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Summary of the LHC Controls and Operations Forum held at CERN on 1-2 December 1999

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Abstract

The LHC Controls-Operations Forum in December attempted to identify the challenges of running the LHC and the implications for controls and equipment. An outline of the forum, its objectives, summaries of the various sessions, conclusions and some recommendations are presented. It is anticipated that this information will act as input into current and future development.

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1. Introduction

In September of 1999, it was suggested that it would be useful and timely to review the operation of LHC as known to date, see how this impacts on equipment and then start to refine the requirements and interfaces for the LHC controls. Thus it was decided to hold a Forum with three half-day sessions, the sessions devoted to operations, equipment and controls respectively. There was also a summing-up session that included a presentation on operational aspects at HERA.

2. Motivation for the Forum

The LHC will be a large and complex superconducting collider. It will store two 7 TeV proton beams (350 MJ per beam) in small apertures within superconducting magnets where a loss of about 10^{-7} of one beam could cause any one of the 1232 main dipole cryomagnets to quench. The superconducting magnets have large dynamic effects, many of which are difficult to predict and affect key beam parameters. They will need precise correction and control via the 1750 magnet circuits and RF systems used in the LHC. The operation of LHC will be challenging and will require careful preparation. No public debate had taken place on operations of LHC since the Dynamics Effects Workshop [1] of February 1997. At that workshop input was heard from other laboratories operating superconducting machines and certain recommendations had been made resulting in further studies. Therefore, it was felt opportune to review the situation.

Optics version 6.1 has now been frozen and the engineering baseline design for LHC is being established. Hence hardware is being designed or even produced meaning that the definition for control interfaces and strategies need to be established. Certain decisions on controls need to be taken already during 2000. LHC will require some controls from an early stage and full availability for beam commissioning. Important milestones are:

- Test String 2 starting in Q4 of 2000,
- Commissioning of the first sector (1/8 of LHC) with anti-clockwise beam injected from March to June 2004,
- Commissioning with beam beginning in Q3 of 2005.

3. Scope and Objectives of the Forum

The Forum was intended as a first overview of the operation and control of LHC. It would also form the first part of the inception phase of a more formal controls specification. The scope of the Forum was limited to:

- Examining the requirements on equipment and controls as the machine follows its duty cycle with beam,
- Taking into account the requirements and services which impact on machine availability, preparation and recovery from fault,

The objectives of the Forum were to provide a broader understanding of the nature and challenges of LHC operations and to identify the consequences of these challenges for the equipment groups and the control system. It was also expected to synthesise the work in progress, correct any misunderstandings or errors and identify any issues not yet addressed or needing clarification.

4. General Remarks

The Forum was a first gathering of operations, equipment and controls specialists. A lot of material was presented in a short time and the speakers managed to stay focused on the objectives. Attendance was open to anyone interested and the Forum attracted a large interest; about 140 registered attendees. The Forum was mainly intended as an internal meeting although we were pleased to welcome five visitors from DESY (HERA).

Proceedings will not be produced. However, the programme, abstracts and a full set of the slides presented at the Forum can be found on the Forum Web page, http://nicewww.cern.ch/LHCP/TCC/PLANNING/TCC/Forum99/Forum.htm. This page can be accessed from "CERN Events" on the CERN homepage, or from "News and Publications" on the LHC Project homepage.

5. LHC Operation

During the first session of the Controls and Operation Forum, the operational scenarios for the LHC were presented, concentrating on the requirements imposed on equipment and controls. Most of the contributions were also presented at the Chamonix SPS & LEP Workshop about two months after the Forum. A summary of the operational scenarios is given, for details the reader is referred to the write-ups' of the contributions in the Chamonix proceedings [2].

The LHC is an accelerator with unprecedented complexity, with two beams and a small geometric and dynamic aperture, and some cross talk between the beams. In order to maximise the delivered luminosity to the experiments efficient, automatic and reliable procedures are required. Limited dynamic aperture, tight constraints on beam parameters combined with changing magnetic field harmonics generate challenging demands on operation, equipment, instrumentation and controls. The presence of magnetic field harmonics that are a function of the current ramp and magnetic history require excellent monitoring of beam and magnet parameters, as well as a real-time feed-back on some systems. Specific challenges for the LHC are the operation with high intensity and high energy beams in the presence of superconducting magnets with an extremely low tolerance to beam loss. With ultimate performance, each proton beam will have an energy of about 350 MJ, about 7 orders of magnitude more than is required to quench a dipole magnet. The energy stored in the magnet system is more than 10 GJ, sufficient to lift one 30 tonne magnet by 30 km. In case of a mishap such as a quench of a superconducting magnet, the magnet's energy has to be safely discharged into resistors, and the beam has to be extracted and sent to a beam dump. Operation of the LHC is therefore not without risks and a sophisticated protection and interlock system is required. A large variety of instrumentation will be provided, not only for beam operation, but also for the control and protection of the complex hardware systems. The demands on the control system are high and it will be needed partially for commissioning and fully from the very start of LHC operation.

5.1 Operation without Beam

To prepare the machine for accepting any beam, complex operational procedures are required. The LHC has eight sectors that are cooled and powered independently (a sector is the part of the machine between two interaction regions). Since it is thus possible to cool down and power a part of the machine, the commissioning of the first sector will already start by the end of 2003. The first step in the commissioning after closing the cryostats is the pumping down of the three vacuum systems: QRL (cryogenic distribution line) insulation vacuum, machine cryostat insulation vacuum, and the vacuum for each beam tube. As soon as the vacuum pressure gets below a certain limit, cool down can start. The objective is to cool down all elements in the 8 x 2.9 km continuous cryostats to a temperature of about 1.9 K. Before the magnets can be powered, the correct status of the cryogenic system, the vacuum system and the powering and protection system has to be checked. The interlock system for equipment protection must be armed. Equipment protection includes energy extraction, magnet protection, powering and post-mortem recording. Only after this verification can more than 1700 power converters start powering about 8000 superconducting magnets contained in LHC.

When a quench of a main dipole or quadrupole magnet in one of the sectors is detected, the following actions are taken: firing heaters on the magnet that quenches, switching extraction resistors into series with the magnets and switching-off the power converters for all magnets in the cryostat. Depending on the energy that the quench releases into the cryogenic system, the subsequent cool down to 1.9 K could take between 2 and 7 hours. A rapid identification of where and why a magnet quenched is required.

Access to all areas of the LHC will be controlled at all times. During operation with beam, it will be not possible to access equipment in underground areas. A daily access of about one-hour for minor maintenance could be granted, and, if required, such access could be extended. The access system must limit overheads to maximise the effective intervention times. After a quench or an access it might be required to recycle the magnets. This should be a simple operation, different cycles should be selectable, and it should be possible to edit cycles.

If any repair of components inside the cryostat were required, at least six cells would need to be warmed up. The vacuum is broken in the two cells between vacuum barriers. The minimum time for a short intervention is about 10 days, for example to exchange a diode or to repair a leak in the magnet interconnects. An exchange of a magnet will require 24-35 days.

5.2 Operation with Beam

In some respects, the beam operation of the LHC is similar to the operation of other colliders such as LEP. The beams are transferred from the SPS and injected into the LHC, ramped, the β functions are squeezed and the beams are brought into collisions. The background and luminosity are then optimised and data taking for physics experiments follows for many hours.

The beams for the LHC come from the SPS at an energy of 450 GeV via two transfer lines with room-temperature magnets that have a total length of more than 5.5 km. (Injection tests are planned for the beginning of 2004.) The aperture of the injection channels is small and the beam should be transported through the channels within tight tolerances. Any drift, for example of the SPS energy or transfer line parameters, would compromise the beam quality. The precision of the power converters for transfer line magnets should be between 10^{-4} and $2x10^{-5}$ depending on the circuit. An interlock on crucial power converters is required to avoid that the high intensity beam hits the aperture in case of a power converter failure. The magnet coils need to be protected against overheating, and the limited air-cooling capacity does not allow powering of the transfer lines for extended periods. Drifts due to temperature variations could have an impact on the beam trajectory. Reliable correction of the trajectory is mandatory, possibly by automatic steering programs.

To preserve the small beam emittance requires monitoring of injection oscillations, profile monitoring in the LHC, and adequate beam observation in the transfer lines. Procedures for the optimisation of the matching will need to be developed. The injection of beam into the LHC should be with a precision of ±1.5 σ of the beam size (all variations included, e.g. power converter drift, kicker ripple, etc.) in order to preserve the small beam emittance and to avoid quenching of superconducting magnets. Mobile beam stoppers/collimators that need to be position controlled, will protect the LHC magnets against quenches when single bunches are injected, and against damage for injection of full batches. The detailed injection scenarios need to be worked out. Supplementary protection through additional collimators in the transfer lines is being considered.

The field quality of the LHC superconducting magnets is mainly determined by coil and magnet geometry, and by the effects of persistent currents. The geometry of the coils, the iron yokes and the iron saturation dominate the transfer function B(I) and those field harmonics that are independent of the powering history. When the magnet is ramped eddy currents, which depend on the ramp rate, are induced. These modify the field harmonics. The effects are large but reproducible and can be cured by slow ramping. When the magnet is set to injection field, persistent currents in the superconductor decay slowly with a time constant of several minutes. As an example, the decay of b3 at injection could be as large as four units during a time of three hours. When the current ramp is resumed, the subsequent snap-back takes place over approximately 20 A current change. The decay and snap-back depends on the powering history, i.e. the duration of the injection plateau, the duration of the waiting time before the injection plateau and the duration and amplitude of the previous coast. The amplitude of the snap-back is nearly independent of the initial ramp rate but could vary for different magnets. Part of the non-reproducibility will be predictable, but this will be not enough to reach the tight tolerances on field quality. Conditioning the magnets with a pre-cycle before injection may be mandatory to improve reproducibility. A strict and rigorous cycling policy will have to be implemented (not yet finalised).

Important beam parameters are tune, chromaticity, coupling and orbit. Due to a small mechanical aperture, orbit errors, β beating and dispersion must also be well controlled. Field harmonics from the superconducting magnets must be minimised using the corrector magnets throughout the cycle to ensure sufficient dynamic aperture for an acceptable beam lifetime. Since the quench level is many orders of magnitude below the beam energy, collimation at all times is required.

The dynamic range for acceleration from 450 GeV to 7 TeV and the large swing of the beta function from 18 m at injection to 0.5 m with colliding beams require some power converters to operate at injection at 3% of the maximum current.

Commissioning of LHC will be performed with reduced beam intensity and smaller emittance than for ultimate performance in order to relax the tight constraints and allow for experience to be gained. However, the nominal beam parameters determine the performance of the correction circuits and the requirements for monitoring and controls.

A correction of the orbit drift during the start of the ramp is required in about 12 seconds intervals due to the random b1 field errors of the dipole magnets. The systematic error of b1 results in an energy error and a tune change. In order to capture the bunches from the SPS, the particle energy stability in the LHC of 10^{-4} could be satisfied by correcting the integral bending field with the horizontal orbit correctors every three minutes during the injection period. The energy error in the machine and the changes of b2 for the main quadrupoles leads to a tune change that implies correction at a level of some percent. Coupling induced by both the uncertainty and random errors of a2 in the dipole magnet requires correction. The systematic time dependent b3 errors in the dipole magnets change the chromaticity by about two orders of magnitude above what is acceptable and requires a correction on a level of one percent, during injection and snap-back. The uncertainty of a3 leads to coupling that depends on the particle energy and is about acceptable for the machine. The random part of a3 should also be tolerable. The systematic error of b4 leads to a detuning with amplitude that could reduce the dynamic aperture and therefore requires correction on a level of 20 %. The random b4 errors are acceptable and require no correction. The dominant b5 error at injection is the systematic error due to persistent currents that implies a correction at injection and the beginning of the ramp.

In order to calculate the correction of the field errors, measurement with reference magnets, orbit and tune measurements, beam transfer function measurements and feed forward is required. Errors depend on the machine history. The control system should allow the use of both feedback and feed forward.

Since the LHC will be operated with a large number of closely spaced bunches (nearly 3000 in each beam), the beams collide with a small crossing angle in all experimental interaction region to avoid parasitic collisions. To operate with high energy, high luminosity and low background requires collisions without offsets, stable bunches that are not oscillating, long luminosity and beam lifetime, and reproducible conditions. For IP2 and IP8 an adjustment of the luminosity is required. To bring beams in and out of collisions a flexible separation scheme is achieved with horizontal and vertical bumps. For both beams, parameters such as vertical and horizontal angle and offsets, as well as the longitudinal position of the crossing bunches must be adjusted. Some spread of the offsets cannot be avoided, but should be limited to some fraction of the beam sizes. The spread is minimised by limiting the intensity difference between bunches to less than 5% and the emittance difference to less than 10%. The orbit control at the crossing point should be in the order of 1-2 μ. Ground motion could separate the beams with a time constant of some 100 s and therefore continuous adjustments of the collisions are required. Ideally, the monitoring of the intensity, lifetime, emittance, position and angle of the collision and the luminosity bunch to bunch should be available. This would allow the understanding of the collision dynamics and tuning of luminosity and background. To keep the beams in collision, some feedback system on the orbits is required, as well as a feed-back on the beam position at collimators (20 μ).

5.3 Protection and Diagnostics

The availability of the LHC for physics will depend critically on the downtime, in particular on the number of quenches, the recovery time from a quench and on the reliability of the components. In particular, failures of equipment installed inside the cryostats would contribute to a prohibitive downtime.

The machine needs a sophisticated protection and equipment interlock system. However, any design of the safety system and its components must bear in mind that the purpose is to maximise operational availability. Interlocks are required to minimise equipment damage and time for repairs, but should not prevent efficient operation.

Since an uncontrolled release of the large energies stored in both beam and magnets could lead to massive equipment damage, the accurate operation of the interlocks must be guaranteed. Before powering magnet or injecting beam, the correct status of many systems is required to give permission (“green light for powering”, “green light for beam injection”). During powering and with circulating beams only the systems that are vital for equipment protection are in the equipment interlock chain and can trigger either beam abort, power abort, or both. An example is the magnet protection – if a quench in one sector is detected, power is aborted, the beam dumps are fired and energy from the magnets is extracted. A second example is a failure of a critical power converter. By dumping the beam as fast as possible, a quench could be avoided. These actions are time critical and a guaranteed response is required. Power converters for magnets in other cryostats, for example in another sector of the machine, will not be shut down. In case of an emergency stop the beams will always be dumped and power aborted. (Breaking of the personnel interlock will cause a beam abort and may also require a power abort.)

Some events that would lead to beam abort without power abort are:

- A deliberate beam dump by the operators,
- Too high loss rate measured by the beam loss monitors,
- Internal failure of the beam dump system,
- Failure of the RF system,
- Trigger from one of the LHC experiments in case of too high a background.

The motivation for an early beam abort is to avoid quenching of magnets to reduce down time. A complete inventory of all events that should trigger a beam dump will be established in the future.

From the operation of other accelerators with superconducting magnets it is known that power and beam abort are a regular part of the operation, and not exceptional incidents. The exact sequence of events leading to an abort needs to be well understood. For operation and protection of hardware and beam systems much instrumentation will need to be in place. All instruments, in particular those in the interlock chain, should be equipped with transient recorders. After an abort, the data is read out and made available to analyse the events. In order to correlate the different signals, a common time stamping reference for the recording is required.

6. Implications for Equipment and Controls

This session aimed at analysing the implications of the operational scenarios and physics tolerances on the equipment and on the controls interfaces and requirements. Brief descriptions of some equipment were also given.

There was good consistency between equipment performance specifications and the accelerator physics tolerances. There is now a better understanding of the real-time requirements. These are based on certain assumptions, notably the level of predictability of magnet behaviour. Reasonable and acceptable levels of bandwidth and data rates were presented which impact mostly on the beam instrumentation, power converters and communications.

Among items not yet addressed is the question of how to deal with the external trigger to the beam abort system. For the moment there is no clearly defined strategy of what elements should trigger the beam abort and the means by which this will be done. Further, the policies of power and beam abort need treating together in a coherent manner.

6.1 Dealing with Dynamic Effects

The decay of persistent currents during injection and their subsequent snapback at the start of the ramp will critically effect key beam parameters. By studying the dynamics of the decay and the snapback and estimating the magnitude of the effects one can give the requirements for beam-based feedback systems.

To smooth out the effects of snapback a so-called baseline ramp is used. This has a smooth parabolic start, followed by an exponential section that leads into the main, linear, part of the ramp function. The dynamic behaviour of the multipoles during the snapback has been modelled and it is hoped that 80% or more of the errors may be anticipated using reference tables, on-line modelling and feed-forward of on-line measurements. Given the base-line ramp and this assumption, estimates of the effect of the snap back on tune, orbit and chromaticity are made. The tolerances on these parameters are given by machine physics.

The smoothing out of the ramp start has the effect of alleviating the problem and the required sampling rates appear reasonable: 10 Hz and 1 Hz for the tune and orbit respectively. It is unlikely that a fast measurement of the chromaticity will be available. The chromaticity will change considerably during snapback and so-called "DC correction" of this parameter is foreseen at something like 1 Hz. More details can be found in LHC project note 221 [3].

6.2 Magnetic References

There will be a strong reliance on magnetic references. These will consist of databases of off-line measurements, models of LHC superconducting magnets and on-line measurements from reference magnets. It is estimated at present that decay and snapback of the magnets in the machine can be derived form the magnetic reference with a predicted accuracy of 80%, implying an error of 20% to be corrected by other means, notably real-time feedback. There is expected to be a learning curve that will improve this situation although this will probably be used to meet the demands of increased machine performance.

A so-called "multipole factory" is envisaged which will generate the required corrections to be applied to the relevant corrector magnet strings. Some of the reproducible corrections will be folded into the ramp functions and refined thereafter with experience. Some adjustments based on on-line measurements will take the form of on-line feed-forward corrections at something like 3 to 10 Hz.

6.3 Beam Instrumentation

Here the focus was on the key systems for beam control and protection during injection and ramping. The first two system enumerated below are distributed systems sharing common acquisition and controls infrastructure. The others are localised systems.

- Global orbit acquisition running at a maximum of 10 Hz. A control loop running at up to 1 Hz might be required during snapback. Data transfer is foreseen via WorldFIP connected to ATM gateways.
- Beam loss in the ring. An absolutely key protection system linked to beam abort and the potential source of a large amount of data. It will provide vital input into the post-mortem system. A 100 Hz measurement rate is foreseen, again data transfer will be via WorldFIP.

- Beam loss at collimators. A small system in each cleaning section whose primary purpose will be collimator adjustment. Fast acquisition is planned allowing for fast loss detection.
- Local orbit stabilisation. This will provide orbit stabilisation in the cleaning sections. There are very demanding stability requirements. A local feedback system is envisaged.
- Tune. There is a wide range of excitation and measurement techniques foreseen with R&D in progress. Feedback is foreseen with a 10 Hz sampling frequency. The foreseen solutions will probably be good enough to handle the non-reproducibility of the persistent current during injection and the start of the ramp, but higher performance might be required.
- Chromaticity. Measurement of the chromaticity is a challenge and any sampling rate will be low. The potentially low accuracy of the measurement will provide a challenge for any feedback system. The aim is to provide measurements for a 1 Hz DC control system.

6.4 Radiofrequency

There will be three main RF sub-systems in the machine: the 200MHz warm cavities for capture during filling, the 400MHz S/C cavities for ramping and physics and the 20MHz transverse dampers. The “Low Level” RF control system will manage the synchronisation, frequency and phase of the cavities.

The main operational cycle and its implications for the RF system may be outlined. There will be 12 interleaved injections per ring. Capture and longitudinal damping will use 3 MV in the 200 MHz warm cavities. The LHC frequency is constant at 400.789 MHz, which implies that the LHC particle energy must be held constant to within 50 MeV. Beam position measurement for the first turns of each batch for each ring will be required: a field error $\Delta B/Binj = 10^{-4}$ will cause an average radial error of 0.15 mm, which is measurable. The transverse dampers will damp horizontal and vertical injection oscillations.

Before ramping, there is a transfer from 200 to 400 MHz buckets. LHC frequency will change by 1 kHz during the ramp to 7 TeV, following a pre-defined function of time. Independent frequency control for the two rings would provide independent beam steering, which will be needed if chromaticity measurements are required for both beams. Independent beam steering will leave beams out of phase and potentially large scale rephasing will be needed before physics. Transverse dampers continue to operate to control emittance. There will be a synchronisation between the “Low level” RF control systems for the two rings.

In physics fine inter-beam phase adjustment will be needed to scan the collision point for maximum luminosity. The 200 MHz cavities will be switched off and will rely on passive damping. Transverse dampers will continue to work.

Work on the LHC RF system is well advanced and the key control issues and requirements are enumerated. Clearly these need to be considered in the framework of a coherent controls solution to avoid fragmented stand-alone solutions.

6.5 Power Converters

As a large and vital component the LHC power converters will need to provide excellent reliability and availability. The demands for high accuracy have provoked the use of digital control techniques to provide excellent resolution. There are more than 1700 LHC power converters of 14 different types installed underground either in the tunnel or in caverns. They are controlled through real-time fieldbus segments (WorldFIP). Each fieldbus could have a maximum of 30 power converters connected to it. About 70 VME crates will connect these to the LHC control network.

The power converter system must achieve precise tracking of the eight sectors of the machine and the precise tracking within each sector. The resolution is 1 ppm of Imax with a linearity of ±2 ppm of Imax. The reproducibility is better than ±10 ppm of Imax.

The functions offered by the low-level power converter system include the individual control of each power converter, the control of groups of converters (e.g. at the start of a ramp), smooth function generation and individual real-time adjustments. Synchronous ramping of several power converters and trimming of groups of power converters will be supported. These operations involve the downloading of the required current profile in each controller, the checking and the conversion of the data in each controller, a synchronised start of the change and the generation of the function. They are synchronised with a 1 ms timing system.

The MTBF at LEP was 100,000 hours. A better reliability is expected from the reduction of components, better design, improved protection and diagnostics.

6.6 LHC Beam Dump Requirements

The key concerns of the beam dump system are reliability, availability and redundancy. The beam dump must work. It must be self-triggering if it detects an internal fault. The layout and key components may already be enumerated and responsibilities in the overall system defined e.g. the beam dump system would not be responsible for the delivery of external dump requests and the interface to an interlock system. External signals will be required with high reliability namely, the revolution frequency, the reference and real energy. Another open question is whether the beam dump system itself will have to synchronise with the abort gap.

6.7 Cryogenics

After a brief description of the cooling scheme of an LHC sector, the possible quench scenarios were illustrated. Because of the division of the helium vessels into sectors, the extent of a quench varies from a single dipole to up to four cells. The effect of this is the loss of helium and the need to re-cool the cold-masses. This recovery can take from 2 to 7 hours depending on the extent of the quench. The failures of the cryoplants and knock-on effects, which are similar to those experienced at LEP, were also mentioned.

During the machine ramp the total cryogenic load increases by 50%. During the squeeze the cryogenic load of the inner triplets increases tenfold. In order to cope with this, the system must be informed of the imminent events. Feed-forward control techniques and pre-heating of the inner triplet will be applied.

The cryogenic control system will provide temperature history (a point every 10 s) time stamped with a precision of 10 ms. This data can be used for post-mortem diagnostic of, for example, a quench event. Also, a signal indicating that the cryogenic system is ready for normal operation will be supplied.

6.8 Vacuum

The beam and insulation vacuum systems and their respective role in the operation of LHC were briefly described. Namely, the three different vacuum systems: the beam vacuum systems and the two insulation vacuum systems for the magnet cryostats and the cryogenic distribution line.

The importance of the quality of the beam vacuum for beam lifetime and the operation of the acceleration systems was stressed. A leak in the beam vacuum can cause a quench via beam gas interactions. The quality of insulation vacuum systems modifies the thermal loads on the cryogenic system.

The instrumentation involved in maintaining the vacuum was listed. It includes a large number of pumps (250 pumping groups and 1300 ion pumps), valves (200 sector valves in the beam vacuum and 500 roughing valves) and gauges (800 gauges). About 300 PLCs will control and monitor their operation. The vacuum systems will provide a green light for cool-down and operation with beam. The ability to monitor and control the sector valves as well as the monitoring of the beam vacuum will also be needed by the operation teams in the PCR.

A synoptic diagram showing the status of the three vacuum systems in the eight sectors will be used for diagnostics. An acquisition rate of about 50 values per second is required to provide proper monitoring and post-mortem analysis capabilities. The ability to compare values recorded during relatively long periods will be a powerful diagnostic tool.

6.9 Protection of Superconducting Elements of LHC

The protection system of LHC continuously monitors the proper operation of the magnets, bus bars and current leads. It prevents the powering of the circuits if the protection system is not armed, detects resistive transitions, and takes protective actions when they occur.

The circuits for the main magnets are equipped with an energy extraction system that consists of a resistor and a switch. On the detection of a quench the protection system fires the heaters in the quenching magnet by discharging the heater power supplies into resistive strips embedded in the magnet coils. It requests the opening of the energy extraction switches, stops the power converter, generates a beam abort and informs the other systems of the event.

The system is equipped with hardwired individual detection and protection at the level of each main magnet. Associated with this, the individual acquisition and monitoring controllers provide the test functions and the diagnostics required for on-line and post-mortem analysis.

This equipment is connected to the LHC control system via a network and a fieldbus. It therefore provides the requisite functions to the operators in the PCR. Individual hardwired lines are provided for beam and power aborts.

6.10 Conclusion

The presentations exposed a large spread in control requirements across equipment types. Therefore a more complete and unified definition of the control requirements is required to refine and complete the picture. Only then, it will be possible to freeze design choices for the LHC controls infrastructure.

7. Controls

The third session of the forum was dedicated to meeting the requirements for controlling the LHC accelerator. In the first part of the session an operational view of the system was presented reviewing the issues of application software for the control room and overall architecture. The second part highlighted some of the work in progress most relevant to operations and control.

An Object Oriented Analysis and Design (OOAD) method with an associated project lifecycle is proposed for LHC application software to replace the Structured Analysis Structured Design (SASD) techniques used in the past during major projects for the SPS and LEP beam handling applications. Software tools, a Java application programming interface for equipment access and a supporting middleware, are being developed. Use case techniques form part of the OOAD approach and were demonstrated in practice during the preparation of the Forum. These studies will continue in order to define a preliminary control system architecture during 2000. In parallel, time scales and milestones for the system must be defined.

7.1 Past Experience and Proposed Strategy

Commissioning of LEP was achieved with equipment oriented application software but an integrated operational approach was essential to improve operational efficiency. The application software for SPS and LEP translates an operational/physics view of the machine into associated hardware values and enables handling of these quantities for a wide range of operational scenarios. In both machines the applications had to encapsulate the equipment interface and for the LHC good performance and design of this layer will be essential for efficient application development. At LEP this suite of software, known as “Sloppysoft”[4], was instrumental in reducing turn round time from several hours to less than one hour. Table 1 shows the project history of Sloppysoft that represents over 15 FTEs of work.

Table 1

Sloppysoft Project History

Phase	Output	Duration	Number of people
Initiation	Global requirements(text), previous analysis, existing data sets	March - Sept 90	4
Analysis	Logical DFDs, new system	Sept 90 - March 91	6
Data Modelling	ERDs	March - July 91	1
Design	Choice of ORACLE, SCs, Program Specs	March - Dec 91	3
Database Implementation	ORACLE table definitions, physical realisation	Aug 91 - Dec 92	2
Prototyping	Database access tests	Aug - Sept 91	2
Programming	Core System	Oct 91 - March 92	4

Concerning software for making measurements neither SPS nor LEP have achieved a good level of integration. It has proved difficult to avoid dedicated applications although good results have been achieved in some areas including LEP orbit and RF.

For complex high-level application suites, a software development method must be followed, pragmatically, from inception to commissioning of software. In the SL Division this has only worked with a single team of around five people working together throughout the development process.

An immediate concern of the LHC Controls community is to establish baseline architecture for controls hardware and software. Novel aspects of LHC running are expected to impact on this architecture. Good architectural design depends on the ability to understand the operational needs of the machine. Although machine commissioning is some years away an urgent challenge is to construct a good model of the operational requirements. On balance, this is the optimum moment to launch the studies to define the architecture. For the Forum a pilot exercise was carried out employing the Use Case Technique [5], which focuses on practical scenarios, to capture control activities during a quench recovery. The participants reacted favourably to the approach and a concrete result was the re-definition of the software interface between the cryogenic control system and the control room.

The operation of the LHC will entail complex operational procedures, involving various technical systems, during the cool down phases before the beams can be injected. These systems include cryogenics, magnet protection, powering and vacuum. Daily beam operation is expected to be coupled with the technical services operation to a greater extent than during running of the current CERN accelerators.

Today the Technical Control Room, TCR, monitors systems including electrical distribution, water, vacuum, control and cryogenics 365 days/year. The respective roles of the beam control room and the TCR and their interfaces must be agreed before the control system architecture can be established. Similarly interactions between the detector control systems and the machine require study. The TCR controls support team has evolved a specific software infrastructure for the integration of industrial systems. Hardware is connected to the accelerator and services computer network. The corresponding choices for systems under the responsibility of the LHC Division need to be made.

7.2 Specific Issues

An adequate communications infrastructure is vital for LHC Control. A wide-ranging, Communications Infrastructure Working Group (CIWG) was established early in 1999 to review the requirements for the general communications infrastructure on all CERN sites. The mandate extends to the technical and safety services and the LHC physics experiments. IP/Ethernet connections will be necessary in all alcoves, pit floors, surface buildings and counting rooms. These will satisfy the demands for monitoring, storage, archival, operator control and intercom. Video could also be carried but this will increase the bandwidth significantly. Special solutions are required for closed-loop beam control - low latency and reserved bandwidth and the telephone system - SDH links. The media choice for all these systems is optical fibre. Care must be taken in the tunnel, as fibres are radiation sensitive. The existing fibre installations need strengthening towards points 2, 3 and 4.

The CIWG will make its recommendations in Spring 2000 and this should lead to first installations in October 2001.

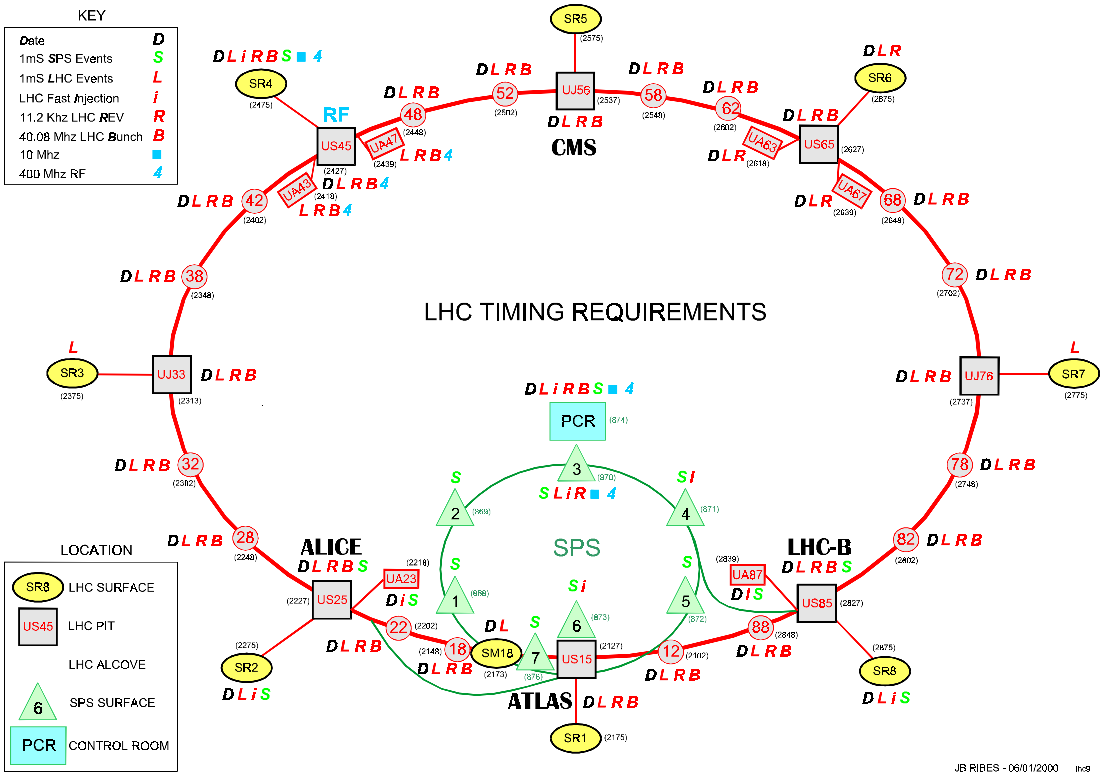

Figure 1 The LHC timing requirements

Another working group, Timing Working Group (TIMWG), is exploring the timing and synchronisation requirements for the machine and experiments. The scope includes beam synchronous timing for fast kickers, experiments, beam instrumentation and RF, cycle timing for ramping elements such as magnets and RF amplifiers, and time stamping for post mortem and archiving. A variety of timing signals are required at speeds ranging from a 1 msec. clock carrying events to the 400 MHz LHC RF frequency. All the signals and the locations for distribution are shown in figure 1. It is proposed to base the time stamping on GPS receivers at all points. This opens the possibility of generating events locally based on transmitting scheduling information over the network. Tests are being conducted on the transmission of GPS data in underground areas using the IRIG B standard and on the WorldFIP fieldbus. The TTC system [6], developed by the RD12 collaboration, is being evaluated for the transmission of beam synchronous and RF clocks on optical fibres. The working group aims to meet all timing requirements with one “fast” plus one “slow” timing system.

The development of the embedded controller [7-8] for the power converters is well advanced in order to meet the requirements for the magnet test benches and String 2. Important properties of these controllers for the LHC operation are the support given to the concepts of ramps, trims and real time control. These are defined as:

- Ramp - a synchronous change in current in most of the magnets.
- Trim - a synchronous adjustment in current in a small group of magnets.
- Real time control - continuous adjustment in current in any combination of magnets.

Ramps and trims will use the same functionality in the controller, preloaded changes triggered by a timing event. Real-time control will be supported by the standard software - no additional hardware will be required.

A unique digital control loop has been proposed and tested. This gives the required accuracy for all the circuits and eliminates the dynamic errors such that the current in the magnet follows the reference function loaded by the application software. Software in the controller will also accept an additional real time component to the reference that can be added to the pre-loaded part. The latter may be set to zero for applications such as orbit control at the collimators. Interpolation strategies for ramp functions are being proposed to users. These are linear, parabolic and cubic. Given a function point and slope only one parabola can satisfy the values of time, current and gradient at the next point when any two are fixed. If all three values are specified then a cubic defines a unique solution. Cubic functions are proposed as a good solution when several converters are to be trimmed to achieve a controlled physics parameter change. Controllers will anticipate changes that cannot be performed by the hardware due to the characteristics of the converter and the load. All operational communication with the controllers will be via the WorldFIP fieldbus. A serial interface will also be provided for stand-alone use and diagnostics.

The WorldFIP fieldbus connecting the power converter controllers is one component of a general real time control infrastructure being prepared for the LHC. A real-time communication/control system may be defined as a system for which the correctness of the result not only depends on the logical behaviour but also the instant at which the result is produced. Typical application areas include process control, signal processing and data acquisition. A common misconception is that real time is equal to high speed. However, for real time systems it is essential that guarantees can be given to meet the time constraints on the system - this implies that the system must be predictable.

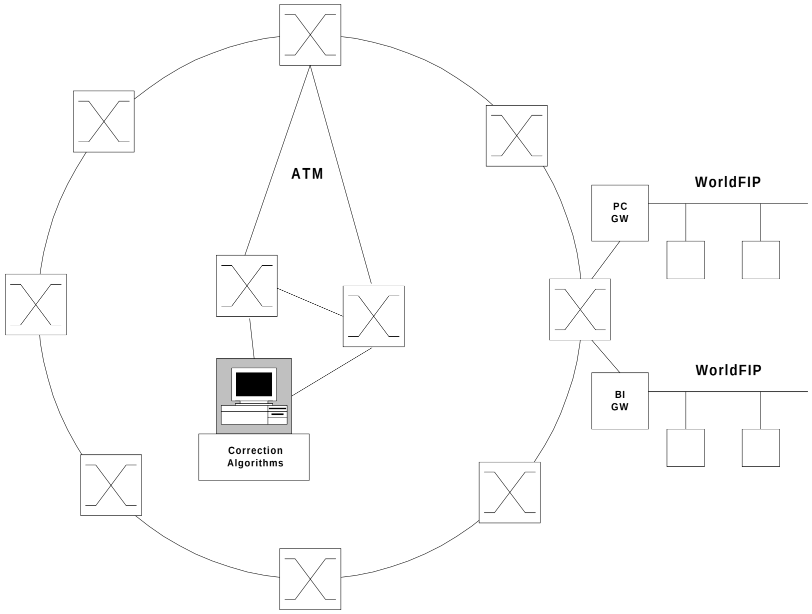

Figure 2 Prototype real-time communications topology

The current accelerator control system offers limited support for time critical applications. There is no support for meeting time constraints in the workstations, network or fieldbus. Time constraints are satisfied by dedicated embedded controllers and the CERN made timing systems. In contrast to existing CERN accelerators the requirement [1] for LHC is to provide for:

- a general exchange of real time data including nodes in the tunnel,
- closed loop control of distributed elements
- and a large number of communicating entities.

A prototype topology has been proposed [9] to match these requirements. The system provides real time guarantees, scalability and redundancy by reconfiguration. Furthermore, it is based on industrial products that are available today. The resulting topology is shown in figure 2. It is considered as a prototype topology as it is important to keep as many options open as possible. ATM offers real time data services with end-to-end quality of service. This standard also features automatic configuration and built-in multicast communications. WorldFIP offers a periodic real time variables service following the producer consumer model. It also meets the requirements of distance and noise immunity for the tunnel and has redundancy support. The gateway is based on the current SL front-end architecture with off the shelf ATM and WorldFIP PMC cards. A WorldFIP driver has to be developed at CERN, this work is critical for the first application in String 2.

7. Recommendations

Two specific recommendations were made at the Forum:

- An Interdivisional Project should be set-up for the controls of LHC - This was proposed by the SL Division Leader S. Myers and supported by the LHC Project leader L. Evans.

- An LHC Interlock Manager should be appointed - This is a person (but later a system) responsible for the integration of interlocks across the LHC machine to provide adequate protection of the machine compatible with efficient operations and personnel security.

Acknowledgements

The authors would like to thank all the speakers at the Forum as well as the chairpersons and scientific secretaries.

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[9] R. Lauckner, R. Rausch, P. Ribeiro, and T. Wijnands, “A Large Flexible Real Time Communications Topology for the LHC Accelerator”, 11th IEEE-NPSS Real Time Conference, Santa Fe, 14-18 June, 1999.

Appendix 1 - Programme of the Forum

Wednesday 1 December / Session 1 - LHC operations

***Chairman*: Jean-Pierre Koutchouk / *Scientific secretary*: Jorg Wenninger**

Time	*Duration*	*Title*	*Session No.*	*Speaker*
08.45	15'	Introduction	-	Paul Proudlock
09.00	20'	Expected behaviour of LHC s.c. magnets	1.1.	Luca Bottura
09.25	20'	Operations without beam	1.2	Roberto Saban
09.50	15'	Operations with beam - overview	1.3	Mike Lamont
10.10	20'	Transfer and injection	1.4	Volker Mertens
	20'	*break*		
10.55	20'	Accumulation, ramp and squeeze	1.5	Oliver Brüning
11.20	20'	Physics	1.6	Werner Herr
11.45	20'	Operational availability and interlock management	1.7	Rudiger Schmidt

Wednesday 1 December / Session 2 - Implications for equipment and controls

***Chairman*: Philippe Lebrun / *Scientific secretary*: Roberto Saban**

Time	*Duration*	*Title*	*Session No.*	*Speaker*
14.00	15'	Dealing with dynamic effects	2.1	Thijs Wijnands
14.20	10'	Reference magnets	2.2	Luca Bottura
14.35	15'	Beam instrumentation	2.3	Alan Burns
14.55	15'	Radiofrequency	2.4	Philippe Baudrenghien
15.15	20'	Power converters	2.5	John Pett
	20'	*break*		
16.00	15'	LHC beam dump requirements	2.6	Johan Dieperink
16.20	15'	Cryogenics	2.7	Philippe Gayet
16.40	10'	Vacuum	2.8	Isabelle Laugier
16.55	15'	Protection of s.c. elements of LHC	2.9	Felix Rodriguez-Mateos

Appendix 1 - Programme of the Forum

Thursday 2 December / Session 3 - LHC Controls

***Chairman*: Steve Myers / *Scientific secretary*: Michel Jonker**

Time	*Duration*	*Title*	*Session No.*	*Speaker*
08.45	15'	Introduction	3.1	Robin Lauckner
Session 3a		Past experience and proposed strategy	-	-
09.05	15'	Experience with SPS and LEP operational control models	3.2	Mike Lamont
09.25	15'	From requirements to control system architecture, how to proceed?	3.3	Marc vanden Eynden
Session 3b		Specific issues	-	-
09.45	15'	LHC technical infrastructure monitoring requirements	3.4	Uwe Epting
10.05	15'	Communication infrastructure requirements	3.5	Pal Anderssen
20'		*break*		
11.00	15'	LHC timing requirements	3.6	Gary Beetham
11.20	15'	Meeting power converter controls requirements	3.7	Quentin King
11.40	15'	Real-time control requirements	3.8	Pedro Ribeiro

Thursday 2 December / Session 4 - Summing-up

Time	*Duration*	*Title*	*Session No.*	*Speaker*
14.00	1h40'	*Reserve*		
15.40	20'	*Coffee / tea*		
16.00	20'	LHC operations	4.1	Jean-Pierre Koutchouk
16.25	20'	Implications for equipment and controls	4.2	Philippe Lebrun
16.50	20'	LHC controls	4.3	Steve Myers
17.15	10'	Remarks from HERA	4.4	Bernhard Holzer
17.30	.	Final conclusions	.	Lyndon Evans