PERSONNEL PROTECTION OF THE CERN SPS NORTH HALL IN FIXED TARGET PRIMARY ION MODE

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Abstract

While CERN's Super Proton Synchrotron (SPS) is able to deliver both secondary proton and primary ion beams to fixed targets in the North Area, the experimental areas (North Hall) are widely accessible during beam. In ion mode all normal safety elements involved in producing secondary beams are removed, so that an accidental extraction of a high-intensity proton beam into the North Hall would expose personnel to a radiation hazard. This has required an injector reconfiguration restricting operation to either ions or protons. However, demands for operational flexibility of CERN accelerators have led to a need to mix within the same SPS super-cycle both high-intensity proton cycles for LHC or HiRadMat and ion cycles for the North Area. We present an active interlock designed to mitigate this hazard: Beam Current Transformers are used to measure the beam intensity, and if above a set threshold, pulsing of the extraction septa is vetoed. The safety function is implemented by means of two logically equivalent but diverse and separate interlock chains. This interlock is expected to be in place once the SPS resumes operation after the first Long Shutdown in 2014.

INTRODUCTION

Demands for operational flexibility in the exploitation of accelerators and to facilitate new heavy ion programs at CERN have lead to plans for the delivery in the same SPS super cycle of ions for the North Area and high intensity protons for other targets, such as HiRadMat or LHC. When the North area is prepared for ions, the TAX absorbers/collimators are set to a position that allows transmission of the low intensity ion beams, but the possibility cannot be excluded that a filling or timing error in the SPS could cause the transmission of an intense proton bunch in place of the ions: this would present a significant hazard to people working in the experimental areas.

In order to protect against this eventuality, an instrumented safety function has been designed to measure the beam intensity in the SPS and to inhibit the extraction septum magnets (MSE and MST), when the beam intensity in the SPS is greater than 2×10^{11} charges. The safety system being installed during the Long Shutdown 1 has been designed to be diverse, redundant, and fail-safe under all fault modes following recommendations by the nuclear authorities. The system also has an automatic self-test function for confirmation of the interlock status before each beam injection.

SPS OPERATION

The CERN Super Proton Synchrotron (SPS) accelerates protons and various types of heavy ions (Pb, Xe, Ar) of different extraction energies and beam intensities [1]. Acceleration cycles to the different destinations are organized into super cycles, which are programmed in advance according to the experiment schedule. SPS will in the future be run in two modes: in *proton mode*, which means that only proton cycles are foreseen in the machine, and in *ion mode*, where both proton and ion cycles can be present within the same SPS super cycle. Normal ion mode operation would involve mixing of four types of cycles within one super cycle:

- Protons to LHC, with fast extraction to TT40 or TT60 tunnels.
- Protons into the TT41 tunnel, with fast extraction to TT40.
- Protons to HiRadMat, with fast extraction to TT60.
- Ions to North Hall, with slow extraction to TT20. As various ion types are possible, the exact beam parameters depend on that choice.

Figure 1 shows a typical future SPS super cycle with both proton and heavy ion cycles.

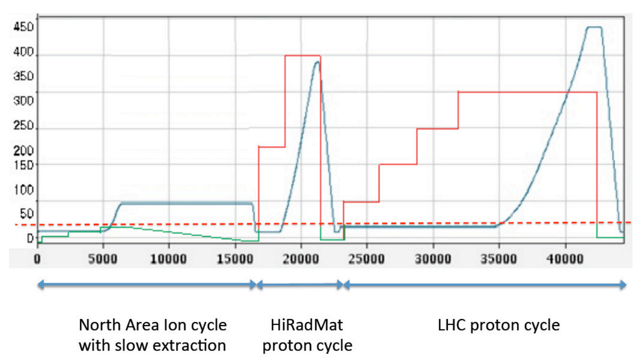

Figure 1: A typical SPS super cycle during a primary ion mode run, comprising an SFTION at 80 GeV/c/charge, a HiRadMat at 400 GeV/c and an LHC cycle at 450 GeV/c. The blue line represents the magnetic rigidity, the green line (red above the 2×10^{11} threshold) the number of charges. The threshold level (dotted line) is exaggerated for the drawing to be readable. The momentum scale is in GeV/c/charge, the time scale is in ms.

INCIDENT SCENARIO

The scenario against which the new interlock is designed to protect involves an accidental extraction of a

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high-intensity proton beam into the North Area during an ion run, when the extraction lines are parameterized to receive a low-intensity ion beam. This kind of erroneous extraction into the North Hall would include the following steps:

1. The extraction line at TT20 is parameterized to receive an ion beam of certain energy within the SPS super-cycle: the TAX is open, micro-collimators have been removed, and the bending magnets are set to a value corresponding to the expected beam momentum.
2. A proton beam (for instance destined to LHC, HiRadMat, or CNGS) is injected into the SPS.
3. After the injections are complete, ramping of the beam energy starts. At the beam energy corresponding to the momentum of the ion-beam in step one (plus-minus an energy tolerance of about 2%) an erroneous beam extraction is triggered towards the North Area.
4. In case of a slow extraction, taking up to 10s as normally programmed for the TT20 line, a fraction of the beam depending on the bending magnet energy tolerance and the ramp speed would reach the target area.

There are three possibilities of a high-intensity proton beam to end up erroneously extracted in this way: 1) either a proton beam was injected into the machine during an ion cycle, or 2) the North Area extraction elements are erroneously triggered during a regular high-intensity proton cycle, or 3) a fixed target proton cycle was erroneously programmed during a fixed target ion run.

The first possibility is fortunately unlikely to happen, as the protons are normally extracted from the PS at a very different magnetic rigidity (14 or 26 GeV/c/charge) from ions (17, 19, or 23 GeV/c/charge, respectively, for Pb, Xe, and Ar ions). It can however not be excluded, as the PS machine and TT2/TT10 lines can be configured to extract protons towards the SPS at any momentum between 3.5 and 26 GeV/c.

The second possibility is more likely and would typically correspond to a timing error leading to triggering extraction elements on a wrong cycle. It could also occur due to equipment tests, if the extraction elements are made to pulse asynchronously for development purposes.

The third possibility is also remote, but a human error can never be completely ruled out in spite of the high level of training of the operating staff. As an additional safety measure, the slow extraction proton cycles will be made non-resident in the super cycle edition programs during the dedicated primary ion runs.

SYSTEM DESIGN

To mitigate the hazard described above, an active interlock has been designed that allows suppressing extraction towards the North Area if a wrong type of beam is circulating in the SPS. The following general requirements existed for the safety system:

1. The interlock should be independent of the beam control system and in particular of any timing information pertinent to the injected beam.
2. As this safety function would only be necessary in the ion mode, the interlock would be controlled by a selection between ion and proton modes via a key in the CERN Control Centre. In proton mode this interlock would therefore be disabled, as different safety conditions applied.
3. During an ion run, the interlock would be solicited continuously. Given a projected annual SPS run time of 250 days of which up to 100 days in ion mode with a super cycle length of the order of 60 s and average 4 cycles per super cycle, the anticipated total annual state switching count of the interlock would amount to around 1-2 million.
4. The response time of the entire safety chain should remain below 570 ms, which corresponds to the worst case with an injection of a high intensity proton beam on an ion cycle programmed to extract at the lowest energy.

The design of the interlock system being implemented follows the general principles of design of redundant and failsafe safety chains:

- The design is done respecting as much as possible the norm IEC 61511 [2], which regulates implementations of safety-instrumented systems for process industries.
- Redundancy and diversity are provided by two separate safety chains implementing the same interlock logic but with different technologies.
- Any non-trivial signal paths are implemented as two separate signal paths, one energize-to-trip, the other de-energize-to-trip.
- Any non-doubled signals are implemented de-energize-to-trip (failsafe).

The principle of protection is illustrated in Figure 2.

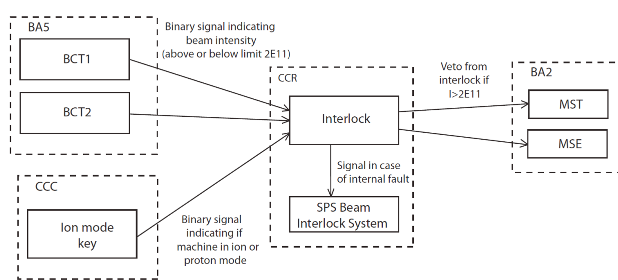

Figure 2: Schematic of the principle of protection.

Two new and dedicated beam current transformers (BCT) [3] will permanently monitor the intensity of the SPS beam. Each is equipped with a comparator to output a logical signal indicating whether the measured intensity is below the threshold of 2×10^{11} charges.

When the SPS is in a fixed target ion mode, the output of each comparator will be used together with self-diagnostic signals to gate the power converter current reference to two independent extraction elements into the

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North Hall (extraction septum MSE and the first dipole MST in TT20).

The interlock logic is implemented in two separate and diverse chains (PLC and wired logic). The interlock will track any fault conditions of both the BCTs and the MSE/MST power converters. In case of a fault in the power converters, which would mean that the inhibition of the extraction might not work, signal is sent to SPS Beam Interlock System (BIS) to dump the beam.

IMPLEMENTATION

The safety system consists of three logically separate subsystems: BCTs as sensors, interlock logic, and power converters as actuators. The BCTs are installed at SPS point 5 (BA5), the interlock logic and ion/proton mode control at CERN Control Centre (CCC/CCR), and the MSE/MST at North Area extraction point 2 (BA2). The geographical layout of the system is shown in Figure 3.

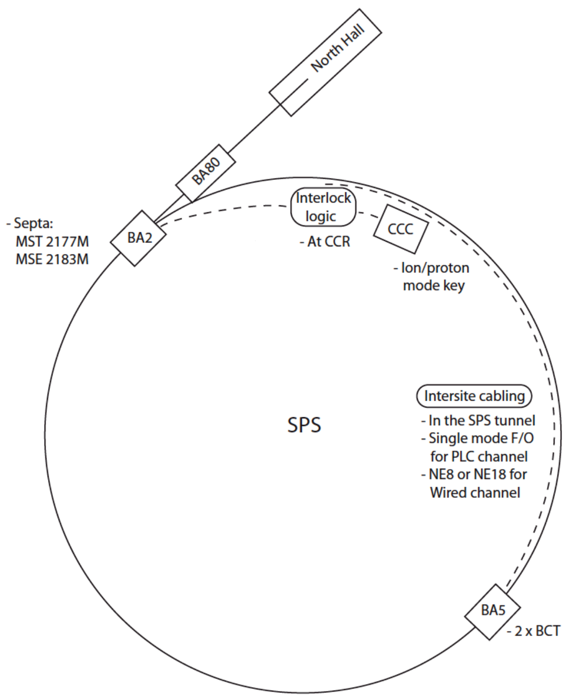

Figure 3: The geographical layout of the safety system components within the SPS ring.

Beam Current Transformers

The beam current transformers used to measure the beam current are of the type Direct Current Current Transformers (DCCT). A DCCT measures the mean value of the total beam current, which corresponds to the flow, continuous in case of coast beam or discontinuous in case of bunched beam, of charged particles circulating in the accelerator.

The BCT subsystem is basically a simple comparator producing a defined signal when the measured intensity is below the set charge threshold. Due to the required level of reliability and availability as a safety system, the device is implemented purely in hardware and no remote setting or selection is possible. As the DCCT is an intrinsically complicated device, a self-diagnostic facility was added to automatically assess equipment status.

Each DCCT delivers two status signals to the interlock, which indicate the level of beam intensity as well as the state-of-health of the DCCT.

The general layout of the system is shown in Figure 4.

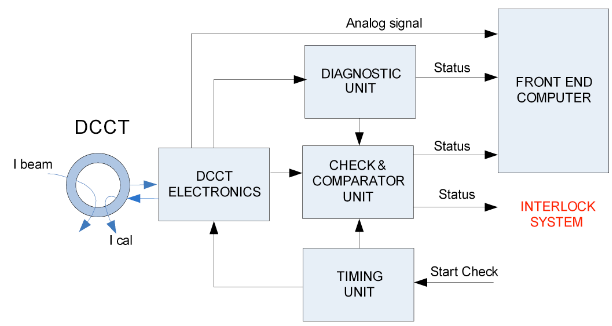

Figure 4: Block diagram of the BCT subsystem.

Even though the system is intended to detect a low value of beam intensity, the DCCT must not be saturated by the higher beam intensities possible in the SPS. Four intensity ranges are used to cover the whole dynamic range: 10^{11}, 10^{12}, 10^{13}, and 10^{14}. All ranges are available simultaneously, thus requiring no explicit selection.

The DCCTs are designed and built at CERN. The new units in the SPS are copies of the monitors installed in the PS Booster and the PS and of the electronics mounted in the LHC. While the DCCTs are not specifically certified for use in safety systems, over 20 years of experience of the 6 units with less than a dozen malfunctions total breeds confidence in their applicability, particularly with the added self-diagnostic capability, which will considerably increase their level of safety.

Interlock Logic and Signal Paths

The interlock is implemented in two separate channels: channel-A is based on Siemens S7 PLC architecture [4], channel-B on HIMA Planar4 wired logic [5].

The PLC channel consists of one CPU315F-2DP PLC with a CP343-1 communications module, and remote I/O ET200M with modules SM321DI, SM322DO, and SM326DI at remote locations. Communications are based on Profibus DP fibre optic links. The PLC has both a safety-related and a non-safety-related part, and the latter is used for supervision of the interlock via Ethernet.

The wired channel consists of HIMA Planar4 safety certified rack-mounted logic boards implementing the various logic gates. The interlock logic is programmed by soldering gate interconnections on the rack backplane. The logic boards are standard and interchangeable without need to touch any logic programming. Tripled opto-couplers are used as signal outputs for speed, durability, and reliability. Supervision of the interlock is done via a Profibus DP module, which delivers the status data to the monitoring interface of the channel-A PLC.

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A photo of the two interlocks together in the test bench is presented in Figure 5.

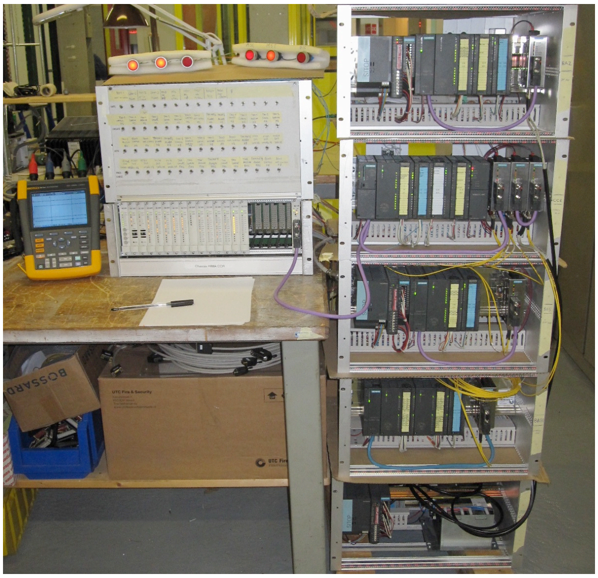

Figure 5: The wired and PLC interlocks in the test bench. The HIMA rack is on the left hand side at the bottom and a switch matrix to simulate different signals at the top. The PLC rack with remote I/Os in separate sub-racks is seen on the right.

MSE/MST Power Converters

The power converters of the extraction septum MSE2183M and the first dipole MST2177M will act as actuators to the safety system. The interlock normally holds a signal high to allow extraction, and if the BCT measures a beam intensity exceeding the threshold, the interlock logic sets this signal low. A control card on the power converters will then set the current reference from the SPS power converter control system (Mugef) to its minimum value causing immediate discharge of the extraction elements, see Figure 6.

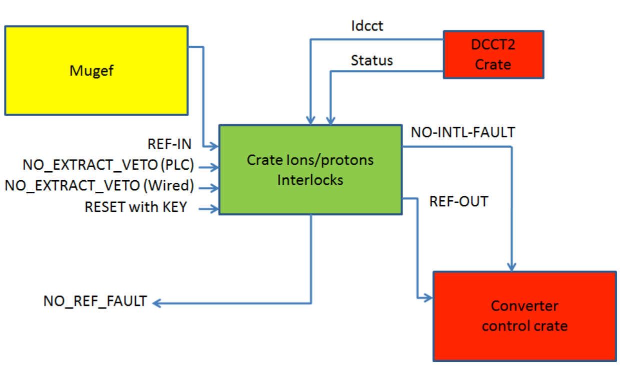

Figure 6: Power converter signal diagram. The reference is sent as an analog signal directly from the SPS power converter control system (Mugef). Interlock signals from both PLC and wired channels are shown as well as the internal safety-check signals from the special DCCT installed.

Two diagnostic checks are implemented: A dedicated DCCT is installed within the power converters to check the converter output current: if, after setting the reference to minimum, the current has not diminished, an error is flagged to the interlock logic. Similarly, if Mugef is giving a power reference compatible with an ion cycle thus enabling extraction, and simultaneously an intensity exceeding the threshold is measured by the BCTs, an error is flagged, and the power converters shut down. As this would correspond to a severe cycle programming error, it can only be reset by key by the safety officer after an examination.

PERFORMANCE

From initial timing tests and theoretical calculations based on individual component data, the response time of the interlock logic and the signal paths to the critical event ($I>2\times10^{11}$) can be expected to be below 55 ms for the PLC chain and below 25 ms for the wired chain.

The response time of the DCCT from measurement to delivering the output signal is of the order of 20 ms. The power converters take considerably longer to reach a fully disabled state (minimum current) due to the exponential nature of coil discharge (70 ms for MST and 190 ms for MSE). However, for the safety system to fulfill its task, full discharge is not necessary. Already a drop in current of 10-20% will ensure that the beam can no longer reach the North Area, a condition normally reachable in less than 20 ms.

Therefore, while measurements with the full safety chain are necessary to ascertain final performance figures, the total system response time looks in any case to remain below 100 ms, clearly satisfying the design criteria.

CONCLUSIONS

A new active safety interlock has been designed and is being installed to the CERN SPS accelerator to allow mixing high-intensity proton and low-intensity ion cycles within the same super-cycle. The main design criteria of the safety system have been diversity, redundancy, and performance combined with simplicity and self-diagnostic capability. The new safety system is due to become operational at the start of the SPS after the Long Shutdown 1 in 2014.

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