CONTROLLING THE BEAM FOR EXTRACTION: DO WE SEND IT?

P. Collier, CERN, Geneva, Switzerland

Abstract

The beam in the SPS must pass a stringent quality control procedure before being delivered to the LHC. Firstly, it must meet the requirements specified by the LHC for the specific injection cycle in terms of bunch pattern, train definition, average intensity and synchronisation. Secondly, the individual bunch intensities, together with the longitudinal and transverse characteristics must be within a pre-defined tolerance of nominal values. Lastly, the systems associated with the extraction, transfer and injection into the LHC will have the final say as to whether the transfer will actually take place. The information, which should flow between the LHC and its injectors, will be outlined, together with some initial thoughts on the diagnostics, decisions and interlocks associated with the quality control procedure.

1 INTRODUCTION

Figure 1 shows the filling pattern and bunch disposition in one ring of the LHC, with the new baseline beam from the PS. In this scheme each batch from the PS consists of 72 bunches with 25 ns spacing. These batches are formed into trains in the SPS, with each batch separated by 225 ns. For the 12 SPS cycles needed to fill an LHC ring, the number of PS batches in the SPS train varies following the pattern:

334 334 334 333

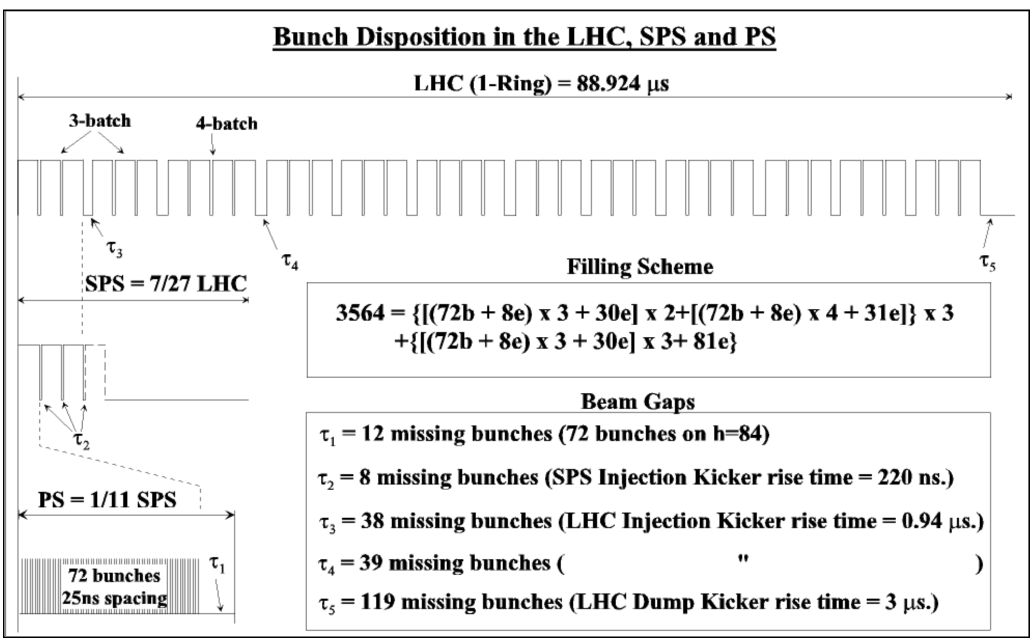

Figure 1: Filling Pattern for one LHC Ring.

Each LHC ring will therefore contain 2808 bunches with a complex pattern of batches, trains and gaps. A total of 24 SPS cycles is needed to complete the filling of the LHC. Each cycle must give a beam that meets the needs of the LHC, including tight tolerances on overall beam quality and bunch to bunch variations. The SPS will have to translate the total tolerances given by the LHC into quality control parameters governed by statistical variations from cycle to cycle.

A general overview of the LHC beam requirements has been given before[1] and is summarised in table 1.

Table 1: Beam Quality Tolerances, from [1]

Bunch-bunch intensity variations	~10%
Spurious bunches	<~5%
Transverse emittance	< 30%
Scraping before SPS extraction	0.5-1.0 eVs
Injection Stability	1.5σ
Energy	10^{-4}

These figures can act as a general guide, but must be significantly refined in order to be useable as quality control parameters for the SPS.

2 VETOING THE EXTRACTED BEAM

The quality of the LHC beam in the SPS is just one aspect of a general system of vetoes on extracting the beam and sending it to the LHC. This, in turn, is a part of the global system of beam requests, interlocks and protection. The more global portions of the SPS will not be treated here.

For the LHC extraction, Two types of vetoes can be defined; 'hardware' vetoes and 'beam quality' vetoes. These are described below:

2.1 'Hardware' Vetoes

These vetoes are based around the readiness of the downstream equipment to take the extracted beam. In this context the sum of the active vetoes can be considered as the inverse of a beam request; i.e. any active veto will remove the request to extract the beam. Typically the LHC machine itself, the transfer line elements and the SPS extraction equipment will generate vetoes of this type.

In some cases the state of the equipment is the only necessary check. This would be the case, for example, with a transfer line stopper - which must be OUT, or IN, before the extraction can be permitted.

In other cases, more information is needed to specify the readiness of the equipment. For instance, a check that the setting(s) associated with the equipment are within a proscribed tolerance might be needed.

For the extraction and injection kickers a more indirect check is required. In this case the requested setting needs to be checked, together with the internal readiness of the charging and firing circuits.

Other classes of vetoes might come from even more exotic checks. In the case of the SPS scraper system a complex action to remove the tails of the beam will be undertaken by the equipment. A 'OK' status must be returned from this equipment to indicate that the action was successfully completed. In this case there is also likely to be a beam quality veto associated with a measurement made on the beam after the scraping process is complete.

The last example shows that many of the hardware vetoes will, in some way be associated with beam quality vetoes. If a bad quality beam is generated during a previous cycle, this might generate hardware vetoes on the current cycle or result in an update of the reference parameters for certain equipment.

2.2 'Beam Quality' Vetoes

As their name suggests these will address the issue of whether the beam is good enough to send to the LHC. In the first place a check must be made on the synchronisation between the two machines and the bunch/train pattern. This must match exactly the request made by the LHC. In addition the major beam parameters must be compared to reference values and cycles rejected which do not come up to scratch. As the filling of the LHC will take place over many cycles of the SPS (and PS), the statistical variation from cycle to cycle must be taken into account when weighing the parameter tolerances.

Two types of beam quality vetoes can be defined: immediate and post mortem. In the case of immediate vetoes a measurement, or series of measurements, lead to the rejection of the beam actually in the machine. Most parameters that can be measured in the SPS ring will be treated in this way. The list includes bunch intensities, emittance and spurious bunch population.

The second type of beam quality vetoes generally involves the beam after it has left the SPS ring. From the point the kickers fire, nothing can be done for the beam in this cycle. However many measurements will be made during the passage of the beam down the transfer line and into the injection region of the LHC. A post mortem on these measurements will have to raise a veto on extraction if the measurements indicate that the beam was not well adjusted. Typical examples here might include the transfer line trajectory, injection errors in the LHC, energy matching between the machines and beam loss monitoring during transfer and injection. To a large extent these are outside the scope of the present paper, but will be an important part of the quality control procedure.

3 INPUT PARAMETER REQUIREMENTS

In order to illustrate the issues to be addressed regarding the beam quality control of the LHC beam in the SPS, an example will be treated in more detail: the bunch to bunch intensity variations. To characterise the bunch to bunch intensity variations in the beam delivered to the LHC, three parameters are needed:

1. The average intensity per bunch.
2. A parameter describing the bunch to bunch variation within a PS batch, and
3. A parameter describing the statistical variation of the average bunch intensity from cycle to cycle in the SPS.

The 72-bunch system was proposed and verified by the PS [2,3] and is now in the LHC baseline. The system involves injecting 6 bunches from two booster cycles into the PS and a series of bunch splitting operations to arrive at the 26 GeV/c extraction with 72 bunches. Systematic checks have not yet been made, but during each phase of the preparation of the beam in the CPS, some intensity variation patterns are likely to be present [4]. A realistic set of bunch to bunch variations can be generated from the following assumptions:

- The booster rings are never perfectly equal (±5%).

- The triple splitting can generate a left-right asymmetry (central bunch OK, left bunch weaker or stronger than the right) (±3%).
- The first double splitting is the least reproducible so far, giving unequal bunches at harmonic 21 (±4%).
- The second double splitting is quite good, but can still give slightly unequal bunches at h=42 (±2%).

The figures in brackets correspond to the bunch intensity variations chosen for the simulation of the resulting bunch pattern, given below.

The simulation involves generating a bunch pattern at each stage of the batch generation process in the PS. The example using the above variations is shown in figure 2.

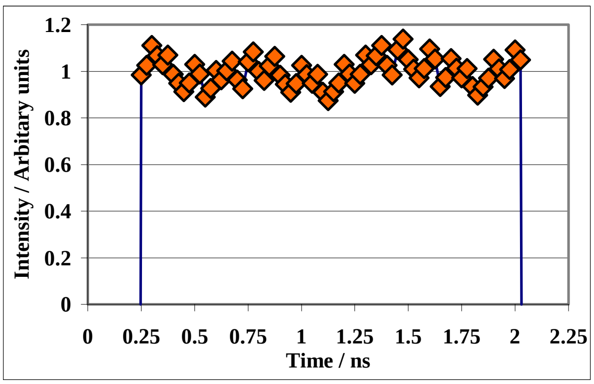

Figure 2: Simulated typical 72-bunch batch extracted from the CPS.

The time distribution of figure 2 is not very informative. However, if the data is plotted as an intensity histogram it makes a little more sense. This is shown in figure 3.

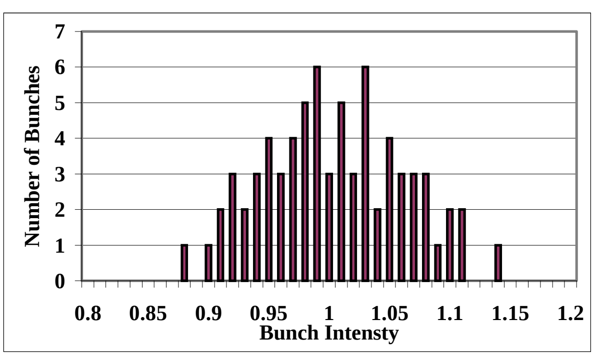

Figure 3: Intensity histogram of a simulated PS batch.

The data of figure 3 corresponds to a single data set with a specific set of variations and a statistical seed for the 6 PSB bunches. Different data sets can be generated with a new seed (while keeping the average intensity constant). Averaging over several data sets tends reproducibly to give a 'triangular' distribution with a total width of ±15%. This is used to represent a normal PS batch. The width of the distribution (±15%) can be used as the figure of merit for the beam and is reduced by reducing the variations at each stage of the batch preparation.

A total of 39 such batches will be injected into each ring of the LHC. Each batch will be slightly different. For the simulation, the triangular structure can be assumed to be fixed. The variation from cycle to cycle corresponds to a statistical variation in the average bunch intensity in a PS batch. Based on the performance of the fixed target beam in the SPS a Gaussian distribution with a σ of 5% seems realistic. Cutting the distribution at 2σ (i.e. rejecting batches with an average intensity more than 10% away from the nominal) and folding the distributions together gives an idea of the intensity histogram to be expected in an LHC ring. The result is shown in figure 4.

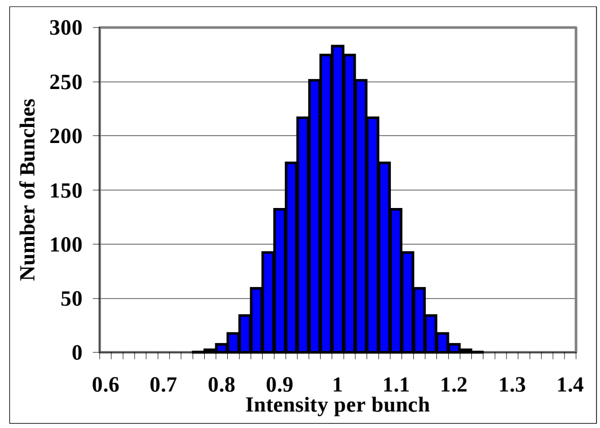

Figure 4: Simulated bunch intensity distribution in one ring of the LHC.

In this case around 25% of the bunches will have an intensity which is different from the mean by at least 10%.

Measurements with the LHC beam in the PS and the SPS will be required to validate the assumptions made for the simulation. In addition, the way in which the different quality control parameters interact to generate a veto on beam extraction need further study.

4 BEAM QUALITY ISSUES

Section 3, illustrates the complexity of the quality control for one particular LHC parameter: the bunch to bunch variations. Similar issues will exist for other measurable beam parameters. Some open questions regarding different beam parameters are given below.

4.1 Spurious Bunches

The LHC beam fills every fifth bucket in the SPS. Beam in adjacent RF buckets can remain captured and will be injected into the LHC. This beam will cause problems for the LHC beam instrumentation and the experiments. In addition, the quality of the bunch intensity measurement in the SPS itself relies on them not being present [5]. It should be noted that the bunch splitting scheme in the PS is likely to generate spurious bunches if it is not well adjusted. The extent to which these bunches will naturally be generated will have to be verified experimentally, once beam observation tools are available.

There are therefore several questions regarding the detection and measurement of these bunches and the perturbation to the normal bunch intensity measurement. At present, the LHC has given a global figure for the maximum intensity of a spurious bunch with respect to the intensity of a normal bunch, <5%. No criteria have been specified for the number of such bunches their spacing and their intensity profile.

4.2 Scraping and Transverse Emittance

Scraping involves the removal of the transverse tails of the beam distribution before extraction towards the LHC. At present the removal of all particles outside 4σ has been requested. A system has been installed in LSS5 of the SPS and tests have started. The scraper blade works in absolute position and may require measurement and correction for cycle to cycle variations in beam position and beam size at the scraper. In addition it can only work for a complete SPS beam. Therefore any bunch to bunch variations in position or emittance will lead to different levels of scraping for each bunch. If these variations are large enough, the individual bunch intensities might be (slightly) affected.

Once the scraping is complete a quality check will be required. This will involve measuring the profile of the beam and looking at the population in the tails. Although this should be possible for the average of all bunches, it is not clear that individual bunches can be measured with sufficient precision to allow the bunch to bunch variations to be checked.

In addition, some investigations of the time required to re-populate the tails will be needed. This will determine the point in the cycle that scraping must take place.

If the transverse emittance measured on the fly in the SPS is deemed to be outside tolerance, the extraction will be vetoed. In this case, past experience tells us that the problem is likely to persist until the injector chain is re-tuned ... which might take some time.

5 WHAT DO WE DO IF WE DON'T SEND THE BEAM TO THE LHC?

Once a veto on the extraction towards the LHC has been generated, the beam will be dumped on the SPS internal dump. An alternative has been suggested; to send the beam to the CNGS instead of dumping it. However this is not (presently) practical for the following reasons:

- If the beam had been destined for TI 8, it cannot then be sent to CNGS as the same dipole power converter is switched between these lines.
- If the beam had been destined for TI 2, then the CNGS would have to pulse the lines in anticipation of beam ...and hopefully not receive any! This would be expensive in electricity.
- The LHC beam has a different bunch pattern, timing and energy to the CNGS beam. The latter change (from 400 GeV/c to 450 GeV/c) would make it very difficult to control the trajectory in the CNGS transfer line and optimise the steering on the target.

Once a beam has been dumped the question arises as to what happens in the following SPS cycles. This depends very much on the particular veto generated. If, for example a hardware veto were the cause, this would presumably remain active until the hardware is ready. For many of the beam quality vetoes, a 'try again' approach can be used. For the beam quality measurements once the beam has left the SPS ring a veto will have to be generated for the following cycles, until the problem is resolved.

6 TIMING

A certain amount of dynamic information is required, each cycle. This concerns primarily the SPS train definition (number of batches) and the selection of the LHC ring and position. The decision about the final destination of the beam in the LHC must be passed to the CPS a few hundred milliseconds before the first beam is injected into the SPS. During the SPS acceleration cycle, but primarily towards the end, a series of measurements and hardware checks will have to be performed to ensure that the beam can be extracted towards the LHC. The final decision on transfer will be a few milliseconds before the extraction itself. Depending on the success of the transfer the LHC then has around 1 second to decide where the next cycle should go. The situation is summarised in figure 5, where the SPS cycle is shown, together with portions of the CPS cycle.

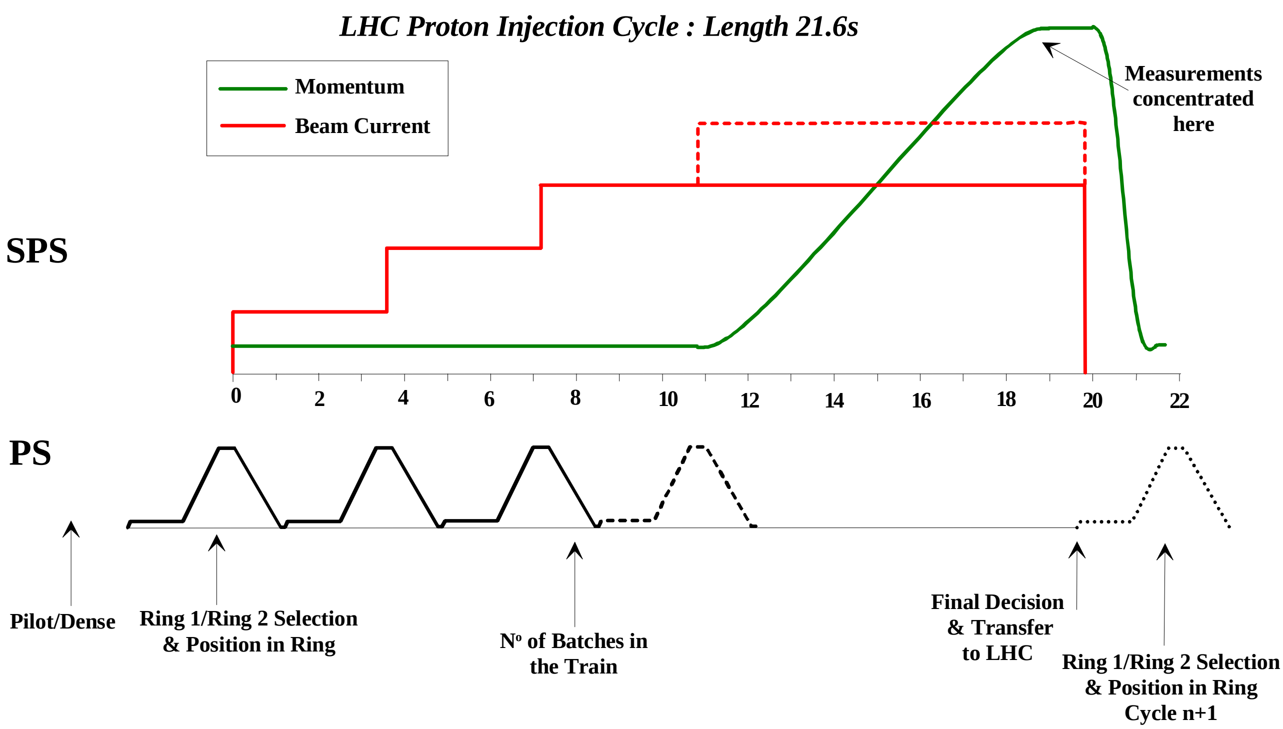

Figure 5: LHC filling cycles for the SPS and CPS showing the timing of the decision making process

7 CONCLUSIONS

The SPS will be required to deal with a complex set of extraction vetoes and warnings for the LHC beam. Some of these are hardware oriented and will involve checks on equipment readiness. They are relatively straightforward, but will involve a large increase in the number of 'inputs' to the beam dump system. Some aspects of the hardware veto system have not been discussed yet. This includes the different levels of readiness, depending on the beam in the SPS. For example, while the LHC injection system might be ready to take pilot bunches from the SPS; it might not be ready to take the normal injection intensities. The exact order of checking equipment will have to be optimised, with the SPS extraction and LHC injection kickers being the final two elements.

Many other vetoes on the extraction will come from checks on the 'beam quality'. These can either be generated by measurements made on the beam currently in the SPS, or by previous cycles which did not come up to scratch. In general, measurements made after extraction (in the transfer lines and at LHC injection) can only act on subsequent SPS cycles.

Several beam parameters will be critical for the LHC. Some of them have been discussed here. In general there are two factors governing the beam quality. These are:

- The allowed tolerance within a given SPS cycle, and
- The statistical variation of the parameter from cycle to cycle.

Most of the tolerances will be fixed. However, a clever system might be devised to vary them as filling of the LHC proceeds.

In addition to the LHC, the SPS has other users and other needs for vetoes and interlocks. The present SPS system needs to be re-designed to take the new requirements into account. It will be a complex problem and specifications will have to be drawn up in the near future covering the requirements for the instrumentation, beam dump hardware and the software. Design work will have to begin in the near future for the beam abort system.

With all this in mind Dr. Interlock for the SPS seems necessary. The responsibility would have to cover all aspects of beam interlocks and vetoes, together with the additional responsibility of ensuring good quality control for the LHC beam.

8 REFERENCES

1. J. Gareyte, *'The needs, desires and requirements of the LHC'*, Chamonix IX, Jan. 25-29, 1999.
2. R. Garoby, *'Status of the nominal proton beam for the LHC in the PS'*, Chamonix IX, Jan. 25-29, 1999, CERN/PS 99-013.
3. R. Garoby, S. Hancock & J.L. Vallet, *'Demonstration of bunch triple splitting in the CERN PS'*, CERN/PS 2000-038 (RF).
4. R. Garoby, private communication.
5. A. Guerrero, *'IBMS results'*, BI-Day Dec. 8-9, 2000.