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UPGRADE OF THE CERN SPS EXTRACTION PROTECTION ELEMENTS TPS

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Abstract

In 2006 the protection devices upstream of the septa in both extraction channels of the CERN SPS to the LHC were installed. Since then, new beam parameters have been proposed for the SPS beam towards the LHC in the framework of the LIU project. The mechanical parameters and assumptions on which these protection devices presently have been based, need validation before the new upgraded versions can be designed and constructed. The paper describes the design assumptions for the present protection device and the testing program for the TPSG4 at HiRadMat to validate them. Finally the requirements and the options to upgrade both extraction protection elements in the SPS are described.

INTRODUCTION

Extraction protection elements (TPSGs) are installed upstream of the magnetic septa in the SPS extraction channels towards the LHC. In Long Straight Section 4 (LSS4), the TPSG4 is installed upstream of 6 thick (MSE) septa, while in LSS6 the TPSG6 is installed just upstream of 2 thin (MST) septa. The first TPSG4 was installed in 2003, while the TPSG6 was installed in 2007 [1]. They protect the magnetic septa against mis-steered beams. This case should remain rare and the current of the extraction bumpers is interlocked to reduce the risk of a full impact. The case of an asynchronous firing of the kicker would result in a sweep of the beam over the diluter and the septa.

In case of full impact the TPSGs will dilute the beam such that the energy deposition and the subsequent temperature rise in the downstream MST septa conductors will stay at tolerable levels. In particular, the energy deposition in the cooling water of the septum conductor is critical, as it provokes shock waves in the cooling water circuit, which may lead leaking water to the beam vacuum.

ACTUAL DESIGN

The present devices were designed for direct impact of the full, so called LHC ultimate, LHC beam. The aim on the device was to properly protect the downstream septa, while surviving itself the impact sufficiently to avoid an exchange. Following updated calculations [2] more robust designs were proposed and built, making use of then state of the art 2D Carbon Reinforced Carbon (CfC). The TPSG4 was modified and the highly stressed graphite was partly replaced by CfC to cope with the dynamic mechanical stresses. With respect to the earlier version the TPSG4 was lengthened up to 3100 mm to compensate for the lower density of the CfC with respect to graphite. The design assumed impact centred around on a septum conductor cooling tube as on the initial calculations [3,4]. For the final design of the TPSG6 the CfC was also used to replace part of the graphite. The final absorbing sandwich is indicated in Table 1.

The graphite and CfC parts of the diluters themselves would sustain a full impact, while the Von Mises stress levels would exceed the maximum values permitted for the metallic blocks at the exit of the diluters. Since this stress level would only be exceeded in a small volume, it was deemed acceptable.

Table 1: TPSG Diluting Structure

	TPSG4	TPSG6
Graphite (CZ5) [m]	0.5	
Carbon reinforced Carbon [m]	1.7	1.75
Graphite (CZ5) [m]	0.3	0.85
Titanium (TiAl6V4) [m]	0.3	0.3
Inconel (Inco 718) [m]	0.3	0.6
Total dilution length [m]	3.1	3.5

The protection requirements for each TPSG (Table 2) are based upon the assumptions that the coil can withstand the same dynamic pressure as the coils are statically tested during construction. The maximum permissible pressure rise is obtained by reducing the pressure of the cooling circuit in operation in the SPS tunnel (25 bar) from the static test pressure. The maximum permissible copper temperature rise is determined by the space available in the yoke for the increase in length of the coil from the normal operating temperature. Finally the maximum water temperature rise in the cooling channels was determined from the permissible pressure rise using the ELSE code [2, 4].

TESTS AT HIRADMAT

To validate the diluter design assumptions, tests were prepared which took place at HiRadMat in 2012. The tests' aim was two-fold: to validate the design assumptions to protect the septa and to validate the assumption exceeding the maximum Von Mises stresses locally in the metallic blocks of the diluter is acceptable. A spare MSE and TPSG4 were made available for this test.

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Hardware Set Up

The spare TPSG4 was prepared for installation in the HiRadMat facility. This entailed the construction of modified support structures and, due to the off axis centre of gravity of the TPSG4, also a new lifting jig with counter weights to allow installation of the TPSG on the beam line. Behind the TPSG a used spare MSE was installed. Both elements were pumped down to a vacuum in the 10^{-7} mbar range and the vacuum was maintained with by means of two 400 l/s ion pumps. As diagnostic equipment, the vacuum gauges could be read out remotely, as well as the ion pump currents. To validate the beam position on the object, radiographic paper was installed at the beam entry window of the TPSG4.

In the HiRadMat facility, cooling water supply wasn't suitable to cool both elements similar to operational conditions. The TPSG4 was connected to the normal HiRadMat cooling system, i.e. at reduced pressure and flow rate with respect to the normal operating conditions. A special water plant was used for the MSE. Since the pressure is one of the limiting factors for the MSE, it is essential that the pressure during beam impact is identical to the operational pressure of the device. In operation a MSE is connected to the water supply line of 25 bar and to the return line of 10 bars, and the subsequent water flow is 120 l/min. The dedicated water plant, permitted to pressurise the MSE cooling circuit statically to 25 bar during the impact. After the impact the system switched to the standard HiRadMat cooling facility to remove the energy deposited in the coil at reduced pressure. The water inlet pressure on the MSE as well as the TPSG4 and MSE temperatures could be monitored during the experiment.

A fast beam loss detector was installed upstream of the MSE to measure the shower of secondary particles during the impact onto the TPSG4.

Test

Initially a pilot beam with only 1.10^{10} protons per bunch was send to verify the diagnostics systems as well as the location of the beam as indicated in the radiographic paper. Once the beam was properly set up and the location confirmed, 4 nominal intensity shots ($1.2\ 10^{11}$ p/b, 288 bunches) were sent onto the TPSG4 with several minutes intervals to remove the heat deposited onto the target with the cooling circuits. The beam spot was focussed at the entry of the TPSG4 and a spot size of 0.5 x 0.5 mm^2. In total less than 1.5 x 10^{14} protons were sent onto the TPSG4, activating the assembly up to approx. 0.7 Sv/h measured 1 hour after impact. The residual activation of the TPSG4 had dropped to 1.3 mSv/h after 1 month.

Analysis

During the test, the vacuum degraded at each impact, but recovered quickly afterwards. This was the first indication that the coil and in particular the hydraulic circuit of the MSE had sustained the impact successfully.

After 1.5 years the experiment was dismantled and the dose rate of the TPSG4 had decreased to 100 µSv/h. Before dismantling the experiment from the HiRadMat facility, the hydraulic cooling circuit of the MSE was pressurised with Helium and a leak detection confirmed that the MSE had successfully withstood the impacts.

The initial thermo-mechanical studies [2] identified the most stressed diluter block were the first 2 graphite and following CfC blocks, together with the metallic blocks at the exit. These blocks were dismantled from the TPSG4, and no damage was observed. Some swelling was noted for the first graphite block in the beam direction of 0.07 mm, for a length tolerance of ± 0.04 mm. A slight blue hue was noted at the exit face of the last Inconel block.

Follow Up

The 2012 HiRadMat test validated the robustness of the TPSG4 and MSE set-up with intensities up to 'nominal' LHC type beams. Since the beam spot size was smaller than specified for normal operation, and closer to the dimensions for the LIU beam, this test validates already the brittle materials of the TPSGs.

For the ductile materials and the MSE, this first test showed the proof of protection principle. However, a test at full intensity is required to validate the assumptions for the ductile TPSG materials and for water temperature rise and water pressure limitations assumed for the MSE. Therefore a request for a follow up experiment at full intensity presently achievable at the end of 2015 was submitted and provisionally approved.

Table 2: TPSG Design Parameters [6]

	TPSG4		**TPSG6**	
	Present	LIU	Present	LIU
Protons per spill [1011]	288 x 1.7	288 x 2.3	288 x 1.7	288 x 2.3
Transverse emittance [µm]	3.5	2.1	3.5	2.1
Beam size at diluter H x V [mm2]	0.86 x 0.50	0.66 x 0.38	0.67 x 0.65	0.52 x 0.50
Diluter length [m]	3.1	≤ 4.1	3.5	≤ 5.2
Max. ΔT in septum conductor [°C]	100		100	
Max. ΔP septum cooling water [bar]	50		25	
Max. ΔT septum cooling water [K]	16		8	
Time structure	25ns x 72 x 4			
Beam momentum [GeV/c]	450			

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LIU REQUIREMENTS

The failure scenarios considered for the LHC Injector Upgrade (LIU) [5] involve mis-steering of the beam by the extraction bumpers and kickers onto the TPSG. The extraction bumpers could impact the circulating beam directly on the TPSG but are interlocked to reduce this risk. In the case of the extraction kicker, the beam may be steered onto the TPSG if triggered asynchronously with respect to the beam, or if the thyratron switch turns-on erratically i.e. without being triggered. Once the pulse forming network (PFN) of the extraction kicker is fully charged, an asynchronous firing will sweep the beam across the TPSG and into the extraction channel where it will be dumped at the LHC injection dump. In the event of an asynchronous turn-on occurring whilst the PFN is charging a new system is foreseen to detect the event and to trigger a second thyratron to reduce the magnitude of current in the kicker magnet and also trigger a beam dump in the SPS. It is foreseen to clip the current quickly enough (within ~1.5 μs) to avoid beam impact on the TPSG. Present studies indicate that in the worst-case scenario, i.e. a trigger occurring towards the end of the PFN charging process, the beam scrapes the TPSG; studies are on-going in this area.

The parameters considered for the present (so called LHC-ultimate) and future LIU beams [6] are summarised in table 2.

IMPACT CALCULATIONS FOR LIU

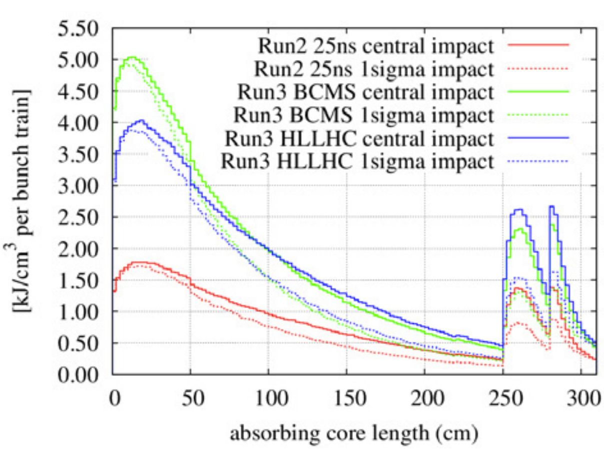

Figure 1: Energy deposition TPSG4 for LIU high intensity (HL LHC) and small emittance (BCMS) beams.

Analysis of the scenarios leading to impact on a TPSG cannot rule out a direct impact, which corresponds to a more severe case than that of a sweep. Studies of other absorbing jaws have found that small impact parameters, of the order of 1 σ, considering the tightest beams, produce higher stresses in initial low density materials, whereas the worst case for later, higher density materials is deep impact parameters with the highest intensity beams. Investigations for the survival of the TPSG absorbers therefore necessitated a range of simulations to ensure the worst case for each material component was considered. The peak energy deposition along the length of TPSG4 is shown, simulated using Fluka [7, 8] in Fig. 1 for the range of LIU simulations considered; 1 and 5 σ impact parameters for higher intensity LIU beams as well as small emittance, so called BCMS, beams. Also included for reference is the same cases run for LHC standard 25 ns beam. The peaks seen in TPSG6 are lower than those shown for TPSG4 due to a larger spot-size on the front face of the absorber.

For the thermo-mechanical calculation a total time of 20 μs was used, in order to simulate thermo-mechanical stresses not only during the pulse time (7.9 μs) but also the effect of the thermal shocks after the impact.

In particular for brittle materials, such as Graphite, three different failure criteria were considered: the criteria of the maximum and minimum principal stress, Stassi and Mohr Coulomb (this last one is the most conservative). For an orthotropic material the criteria of the maximum and principal stress were used. For ductile materials the Von Mises failure criteria as well as the maximum and minimum principal stress failure criteria have been evaluated [9, 10].

All the material models considered only the elastic region, the goal being to check their ability in withstanding the most pessimistic impact while still remaining in the elastic region.

The results [11] show that both the TPSG4 and the TPSG6 will not be able to entirely withstand the impacts. In the TPSG4 all the materials, except the CfC, will go beyond the elastic region. In the TPSG6 the ductile materials will suffer the most and go beyond the elastic region.

Further investigations, taking into account the plastic region of the material, need to be done in order to draw precise conclusions on how the materials will behave beyond the elastic region.

CONCLUSION

Tests at HiRadMat have been done and will be continued to validate the assumptions to design the SPS extraction protection elements. The first test with so called LHC nominal intensity beam was sustained successfully and next the test will be repeated with present LHC (ultimate) beam. The results of these tests should allow the design of the diluters for the more challenging LIU beams in the future. First simulations indicate that the present systems will not suffice. Different dilution materials will be required and very likely more diluter length will be needed. The first studies on how to allocate more space to the TPSGs have been launched.

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