INITIAL BEAM COMMISSIOMING OF INJECTION AND BEAM DUMP

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Abstract

The initial commissioning of the LHC injections and beam dumps allowed the basic functionality of the systems to be verified, together with progress to be made on some of the systematic checks and measurements foreseen in the detailed commissioning programme. The observations and measurement results are summarised, including comparisons of element strengths and synchronisation, details of the local aperture measurements and some performance data for specific equipment sub-systems. The lessons learnt for the future LHC commissioning are emphasised.

INTRODUCTION

Beam commissioning of the LHC injection and beam dump systems was started in 2008 with the sector tests [1] and the short period of full LHC ring operation from September 10th to 19th. During this time the basic functionality of the systems was demonstrated, and a start was made with the detailed measurement programmes which had been devised to ensure that the equipment and concepts were according to the specifications. The very impressive efficiency with which the beam commissioning was able to proceed was due to the painstaking preparation and experience gained with beam commissioning of the SPS to LHC beam transfer systems over the previous years, culminating in the continuous testing of the systems from the control room for most of 2008.

This paper focuses on the beam commissioning results, and first describes the performance of the injection systems, followed by that of the beam dump systems. Some particular sequencing and machine mode aspects are described, and finally the lessons learned and the inferences for 2009 are detailed. The performance of the beam instrumentation has been described elsewhere in these proceedings [2], and an overview of the controls performance has also been made [3]. These systems are therefore only alluded to where specific concerns or issues have arisen.

INJECTION SYSTEMS

The LHC injection systems comprise septa MSI, kickers MKI, protection devices TDI, TCDD and TCLI, various beam instrumentation and associated controls hardware and software. Good progress was made with commissioning with beam during 2008 due to the three weekends of sectors tests in August and September, during which the systems were debugged and the detailed measurement programme launched.

Element strengths

The strengths of the different injection elements were verified from checking the positions on the injection screens, Fig. 1, and from the injected trajectory. The strengths were correct to the resolution of the measurement – MKI to within about 2% and MSI to within 0.4%. No trims of these element strengths were needed at this early stage.

One unforeseen problem discovered was the periodic displacement of the circulating LHC beam closed orbit by about 0.5 mm, which seems to be due to the pulsed leakage field of the MSI magnets. The solution of powering these magnets DC is being investigated – this is possible from the magnet power dissipation and the power convertor side, but the control and interlocking implications need to be investigated.

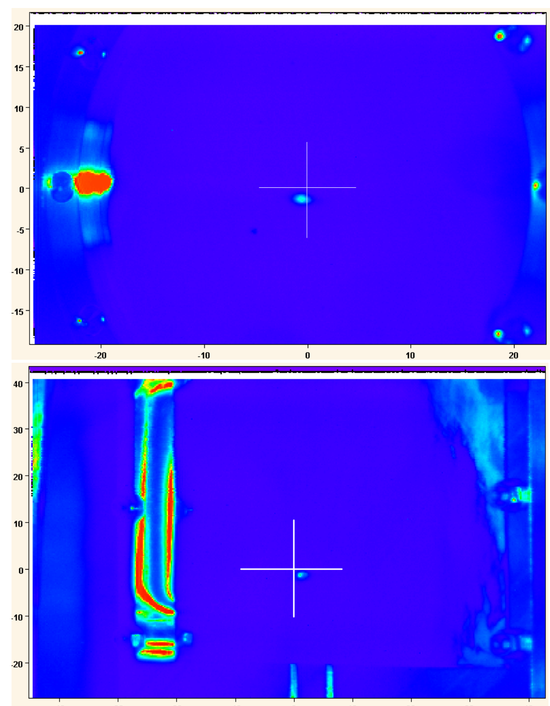

Figure 1: Injected beam 1 on screens in IR 2, with expected beam positions marked by white crosses (scales in mm). The top screen is at the exit of the MSI, and the bottom screen just upstream of the TDI, after the MKI.

Synchronisation

The synchronisation between SPS extraction and LHC injection worked well, after the initial kicker timing-in procedure was carried out as expected. The dynamic destination was implemented in SPS, which should allow the correct injection sequencing for LHC filling in 2009 and beyond. The adjustment of the rough injection kicker timing worked correctly, and the single bunch injected near the centre of the MKI kicker pulse, Fig. 2. The adjustment procedure tricky for the timing in was complicated to some extent by the kicker noise on transfer line BCT signals – this has been upgraded for 2009 with the addition of tri-axial shielded cables.

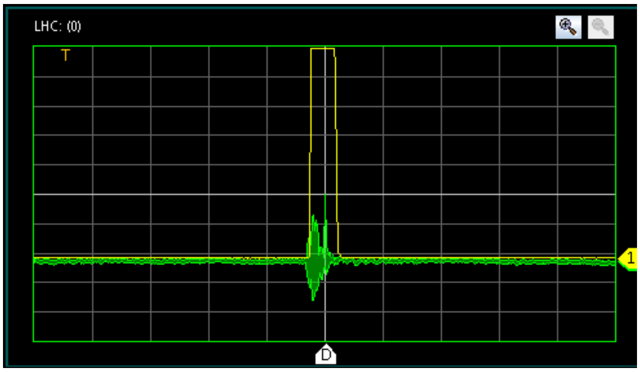

Figure 2: Injection of a pilot bunch, showing the kicker waveform in yellow and the downstream TI 2 BCT signal in green. The beam signal is visible after the kicker noise.

Aperture measurements

The apertures in the injection region were measured using the single pass technique of unclosed oscillations at various phases, which was already used extensively for the measurements of the transfer line apertures in preceding years [4]. The job was made much easier by the excellent tools available in the control system, in particular MadX-online which allowed dynamic configuration and visualisation of the measurement bumps in the control room.

The apertures were measured with a pair of correctors using oscillation phases 0f of 0, 30, …330 degrees, with a small emittance pilot beam (ε_n of about 1 μm per plane). The 20 mm aperture of the MSI protection device TCDIM was confirmed, with the beam well-centred in IR2 and displaced vertically by about 2 mm in IR8, Fig. 3. In IR2, however, during the first sector test it was quickly apparent that the aperture between the MSI and the downstream Q5 quadrupole was about 6 mm smaller than expected in the vertical plane, towards the bottom of the machine. A radiation survey after the test confirmed a hot-spot of about 3 μSv/h on the vacuum valve assembly VANMF.5L2, and checks with the vacuum group revealed that this element was installed 10 mm too high. A vertical re-alignment was made and the next check with beam showed that the aperture was as expected.

The potential limits in the vertical aperture at D1 with MKI off were planned to be checked using RCBYV.4, but this was not done due to lack of time. In addition no systematic circulating beam aperture checks were made, in particular at the MSI and TDI, although the TDI for beam 1 was moved in to the protect position while beam 2 was circulating, with no beam losses detected.

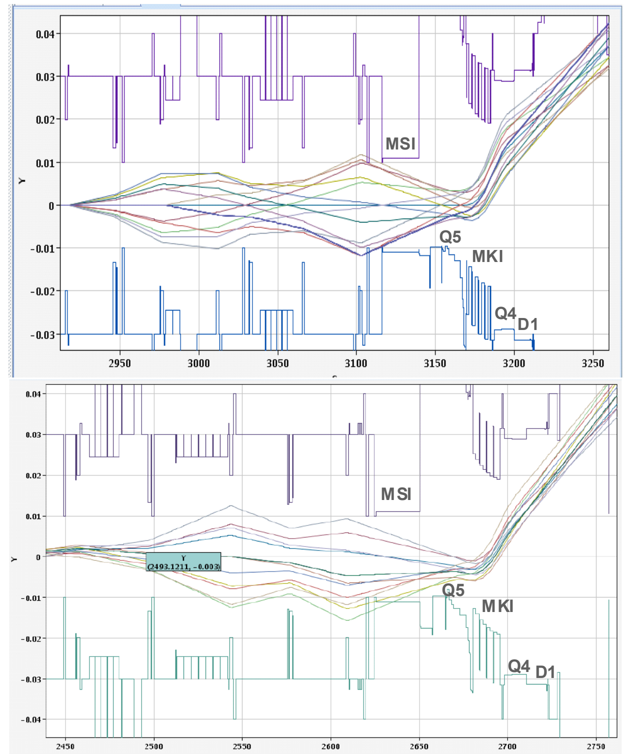

Figure 3: Vertical aperture scans of injection regions in IR2 (top) and IR8 (bottom). The estimated edge of the beam envelope is plotted, calculated by adding the actual trajectory to the beam size. The MKI are off, and the beam direction from left to right in both cases.

Steering and stability

The first injection steering was done for beam 2, which was initially several mm off in the vertical plane (see Fig. 3). The autopilot algorithm converged correctly; there was not time however to remeasure the aperture and also to revisit the MSI and MKI strengths.

The short-term (~1 h) stability was measured for beam 2 at the injection point using the screens in LHC point 8, Fig. 4, from which very accurate position data was obtained on a shot-by-shot basis. The measured RMS jitter was 0.27 nominal beam sigma in the horizontal plane and 0.13 nominal sigma in the vertical plane, compared to the specification of ±1.5 nominal sigma error (RMS) in both planes. From this data an upper limit on the MKI kicker instability from the charging voltage was also made, of about 1.7×10^{-3}, compared to 5×10^{-4} specified. SVD analysis of the data sets to try and find the source of the perturbations were not considered worthwhile, due to the poor phase sampling – however, this can be envisaged if stability data were to be taken using all screens (16) in the transfer lines and injection region. The measurement of the MKI waveform flat-top, using the kick delay, was not measured due to a lack of time.

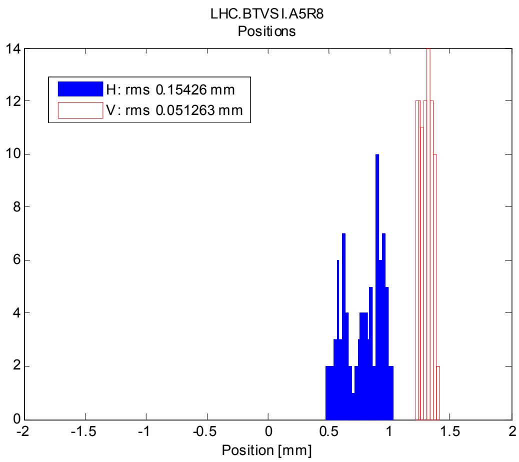

Figure 4: Distribution of measured horizontal and vertical beam positions on injection screen BTVSI.A5R8, over about 1 hour. At this location the stability (RMS) is about 150 μm in horizontal and 50 μm in vertical.

MKI kicker flashovers

Flashovers of the IR2 injection kickers were seen on two occasions. The first occurred at about 19:15 on 9th August 2008 on kicker C, during the SoftStart, after the aperture measurements described above, where the MKI were switched off. During the measurement the pilot beam was lost several times on the VANMF.5L2 aperture limit upstream of Q5, with a total loss of about 5×10^{10} p+. The flashover happened some 30 minutes later when the kicker was switched back on and the voltage being increased to nominal. An analysis of the logged data showed that the beamlosses were visible on the measured vacuum signal, Fig. 5, as physically impossible dips in the pressure reading probably resulting from ionisation in the HT feedthroughs. The sensitivity to the beamloss is worrying – to provide more exact data BLMs were installed for 2009 on the MKI kickers themselves, and the beamloss signal from these monitors will be interlocked or alarmed to try to avoid this.

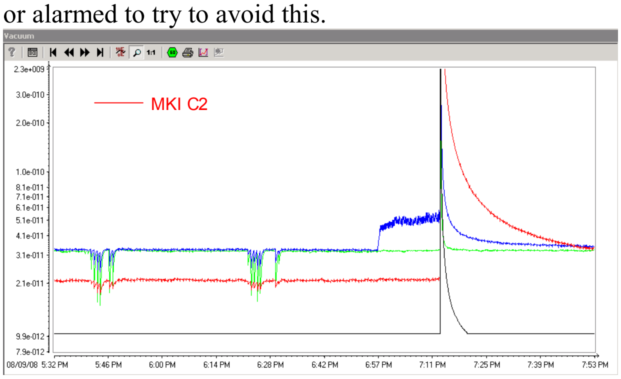

Figure 5: Flashover on MKI.C2 on 9/08/08 after upstream beamloss.

A second flashover occurred in IR2 on the MKI D, the first magnet seen by the beam, on 7th September 2008 at about 04:40 during a polarity measurement of magnets in the LHC arc. This happened during the beam passage where the MKI was on, and where there was no preceding beam loss in the region. The injected trajectory, Fig. 6, showed a clear overkick of the magnet D by about 40 urad, which is 20% of the magnet kick and corresponds to a 5 σ oscillation, which indicates that the magnet broke down some 60% along its length. The logging of the MKI waveforms show the affected pulse, Fig. 7. This failure demonstrates clearly the need for the TDI protection to prevent damage to the downstream arc.

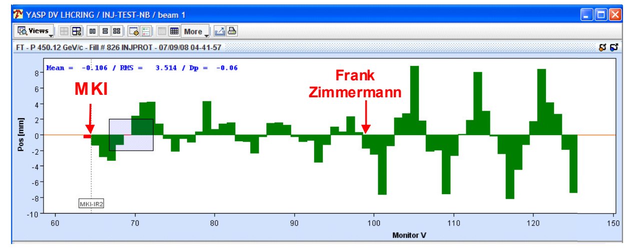

Figure 6: Vertical difference trajectory of miskicked beam in arc 23 after flashover of MKI.D2 on 7/09/08. The initial oscillation amplitude is about 5 σ.

Operational aspects

The injection systems are complicated with a lot of dependencies, which means that injection requires a lot of preparation for OP. The steps needed are:

- Injection kicker SoftStart
- Beam permit loops
- SPS and LHC modes
- LBDS arming
- Beam extraction from SPS
- Kicker-beam synchronisation check
- Beam to TED, TDI and into LHC

Because of the complexity, the operators were frequently stressed or thwarted with the SoftStart seconds running out. The systems has been improved where possible for 2009, including a new SoftStart which shorter with no 'cheats', and improved arming and sequences. The MKI application software is being updated, and operator training is also planned. In addition, the first version of the injection quality checks should be ready in 2009 to check kicker pulses, BLMs and the filling pattern.

BEAM DUMP SYSTEMS

The LHC beam dump systems comprise septa MSD, extraction kickers MKD, dilution kickers MKB, protection devices TCDS, TCDQ and TCSG, the beam dump block TDE and various beam instrumentation and associated controls hardware and software. Some progress was made with commissioning with beam during 2008 due to the final sector test in September and the few days of full LHC operation, during which the systems were essentially debugged to an extent.

The beam dump was initially commissioned using horizontal corrector pairs excited at fixed current to steer the beam into the extraction channel without having to worry about the MKD timing or strengths. Once the beam extraction was assured, the kicker timing was advanced to extract the beam, which for both rings worked well first time. Fig. 7 shows the screenshots from the three screens in the beam 2 dump line, for the first beam extracted with the kickers. The corrector extraction was implemented in the control system as a knob which will also be used for the measurement of the simulated MKD failures and the aperture scans.

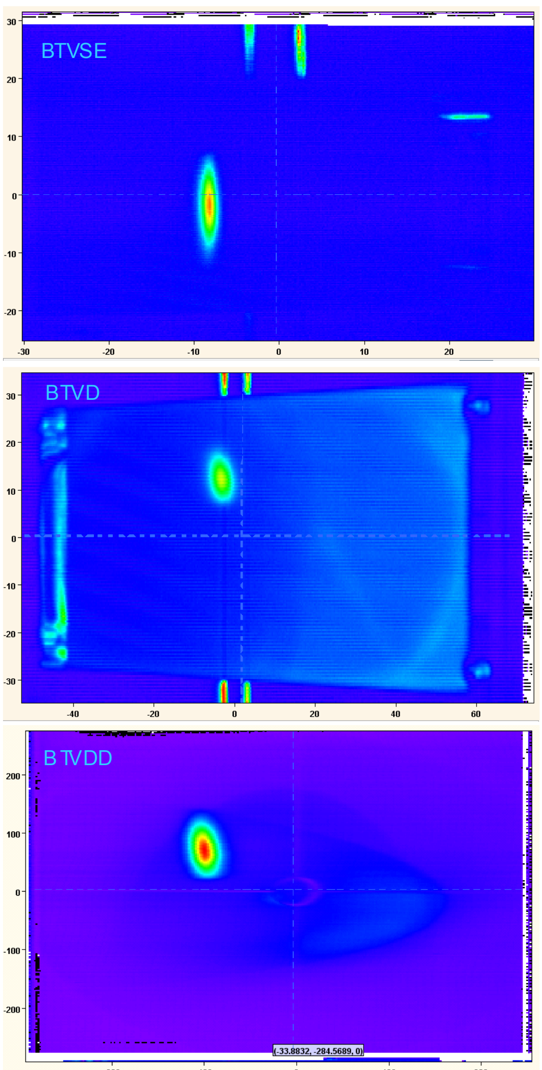

Figure 7: First beam extracted in TD62 onto the TDE in UD62 using the full beam dump system.

Strengths

During the first beam dump beam tests it was clear that the MSD strength was too high, as shown by the trajectory reconstructed from the measured beam positions on the screens, Fig. 8. The MSD septum strengths were initially too strong by 200 µrad (2.6 mrad instead of 2.4 mrad nominal) which gave very bad trajectories during the 3rd sector test when the beam was first dumped. When this error was corrected, which required a tunnel access to update lookup tables in Energy Tracking System, the vertical and horizontal trajectories looked good in both dump channels.

The MKB dilution kicker strengths looked reasonable as deduced from parasitic sweep data (see below).

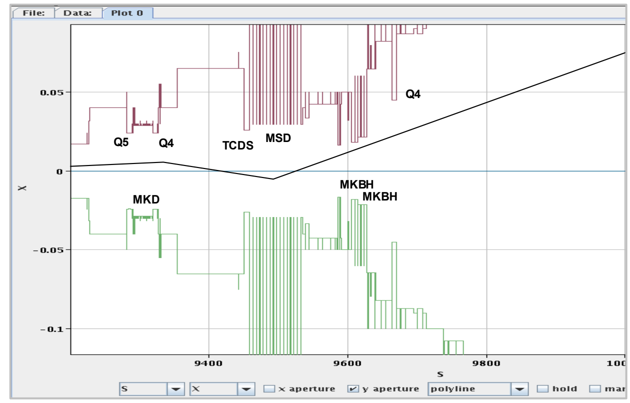

Figure 8: First vertical trajectory of extracted beam in TD62. The error from the MSD strength is clearly visible.

Synchronisation

The TSU locking and arming worked very well and this was extremely stable. The two TSU PLLs per beam were locked to the 11 kHz revolution frequency with a precision of better than 5 ns, Fig. 9.

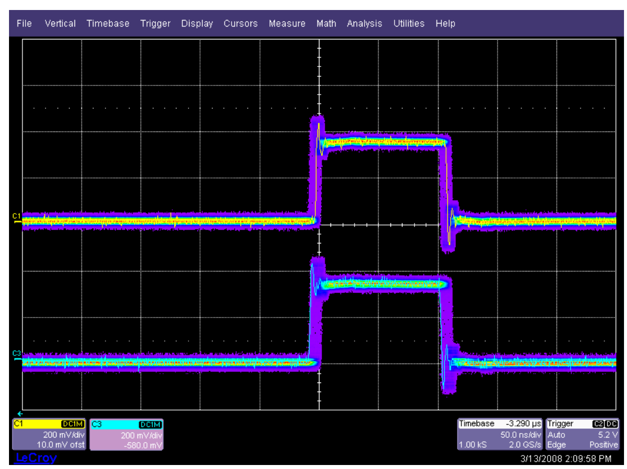

Figure 9: Synchronisation of the two redundant PLLs with the revolution frequency for beam 1.

For the kicker timing, the rough timing in and synchronisation was done, and the beam extracted near the centre of the MKD kick waveform.

The abort gap keeper AGC signal was generated and synchronised with the beam abort gap in the TSUs, and sent to the injection systems. Validation was made of the transmission of the 11µs AGK window from the LBDS to injection kicker systems over the single mode optical fibre, and of the implementation of the fast inhibition of the injection prepulse with the AGK signal, but unfortunately there was no time to test with beam.

Aperture measurements

Only a very short dedicated time was available for aperture measurements. Some initial data were taken from

00:00 to about 04:00 on 19/10/08, but were interrupted by problems with arming the LBDS then the sector 34 accident. As a result only a few phases were checked for B1. No obvious problems were seen, however, and "loss free" extractions were recorded. The measured aperture at the TCDS of 6.5 σ_x needs careful checking in 2009.

Diagnostics and XPOC analysis

The automatic XPOC analysis for MKD and MKB kickers proved to be mature and was used throughout 2008 for the reliability run, dry runs and commissioning. This produced good results, including the finding of some disconnected trigger cables which led to a repair and an update in the procedure for maintenance. The analysis of BI systems started with beam, which was mainly the BTVDD screen. The analysis results and references agree well, Fig. 10, which shows that the MSD, MKD and MKB strengths are all reasonable. The XPOC will be finished in 2009 and embedded in the PM system

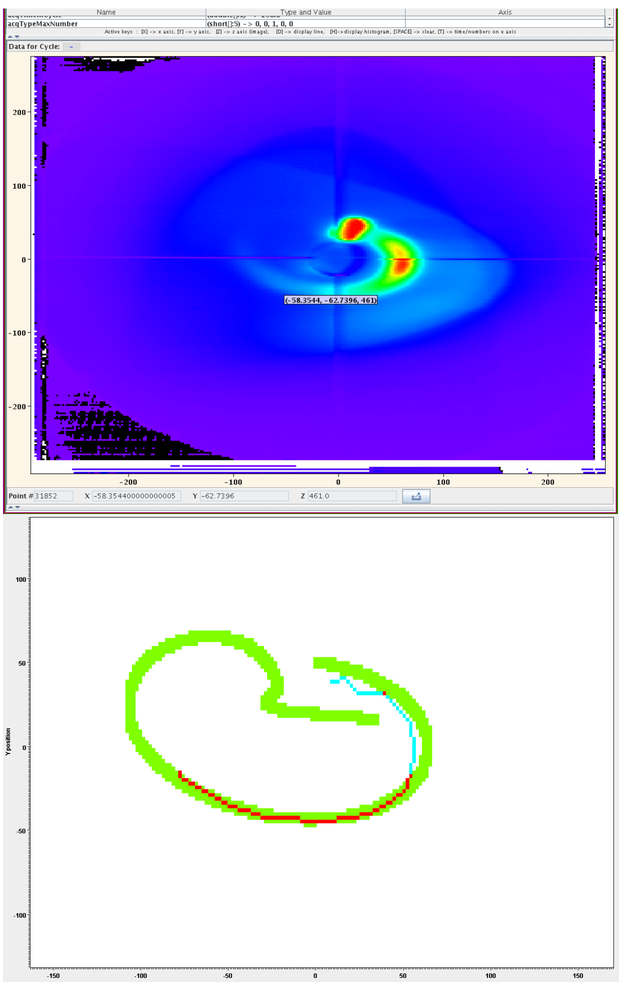

Figure 10: Beam sweep measured on BTVDD (top) and XPOC analysis (bottom). The XPOC analysis shows the comparison between analysed extraction sweep (blue) and simulated sweep (green).

Sweep characterisation and asynchronous dumps

The few days of LHC operation produced an interesting gallery of different beam dumps, with uncaptured beam, sweeps, different parts of kicker waveforms, unstable beams and timing errors. Some of these have been used to validate the XPOC analysis which has also allowed the element strengths to be checked. In addition, the data are being correlated with the beam losses at extraction elements and around LHC, which could give some experimental data for some of the simulations on failure cases. Here there is the problem that the data sets are huge and the available tools for browsing the logged BLM data are not adequate.

SEQUENCING AND MACHINE MODES

Many different sequences were developed and tested for injection and dump systems, including injection, SoftStart, arming, inject and dump and circulate and dump. These all functioned correctly and some improved versions now available with better exception handling and error messages. The question of unskippable tasks for these critical systems needs to be addressed. Some aspects of the RF prepulses still to be tested, for example rephasing for bucket selection.

For the timing system all required timing tables had to be maintained, loaded and unload at the correct times, which was somewhat susceptible to error and may be improved.

Concerning the machine modes, Inject and Dump mode worked well and was tested that it could dump both beams on the initial turn, for bunch 1 in batch. This needs still to be tested for other bunch numbers, and there is a conceptual issue to fix on the PM suppression which limits the maximum delay to ~20 turns instead of 1000. The Circulate and Dump mode worked without problems, where the beam was dumped with a timing event with a delay set in ms. A slight improvement in the way to adjust the injection – dump delay is needed.

SUMMARY OF PROGRESS

In 2008 the beam commissioning was very efficient and productive despite the short time available, due to the intense preparation, the dry runs and the Sector Tests with beam. For the pilot beam, about 50-60% of the beam commissioning program for the injection/transfer lines and about 10-20% of the commissioning program for the dump was completed. Tables 1 and 2 summarise the progress made with the two systems, and the remaining tasks with the pilot beam.

Table 1: Progress with injection and transfer line commissioning

	Beam 1 (TI2/P2)	**Beam 2 (TI8/P8)**
Transfer line optics	Done	Still question of dispersion match
Injected beam aperture	Done (after vac. re-alignment)	Done
Kicker synchronisation	Done (rough)	Done (rough)
Injection element strengths	Done	Done
Beam instrumentation checks	Done	Done
Check injection stability	Started (data to evaluate)	Done
Interlocks	Started	Started
Circulating beam aperture	To do	To do (TDI moved in - OK)
Injection steering	To do	Started (rough)
Kicker waveform measurement	To do	To do
Detailed optics matching to LHC	To do	To do
Injection protection systems setup	To do	To do
Injecting onto Xing/sep bumps	To do	To do
Abort gap keeper	To do	To do

Table 2: Progress with beam dump initial commissioning

	Beam 1 (TD/UD68	**Beam 2 (TD/UD62)**
Inject and dump setup	Done	Done
Circulate and dump setup	To do	Done
Dump region aperture	To do	Started (some phases)
Detailed kicker synchronisation	To do	To do
Extraction element strengths	Started (corrected MSD)	Started (corrected MSD)
Beam instrumentation checks	Started	Started
Interlocks (BPMSA, TCDQ, …)	To do	To do
Sweep waveform measurement	To do	To do (parasitic looks reasonable)
Dump protection systems setup	To do	To do
PM and XPOC	Started	Started
Tracking tests	Started (2 sectors only)	Started (2 sectors only)
Abort gap keeper	Started	Started

SPECIFIC PROBLEMS ENCOUNTERED AND GENERAL LESSONS

Short summaries of the different problems encountered are collected below:

- Kicker noise on BCT signal used for timing-in kickers – being fixed with better EMC shielded cables.
- 0.5 mm displacement of LHC circulating beam orbit when pulsing transfer lines – seems to be due to MSI pulsing and should be solved by powering these in DC in 2009.
- Flashover on MKI, both due to beam loss and spontaneous discharge – extra BLMs added and interlocking/alarms to be updated. Reinforces need for early and careful setting up of the TDI system.
- Aperture limit at VANMF.5L2 – wrongly installed valve group was realigned during an access and the restriction vanished.

- LHCb sensitive to beam passage through injection screens even for thin Ti – interlocking or procedures to develop.
- Wrong setting of MSD septum in controls DB – operator error, corrected for subsequent sector test.
- Inversion of injection screen images BTVSI.A5R8 and BTVSI.B5R8 – corrected before the 10th September.
- Inject and dump limited to about 20 turns delay instead of 1000 – due to fixed 2 ms PM inhibit timeout, which will be fixed for 2009.

In general the commissioning went well with good procedures, diagnostics and communications – the preparation of the tools for the different measurements was an important contribution, and regular preparation throughout 2008 and even before was instrumental in preparing the systems and also the people for the time with beam. The sector tests were a huge help and should be repeated if at all possible.

PREPARATION FOR 2009

For 2009 there are many small and not-so-small changes to the systems which have to be checked and rendered operational. The scheduling of transfer line beam tests is already tentatively made for June, with all the implications to check with the different parties concerned. The individual systems tests (ISTs) integration tests (ITs), dry runs (DRs) and machine checkout will again be key components in preparing the systems, and the work here has already started.

No reliability run is planned in 2009 but a lot of updates, modifications and new hardware and software must be validated. The same people, teams and organisation will be used as for 2008.

The question of formalising the interlock testing and/or acceptance remains open – this could be improved with respect to 2008.

One important point is that time must be schedule in the machine checkout for essential checks, like the energy tracking of the beam dump, because in 2008 the machine checkout time for this simply evaporated under the 10/09 floodlights.

CONCLUSIONS

The LHC injection and beam dump systems so far perform as expected, and the beam commissioning has started well. To date no major issues have been found, but a lot of work remains until the systems are fully qualified. Some of the main challenges for 2009 will be increasing intensity, abort gap cleaning and setting up of protection devices.

The tools, techniques and teams used in 2008 have performed well, and it is planned to keep essentially same organisation for 2009. Some minor improvements of diagnostic and analysis are tools needed and are in progress. Improvements have been made in sequencing, arming and software to make operations' life easier, and the full XPOC and Injection quality check deployment is planned. All hardware and software changes since 2008 need thorough validation

There is some concern about MKI flashovers with beam, for which an operational strategy needs to be defined. The systems integration and dry runs being organised and scheduled, to follow immediately the individual systems tests. It should noted that the progress in 2009 is some months behind the schedule with respect to the 2008 preparation, due to the impact of the LHC shutdown work.

The planned transfer line and sector beam tests in 2009 will speed up ring beam commissioning, and these should be firmly kept in the schedule, with the dependencies and impact worked on.

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