CHANGES IN SPS INTERLOCKING

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Abstract

This document presents the current status of interlocking and machine protection at the SPS. The machine protection incidents that occurred in the period 2006-2013 are presented together with their mitigation. Future needs of the SPS in terms of machine protection will be discussed.

SPS MACHINE PROTECTION

All information relevant for the SPS Machine Protection System, which has been accumulated since the restart of the machine after the 2005 shutdown year, is concentrated on a dedicated WEB site [1]. This site stores information on configuration, MP tests, incidents as well as reports relevant for SPS MP and for SPS extraction MP.

The SPS MPS is not as tight as LHC MPS, but the risk is also much reduced since the maximum stored energy is ≈ 2 MJ per beam as compared to 360 MJ in the LHC. But even a high intensity SPS beam can cause damage, as will be shown in some examples below. The SPS ring has a very basic protection by Beam Loss Monitors (BLMs) and Beam Position Monitors (BPMs, only for horizontal plane). The SPS MP is relying heavily on the Software Interlock System (SIS), which is now widely used across CERN accelerators but that was originally designed for the SPS [2]. Multi-cycling poses a real challenge to the MPS, both to the Beam Interlock Systems (BIS) and to the SIS, due to cycle dependent settings, vastly different beam characteristics, gains (e.g. for the BLMs), etc.

The period 2006-2013 saw 5 MP incidents. Two incidents resulted in equipment damage (an electrostatic separator ZS and a dipole magnet MBB), the others were near misses.

In the short term (up to Long Shutdown Two / LS2) no major improvements are foreseen to the SPS ring MPS. The next major upgrade consists of new BLM electronics (with multiple integration windows as for the LHC system, but with fewer integration windows). The planned improvement of the BPM interlock system (new design, protection in both planes) did not work out due to reliability issues.

ZS incident

In the fall of 2007 the septum wires of one electrostatic septum (ZS1) were cut by slow extracted beam with an intensity of 9×10^{12} protons. Due to a high level controls problem, the slow extraction to the North Area through the LSS2 extraction channel was *de facto* transformed into a fast-slow extraction. As a consequence the entire beam was swept over the extraction septum in a few milliseconds. Due to the large losses that are associated with the slow extraction, the thresholds of the BLM in the extraction area that can react in a few µs were set too high to catch this failure. The BLMs downstream of the extraction area on the other hand were too slow. The following actions were put in place:

- Control system protections (limitations on some current) were put in place in the LSA controls database,
- One BLM channel at the entrance to TT20 that could have caught the failure was moved to the crate with the fast electronics. As a consequence its reaction time was lowered from 20 ms to some µs.

Details on this incident can be found in Reference [3].

CNGS - 2008

In June 2008 a problem in the Master Timing Generator (MTG) led to a ‘freeze’ of the timing in the SPS. As a consequence the CNGS beam that had just been injected was neither extracted nor correctly dumped at the end of the SPS cycle. The beam was still inside the ring when the magnetic fields started to ramp down. The beam became vertically unstable and impacted inside dipole MBB.12530. The vacuum chamber was ripped open by the beam of 3×10^{13} protons. Again the BLM reaction was not fast enough (20 ms reaction time of the ring BLMs), and the fast beam position interlock only protects the horizontal plane. As an action three protection layers were added against such timing failures. More details on the incident and the actions can be found in Reference [4].

SPS BIS

The SPS was the first CERN machine where the new ring BIS designed for the LHC was installed and used operationally [5]. The phasing out of the old SPS interlock system happened between 2006 and 2007. In 2007 the conversion had been completed. This also concerns the new JAVA-based SIS [2]. Both BIS and SIS have been operated without any problems since they were introduced.

Contrary to the LHC case where the BIS loop is manually rearmed together with the LHC Beam Dumping System (LBDS), the SPS BIS rearms automatically as soon as all inputs to the Beam Interlock Controllers (BIC) have returned to the ‘TRUE’ (OK) state. This strategy was necessary because the SPS is a relatively fast cycling machine where a manual reset cannot be done after each dump. To ensure that the next cycle/beam can be executed, the BIS re-arms automatically. The SPS SIS takes care of stopping beams where for example beam losses or large beam excursion are observed in consecutive cycle executions.

It was decided that the Safe Beam Flag (SBF) would not be used for the SPS ring BIS: the SBF state is forced to TRUE (safe beam state) for all the BICs. There is an accepted risk of masking certain interlocks with unsafe beams (in general beams are only unsafe at the flat top). Note that the SBF is used for the fast extractions.

SPS Emergency Dump

Currently the SPS emergency dump installed in BA1 is not synchronized to the beam (gap). All emergency dumps are always asynchronous which is acceptable in the LHC. It is foreseen to install a Trigger Synchronization Unit (TSU, similar to the LHC) during LS1. This will, however, introduce a dump trigger delay of up to 1 turn, which is acceptable for the SPS.

The SPS injection kicker MKP is directly inhibited by the SPS dump system (and not across the BIS loop like in the LHC), which creates a slight complication. In addition the MKP is directly connected to the power converter (PC) of the dipole corrector MDSH.119 (kick of 2 - 4.5 mrad), which is pulsed when the MKP is inhibited. This dipole corrector sends the injected beam cleanly into the injection dump.

SPS EXTRACTION INTERLOCK SYSTEM

The following extraction interlocks systems were installed in the SPS in 2012/2013 (see Fig. 1):

- in LSS4 : CNGS and LHC,
- in LSS6 : LHC and HiRadMat.

The following changes are expected sometimes after LS1 (new extractions to be confirmed, both would arrive around 2016):

- in LSS4 : CNGS is replaced by AWAKE (a proton plasma acceleration experiment) [6],
- in LSS2 : a new fast extraction using the MKP for a possible new neutrino facility SBLNF [7].

There is no extraction interlock system for the slow extraction in LSS2: this is due to the fact that it is difficult to interlock a slow extraction as there is no element like an extraction kicker that can be inhibited. The only possible MP action for the slow extracted beam is to dump the beam in the ring.

In the LSS where different beam types are extracted, the selection of the correct extractions BICs (and therefore interlocks) is based on energy flags (generated by the SPS Safe Machine Parameters (SMP) system, with windows of ± 2.5 GeV):

- CNGS : 400 GeV,
- LHC : 450 GeV,
- HiRadMat : 440 GeV.

This concept turned out to be simple and very reliable. New energy windows will have to be defined for:

- AWAKE: ≈ 400-430 GeV,
- SBLNF: ≈ 100 GeV.

The fast pulsing interlock signals (based on failsafe logic, with pulse widths of a few ms for PCs) required special applications to help OP crews to digest the rapidly varying BIS states. A top to bottom approach was used to present an "OP view" of the interlocks starting from the BIS output that is sent to the extraction kickers. This software presents the summary for a selection of cycles or dynamic destinations for the last 15 cycles, giving a simple and rapid overview over the situation. Special extensions where configured for each SPS beam/line combination. It is planned to merge this GUI back into main BIS application after LS1.

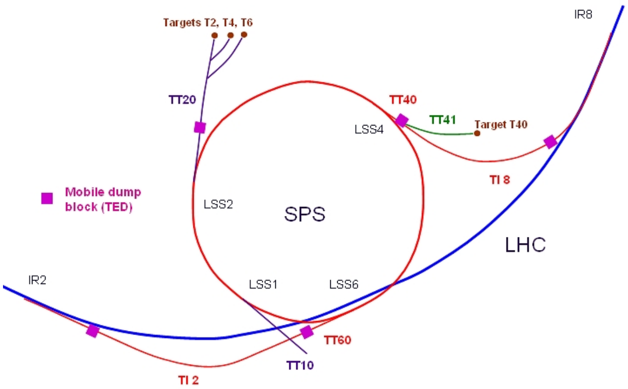

Figure 1: Overview of the SPS extractions and transfer lines.

Between 2006 and 2011 the overall reliability and safety of the extraction interlock system was excellent. In particular the interlocking of over 200 PCs in the LHC and CNGS transfer lines was crucial to ensure safe operation, and it worked extremely well! The Machine Critical Settings (MCS) system was used to protect the PC interlock settings (references, tolerances and configuration). Only the interlock reference of the smaller orbit corrector dipoles could be changed by the shift crews. All other settings required Expert or even Guru level authorization.

CNGS

The CNGS beam has been operated with high intensity from 2008 to 2012, with 1.5 MJ beams extracted routinely with high efficiency and without causing any damage, see Fig. 2. A total of 10 million extractions were triggered with beam and 1.8×10^{20} protons were delivered on the T40 target. This corresponds to a total energy of 7.5 PJ. The RMS beam stability on target was in the range of 40 – 100 µm (for an interlock limit at 500 µm). The position drifts at the T40 target were very small, see Fig. 3, and steering was only required every few days, or whenever the power on the target was changed. The beam losses in the TT41 transfer line were unmeasurable with BCTs, a very low residual activation at the level of some µSv/h can, however, be measured just above the natural background in the locations with high dispersion.

Things that did not work so well

The interlock on the beam position at extraction (interlocking of the maximum orbit excursion of the extraction bump, Fig. 4) is the only interlock that clearly "under performed". The performance was just acceptable for CNGS beams (200 MHz RF structure beam), but it was not so good for LHC beams (limits had to be opened to 2 – 3 mm). This issue is due to the fact that the interlock was relying on position acquisitions by the MOPOS orbit system, which has known issues with LHC beams. A new system based on electronics using logarithmic amplifiers was tested, but the result is not conclusive.

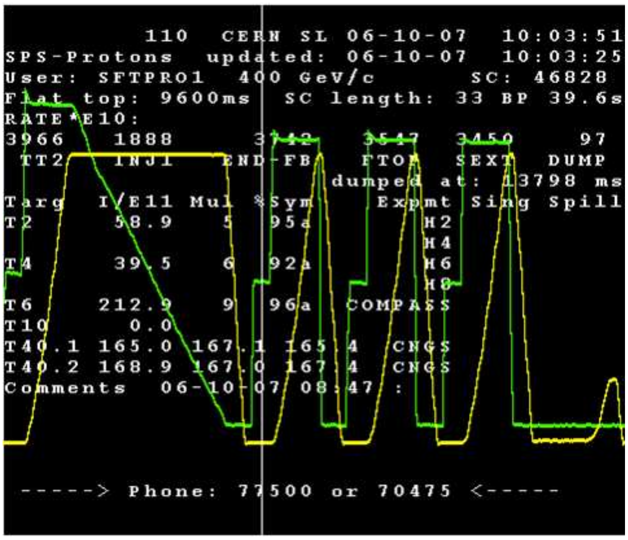

Figure 2: SPS super-cycle with the standard 3 CNGS cycles.

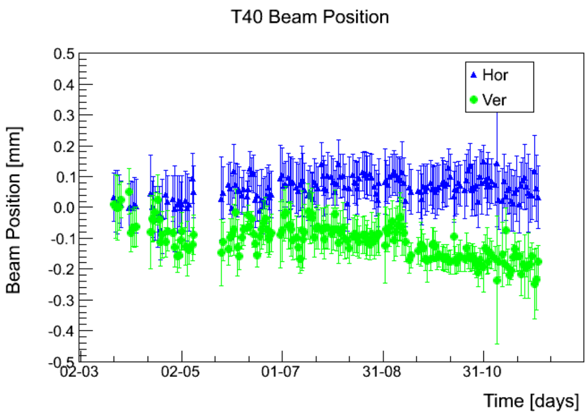

Figure 3: Beam position at the T40 target along a complete run.

SIS

The Software Interlock System was initially designed for the SPS to replace an existing system that could not cope with LSA, JAVA, FESA and other new features of the control system that were introduced in 2005/2006 [2]. The SIS plays a crucial role for SPS protection, and it is structured by geographical zone (transfer lines, extractions). In the SPS SIS acts always on 2 levels:

- It sets/clears an SIS interlock in a selected BIC module (ring or extraction).
- It set/clears an inhibit at the level of the MTG to stop beam production at the source according to the beam DESTINATION.

The SPS is a difficult environment for the SIS due to the multi-cycling. The relation between interlocks and beams (*Should this interlock be evaluated in the current cycle?*) is currently done through the USER names. This schema must be revised in the future since LSA cycles names should replace the standard user names in the future. This modification will require a clean and strict naming convention for LSA cycles. The management of reference settings is rather simple as long as the reference applies to a beam type (LHC, FT, CNGS), but it is currently very difficult to manage settings at the level of each individual cycle. One will have to evaluate the need for more flexibility and weight this against the increased complexity.

The SPS SIS acts normally at the end of the cycle when all data has been collected. There is one exception for the economy management, but in that case it is not an MP function of the SIS. The MTG is typically reacting in the following super-cycle. The interlock matrix between SIS and MTG destinations (dynamic or static) will have to be updated to account for AWAKE and SBNLF.

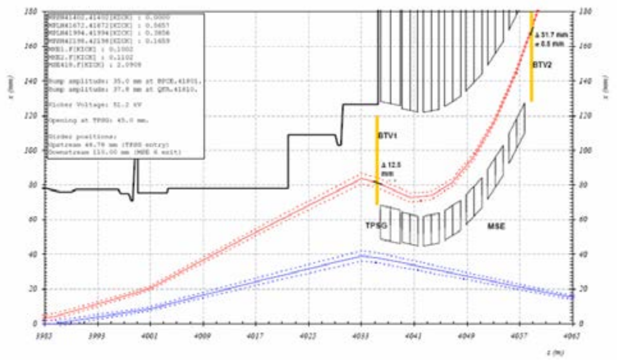

Figure 4: Layout of the fast extraction in LSS4. The amplitude of the extraction bump in the SPS is interlocked using the MOPOS system.

TIMING

A complex timing logic has been implemented to digest LHC beam requests and to ensure a coherent state of the machines. The diagnostics of timing problems for LHC beams remains rather tricky and more work on OP diagnostics is welcome. In 2012 a rather innocent looking change of injection timings in the SPS led to a problem where the LHC was expecting beam in one ring, and the SPS ended up sending the beam into the other ring. The wrong LHC injection kicker pulsed, and the beam was dumped on the injection protection collimator TDI. The problem has been understood and will be fixed, backed probably by some SIS interlocks.

OTHER CHANGES

The SPS Beam Quality Measurement system (BQM, longitudinal plane) will be based on new and better hardware. The core functionality will remain unchanged, but improvements will be introduced in the form of better diagnostics for satellites (number, location).

The existing tail scraper system will remain in place in BA1. A review has recommended to keep the current system [8]. Some actions have been defined for the existing scrapper. A system based on a fixed absorber and a magnetic bump (in LSS6) will be kept as "hot design spare".

The mixed p-Pb operation came with the issue of ensuring that the species are send to the correct ring since RF settings (frequency) are very different. The LHC SIS instance provides the protection by matching the TT10 PC settings (17 GeV for Pb, 20 GeV for proton) with the LHC ring frequency. One could consider more robust options in the future.

During LS1 the front-end control of the SPS power converters will be migrated from ROCS to FCG. The ramp cards that drive the actual converters remain in place. To first order this modification should be transparent, even if the state machine of the PCs will change. The PC interlocks (FEI) with MCS protection will have to be re-implemented. At the same time one should consider extensions of the PC surveillance to the SPS ring and to the fixed target operation of TT20.

A strong horizontal orbit corrector in LSS1 (MDHD.118) may be used to correct the orbit for the Q20 optics. This will require a hardware interlock, most likely an extension of the FEI concept.

Crab Cavities

It is planned to install prototype crab-cavities (CCs) in LSS4 (the only place with cryogenics in the SPS) during the 2015/2016 shutdown, see Fig. 5. CCs will be installed on a Y-chamber that can be moved in/out of the beam axis. Due to the limited aperture of only 84 mm and the fact that the CCs are inside the extraction bump for LSS4, it is unlikely that CCs are compatible with regular LHC beam operation.

New hardware interlocks (and probably a number of SIS interlocks) will have to be added:

- An extraction interlock in LSS4 if the CC is in beam (if not compatible LHC).
- A ring beam interlock if the Y-chamber is at an intermediate position.
- Interlocks on the CC state, etc.

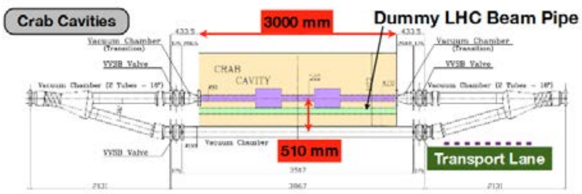

Figure 5: Layout of the crab-cavities in LSS4.

SBNLF

A project for a new neutrino beam from the SPS (North Area, short baseline) is currently under study. The beam energy will be just above 100 GeV (to avoid the forbidden energy region of the SPS emergency dump: 37 – 100 GeV). The beam will be a fixed target type 200 MHz beam, with CNGS-like intensities of 4.8×10^{13} protons. The stored beam energy is ≈ 750 kJ, and the beam will be extracted in 2 batches. This stored energy value is close to the SBF limit when scaled to 100 GeV. The fast extraction will be non-local using the SPS injection kicker MKP as fast pulsing element, with orbit oscillations along the arc from LSS1 to LSS2 where the beam passes the MST and MSE septa magnets, see Fig. 6. SBNLF will not operate at the same time as standard fixed target beams (the electrostatic septa must be retracted to a safe position for SBLNF).

SBNLF requires a new extraction interlock system. The well understood concepts with slave-master BICs will be re-used, and the interlock system will cover 3 SPS BAs (BA1, BA2 and BA3) as shown in Fig. 7. The orbit correctors in sextants 1 and 2, as well as the main quadrupole (tune) and sextupole PCs (both located in BA3) must be interlocked at the level of the PC current. The use of an Extraction Permit Loop that would cover all the SPS rings and be connected to all extractions is being considered. Such a loop would also allow to close some gaps for LHC beam interlocking.

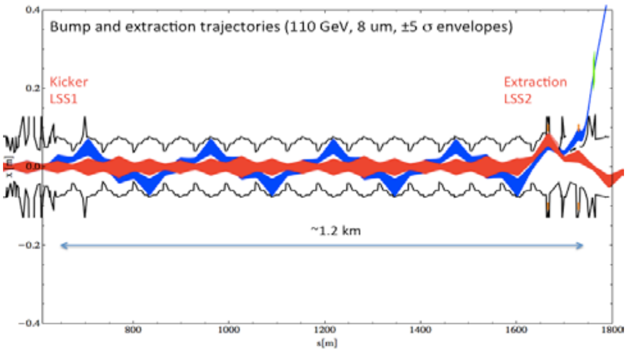

Figure 6: Extracted beam trajectory from LSS1 to LSS2 for SBNLF (in blue).

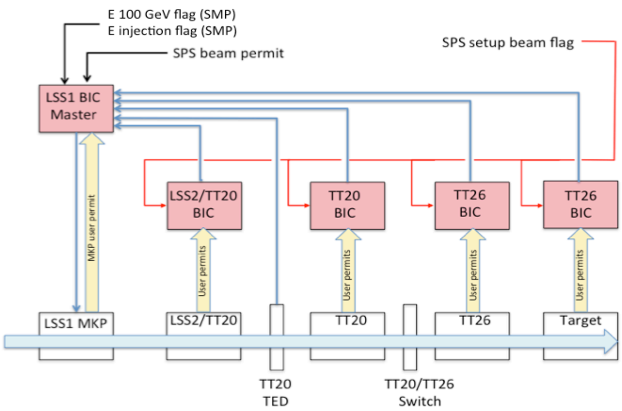

Figure 7: Schematic layout of the BICs for SBNLF.

SUMMARY

There are no major changes on the SPS side for MP during LS1, but a number of smaller items and a rather major change of the PC controls.

- The SPS emergency dump will be equipped with a TSU to avoid the asynchronous emergency dumps.

- The PC interlocks to be re-implemented and extended under the FCG umbrella.
- The SIS interlocks and diagnostics must be revised. The triggering will have to be adapted to cope with the change from FESA users to LSA cycle names.
- The SPS MPS will have to be prepared for new extractions that are expected to appear in 2016.
  - SBNLF in LSS2 will require many of changes and new hardware,
  - AWAKE in LSS4 will re-use the CNGS MPS/BIC infrastructure.

One question that remains open concerns the BPM interlocks for the ring and the extractions. This will have to be followed up with the BI group.

And a final point: a new Mister / Misses MP is needed for the SPS, since the author's term ended 'naturally' at the end of 2011. This role is very important in such a flexible and complex machine. A large test campaign will have to be organized after LS1, and daily issues must be followed up.

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