TRANSFER LINE DAMAGE DURING HIGH INTENSITY PROTON BEAM EXTRACTION FROM THE SPS IN 2004

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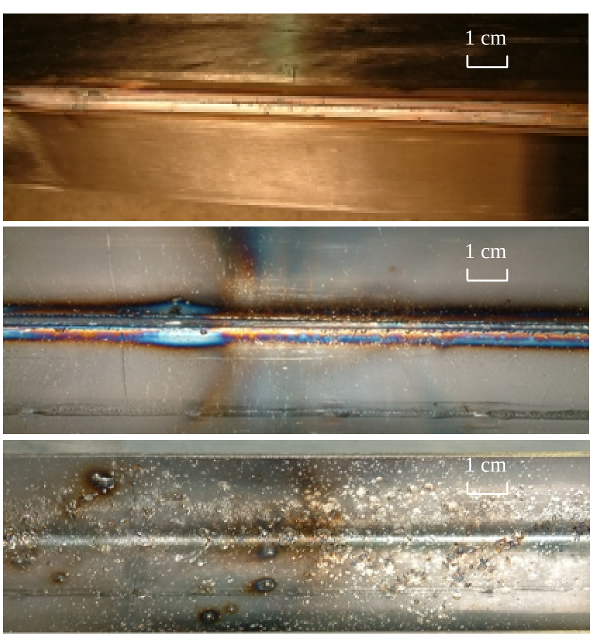
Abstract

During high intensity extraction from SPS in 2004 an incident occurred in which the vacuum chamber of a transfer line magnet was badly damaged. Deficiencies in the extraction setting-up process, in the interlocking and in the operational procedures used for the high-intensity test were all contributing factors. The incident causes are identified, the details reconstructed from the logged data, and the remedial measures which have already been taken are explained.

INTRODUCTION

The extraction from SPS LSS4 [1] into TT40 of nominal intensity LHC injection beams was required in 2004, for robustness tests of the prototype LHC collimator, for CNGS target rod tests and for materials tests to benchmark energy deposition simulations [2,3]. During the test, the beam was extracted with a wrong trajectory, due to a switch-off of the extraction septum (MSE). A downstream magnet vacuum chamber was severely damaged [4], Figs. 1-3. A cut approximately 25 cm long was visible about 70 cm from the start of the chamber. When the chamber was cut open the beam impact side was confirmed to be consistent with insufficient MSE deflection. A groove approximately 110 cm long where the chamber material had been removed was visible, and on the non-impact side, the wall was covered with condensed drops of steel.



Figures 1-3. Vacuum chamber damage observed on the outside (top), inside at the beam impact area (middle) and inside opposite the beam impact (bottom).

INCIDENT ANALYSIS

Comprehensive logging of all the beam and instrument data allowed reconstruction of the incident. After delays during the day, problems with MSE trips occurred with high beam intensity, and due to time pressure, the investigation of the problem was made in parallel with the high-intensity extraction. The MSE interlock was disabled by software, but the trips continued. For the final (fatal) extraction, the MSE tripped just before the extraction, and this was not seen by the interlock system in time. The logged MSE current was 500 A (about 2 %) lower than nominal.

The MSE trips were due to high-frequency pick-up from the beam, captured on the PT100 temperature probes on the magnets. This caused the PLC controlling the MSE to generate an interlock signal, which cut the current of the septum power supply. Although these ‘fake’ temperature interlocks were masked in the PLC, the beam signal pick-up was propagated to the PLC on the long cables, and caused other interlock channels to spuriously trigger.

There was a clear problem with the logic of the interlocking, since the PLC should first have sent a signal to the extraction interlock controller to inhibit beam extraction, before sending a signal to switch off the MSE power supply.

The probable trajectory of the badly extracted beam was reconstructed by varying the MSE kick and constraining the beam position to be those measured by the BPMs and BTVs. An impact at the QTRF4002 vacuum chamber was imposed. The resulting trajectory is shown in Fig. 4. The MSE error was constrained to be -5.1%, and the impact angle about 0.6 mrad. The beam σ at this location is 0.7 mm in both planes.

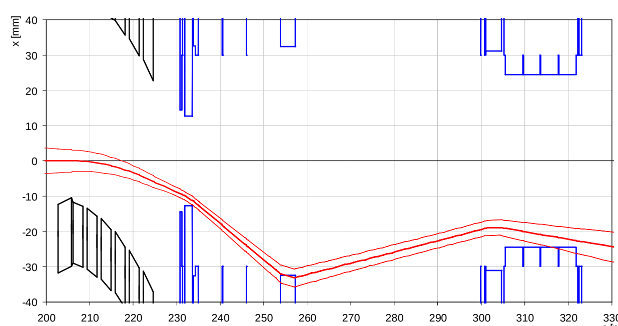


Figure 4. Reconstructed trajectory with MSE kick at 5.1% below nominal (H plane, ±3.5 σ beam envelope).

The 23 ms time constant of the MSE circuit means that the current decays very rapidly when the power convertor is switched off. The current was surveyed by software in the front end, with a 'slow' response time of about 7 ms. A simulation of the power supply current was made, Fig. 5:

- 13 ms before extraction, the power supply tripped;
- 7 ms before extraction, the surveillance saw a -0.5% error, which was still in tolerance;
- 3 ms before extraction, the logging gave -2.5%;
- At extraction, the current had decreased to -6%.

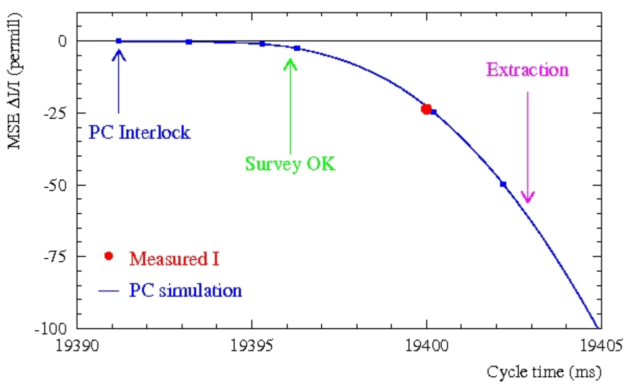


Figure 5. Simulation of the MSE current. The current at the extraction time is predicted to be -6%.

With the impact parameters known, a FLUKA model was made to check if the observed damage profile could be reconstituted. Fig. 12 shows the energy deposition profile obtained, for a test geometry with a 5 m long chamber equipped with entrance flange only. The maximum temperature reached in the peak of the energy deposition in the pipe, made of stainless steel 314L, is only 1350˚C, Fig. 6, compared to the melting point of 1400˚C. It was very difficult to reconstitute the observed physical damage in a simulation with limited knowledge of the input conditions.

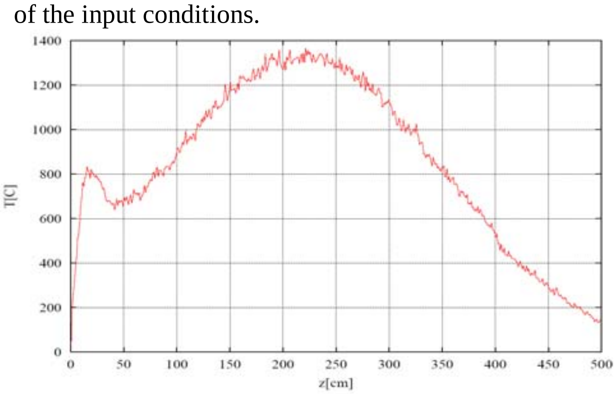


Figure 6. FLUKA simulation results of ΔT in chamber.

INTERLOCKING MODIFICATIONS

A direct link to the BIC was added, such that a fault detected in the septum *first* inhibits the beam extraction, and only after a delay of about 10 ms is the signal sent to stop the power convertor.

The SW integration window was displaced to 2 ms before the extraction and shortened to 1 ms.

The temperature sensors were disconnected from the MSE, to stop spurious interlocks.

A new interlock is being added to 14 'critical' [5] power supplies which sends a direct signal to the beam interlocking system within 1 ms in the event of an internally-generated power supply interlocks (about 70% of trips).

The voltage across the 14 critical magnets is monitored at the power supply with a new FMCM system [6] developed at DESY, which internally simulates the electrical circuit and which can react to very small current changes within a very small time. The system has been tested and for the most critical MSE supply will be able to react within 0.1 ms to a 0.1 % current change.

SUMMARY OF PROBLEMS AND CONTRIBUTING FACTORS

The analysis of the event revealed a number of hardware, software and procedural problems. Not all of these contributed directly to the actual incident; nevertheless, these issues have been addressed in the interlocking or commissioning procedures. The identified problems and contributing factors are listed below.

1. Lack of preparation for the high intensity beam commissioning. No formal procedures were established, so steps were overlooked or ignored.
2. Inadequate acceptance tests of the interlock and surveillance systems working together with the equipment, without and with beam.
3. Insufficient understanding of the high risk elements in the commissioning.
4. Incomplete interlock logic was not complete for the MSE septum, leaving a few ms risk window.
5. Commissioning and tests were combined, with no clear separation of preparation, procedures, people, time, objectives and responsibility.
6. Delays and equipment problems encountered, reduced the time available and increased the pressure to deliver the beam.
7. Problems which occurred were not solved before continuing to increase the beam intensity.

RECOMMENDATIONS FOR FUTURE HIGH INTENSITY COMMISSIONING

In the light of the analysis a set of recommendations was made at the time [2] to improve the safety of high intensity beam commissioning. The recommendations, together with the relevant implementation or follow-up results, and listed below.

1. Commissioning must be carefully prepared, with procedures, tests and commissioning steps clearly defined, agreed, communicated and followed. Full formal acceptance tests of the machine protection

system, with all subsystems working together, must be defined and performed. → This has been implemented with full interlock lists, procedures and acceptance tests worked out with specialists. Detailed documents [7,8] have been released.

2. Responsibility for beam commissioning must be defined and communicated, and separated from the tests to be made once the beam is fully available. Commissioning must be clearly separated from operation or test phases. → Responsibilities have been established for most beam commissioning activities, and dedicated beam commissioning and interlock test periods have been scheduled.
3. Strapping or by-passing of interlocks must be rendered impossible for high (dangerous) beam intensities. Changes to pre-defined settings must only be possible after repeating a subset of the acceptance tests with beam. → This has been done where possible: LHC-style interlocking has been implemented in SPS and transfer line [9,10], with safe beam concept to allow flexibility. For critical software settings, a new 'secure' software system (MCS) is being developed [11] to manage settings in equipment front ends.
4. Problems encountered must be solved before commissioning can continue. For high intensity commissioning, machine protection must take priority over efficiency. → These 'cultural' changes will be the most difficult to enforce – awareness has certainly been heightened by this incident; beam commissioning in 2006 will show how much progress has been made.

CONCLUSION

The incident in which the full SPS beam was wrongly extracted destroyed a transfer line magnet and caused several days' lost beam time. However, the incident has certainly been beneficial. It has increased the awareness of the risks associated with high beam intensities. The incident highlighted weakness in HW, SW and commissioning procedures, and the subsequent analysis revealed other unrelated flaws which could be addressed. The fact that damage occurred despite the existence of a functioning prototype interlock system has fully justified the level of effort which continues to be made in the SPS and LHC interlocking and machine protection. It has also forced a greater degree of synergy between MP, OP and equipment specialists, with an attendant increase in the communication and consultation.

In reaction, remedial steps have been put into place, some already for the second high intensity test successfully carried out at the end of 2004. Specific issues have been addressed and remedies implemented including general changes to the interlocking, formalised commissioning procedures and improved test organisation.

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