SUMMARY OF THE EVIAN BEAM COMMISSIONING WORKSHOP

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Abstract

An LHC beam commissioning workshop was held on the 19-20 January 2010. The goal of this workshop is to review the 2009 LHC beam commissioning and beam operations experience, and to look forward to the continued commissioning and operation of the LHC with beam in 2010.

Beam related experiences from injection to stable beams were discussed. Issues addressed covered the measurements and observations versus expectations; problems encountered; the performance of software and controls; and necessary improvements. The readiness for 3.5 TeV running was also covered. As an outcome, the workshop proposed a 2010 beam re-commissioning plan for 3.5 TeV operation. This plan addresses the strategies for increasing the beam energy, intensity and specific and integrated luminosity to the targets required for 2010.

INTRODUCTION

The initial beam commissioning of the LHC saw remarkably rapid progress in the three and half week available in November to December 2009. All main commissioning goals were achieved [1]. All key systems went through at least their initial commissioning phases. Collisions with 'stable beam' conditions were established at 450 GeV, and the ramp to the maximum energy of 1.18 TeV was successful attempted. Most beam-based systems became operational and LHC operations managed to start to master the control of a hugely complex system.

During this period operations was very much in commissioning mode and this initial phase must be seen as part of a necessary learning process with a furious amount of problem resolution and debugging going on.

The main aim of the workshop was to review this initial commissioning period and draw from it lessons and necessary improvements to be made for continued commissioning in 2010. The session titles are listed below.

- Review of 2009 LHC beam operation and models
- Beam diagnostics
- Injection & Ramp & Squeeze & Adjust & Stable beam
- Machine protection
- Controls and operational aspects: going from commissioning to operational regime
- 2010 operation

The speakers were asked to "bury Caesar, not to praise him".

PREPARATION

The initial commissioning phase benefited enormously from meticulous preparation. This included a full series of injection tests, extended dry runs of all accelerator systems both separated and combined, and full hardware commissioning of the cold magnet circuits. The curtailed commissioning with beam in 2008 was also very useful in identifying a number of issues that were resolved for the 2009 run.

MILESTONES

The main milestones of the 2009 beam commissioning period are outlined in table 1.

Table 1: main commissioning milestones 2009

Date	Milestone
20th Nov.	Injection of both beams – rough RF capture
21st Nov.	Circulating beam 1
22nd Nov.	Circulating beam 2
23rd Nov.	First pilot collisions at 450 GeV First trial ramp
26th Nov.	Pre-cycle established Energy matching
29th Nov.	Ramp to 1.08 TeV and then 1.18 TeV
30th Nov.	Experiments' solenoids on
1st – 6th Dec.	Protection qualified at 450 GeV to allow 'stable beams'
6th Dec.	Stable beams at 450 GeV
8th Dec.	Ramped 2 beams to 1.18 TeV – first collisions at 1.18 TeV
11th Dec.	Stable beam collisions at 450 GeV - 4 bunches with 2 10^{10} per bunch
14th Dec.	Ramp 2 on 2 to 1.18 TeV - quiet beams - collisions in all four experiments
14th Dec.	16 on 16 at 450 GeV - stable beams
16th Dec.	Ramped 4 on 4 to 1.18 TeV - squeezed to 7 m in IR5 - collisions in all four experiments
16th Dec.	End of run

The commissioning process can be briefly summarized thus:

- 3 days for first observed collisions at 450 GeV;
- 9 days for first ramp to 1.18 TeV;
- 16 days to establish stable beams at 450 GeV;
- 18 days to take two beams to 1.18 GeV and observe first collisions at this record energy.

A more detailed look at the main operational phases involved follows.

Injection

The transfer and injection process from the SPS into the LHC is delicate and complex but operation was well established.

- The transfer lines were well optimized after a rigorous measurement campaign.
- Re-phasing of the beam in the SPS, synchronization between the machines and subsequent capture

worked well with only some RF controls and procedural issues as negatives.

- Injection sequencing dealt with requirements of multiple injection schemes that covered multi-bunch injection, two beams, and collision scheduling.
- The routine conditioning of the injection kickers (the so-called kicker soft start) is now part of the standard process.
- The injection quality check (IQC) process was deployed, debugged, and became operational.
- The abort gap keeper was commissioned (this prevents injection of beam into the abort gap).

A full program of beam-based checks was performed including: positioning of injection protection devices (TDI etc.) with respect the beam, positioning of transfer line collimators, aperture checks, and kicker waveform checks [2,3].

A number of issues were identified, including:

- Problems when over-injecting. Here a pilot is kicked onto the TDI – this process caused a beam loss monitor (BLM) beam abort.
- The BLM system was observed to pull a beam abort during the injection process (beam loss on transfer line collimator for example). There is a general issue with fast losses at injection and the BLM threshold on shorter timescales.
- Related to this problem is the need to scrape the beam in the SPS. The strategy for scraping in the SPS needs to be fully defined.
- The injection kicker was observed not to trigger under certain circumstances.

Generally the performance at injection was good and clearly benefited from the experience gained during the injection tests. For the moment, however, one would worry about routinely injecting unsafe beam.

It is to be noted that so-called 'quenchinos' were again observed with two accidental quenches caused by intensities as low as 2×10^9 protons.

450 GeV

A full set of instrumentation and associated hardware and software was commissioned and made more-or-less operational. Measurement and control of the key beam parameters (orbit, tune, chromaticity, coupling, dispersion) was routine. Besides this the BLM system performed impeccably. Beam size was measured using the synchrotron light monitors and wire-scanners. Lifetime optimization via adjustment of tune, chromaticity, and orbit became routine.

Energy matching between the SPS and LHC was performed and revealed only small differences between the two beams. A full program of aperture checks was performed covering the arcs and insertions.

The experiments' solenoids were brought on without fuss and the coupling and orbit perturbations corrected. LHCb and Alice's dipoles were brought on at 450 GeV. There are some issues with transfer functions of these dipoles and the associated compensators which are to be resolved.

Two beam operation was established both with and without separation bumps. Optics checks were performed and the beta beating measured and first attempts at correction made. A full program of polarity checks of correctors and beam position monitors was executed with only a few errors being found [4].

The availability of hardware, instrumentation and software was very impressive reflecting good preparation, very fast problem resolution and the clear benefits of leveraging 21st century technology.

Collisions at 450 GeV

Although successful, it is probably worth noting that the LHC was not designed to do collisions at 450 GeV [5]. Nonetheless a full program of machine protection, collimation, aperture and beam dump system checks allowed 'stable beams' to be declared. This permitted the experiments to fully turn on their detectors and start an intense period of commissioning with beam themselves.

Multi-bunch and higher intensities were achieved with a maximum of 16 bunches and a total beam intensity of 1.85×10^{11} being brought into collision. Luminosity scans were tested gently and successfully [6], and hundreds of thousands of events were collected by the experiments.

8 kHz and the hump

One clear issue at 450 GeV became apparent: the activity in the vertical tune spectrum and associated vertical emittance blow-up. The cause of the 8 kHz line was tracked down to the UPS, however the source of the hump is not understood and systematic investigations as to its source will be pursued in 2010 [7].

Aperture

A systematic set of aperture measurements was performed of the arcs and insertion regions [8]. The beam clearance in general seems to be OK, and is above or equal to. Some measured bottlenecks agree with model predictions using measured beta functions.

However the aperture is out of budget due to the large-beating with $n_1 < 7$ even with reducing the closed orbit budget to the measured 3.2 mm peak closed orbit. This implies that correcting beta beating is mandatory at 450 GeV.

Beta beating

The availability of measurement and impressive analysis tools should be noted. The uncorrected, measured beating was good although outside the accepted tolerance of ~20% [8]. Several potential sources of error were identified with possible candidates including the warm magnets in IR3 and IR7 (large corrections required). Potential, somewhat large, corrections were also noted in the triplets in IR2 & IR8. The correction strategy will need to be carefully considered.

The pre-cycling strategy of certain classes of magnets will be revisited for 2010 (e.g. Q6 was not pre-cycled and should be) to avoid any potential errors arising from

leaving magnets on the wrong branch of their hysteresis curves.

In 2010 it will be important to correct the beating early on to avoid having to re-visit collimation and other optimization after any beating corrections.

Ramps

A fully consistent set of machine settings was deployed at injection and for the ramp. These incorporated the output of the LHC magnet model (FIDEL) which consists of all main transfer functions, dipole harmonics etc. For the RF system the necessary parameter space was in place including frequency and voltage control in the ramp.

8 ramp attempts were made (see table 2) with notable success [5]. Reproducibility in the ramp looked very good enabling tune feed-forward to be deployed successfully. Tune feedback based on the continuous FFT mode of the BBQ tune system worked pretty much first time and was then used systematically during the ramp [7].

Real time acquisition of the closed orbit in the ramp was immediately available. The orbit clearly moves during the ramp but total deviations were small enough to allow good transmission. A feed-forward strategy is to be established.

The bare tunes (i.e. those that would have been seen had no corrections been applied) were seen to swing considerably. The effect is bigger in the horizontal plane and for beam 2. The origin of the swing is not yet understood. Appropriate 450 GeV trim incorporation methods have yet to be deployed.

Table 2: Ramp attempts during 2009 commissioning

No.	Date	Energy [GeV]	Comment
1	24/11/09	560	Beam 1 - lost to tune excursions
2	29/11/09	1043	Beam 1 – tune to third integer
3	30/11/09	1180	No precycle, feed-forward, no feedback.
4	8/12/09	1180	B1 lost after 3 minutes at top energy. Feedback on B2
5	13/12/09	800	Feedback on both beams from here. Lost B2 – BPM interlock
6	14/12/09	1180	1 hour “quiet beams” – collisions in all 4 experiments
7	15/12/09	1180	Beam lost to rogue RT packet
8	16/12/09	1180	Trial squeeze in IR5

Squeeze

One successful attempt was made to test the squeeze procedure in IR5 [10]. Although not exactly smooth in terms of procedure, the attempt managed the three planned steps: the shift to collision tunes; squeeze 11 to 9 m.; squeeze 9 to 7 m. Clearly there is some tidying up to do but to get this far on the first attempt was encouraging. The settings strategy worked and respected the need for smooth round off of power converter functions at the intermediate optics points. Single quadrant power converter limitations were taken into account – the ramp down of some insertion quadrupole in the squeeze defines the length of the process.

Beta beating and dispersion measurements showed better agreement with the machine model at the intermediate points of the squeeze than at 450 GeV and the extrapolated values of beta* were closed to nominal. For a full discussion, see [10].

SYSTEM COMMISSIONING

LHC Beam Dump System [LBDS]

There was a rigorous program of measurements and tests to qualify the LBDS with beam [11]. These included:

- beam based alignment of TCDQ and TCS;
- aperture scans;
- extraction tests;
- asynchronous beam dump tests with de-bunched beam;
- commissioning of the various sub-systems i.e. Beam Energy Tracking System (BETS), External Post Operation Checks (XPOC), internal post operation checks (IPOC);
- interaction with the timing system, synchronization with RF (abort gap etc.);
- inject & dump, circulate & dump mode were successfully used operationally.

A number of issues were resolved and the performance of the LBDS was in general very good and experience thus far gives confidence in its ability to perform within its very tight specifications.

The only real failures were the synchronous-asynchronous dumps, which were solved after a TSU firmware upgrade. Many tests with beam are outstanding: dumps at intermediate energies; precise positioning of protection devices; a whole series commissioning procedures for increasing energy and intensity.

Again it was noted that operations need to converge to a more standard way of running sequences to avoid unnecessary procedural errors.

Abort gap cleaning

The undulator and synchrotron light monitor successfully commissioned for beam 2 paving the way for a first look at abort gap monitoring and cleaning. Encouragingly abort gap cleaning had a good first run out but needs to be further optimized to clean over the full 3 μs abort gap while limiting the losses outside of the abort gap. Around 10 % of the beam in the gap was left in the gap. A clear interlock and dump strategy needs to be established and thereafter there is the need to commission the Abort Gap Monitoring Interlock.

Collimation System

The collimation system saw excellent initial beam based commissioning following careful preparation and tests [12]. The initial phase include a full program of beam based positioning during which the hierarchy was established. Encouragingly this appeared to be respected in planned and unplanned beam loss tests there afterwards - provided the orbit had been corrected to the reference.

The collimation setup remained valid over six days, given orbit reproducibility and optics stability. The system works as designed. Expected cleaning and leakage processes were seen. It was possible to verify passive protection with losses at primary collimators. The collimation/protection devices hierarchy was established and respected in tests. TOTEM also saw the first operational tests of their Roman pots with beam.

A number of issues were identified.

- Beam-based settings were different from theoretical: this needs to understand in more detail.
- The wrong sequence has been played leading to collimators hitting interlock limits. This is safe but not nice. Strict adherence to fully debugged sequences is essential. Setup by hand is out of the question.
- Abnormal losses in right dispersion suppressor of IR3 were noted – since tracked down to BLM noise.
- A power cut locked all collimators. They could be reset by the piquet reasonably quickly (~2h). This is a feature, as collimator controls are on UPS, but not the high power drivers.
- Faster analysis for loss maps, collimator movements, interlocks etc. is required.

Machine Protection System

The machine protection system (MPS) is mission critical and will clearly be vitally important for LHC operation over the safe beam limit. In essence it comprises the beam interlock system (BIS) and the safe machine parameter system (SMP) [13, 14]. The BIS relies on inputs from a multitude of users. The SMP relies on services from other systems (e.g. the timing system and the bunch current transformers).

Besides this the beam drives a subtle interplay of the LBDS, the collimation system and protection devices, which rely on a well-defined aperture, orbit and optics for guaranteed safe operation.

The MPS itself worked as advertised, always pulling a beam abort when called upon to do so. It has been operational since 2006 and the deployed system has seen 99.996% availability. The system has been externally and internally reviewed and will be ready for 2010 operation with only minor changes.

During initial beam commissioning here were some issues with the inputs into the SMP but the system failed safe. It is clear that the SMP system depends on other systems. These dependencies include the bunch current transformers for intensity information. Here the dependability (safety, reliability and availability must be clarified). The timing system is used for transmission of the SMP system; here cross checking and failsafe mechanism must be fully deployed. In short there are known limitations with the 2009 implementation and the 2009 system for 2010 was reinforced at the start of 2010. However, the final LHC SMP system will only be ready in 2011 for nominal energy and intensity.

The first attempt to establish the LBDS, orbit, and collimation as safe for the given aperture and optics was successful at 450 GeV and tests with beam demonstrated that the system setup was effective. Guaranteeing this at all phases of operation has yet to be demonstrated.

Beam Instrumentation

Details of the individual systems are presented in proceedings of the Evian workshop. A brief summary of the performance of each system is given in table 3.

Table 3: overview of BI performance in 2009

System	Performance overview
BPM [14]	In general very good, FIFO mode as used as in the injection tests. Capture mode was commissioned enabling multi-turn acquisition and analysis.
BLM [15]	Excellent performance following full deployment during injection tests delivering a close to fully operational tool. Some issues with the SEMs; some thresholds to be adjusted.
DBCT FBCT	Along with lifetime measurement, the systems were commissioned and operational. Some calibration & controls issues.
BTV	Fully operational
BWS Wire scanners	Operational, calibrated and giving reasonable numbers.
AGM Abort Gap Monitor	First tests were encouraging.
BSRT [16] Synchrotron Light	Beam 2: undulator commissioned, operational at 450 GeV and 1.2 TeV. Beam 1: undulator not commissioned, operational at 1.2 TeV
Tune	BBQ FFT used routinely from day one: tune, coupling, and chromaticity. Used for tune feedback in the ramp. MKQA tune kickers operational PLL – good progress, feedback to be tested, radial modulation tested.
Chromaticity	Measured using: standard delta RF method; semi-automatic BBQ peak analysis; and radial modulation. Some effort required to ensure fast reliable method is available.

Orbit

The closed orbit was observed to be very stable (vertical drift ~ 15μm/h) [4]. Time should be devoted in

2010 to establish a better global correction (and avoid strong local corrections) before setting up the collimators. Open issues include: the observed rifts between IP7 and IP1; the vertical offsets observed in arcs 23, 34, 45 (aperture to be checked with beam to see if orbit is centred or not); the switch of BPM high/low sensitivity with beam intensity to be tested. The orbit feedback is basically operational, but time is needed for testing; it is view as essential for a fully operational ramp and squeeze.

BLMs

The BLMs correctly removes the beam permit if measurements are over threshold. No reliability issues were observed. The system is well understood since it has been up and running for more than a year [15].

There were some availability issues (false dumps) at energies higher than the injection; thresholds are to be adjusted in some regions. Continuous monitoring of noise is required. Sequencer initiated tests will be enforced to be run regularly.

More tests to verify and adjust the threshold values are needed and investigation of spurious signals from the SEMs are ongoing and first corrections are being implemented.

Magnet Model

A long and thorough magnet measurement and analysis campaign [17] meant that the deployed settings produced a machine remarkable close to the untrimmed model. In terms of tune and momentum, remarkably small discrepancies between the model and the measure machine were observed. For example, the largest momentum offsets by sector seen were: -0.27 per mil in sector 56 for beam 1 and +0.32 per mil in sector 78 for beam 2.

The precycle was fully deployed with precyling prescriptions in place for nearly all circuits with only a handful still missing. The result was very good reproducibility. Some optimization of total length is still possible; it was taking over an hour for the full precycle. There were a number of trips of circuits during the process and it's clear that the precycle stressed the quench protection system (QPS) and power converters.

Future priorities include: trying track down the origin of beta beating; the spectrometers and compensators transfer functions; correction of the snapback at 6 kA – new equations to be implemented; the origin of tune drift during ramp; better understanding of tune and Q' trims used at injection; implementation of hysteresis in LSA; continuation of measurements on dipoles to characterize them with the 3.5 and 5 TeV precycle.

The careful crosschecking of the large parameter space by the FIDEL team proved invaluable and must be continued.

Power Converters

Superb performance of the power converters was observed with excellent tracking between reference and measured and excellent tracking between the converters around the ring.

Radio Frequency

In general, there was good performance from the key RF systems: power, beam control, low level and diagnostics. Establishing capture was fast and efficient, the frequency and voltage ramps passed on the first attempts. Cogging worked well with the interaction point being re-positioned to the satisfaction of the experiments.

There were, however, a number of controls issues with the de-synchronization/re-synchronization process being particularly problem prone. The interaction of the power converters, klystrons and associated circuit breakers was opaque from the CCC. This issues and other are being addressed [18].

- Power system: minor hardware problems have been understood and addressed.
- There is concern over klystron collectors, which have been limited to around 80% of nominal power because of overheating due a collector design fault.
- Time is needed to commission variable cavity Q.
- Controls & software: the major operational problems have been solved.
- Low level and synchro: various causes for synchronisation problems are understood and resolved.
- Readiness for unsafe beam: addition of interlocks on cavity sum, frequency and synchro.

The to-do list includes: commissioning of change of Q; one turn feedback, longitudinal feedback, and emittance blow-up.

Commissioning of the transverse damper with beam started. Dedicated time in 2010 is still required.

Control system

The numerous elements of the control system were deployed and tested in good time. A non-exhaustive list of the systems and components follows.

- **LSA** provided the core high-level software (settings generation, trim, drive, cycle management etc.). Given the deployment on the SPS, transfer lines, LEIR during the previous years, the whole product was remarkably mature.
- **Logging** did a remarkable job of capturing and making accessible the huge amount of data generated. Again a long rollout and mature product.
- **YASP** provide orbit correction and lot more besides, a powerful and mature tool.
- **Sequencer** was heavily used. The cut and thrust of full operations revealed some features that are being addressed.
- The **on-line model** was successfully deployed and used routinely.
- **Management of critical settings** (MCS) was deployed.
- **Role base access control** (RBAC) having been deployed progressively over the last couple of years was operational but not in 'strict' mode as of yet.

- The **alarm system** was operational but not used systematically.
- The **timing system** performed very well following a staged deployment and thorough testing over the last few years.
- **Oasis** (analogue acquisition system) was heavily used and worked well.
- The **post mortem system** was in place, although beam based features have not been extensively used as of yet.
- **Fixed displays** were fully deployed, although they appear not to be fixed enough for nominal operation.
- **Injection Quality Check** (IQC) which serves to check beam loss, injection efficiency etc. was available.
- The communication between the LHC and experiments (DIP/Handshakes) was well used and despite some hiccups performed OK.
- The standard **middleware** (CMW/JMS) solutions struggled with the huge load. It is questionable as to whether or not the chosen technical solutions are fully appropriate to the foreseen data rates. The control group is addressing the issues.
- Similarly, **proxies** suffered. These were put in place to help shield the front-ends from becoming over-subscribed.
- The **concentrators** of the copious BLM and BPM data work well, although there were some issues with re-publishing of the data.
- The **electronic logbook** (eLogbook) deserves special mention for firstly dealing with everything the operation crews threw at it, and also, importantly, allowing browsing of the data by a large number of interested parties around the world.

The heavy load that commissioning put on the system exposed a number of issues [19]:

- Infrastructure – disk space, console performance
- CMW – proxies, subscriptions, …
- FESA – front-end instabilities
- RBAC – introduction of STRICT policy
- JMS – data publishing
- BE-CO Development Process

All are being address by the controls group.

OPERATIONS

It should be noted that control systems for equipment and instrumentation that are not safety related may also contribute to safety and should be properly designed, operated and maintained.

Where their failure can raise the demand rate on the safety related system, and hence increase the overall probability of failure of the safety related system to perform its safety function, then the failure rates and failure modes of the non-safety systems should have been considered in the design, and they should be independent and separate from the safety related system.

The LHC in general does not rely on the control system for machine protection (networks, front-ends, software, databases, timing system etc.), however, it is already clear from the initial commissioning period that operations and the interplay with controls, hardware, and instrumentation, is capable of unnecessarily stressing the machine protection system.

Operations and controls can help machine safety.

- They can reduce the load on machine protection by catching errors, enforcing procedures, catching problems by appropriate surveillance and software interlocks.
- They can impose limits and secure settings.
- They can provide diagnostics: post-mortem, logging, and alarms.
- They can ensure full monitoring of the status of the MPS and critical components.
- They can ensure reliability via XPOC, checking functionality with test sequences of acquisition system, system response etc
- They can impose procedural standards.

On the other hand operations and high-level controls can hinder the process.

- They can lower availability, losing time to problem resolution;
- They can reduce reliability by loss of diagnostics.
- Failures of gateways, networks (band width, response), servers, databases, timing can cause loss of critical signals, displays, functionality etc.
- They can be a source of false manipulations. These can be bugs in software, poor ergonomics, poorly conceived sequences, errant feedback loops etc.

As well as the positives, it is clear that LHC operation saw all the negatives listed above [20,21]. The issues are too numerous to list here. They all must be resolved before the LHC goes much beyond the safe beam limit.

2010

The main objectives of LHC operation in 2010 are itemized below [22].

- Beam commissioning continued with the main, final objective of this phase being colliding, safe, stable, squeezed beams.
- This will be followed by consolidation and routine "pilot" physics at the safe beam limit for an extended period with machine development periods as required.
- Increased intensity phase one and associated machine protection qualification. The aim is to establish secure and reproducible operation under these conditions. This phase will move the total beam intensity above the safe beam limit.
- Consolidation and routine physics, again for an extended period.
- Increased intensity phase two and associated machine protection qualification etc.

Machine protection is clearly hypercritical once the safe beam limit is passed, as is fault free operations and operational procedures. It could take some time to fully establish the latter.

Commissioning

The breakdown of beam commissioning is given below.

- Global machine checkout
- Essential re-commissioning and checks with beam at 450 GeV. Machine settings will include the updated FIDEL model and minor optics modifications. Injection setup will be the standard operational configuration with separation bumps on. A golden orbit will be re-established and the energy matching between the machines checked. Beam instrumentation commissioning will continue.
- The outstanding issues from 2009 will be addressed. In particular, the origin of the "hump" should be identified [7].
- Optics correction and verification. The aim is to bring beta beating within tolerance before detailed optimization of collimation and LHC beam dump system (LBDS).
- The collimation, LBDS, and machine protection systems must all be re-qualified with beam.
- The above step will precede provision of two to three shifts of colliding beams at 450 GeV.
- The ramp will be commissioned directly to 3.5 TeV. This will include commissioning of beam instrumentation and feedback systems (Tune, Q', coupling, orbit, feedback systems) and other systems (beam dumps, collimators, RF). Beating measurements will be made during the ramp to quantify dynamic optics changes.
- For the ramp and 3.5 TeV, in the first instance, machine protection appropriate for safe beam will be re-verified: fast magnet change monitors (FMCM), power interlock controller (PIC), collimators, protection devices, beam loss monitors (BLM), beam position monitors (BPM), interlocks, safe machine parameter system (SMP), RF frequency, and LBDS.
- Flat top parameter and optics checks at 3.5 TeV.
- Establish stable safe beams at 3.5 TeV un-squeezed as a necessary perquisite for colliding beam at this energy.
- First collisions at 3.5 TeV (see below).
- Commission squeeze including collimation, feedbacks, apertures checks etc.
- Parameter and optics checks at final squeeze values.
- Established stable safe beams at 3.5 TeV squeezed
- Collisions with stable beams at 3.5 TeV squeezed

Planning

An estimate of the time required for the above phases in shown in table 4. Detailed shift-by-shift planning will be drawn up covering the first 4 weeks.

Given that first collisions at 3.5 TeV will be a media event, commissioning of ramp (and possibly squeeze) will be done with non-colliding bunches. Stable beams will be established with non-colliding bunches. The first attempt to deliver colliding beams to the experiments under stable beam conditions will need to be planned some days in advance.

Table 4: time estimate for 3.5 TeV beam commissioning

Phase	Days	Key objectives
Circulating beam	2	Essential checks
450 GeV commissioning	7	Injection, tune, Q', C-, orbit, collimators, LBDS, instrumentation
450 GeV optics checks	3	Beating, energy matching tuning
450 GeV two beams	1	Bumps as standard, TDI adjustment.
450 GeV collisions	2	Experiments on at 450 GeV, stable beams.
Ramp to 3.5 TeV	5	Commission essential machine protection, bring experiments' dipoles on in ramp, commission orbit and tune feedback
Pilot collisions un-squeezed	3	Stable beams
Commission squeeze	4	Orbit and tune feedback, collimation, aperture, bumps, machine protection checks, beam dumps etc.
Collisions squeezed	7	Stable beams up to the safe beam limit

Increasing intensity

The pre-requisites and detailed planning for increasing intensity should be revisited and formally reviewed. Existing planning foresees:

- Aperture fully mapped;
- Orbit established and locked down;
- Beam dump and associated protection devices fully locked down;
- Collimation hierarchy established, tested and fully locked down;
- Injection protection (TDI & TCLI) and the injection process fully optimized;
- Multi-bunch behaviour of all beam instrumentation tested and guaranteed;
- All systems tested with unsafe beam at 450 GeV;
- Transverse dampers commissioned and operational;
- Reproducible transverse and longitudinal emittances and intensities from the SPS. Blow-up available as required;
- Beam quality check system (BQC) in the SPS fully operational;
- Injection quality check system (IQC) in LHC fully operational;
- Intensity limit interlock fully operational;
- Scraping in SPS as required;
- Abort gap monitoring and cleaning commissioned and operational;
- BIS, BIC, WIC, PIC, SIS, SMP all fully tested and absolutely guaranteed with no interlocks masked; All

user inputs fully tested; Logging and post mortem fully tested;
- All other machine protection tests performed as specified;
- Management of critical settings (MCS) locked down;
- Role based access control (RBAC) locked down;
- RF and associated interlocks locked down;
- Beam dump, collimation, and beam loss monitors all fully qualified throughout all operational phases;
- BIS implications of safe beam at 450 GeV, unsafe at 3.5 TeV fully checked;
- Tune feedback operational – failure modes tested;
- Orbit feedback operational – failure modes tested.

This list is not exhaustive. Resolution of all procedural, operation, controls, MPS, instrumentation, hardware issues that have been raised at this workshop must have been addressed.

Phased intensity increase

It is clear that above will not happen overnight and that a full and careful program of tests and checks is required. An extended operational running period (i.e. physics) at safe beam limit with all prerequisites in place should be pursued. This will allow confirmation that all operational procedures, controls, and instrumentation are fully and faultlessly functional.

Working at the safe beam limit of 3 x 10^{10} at 3.5 TeV is around 17 kJ. Circulating unsafe beam variants at 450 GeV can be explored to test key systems and behaviour of feedbacks, and instrumentation.

Obviously machine protection must be fully qualified before any step up in intensity. The first steps up in intensity will involve ramping safe beam at 450 GeV that is unsafe at 3.5 TeV. For example 1 x 10^{11} at 3.5 TeV is 56 kJ; 7.5 x 10^{11} at 3.5 TeV is 0.5 MJ. Each step up must be followed by an extended running period.

2010 POTENTIAL

The details of the potential variation in intensity, bunch configuration and optics are covered in detail elsewhere in these proceedings [2]. Suffice to say:

- Start with crossing angles off;
- Target betas: 2/10/2/2 m. in IPs 1,2,5,8 respectively;
- Rapidly move to around the safe beam limit;
- A proposed staged increase in intensity to a total single beam energy of 2 MJ has recently been approved. The resultant luminosity and estimates for the integrated luminosity are shown in [mike]. Here a simple Hübner factor of 0.25 has been assumed to give some indication of expected performance. The machine will still be in a commissioning phase, treading carefully as experience is gained with potential dangerous beams.
- The first 5 months will hopefully deliver a final luminosity of 10^{31} $cm^{-2}s^{-1}$ - a useful and encouraging first stage deliverable.

The potential steps towards a luminosity of around 10^{32} $cm^{-2}s^{-1}$ are shown in [23]. Given the proposed steps to 2 MJ and a conservative approach to intensity increase it is clear that the final steps to over10^{32} $cm^{-2}s^{-1}$ will probably not be realized in 2010 and represent target for a mature, well optimized, well tested machine that one might hope to see in 2011.

CONCLUSIONS

A lot of hard work over the years has enabled a truly impressive period of initial commissioning with beam.

Given initial indications, the LHC is reproducible; is magnetically well understood; is optically in good shape. It is armed with a powerful set of instrumentation, software, and hardware systems.

It is also clear that the devil's in the details and we've still considerable detail to sort out. There is still a long way to go in 2010 before we are ready for unsafe beam.

If things go well, it will take about 4 weeks to establish stable, safe, squeezed beams at 3.5 TeV. The clear point here is the demand for stable beams, allowing the detectors to turned on fully.

This will be followed by an extended running period at or around the safe beam limit to bed in machine protection and operations. Blocked machine development periods will be taken as required.

Intensity increases will be a judicious and stepwise process. Each step will be followed by an extended running period.

A formal review of the machine protection system and its coupling to the full machine cycle is strongly recommended before exceeding the safe beam limit by an significant amount.

ACKNOWLEDGEMENTS

Many thanks to Malika Meddahi for making it happen; to Sylvia Dubourg for taking care of the logistics and Indico; to Brennan Goddard for editing the proceedings; and to Steve Myers for his support.

The chairman and scientific secretaries did an excellent job as did the speakers who made a considerable effort in analyzing data from the commissioning period despite the short notice.

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