

[1] M.Lamont. "Sector Test: Overview, Motivation and Scheduling", Proceedings of the 2006 Chamonix Workshop on LHC Performance, 2006.

[2] L.Bottura, "Magnets", Proceedings of the 2006 Chamonix Workshop on LHC Performance, 2006.

[3] L.Jensen, "Beam Instrumentation foreseen for the LHC sector test", Proceedings of the 2006 Chamonix Workshop on LHC Performance, 2006.

[4] R.Lauckner, "Control Requirements", Proceedings of the 2006 Chamonix Workshop on LHC Performance, 2006.

[5] R.Saban "Hardware Commissioning", Proceedings of the 2006 Chamonix Workshop on LHC Performance, 2006.

[6] V.Kain, "What is required to safely fill the LHC", Proceedings of the 2006 Chamonix Workshop on LHC Performance, 2006.

[7] M.Lamont, "Field model deliverables for sector test and commissioning: when and what ?", Proceedings of the 2006 Chamonix Workshop on LHC Performance, 2006.

[8] A.Koschik, "Magnet Quenches with Beam", Proceedings of the 2006 Chamonix Workshop on LHC Performance, 2006.

[9] H.Vincke, "Radiation Issue", Proceedings of the 2006 Chamonix Workshop on LHC Performance, 2006.

[10] A.Verdier, "First turn in LHC", LHC Project Note 308, CERN, 2002.

[11] J.Wenninger, "LHC Threading"", minutes CERN AB LTC meeting June 2005.

[12] J.Wenninger et al., "Optics Studies of the LHC Beam Transfer Line TI 8", Proceedings PAC'05 Particle Accelerator Conference, 2005.

[13] V.Kain et al., "Management of Critical Settings", Functional Specification, to be published 2006.

[14] B.Goddard et all., "Aperture Studies of the SPS to LHC Transfer Lines", Proceedings PAC'05 Particle Accelerator Conference, 2005.

[15] O.Brüning, "The Minimum Machine and the first 1000 turns (or so)", Proceedings of the 2003 Chamonix Workshop on LHC Performance, 2003.

[16] J.Wenninger, "Determination of LHC Main Dipole Field Errors during a Sector Test using Trajectory Analysis", LHC project note 314, CERN, 2003.

[17] J.Wenninger et al., "Beam Stability of the LHC Beam Transfer Line TI8", Proceedings PAC'05 Particle Accelerator Conference, 2005.

[18] B.Goddard et al., "Aperture and delivery precision of the LHC injection system", Proceedings EPAC '04, European Particle Accelerator Conference 2004.

[19] V.Kain et al., "Beam Based Alignment of the LHC Transfer Line Collimators", Proceedings PAC 2005 Particle Accelerator Conference, 2005.

[20] W.Herr, "The Solenoids and Dipole magnets of LHC experiments", Proceedings of the 2006 Chamonix Workshop on LHC Performance, 2006.

[21] http://lhc-injection-test.web.cern.ch/