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LHC Injection Scenarios

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Summary

Injection of nominal beam intensities from the SPS into the LHC must be done under well - controlled conditions since an abnormal state of one or more elements in the LHC could lead to severe damage of LHC machine components. This note proposes some general principles to be applied for injection into the LHC. Firstly, only low intensity beams below damage threshold can be injected into an empty machine. Secondly, high intensity beams can only be injected when some beam is already present in the machine. Procedures for injection and failure scenarios are discussed.

1. General principles for injection of beam into the LHC

The injection of beams into the LHC could damage equipment, if the beam intensity is high (for example for a batch with nominal intensity) and one of the LHC elements has wrong settings or is in a fault state. Since it is not possible to observe the losses and to dump the beam in less than several turns, existing safety systems cannot prevent such damage. As an example, if one of the 900 orbit corrector magnets were at maximum field during injection, the beam would be deflected directly into the magnets and damage components of the vacuum system and magnet coils.

Before injection, the correct state of the LHC equipment will be verified by software, but we consider this procedure insufficient. The following general rule for injection is therefore proposed:

1. If there is no beam circulating in the LHC, it is only allowed to inject beam with limited intensity, and <u>not</u> beam with large intensity.

2. To inject beam with large intensity, beam must already circulate in the LHC.

Whenever there is no beam circulating in the LHC, the following procedure must be enforced:

1. Only injection of a beam with intensity below damage threshold (pilot or somewhat above) is permitted. Beam Intensity Ranges (BIR) must be defined, and BIR=1 corresponds to a beam intensity which cannot damage LHC equipment during injection.

2. While a beam is present, injection of a more intense bunch/beam is possible. If the low intensity bunch is a pilot, the new beam can be injected onto the pilot bunch, which will be kicked onto the TDI, an absorber block installed in the LHC just downstream of the injection kicker to protect the LHC against misfiring of the injection kickers. This guarantees that there is no interval without beam during which some equipment might go wrong.

If the low intensity beam drops below a threshold to be defined, extraction from the SPS and injection into the LHC will be inhibited for beams above the lowest intensity range. This ensures that high intensities cannot be injected in a machine that could be in a poor state. As a consequence, two LHC beam current transformers (BCT), one for each beam, must be wired to the interlock system. There are two options:

- To send the signal to the Beam Interlock System [1] (via the Beam Interlock Controller module) which would break the Beam Permit Loop, and injection would be inhibited. This action will automatically inhibit extraction from the SPS and cause the LHC beam dump to fire.
- To inhibit injection by a signal to the injection kicker, and possibly to the SPS extraction kicker without taking away the Beam Permit.

The first solution preferred over the second one, but some precautions need to be taken with respect to the LHC post-mortem acquisition system [2] to avoid unnecessary or false triggers. It is assumed that the intensity of the beams can be changed throughout the injector from cycle to cycle.

2. Injection and dump operation

During first commissioning or for injection studies, it can be desirable to inject a pilot bunch and dump it “immediately”, i.e. within a few turns or within some tens or hundreds of milliseconds. As a general rule, a check of the beam dumping system must be carried out after each dump action. This implies that injection will be inhibited for some 10 seconds following a dump at 450 GeV. This mode of operation is very similar to the “inject and dump” mode that existed for LEP and has already been proposed at an earlier stage [3]. It requires a beam dump action with a given delay relative to the LHC injection event. If the delay is set to its minimum, the beam will be dumped directly during the first turn: beam injected in IR2 will travel over IR4 to IR6 where it will be dumped after only half a turn, beam injected in IR8 will travel through only 2 sectors to IR6. Synchronization of the beam dump with the beam abort gap must still be evaluated for this mode.

This injection mode will ensure that during the early commissioning the beam is being properly disposed of. This is also important whenever the beam does not immediately circulate in the machine due to improper settings of some machine parameter (tune, chromaticity) or for setting up of dampers, RF capture… Such a mode is also very useful for injection steering of the transfer lines and of the septa and kickers at the end of the lines. While some adjustments can be performed with the TDI in closed position where it intercepts the beam, the final tuning of the trajectory at the end of the lines is best done by observing the beam oscillations over at least one LHC arc.

The general rule that a low intensity beam must be present in the machine before a higher intensity can be injected applies also for this situation. For injection & dump of an intense beam, it is necessary to inject a low intensity beam that must circulate normally before the intense beam is injected (and dumped). This sequence must be repeated for each individual inject and dump shot.

3. Injection scenarios

We consider now several injection scenarios. Table 1 defines the logical signals that are used and set for the different systems that are involved.

3.1. First injection(s)

Following a period without circulating beam the first condition that must be fulfilled is to obtain the Beam Permit from the LHC Beam Interlock System, i.e. the state of the Beam Permit Loop must go from BeamPermit=NO to BeamPermit=YES. This ensures that there is no failure in the powering system and that all vital systems (beam dump, collimators, vacuum valves) are ready for beam operation. This verification check that is done by software does however not guarantee that all equipment of the LHC machine is set to the correct injection parameters. The BeamPermit signal must be connected to the SPS extraction interlock system and extraction from the SPS must be inhibited whenever BeamPermit=NO.

Provided the magnets have been ramped to injection current and are set within tolerances, and all devices are in the correct state (collimators, RF…), a request is sent to the SPS for beam in the intensity range BIR=1. The intensity of the beam that is injected from the PS into the SPS and accelerated to 450 GeV must be measured just before extraction. If the intensity is in the correct range and LHCBeamPermit=YES, extraction from the SPS is enabled, SPSExtractionPermit=YES. At the same time, provided that LHCBeamPermit=YES is still valid, injection permit is given to the LHC injection kickers, LHCInjectionPermit=YES. All conditions are met to extract the beam and inject into the LHC.

While the beam is circulating in the LHC in good conditions, the operator may request from the SPS a more intense beam that could potentially damage LHC equipment, i.e. BIR=2. Again, before extraction from the SPS the beam intensity is measured and SPSExtractionPermit=YES is set if the intensity matches the request. To enable the LHC injection kickers and the SPS extraction elements, the presence of beam in the LHC is checked a last time a few milliseconds before extraction from the SPS. If the beam is still present, LHCInjectionPermit=YES is set. This should be done at the last possible moment and depends on the minimum delay required to properly detect the presence of beam and enable the SPS extraction and LHC injection kickers. The check should be simple, since we are only interested in severe problems. The presence of the beam is likely to be sufficient to exclude any fault that would cause the loss of the injected beam within one or a few turns. The probability that an element fails during the small time interval between the check and injection is very small.

After the injection of the beam with an intensity BIR=2, beam is circulating in the LHC. When the next batch is requested from the SPS, the same procedure of detecting circulating beam in the LHC is applied to continue injection of beam with large intensity.

Signal Definition	State	Meaning
LHCInjectionPermit	NO	Injection disabled
	YES	Injection enabled
SPSExtractionPermit	NO	Extraction disabled
	YES	Extraction enabled
LHCBeamPermit (Beam Permit Loop)	NO	Beam not permitted
	YES	Beam permitted
BIR (Beam Intensity Range)	1	Intensity below damage threshold
	2	Intensity above damage threshold

Table 1: Definition of signals and logical states. It is of course possible to define more than two intensity ranges to allow an even more flexible setup.

3.2. Injection failures

We consider here several failure scenarios for this injection procedure. We will start from the SPS and work our way into the LHC.

3.2.1. Failures related to the SPS

1. **SPS intensity outside requested range**

In such a case extraction from the SPS is never enabled, i.e. SPSExtractionPermit=NO is not removed. The beam is not extracted but dumped onto the SPS beam dump (this happens at the latest at the end of the beam-in segment of the cycle). We assume here that the intensity problem affects only fraction of all SPS shots. This intensity interlock prevents injection of a poor batch that would require a complete refill of the corresponding LHC ring. If the intensity problem is 'permanent', the injector chain must be retuned or the request of the LHC adapted to the possibilities of the injectors.

2. **SPS and transfer line energies are wrong**

For the first injection with low intensity (i.e. when the LHC is empty) there should be no harmful consequence for the LHC machine. Depending on the size of the energy offset, the beam may or may not circulate for a few turns. The energy mismatch can be determined using beam position measurements. In principle it is possible to avoid large energy offsets at the first injection by software interlock once the relation between the LHC and SPS settings and dynamic effects are known with sufficient accuracy. If the energy error affects only the SPS, the energy offset will be already visible in the transfer lines. Depending on the size of the error, the beam may reach the LHC ring or be lost in the line.

For the injection of beam in the range BIR=2, the presence of the BIR=1 beam in the LHC implies that the energy settings were correct at some earlier time. An energy change can occur if the energy of the SPS or of the transfer line was modified by a deliberate trim to the settings. This situation can be avoided if trims to the machine energy at extraction are forbidden and/or password protected. Alternatively, if the SPS extraction kickers are fired before the beam reaches the flat top (because the timing event arrives too soon), the beam could be extracted with a wrong energy. This scenario requires adequate protections through the SPS interlock system.

3. **Transfer line magnets in a wrong state**

A wrong setting of a critical magnet in the transfer lines must be detected by the power converter surveillance connected to the SPS extraction interlock system. The extraction from the SPS must never be enabled. Collimators at the end of the beam transfer line could be used in the protection against such errors.

4. **Injection oscillations**

Large injection oscillations in the LHC due to the orbit in the SPS, drifts of the transfer lines,… can obviously not be prevented by observing a low intensity circulating beam. A collimator at the end of the transfer line must be used to catch a beam with excessively large oscillations generated in the SPS or in the upstream part of the transfer line. Injection oscillations due to wrong injection kicker or septum settings cannot be prevented. A monitoring of those settings must be therefore performed. Trimming of those settings must be handled with great care.

3.2.2. Failures related to the LHC

1. **Beam Permit Loop state to beam off**

If LHCBeamPermit=NO is set before extraction from the SPS, an extraction veto is sent to the SPS which forces SPSExtractionPermit=NO and LHCInjectionPermit=NO. The beam is then dumped in the SPS. If LHCBeamPermit=NO arrives after extraction from the SPS (or too late to prevent the extraction), the status LHCInjectionPermit=NO will prevent the firing of the LHC injection kickers and the beam is dumped onto the TDI.

2. **Circulating beam in the LHC disappears**

Here we assume the LHC requests a beam in the intensity range BIR=2. If the beam circulating in the LHC disappears before injection, SPSExtractionPermit=NO and LHCInjectionPermit=NO for a BIR=2 beam request. Depending on the exact moment when the circulating beam "disappears", the requested BIR=2 beam will be dumped in the SPS or on the TDI (see above).

3. **LHC energy drifts**

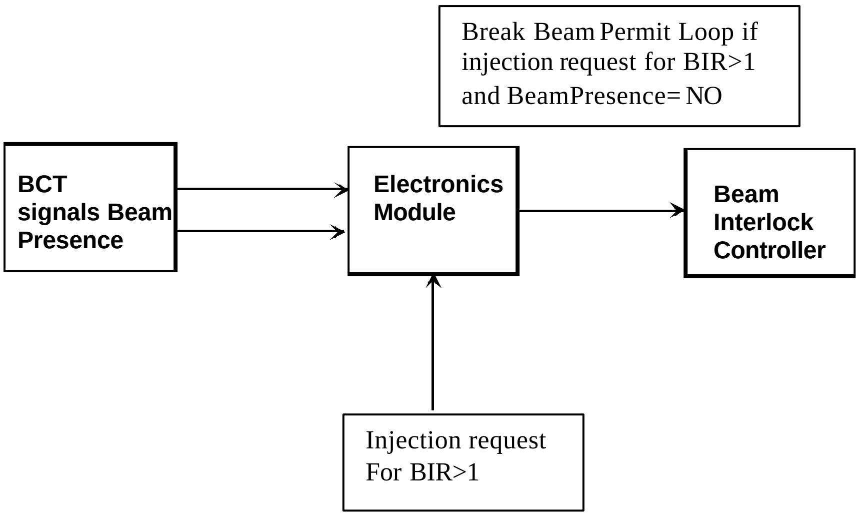
If a low intensity beam is present in the LHC and the energy drift due to the b1 field error decay is not continuously corrected with the orbit correctors, the energy of a high(er) intensity injection may be mismatched. Since the decay corresponds to a relative momentum error of $\sim 3 \times 10^{-4}$, the beam will circulate for some time but the beam losses induced by the orbit oscillation or a bad capture will trigger a beam dump if they exceed a defined threshold. During injection, any trims of the integrated B-field must be kept within limits to ensure correct injection of the next batch.

4. **<u>Injection with the wrong phase</u>**

When a beam is injected with the wrong timing, it may be decelerated by the LHC RF system. The maximum deceleration is ~ 20 MeV/turn, i.e. a relative energy error of 5×10^{-4} after 10 turns. The resulting orbit oscillation in regions with dispersion will induce beam losses, which will trigger the beam dump if they are above a defined threshold.

4. Electronics Module

An electronics module is required to interface the BCT to the Beam Interlock Controller. This module must send an interlock signal, which depends on the requested intensity range and the actual beam present in the machine. This signal must be fail-safe. Care must be taken to avoid that breaking the Beam Permit loop will not generate unnecessary post-mortem triggers.



5. Reliability Estimates

For a (pessimistic) Mean Time Between Failure (MTBF) estimate for the power converters of 20000 hours, there will be one PC failure every ~ 10 hours. If a delay of 10 milliseconds is required to enable the extraction in the SPS, the probability that a PC fails inside this window is $3\ 10^{-7}$ corresponding to one failure every $3\ 10^{6}$ injections. In practice the delay might be even shorter. In addition it must be noted that not all those failures will have severe consequences.

With the intensity check, the time window during which something can go severely wrong is therefore extremely short. If this intensity check is not performed, the equivalent time window spans the few seconds between the moment of the dump of an LHC beam and the injection of new beam. This delay is required to re-activate the LHC beam dump. During such a few seconds time window, the probability of failure would be more than 2 orders of magnitude higher than for the proposed scheme.

6. Conclusion

Safe operating conditions can be obtained for the LHC provided a few simple rules are consistently applied for injection. Only low intensities can be injected into an empty ring, higher intensities requiring the presence of a circulating low intensity beam. We propose to assign to one of the BCTs of LHC per beam the role of measuring the beam intensity. The signal of this BCT must be connected to the LHC interlock system over an electronics module that will combine this information with the intensity request from the machine operation. It must be noted that in the future, the SPS BCT will have a very important role since it must prevent injection of beams with the wrong intensity into the LHC.

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8. References

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