Implications for Equipment of LHC Operations

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Abstract

A brief summary of particular implications identified during the CO-OP forum is presented. The equipment systems considered are Reference Magnets, Radio Frequency, Beam Dump and Power Converters. These are all ramping systems, with tight synchronisation requirements.

1 INTRODUCTION

In many ways, LHC is just another collider. However, for the equipment groups, it is an extreme machine in almost every way. For many systems, LHC is really two accelerators, which implies that a lot of equipment will be needed. This is just one of the global implications of LHC operations. Table 1 summaries some others.

Table 1: Summary of Implications of LHC operations

Feature	Consequence	Implication for Equipment
Large machine (nearly two machines)	Lots of equipment	Very high availability required
Very high beam and magnetic energy	Risk of self-destruction	Very high reliability required
Small physical and dynamic aperture	Low tolerances on physics parameters	Very high accuracy required
Non-reproducible behaviour of magnets	Feedback required	Real-time beam instrumentation, networks and control required

Not every implication listed in Table 1 applies to every equipment system. In many cases, a particular system faces a particular challenge due to the extreme nature of LHC, for example:

- The Beam Dump system must have *very high reliability*.
- Some Power Converters will require *very high accuracy* in the control of current.

2 REFERENCE MAGNETS

Reference magnets provide a way to handle the non-reproducible behaviour of the super-conducting magnets. Instrumented reference magnets (2) are used at HERA. They are in series with the magnets they represent. However, for the LHC this would be very expensive as additional civil engineering would be needed underground. Instead, the reference magnets will re-use the magnet test facility infrastructure, once magnet tests are complete. This is a much cheaper solution, however, it is more complex to control, as there will no longer be a one to one relationship between reference magnets and magnetic circuits.

To accommodate this, the reference magnets will be just one part of a real-time **Magnetic References** system, sometimes referred to as a **Multipoles Factory**. The other part of this system will be a database of magnet test measurements and two computational models:

- A Linear Physical Model of reproducible effects based on a database of series measurements of all the magnets.
- A Non-linear Model for non-reproducible effects such as persistent current decay and snap back, based on a database of detailed measurements of 10% of the magnets.

The system will provide a real-time service to the LHC control system. In return for information about the state of a magnetic circuit (current, rate of change of current and temperature) and its history, the **Multipoles Factory** will supply an estimate of the average multipole strengths in the magnets in that circuit. The quality of the estimate is expected to be in the range 5-30%, however, with operational experience, this should improve.

The Reference Magnets themselves will be instrumented with various pickups, including rotating coils, fixed coils, NMR probes and special high speed probes. These will provide measurements of varying quality and rate. In general, the most precise ($\pm 10^{-6}$) will operate at no more than 1 Hz, and the least precise ($\pm 5\%$) at no more than 10 Hz.

Control of the current in the reference magnets will be done using the same Power Converter controllers that will be used in the rest of LHC (see section 5 below). These will support both predefined functions of current against time, and real-time control. Both modes of operation will probably be used for the reference magnet circuits, though a controls strategy has not yet been defined.

The magnet test facility will be able to accommodate up to four dipole and two quadrupole magnets. So one challenge will be to manage the reference magnet currents in relation to the eight dipole and 24 quadrupole circuits in LHC, since the circuits will not have identical currents or powering histories.

3 RADIO FREQUENCY

3.1. The Equipment

Four main RF systems can be identified:

1. The 200 MHz capture and longitudinal damping system[1]: It consists of four warm cavities per ring, located on each side of IP4. It provides a bucket for capturing the SPS beam (2 ns long bunches, 0.5 to 1 eVs longitudinal emittance). Its maximum voltage of 3 MV is sufficient to damp an injection phase mismatch of 22 degrees at 200 MHz, and an energy mismatch (LHC dipole field error) of 45 MeV. Each cavity is powered by four tetrodes located in the gallery running parallel to the tunnel. Strong local RF feedback will compensate for beam loading.
2. The 400 MHz main acceleration system [2]: With 8 single-cell superconducting cavities per ring, located in IP4, it provides a maximum voltage of 16 MV which is sufficient to accelerate the beam and to keep the bunch length down to 1 ns at 7 TeV. The longitudinal emittance is 2.5 eVs at top energy. Each cell has a dedicated klystron located in the nearby gallery with local RF feedback.
3. The tranverse dampers [3]: They have been designed in collaboration with JINR (Dubna, Russia). Four vertical and four horizontal deflectors per ring will be installed in IP4, with a tetrode amplifier underneath each deflector (one tetrode per plate). The system must damp the transverse oscillations at injection (1 MHz power bandwidth, ±1.42 μrad kick strength at 450 GeV). With its 20 MHz full bandwidth (at a lower power) it will also reduce the apparent transverse impedance of the machine and will stabilise the beam.
4. The Low Level: This complex system synchronises the transfer from the SPS, controls the capture and the change-over from 200 MHz to 400 MHz as explained below, controls the acceleration using beam feedback loops (phase loop and synchronisation loop) and finally adjusts the collision point. It will be located in SR4 (the surface building above IP4).

3.2. Operation through the LHC duty cycle

Filling: Each of the two rings is filled by twelve injections from the SPS [4]. The LHC frequency is kept constant during this time. Assuming that the energy of the beam extracted from the SPS is constant, a drift of the LHC dipole field B will translate into a radial position error ΔR [5]:

$$\frac{\Delta R}{R} = -\frac{1}{\gamma_{tr}^2}\frac{\Delta B}{B} \qquad (1)$$

where R is the machine radius (4.10^6 m) and $\gamma_{tr} = 53.7$. A tolerance in the dipole field of $\Delta B/B = \pm 10^{-4}$ will thus displace the first turn by ±0.15 mm. We therefore suggest that a measurement of the orbit of the first turn be available for each batch of each ring in order to monitor the stability of the dipole field during filling, as this stability will be critical for a good RF capture: The 10^{-4} tolerance in B at injection causes an energy mismatch $\Delta E/E = 10^{-4}$ (45 MeV at 450 GeV). A phase mismatch of 22 degrees at 200 MHz between the SPS and the LHC must also be taken into account [6]. With 3 MV the 200 MHz bucket can capture the 2 ns long, 1 eVs bunch in this situation. It will damp the longitudinal oscillations fast enough so that filamentation increases the emittance by 30 percent only. The bunch will then be accepted by the 400 MHz bucket (see below).

The transverse oscillations at injection are damped by the transverse dampers. They remain in operation between injections.

Ramping: Before the acceleration ramp starts, the bunch will be transferred from the 200 MHz bucket into a 400 MHz bucket. The above mentioned stability of the LHC energy during filling is essential for this transfer to be done without loss of particles: If the energy error at injection is greater than 45 MeV the longitudinal damping system will not be able to fight against filamentation fast enough to create a bunch that fits into the 400 MHz bucket [6]. Acceleration proceeds with the 400 MHz system. The frequency increases from 400.789 MHz (450 GeV) to 400.790 MHz (7 TeV). This frequency ramp can be driven by a programmed function (following the programmed rise of the field). A direct measurement of the field is not needed.

For the RF the two rings are separate during the acceleration. The issue of independent fine frequency adjustments (independent radial steering) for the two rings was raised. The costs and potential benefits have been debated in the Reserve Session. The conclusion is that this complexity is not needed.

The transverse dampers remain in operation during the ramp to fight against transverse instabilities.

Collision: Before collision the emittance will be blown up from 1.3 eVs to 2.5 eVs to make the intra-beam scattering effects negligible during storage. The 400 MHz voltage is raised to 16 MV to reduce the bunch length to 1 ns.

There is a rendez-vous between the Low Level systems of the two rings and the phase of one ring is fine adjusted to optimise luminosity.

The 200 MHz amplifiers are switched off and the cavities passively damped in coast. The transverse dampers remain operational.

4 BEAM DUMP

The Beam Dump systems for LHC will be fundamental to machine safety, so reliability will be of critical importance. The systems for the two beams will be mirror images of each other, and will be completely independent. Each system has three groups of active components and a passive absorber block within the machine:

- 14 Kicker magnets
- 15 Lambertson septum magnets
- 10 Horizontal and vertical diluter magnets
- 1 Absorber block

The distance from septum to absorber will be 750 m, and the target diameter will be a few centimetres only. This implies a certain accuracy in the field within the septum magnet, which is currently being analysed. Likewise, the dimensions and distance between septum and kicker imply an accuracy in field strength within the kicker, which has been studied and permits the failure of one of the 14 kicker magnets without damage.

The trigger to dump the beam may come from an external system or from internal surveillance sub-systems within the Beam Dump controls. These sub-systems will verify the beam abort gap synchronisation, septum field strength and kicker power supply voltages amongst other things. Both the septum magnet current and kicker voltages must match the beam energy, and will be ramped synchronously with the rest of LHC. For security, the surveillance sub-systems require redundant local information about the beam energy and the position of the beam abort gap.

The reliability specification for the Beam Dump System is exceptionally rigorous, in keeping with its critical importance. It is classified as needing to be "Failure Free" which in reality means that it should be extremely unlikely that a dump request fails to trigger the system. This will require exacting failure mode analysis during development and quality control during fabrication and maintenance. In particular extensive post mortem analysis of each dumping action will be needed to detect faults and/or wear-out. It is inevitable that some elements of the system will use redundancy to improve security. However, these reliability improvements are at the expense of availability. That said, the availability will need to be at least as long as a physics run, and the rate of self-triggering is specified to be less than once per year.

5 POWER CONVERTERS

LHC will have over 1700 magnet circuits. Control of current in these circuits will follow the same basic model which was successfully used in LEP:

- One controller per power converter.

Table 2: Functions supported by the LHC controllers

Test Functions	• Sine • Square • Steps
Predefined Functions	• Parabolic - Linear - Parabolic (PLP) • Parabolic - Exponential - Linear - Parabolic (PELP)
Interpolated Functions	• Linear Interpolation • Parabolic Interpolation • Cubic Interpolation

- Up to 30 controllers will be linked using an industrial fieldbus to a gateway system.
- Gateways will be linked to the top level control system using a local area network.

For LHC, there will be between 60 and 100 gateway systems, and both the fieldbus and local area network will need to support real-time transmission in order to accommodate feedback on physics parameters.

5.1. Accuracy

The most demanding requirement for LHC power converters is the accuracy with which the current must be controlled in the main circuits. Around 50 of the 1700 circuits will need to be controlled with an absolute error no bigger than a few parts per million (ppm) of maximum current.

This will be achieved by using digital regulation of current instead of the traditional analogue regulation used in previous accelerators. High precision current transducers are in development, and a matching (22 bit) analogue to digital converter (ADC) has been developed and tested. A system level absolute calibration method is also in development which will link the current measurement to absolute standards maintained at CERN.

The power part of the converter behaves as a voltage source with a fixed gain. The controller will uses a high resolution (20 bit) digital to analogue converter (DAC) to produce the analogue voltage reference for the voltage source. Unlike previous designs in LEP and SPS, the absolute accuracy of the DAC is no longer important because it is within the current regulation loop.

5.2. Synchronisation

Synchronisation between controllers should be better than 1 ms, since 1 ms at the nominal ramp rate of 10 A/s in the main dipoles equals ~1 ppm of maximum current. The fieldbus chosen for the system, WorldFIP, supports the global distribution of synchronised timing to much better than 1 ms. In fact, if communication is lost, the local clock in the controller will remain synchronised to within ±1 ms for at least 30 minutes. This facility removes the need for an independent timing network as used in LEP, however, it does imply a different way of operating. For LEP, the timing network could transmit an event within one millisecond, so state changes (e.g. start ramp) could be triggered instantly across the machine. With LHC, all the controllers will have precisely synchronised absolute clocks, so synchronous activity will be triggered by broadcasting the absolute time of the event a few hundred milliseconds in advance.

5.3. Reference Generation

To fully exploit the high precision control provided by digital regulation, more advanced current reference function definition techniques are required, compared to the simple linear interpolation supported in LEP and SPS. The LHC controllers will provide three types of reference functions, as listed in Table 2.

Furthermore, real-time control of current will be possible to support feedback on beam parameters such as orbit and tune, as well as feed forward from operator real-time knobs or multipole estimates from the multipoles factory.

The network infrastructure will support the real-time transmission of one floating point number to every controller every 10 ms. This number may be used in different ways by the controller. In fact, there will be four different real-time modes, as listed in Table 3 (where $I(t)$ is the predefined function of current against time and ΔI_{rt}, G_{rt} and I_{rt} are different ways of using the real-time value). The last RT mode, *Direct*, is special because it implies that no predefined function is in use. This means that synchronised events have no meaning to the controller.

Table 3: Real-time Modes

RT Mode	Reference
Off	$I_{ref} = I(t)$
Sum	$I_{ref} = I(t) + \Delta I_{rt}$
Gain	$I_{ref} = I(t)(1 + G_{rt})$
Direct	$I_{ref} = I_{rt}$

5.4. Reliability

In LEP, the mean time between failure (MTBF) for power converters is slightly less than 100k hours. LHC will have nearly twice as many power converters as LEP, so for a similar failure rate, the MTBF will need to be doubled. With 1700 systems, an MTBF of 200k hours will mean between one and two failures per week. To achieve even 200k hour MTBF will not be trivial, so strategies to cope with converter failures will be needed.

This is especially true for the orbit correctors. These converters account for half the total number and will be installed in the tunnel where radiation will be a serious issue. It will be very important for the orbit correction system as a whole to be tolerant of corrector failures.

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