ROUTINE OPERATION OF THE LHC

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Abstract
The aim of this presentation is to outline the main operational phases associated with nominal LHC operation. A more detailed description of these phases can be found in [1]. I will concentrate on the areas that will be under the responsibility of the operations group and much less on cryogenic issues etc. I will not cover specialized machine development beams or the commissioning phase.

INTRODUCTION

In this context, routine operation can be defined as: "A standard pre-programmed sequences of events that are performed on a reproducible basis in order to fill and operate the LHC". The aim of this "routine operation" will be to produce the maximum integrated luminosity for the LHC experiments in the first physics run.

Operation of the LHC is described in a series of phases: Injection, Filling, Ramp, Squeeze, Collisions, Dump & Recycle. The procedures applied during each of these phases will have to be designed to perform each phase as efficiently as possible, whilst minimising the number of interruptions. For example, a quench costs several hours of possible physics time. In addition, all possible steps must be taken to avoid damage to machine hardware, since changing a damaged magnet will require several weeks of downtime.

A strategy to produce the maximum amount of integrated luminosity will have to be defined. A reasonable starting point for such a strategy would be to fix the bunch spacing 25 or 75 ns; fix the β* and the beam crossing angle and then maximise the bunch current (and hence luminosity) for each fill. Hopefully this bunch current will be increased as operational experience grows.

WHAT BEAMS WILL BE NEEDED?

It is proposed to have three types of beam available for a routine LHC fill: -

- PILOT BUNCH. A single bunch with emittances similar to the physics beam ($5\ 10^{9}$ protons/bunch)
- NOMINAL BUNCH. 216 (72) or 288 (96) bunches with nominal emittance at the selected bunch intensity ($2.0\ 10^{12} – 3\ 10^{13}$ protons/batch)
- INTERMEDIATE. 12 (4) NOMINAL bunches. This is a single PSB ring on a standard LHC filling cycle ($1.2\ 10^{10} – 1.2\ 10^{12}$ protons/batch)

The injectors will have to be able to switch quickly between these cycles on a cycle-by-cycle basis according to the LHC request.

LHC CYCLES

Two standard cycles will be used for LHC operation these are shown in figures 1 & 2. [1]

The standard cycle covers all phases of the LHC operation (Injection, Filling, Ramp, Squeeze, Collisions, Dump & Recycle). If, however, there is a problem, such as a magnet quench or a power supply failure, that changes the magnetic history of the machine, it will be necessary to recycle the machine in order to re-establish the magnetic history. The complete recycle takes about 1 hour.

Figure 1: Standard cycle.

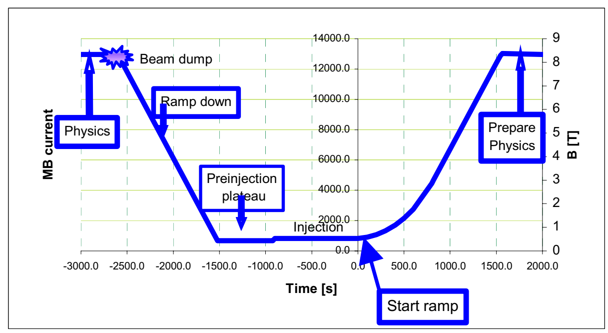
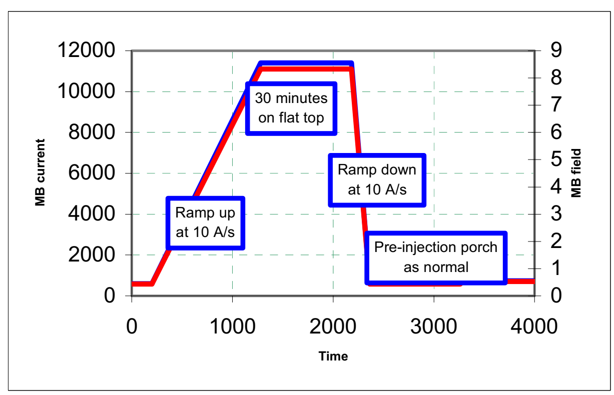


Figure 2: Recycle.



PHASES OF LHC OPERATION

Pre-Injection plateau

Following a ramp down after a Dump or a Recycle the machine is ramped to the pre-injection plateau. This is a flat-bottom below the injection field. Here all the LHC hardware: interlocks, feedback systems, multi-pole factory, RF, collimators etc. will be checked. Once the LHC, experiments and the Injectors are 100% ready, the LHC will move to the Injection Plateau. There is no time restraint on how long the machine can wait on the pre-injection plateau. However, once the LHC is on the injection plateau, the clock starts ticking.

Injection

As soon as the LHC arrives at the Injection Plateau, the persistent current effects in the magnets begin to decay, causing a time dependant change in the multi-pole fields etc. This decay is exponential with a time contact of around 30 minutes. However, these currents "snap back" to their initial values as soon as the acceleration ramp starts. Therefore there is a trade-off between waiting too long at injection and negotiating a bigger "snap back" and trying to inject during the large initial drift of the persistent currents. Currently it is planned to wait longer at injection to have a more stable injection and deal with the larger snapback using multiple feedback and feed-forward systems. For a more detailed look at the issues surrounding LHC injection see [2]

As soon as the persistent current decay has reached acceptable levels (30 minutes), a PILOT beam will be injected into each ring. This beam will be used to verify machine settings (tune, chromaticity, orbit) as well as collimator settings, loss rates and all the feedback loops etc. As many pilots as necessary can be injected for this phase of the set-up. The circulating pilot is lost onto the TDI (a dump downstream of the injection kicker) as the new one is injected. Once the LHC is ready then an INTERMEDIATE beam is injected into each ring. This beam will allow a complete check of the LHC with a beam that looks exactly like the nominal beam but with 1/18th of the intensity. Once this check is complete, then the filling can begin. Due to beam loss considerations for the TDI, it may be necessary to dump the INTERMEDIATE beam and re-inject a PILOT before starting the fill. This respects the constraint that it must never be possible to inject a beam that can damage hardware into an LHC ring, in which there no beam circulating [2].

Filling

It looks best to fill both LHC rings in parallel. This maintains similar currents in each ring and avoids problems of "blinding" the BLM's with an intense circulating beam in one ring, while trying to set up the second. It also ensures equal intensities in both rings at the start of acceleration. However, such a mode of operation requires that the SPS can switch rapidly between LHC Ring One and Ring Two and that both SPS-LHC transfer lines can be pulsed simultaneously.

The SPS will supply beam to the LHC according to the pre-determined filling pattern. The quality of the beam injected into the LHC is very important both to avoid equipment damage and to provide optimum physics conditions for the experiments. Therefore there will be a certain number of interlocks on the SPS extraction to LHC. These interlocks will check number of bunches, bunch distribution, SPS-LHC RF synchronisation etc. and the transverse beam size by collimation in the SPS. Ejection to LHC will be inhibited if the beam is outside preset tolerances. In this case the timing system will have to allow the missing batch to be repeated and then continue the normal filling cycle. It is also possible that a batch will be badly injected into the LHC In this case the wrongly injected batch can either be replaced by repeating that injection or the whole fill dumped, the LHC re-cycled and the fill restarted.

Once both rings are filled the beams will be accelerated up the ramp to 7 TeV.

Ramping

During the ramp pre-programmed functions (feed forward) and feedback systems will control the important machine parameters (tune, chromaticity & orbit etc.). The collimator positions will be essentially the same as for injection as the machine optics remains the same through the ramp. In about 25 minutes the machine will (hopefully) reach 7 TeV!

Squeeze and prepare for physics

The squeeze reduces the β^* at the insertions from the standard 18m at injection to the value for maximum luminosity (0.55 – 1m). The squeeze will be a particularly delicate operation as the change of optics will require on-line modification of the collimator settings. Susceptibility to quenches is also much higher at top energy than at injection. Once the squeeze has been completed the beams will put into collision, background levels checked, luminosity optimised and then the beams will be given to the experiments for around 10 hours of stable colliding beam physics. During the collision period, backgrounds, luminosities, beam lifetimes etc will be optimised as required. After 10 to 12 hours of physics the beams will be dumped.

Dump and recycle

Before dumping the beam the injectors must be fully ready to supply all the beams needed for the next fill! Once the LHC beams have been dumped the machine can be ramped down to the pre-injection plateau to begin a new fill.

Problems

Equipment problems that have not caused an unscheduled beam loss can be fixed during the ramp down and on the pre-injection plateau.

After a magnet quench, time will be needed to analyse the post-mortem data, decide what happened, cool down the quenched system and recycle the machine. This will take 2-6 hours depending on the severity of the quench etc.

For an unscheduled beam dump (without a quench) a similar post mortem analysis will be needed. At the same time if the dump was due to equipment failure, time to repair and recycle will also be needed. Again this will be measured in hours.

If machine hardware gets damaged (by the beam) several days or weeks will be needed for repair!!

Therefore we can conclude that almost any problem will cause a delay of several hours.

How long will it take?

Table 1 shows the minimum time that is estimated to be necessary for each phase of LHC operation. However, these are absolute minimum figures. As stated above almost any problem will add several hours to the operational cycle. So, it is prudent to assume one fill for physics per 24 hours, for 10 to 12 hours of colliding beam physics operation.

Pre-injection plateau	30 mins.
Injection	30 mins.
Ramp	30 mins
Squeeze & prepare for physics	30 mins
Physics	10 hours
Ramp down	30 mins.

Table 1: Minimum time estimations

Injectors

The Injectors will have to have beam available for the LHC "on-demand" from some time before one fill is dumped until the following ramp has been successfully started. This is a minimum of 3 hours in every 13 (see Table 1). However it is more likely to be 12 hours in every 24, if we assume one fill per day. Therefore, prudent scheduling dictates that the SPS will need to be able to supply beam to other users (CNGS and the FT program) in parallel with the LHC. This is not the case at present. Therefore fundamental modifications to the SPS control and timing system will be needed. Plans for these modifications are already underway inside the AB Division. There is also the problem of switching the beam rapidly and often between the LHC and CNGS. Here some hardware upgrades will be necessary to the switching power supplies and magnets.

The multi-cycling capability of the other injectors (PSB and PS) is considered to be sufficient.

Conclusions

It will be a challenge to routinely "fill a very small, very cold hole with and very high intensity, high energy beam!" In fact operation of the LHC will probably never be "routine" in the sense that it will always be challenging and difficult.

Great care will be needed, as any problem will cost several hours in downtime.

Real multi-cycling capability for the SPS will be needed to supply other SPS users with sufficient beam during LHC operation.

REFERENCES

[1] O. Brunning, A. Butterworth, M. Lamont, J. Wenninger. LHC Project Note 313: The nominal operational cycle of the LJC with beam (version 1)

[2] R. Schmidt & J. Wenninger, LHC Project Note 287: LHC Injection scenarios