

## WHAT DID WE LEARN WITH BEAM IN 2008?

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### *Abstract*

2008 saw a series of injection tests and the start of beam commissioning in the LHC. The latter was curtailed by the sector 34 incident. Despite the short time with beam remarkable progress was made; this session was aimed at detailing this progress and elucidating the lessons learnt and the issues still to be addressed before the restart of the LHC with beam in the latter part of 2009.

### INJECTION TESTS

The injection tests proved to be a remarkably useful exercise for a number of reasons. They acted as a long term milestones and invoked painstaking preparation which resolved a large number of technical issues [1].

Although many controls, instrumentation and configuration issues did arise during the tests with beam, the problems encountered were rapidly overcome. The quality and sophistication of the measurements that were performed are unparalleled in initial accelerator commissioning. Among the contributory factors might be included:

- three years of preparation during which prerequisites, requirements, measurements, software, controls was revisited in depth a number of times;
- analysis of operational requirements and development of core software to provide the required functionality;
- deployment of software and controls components with enough lead time to allow in-depth pre-testing;
- 8 months of dry runs allowing individual system and integration tests;
- excellent performance of the key beam instrumentation all the way through the acquisition chain;
- a robust and complete magnet model based on processing and analysis of measurement data;
- a highly motivated and reasonably well organized team and excellent support from the numerous teams involved in preparing and running the LHC.

From the start of the, now distant, original discussions on the need for sector tests, it has always been argued that they are essential precursors in the preparation for full beam commissioning for any accelerator. This has been well proven to be true for the LHC.

### OPERATIONAL EXPERIENCE WITH CIRCULATING BEAM

Given the short period of having the whole ring available to take beam (10<sup>th</sup> – 12<sup>th</sup> September) a remarkable amount was achieved [2].

Beam Instrumentation commissioning saw the operational use of Beam Loss Monitors, Wire Scanners,

Beam Current Transformers and Beam Position Monitors with circulating beam. Importantly the BBQ based tune meter was also rapidly available in two modes enabling first measurements of tune, coupling and, perhaps, chromaticity. Closed orbit measurements were also available at 1 Hz allowing a first systematic analysis.

RF system commissioning progressed quickly and having established capture, the RF team were able to adjust the phase, the frequency and make first adjustment of the beam control loops. Momentum matching between the SPS and LHC was established. The effect of the recycling strategy was clearly visible in the close orbit.

Beam dump commissioning with beam continued and the system reacted correctly to the first emergency dump with circulating beam when the main bends in sector 23 tripped off.

Progress was so rapid in fact, the carefully laid out commissioning plan was not rigorously adhered to. In the circumstances, this was not really a problem: firstly because the beam intensity was safe, and secondly because consolidation was possible during the enforced days without beam that followed. However, increased rigour will be required when the moves to higher energies and intensities are made.

### BEAM-BASED MEASUREMENTS

During and following the time with beam, in-depth analysis of beam based measurements has been performed [3]. This had been based on the limited dataset that was taken in process of initial beam commissioning (the next phase of the commissioning sequence foresees dedicated measurements). Despite this some impressive results have been obtained and powerful techniques have been implemented to help identify optics errors and possible aperture problems.

Among the measurements and associated analysis performed are included:

- Aperture scans: both free betatron oscillation scans and closed orbit bumps at specific locations;
- Polarity checks of correctors, quads, higher order circuits – these have exposed both database & cabling errors;
- Beta beating analyses, after a lot of work, have shown acceptable beating in the horizontal plan and less good behaviour in the vertical plane has been tracked down at least partially to a quadrupole cabling error;
- Coupling analysis.

These analyses have given us both confidence in the tools themselves and in the quality of the measured optics and by implication the quality of the magnet model and machine alignment.

## TRANSFER LINES AND INJECTION: RESULTS FROM MACHINE STUDIES DURING BEAM COMMISSIONING

Spurious dispersion was measured in the LHC. This was rapidly tracked down to its origins at the end of TI8 which gives mis-matched entry conditions which then propagate into the LHC [4]. It is a relatively large effect and must clearly be resolved to avoid blow-up of the injected beam.

The measured dispersion in the majority of TI 8 is in good agreement with the model and iterations to check and improve this agreement have been made. Very thorough checks have been performed of alignment of all elements in the lower part of the line. A number of other measures have also been adopted:

- Alignment and corrector settings included in the optics model;
- Additional BPMs installed to provide better sampling;
- Dispersion free steering has been included in the trajectory steering program (YASP);
- Full TI 8 to LHC model to be used.

Apparently there is no golden bullet and it is hoped that the cumulative effects of the above measures will be enough to bring the problem under control. The problem will continue to be studied carefully, in particular during the transfer line and injection tests planned for 2009.

## INJECTION AND BEAM DUMP

### *Injection*

Injection is clearly a critical process, the damage potential of 450 GeV LHC beam is now well established. A full program of checks, tests and measurements are in place and well documented [5]. Given the injection tests and time with beam in 2008 around 40-50% of the initial (pilot) beam commissioning has been completed. Among task covered so far:

- MKI kicker strengths and MSI septum strengths as measured with beam look perfect;
- SPS extraction & LHC injection kicker timing-in worked well;
- injection region aperture checks were OK except a 10 mm vertical realignment of vacuum valve assembly which was quickly fixed;
- short-term (1 hour) stability looks good at the injection point;
- There are some concerns about MKI flashovers with a strategy for operation with beam to be established.

### *Beam dump*

Given its role as an absolutely critical safety system, painstaking tests, checks and measurements must be performed with beam [5]. Again detailed, well-documented procedures exist and it is estimated that

around 10-20% of initial beam commissioning has been performed:

- dump element strengths and synchronization looks good;
- dump region aperture measurements have revealed no obvious problems so far – and “loss free” extractions performed;
- dump diagnostics including XPOC analysis is in good shape;
- a number of examples with various sweep characterization and “asynchronous” dumps have been collected; analysis is in progress
- sequencing and special machine modes worked well with some operational aspects to be addressed. It must be noted that the injection and beam dump systems are complicated with a lot of dependencies on external agents.

For both injection and dump systems there is still a lot to do and again much mileage can be made from the planned transfer line and injection beam tests in 2009.

## FIRST RESULTS FROM THE LHC BEAM INSTRUMENTATION SYSTEMS

The first results from the use of the LHC beam instrumentation with beam were truly impressive and a testament to the years of planning, testing & HW commissioning within the BI Group, with the help of many other groups & external collaborators [ 6]. Of note:

- **Beam Loss Monitors** which worked well from first injection tests. There were logging issues linked to data rates - these were quickly sorted out. Data concentration, on-demand capture and continuous monitoring were tested. It should be noted that 2009 sees hardware re-installation and modifications, software and FPGA extensions.
- The **Beam Position Monitor** system, in asynchronous bunch by bunch (FIFO) mode, was used for threading & first few 100 turns. This mode worked first time on both beams for injection tests and on 10th September. The asynchronous orbit mode provided filtered data for 1 Hz orbit update to YASP and the feedback controller and worked as soon as beam was circulating for more than a few seconds.
- Also commissioned were the BBQ tune measurement systems, the BBQ tune on-demand system, the Bunch Current Transformers and the Wire Scanner.

It should be noted that there is still a lot of work to do. The main shutdown work had been heavily loaded, with BPM and BLM consolidation required following considerable dismounting & remounting both in sector 34 and as a result of compensatory measures elsewhere in the ring.

Improvements to the synchrotron light monitor optical layout are planned; installation of US-LARP luminosity monitors (fast ionization chambers) will take place.

Commissioning in 2009 foresees full re-commissioning of the already tested systems. This will involve systematic measurements and fine timing adjustments. Commissioning for the first time of other systems such as the synchrotron light monitors, Schottky, luminosity monitors, abort gap monitors, PLL tune measurement and the orbit, tune, coupling and chromaticity feedback systems will also be required.

## CONTROLS & SOFTWARE

Given an acceptable level of hiccups, the control system functioned well during the preparation for, and execution of beam commissioning [7]. Testing of infrastructure, components, and individual systems proved, perhaps not surprisingly, to be very useful. These tests culminated in full scale integration tests which revealed a number of issues which were successfully addressed.

Also useful was component deployment on other machines as precursor to their use in the LHC. These components included: sequencer, the software interlock system, fixed displays, alarms, and the analogue acquisition system (OASIS).

Timing and synchronization, a complex and critical coupling of systems, were de-bugged successfully during injection tests. The logging system had to deal with a terrific through-put. Hardware, CPU, software upgrades were required, but the system was generally successful in deal with huge volumes of data involved. A number of middleware (CMW/JMS) issues were resolved as the LHC equipment and instrumentation was progressively deployed.

The high level software (LSA) which provides the machine settings management, on-line magnet model, interfaces to equipment and instrumentation, machine cycle etc. worked well. The deployment of Role Based Access Control (RBAC) which aims to prevent unauthorized access to LHC equipment and instrumentation was successfully deployed following a fruitful collaboration with Fermilab.

For controls in 2009 it will be the same again and more with the need to (re)-deploy existing and new functionality followed by rigorous and extensive testing.

## FIRST FIELD TEST OF FIDEL, THE MAGNETIC FIELD DESCRIPTION FOR THE LHC

The LHC magnet model FiDeL provides a full-blown transfer function model for main magnets; simplified transfer function model for correctors (linear + saturation) and full-blown b3, b5 errors for the MB's (static + dynamic) on a circuit-by-circuit basis [8]. In addition to the complete off-line analysis and supporting tools,

FiDeL has been implemented as an integral part of the LHC controls software (LSA).

To the best knowledge of the team, FiDeL is the most advanced model of the magnetic field in accelerator magnets ever used - based as it is on recent advances in physical understanding and the largest measurement database ever available.

Careful comparisons of the model's predictions were made with beam based measurements of momentum, tune, coupling, beta beating, and chromaticity. The conclusion was that the model was in the right ball park for all settings. Non-nominal cycling of the magnet circuit during the start-up with beam is most likely the reason for the reproducibility issues observed.

## CONCLUSIONS

Injection tests are clearly a vital pre-cursor to successful beam commissioning. The preparation and testing that these beam based milestones engender are essential to subsequent beam commissioning. Clearly they should be on the schedule in 2009.

The curtailed but productive beam commissioning period coupled with the results from the injection tests have given us some confidence in numerous aspects of the LHC's potential operation, namely: magnet model, magnet field quality, machine aperture, machine alignment, optics, injection and beam dump systems, collimation, beam instrumentation, controls and software.

It also had to be noted that only limited progress was made into the full beam commissioning program and that a lot remains to be done before we reach the first major milestone of the program - colliding low intensity beams at high energy. Systematic and careful progress will be essential if the potential dangers of even moderate intensity beams are to be dealt with properly.

## REFERENCES

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