DESIGN AND CONSTRUCTION OF THE CERN SPS EXTRACTION PROTECTION ELEMENTS FOR LIU

B. Balhan*,C. Baud, J. Borburgh, M.A. Fraser, M. Hourican, L.O. Jorat, F-X. Nuiry, S. Pianese,
CERN, Geneva, Switzerland

Abstract

At CERN, the SPS synchrotron is equipped with two fast extraction channels towards the LHC. As a part of the LHC injector upgrade project (LIU), the protection devices upstream of the septa in both extraction channels will be upgraded. Various failure scenarios have been studied and presented in the past, but the definitive approach for the equipment protection upgrade for each channel has now been determined. This paper describes the consequences of the most significant failure scenarios and the impact of the heat deposition in the diluter. The resulting material stresses are evaluated. The detailed layout for the extraction protection equipment for each extraction channel is outlined. The final layout consists of a extended diluter in Long Straight Section (LSS) 6 (TPSG6) and the installation of an additional movable absorber (TPSC4) upstream of the quadrupole in front of the existing protection equipment in LSS 4. The detailed mechanical design of the TPSC4 and the construction status of both TPSC4 and TPSG6 are discussed.

INTRODUCTION

At CERN, the SPS synchrotron is equipped with two fast extraction channels towards the LHC. The extraction septa (MST and MSE) are protected from accidental beam impact by extraction protection devices. The existing protection devices (TPSGs) are designed to dilute the beam such that the energy deposition and subsequent temperature rise in the conductors of the downstream septa remain below tolerable thresholds in the unlikely event that the beam is mis-steered. The existing devices were designed to protect the downstream septa from the direct impact of the full LHC ultimate intensity (a single shot) without sustaining irreversible damage. These requirements remain the same for the upgrade. The intensity and brightness of the beam however is to be significantly increased in accordance with the LHC Injector Upgrade (LIU) beam parameters.The relevant beam parameters for the specification of the LIU-TPSG devices are shown in Table 1. Not only will the bunch intensity increase but also the transverse emittance will decrease significantly.

The protection requirements for each TPSG are based upon the assumption that the coil can withstand the same dynamic pressure as the pressure at which the coils are statically tested during construction. The maximum permissible copper temperature rise is determined by the space available in the yoke for the adiabatic thermal expansion after beam impact. Finally the maximum water temperature rise in the cooling channels is determined from the permissible pressure rise using the ELSE code [1, 2]. This yields limits

* bruno.balhan@cern.ch

of 20 bar pressure rise in the MST septa cooling channel, 50 bar pressure rise in the MSE cooling water channels, corresponding to a 4 and 6 °C temperature rise in the MST and MSE cooling water respectively. The copper conductor temperature should remain below 100 °C.

Up to the Long Shutdown 2 (LS2, 2019 - 2020) both the extraction protection devices in LSS4 and 6 made use of state-of-the-art 2D Carbon Reinforced Carbon (CfC). The absorbing sandwiches [3] have a total length of 3.1 m for the TPSG4 (extraction towards the CCW LHC beam) and 3.5 m for the TPSG6 (extraction towards the CW LHC beam). The new beam conditions require upgrades to both extraction protection systems, i.e. a new complementary unit TPSC4 (see Fig. 1) in LSS4 and an additional unit TPSG6 in LSS6.
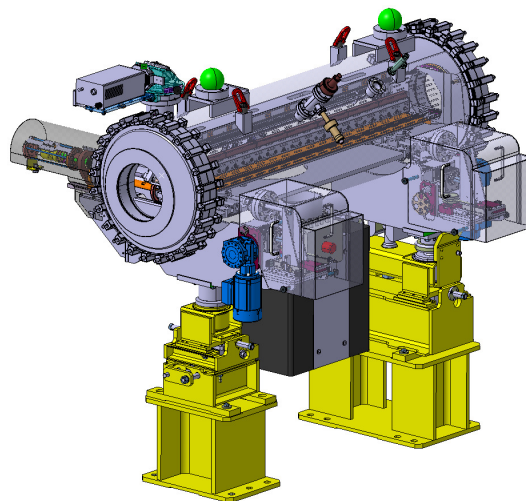

Figure 1: General assembly of the TPSC4 showing displacement system, adjustable supports, and pumping equipment.

LIU FAILURE CASES

The failure scenarios considered for the LIU project [4] cover mis-steering of the beam by the extraction bumpers and kickers onto the TPSG. The extraction bumpers could also potentially steer the circulating beam directly on the TPSG but the current of these devices are interlocked to eliminate this risk and protected by BLMs. Once the pulse forming network (PFN) of the extraction kicker is fully charged, in the case of an asynchronous trigger, or if the thyratron switch turns-on erratically without being triggered, the beam may be swept across the TPSG and into the extraction channel where it will be dumped on 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 9 within ~1.5 µs) to avoid beam impact on the TPSG. Present studies [5] 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. For the thermo-mechanical stresses in the absorber material, the brightness (depending on the beam emittance and intensity) is a critical parameter, whereas for the survival of the vacuum tank of the device, and other downstream equipment, it is the total intensity that will play a significant role [6].

Table 1: TPSG Design Parameters [7]

Parameters	TPSG4 Present	LIU	TPSG6 Present	LIU
Beam momentum [GeV/c]	450	450	450	450
Protons per spill [10^{11}]	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 [mm]	0.86	0.66	0.67	0.52
Beam size at diluter V [mm]	0.50	0.38	0.65	0.50
Bunch train lenght [µs]	7.8	7.8	7.8	7.8

DILUTER UPGRADE

The increased intensity and brightness of the LIU specification demands longer diluters to provide sufficient attenuation and emittance dilution to protect the downstream septa. The increased footprint caused significant integration problems in the limited space in LSS4. Different design solutions were considered to integrate a longer diluter, see [8,9]. First conceptual studies of an absorber with an increased length and containing both graphite R4550 and 3D Carbon were carried out [10–13]. As it was impossible to extend the existing TPSG4 sufficiently, it was decided to split the protection device either side of quadrupole 418 [12], see Fig. 2. In many ways the alignment and operation of a non-local protection for the septum in LSS4 is similar to the alignment of the TPSG and MST in front of the MSE installed already in LSS6. Up to LS2, the TPSG6 was composed of two identical tanks, each containing a 1.75 m long sandwich of materials. Unlike LSS4, in LSS6 sufficient space could be freed up to accommodate an extended diluter directly upstream of the septa, installed on a common girder. Since it was demonstrated by the detailed calculations concerning the diluter upgrade in LSS4 that 1.35 m of additional 3D carbon diluter was sufficient, it was decided to add a full TPSG6 tank (i.e. 1.75 m of dilution material) since this will be largely sufficient to cope with the new LIU beams see Fig. 3. This decision was strongly influenced by the minimal cost needed for the design of the TPSG6 upgrade, since the manufacturing drawings of the individual tanks were already existing.

FAILURE SCENARIOS STUDIES

In order to validate the split-diluter scenario chosen for LSS4 (now called TPSC4 for the additional stage in front
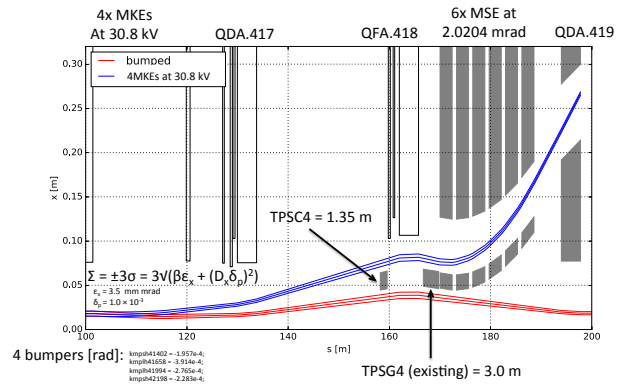

Figure 2: Final design choice for the LIU TPSG4 upgrade with the TPSC4 installed upstream up QFA.418.
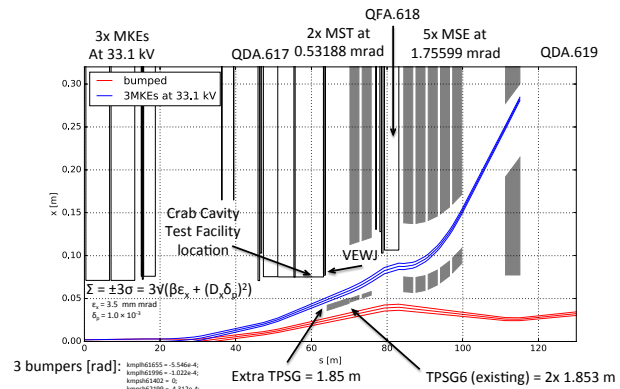

Figure 3: Final design choice for the LIU TPSG6 upgrade with a third tank installed upstream.

of quadrupole 418 and the unchanged TPSG4), the geometry of the entire extraction region was modelled in FLUKA and further simulations were carried out [14, 15]. This was primarily to include the effect of the magnetic field of the QFA.418 located between the TPSC4 and TPSG4 and the potential impact it might have on the dilution efficiency. A few scenarios with a 1-5 σ impact parameter on the inner and outer edges of the TPSC4 were studied and followed up with ANSYS® thermo-mechanical simulations. In all scenarios the TPSC4 and TPSG4 are expected to survive and protect the downstream MSEs. The worst-case scenario for the downstream elements is the 1σ impact case on the outer edge of the TPSC4, however, the MSE water temperature rise remains limited to 4 K. The transient structural analysis showed that the instantaneous temperature rise up to 305 °C generates equivalent stresses which remain below the material's yield stress limit. The studies investigating the shape of the TPSC4 (tapered or rectangular) highlighted the sensitivity of the energy deposition in the downstream end of the TPSG4 with respect to the alignment of the TPSC4 with the beam [16]. To reduce the sensitivity to misalignment, the TPSC4 uses a tapered shape. The effect of thermal load on the part of the TPSG4 sandwich containing materials with high-Z (atomic number) (see Table 2) caused by the direct

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impact of secondary particles deflected by the magnetic field of quad 418 was shown to be acceptable [17].

A similar study was performed for the TPSG6 diluter upgrade, by installing a 3rd unit upstream of the existing TPSG6s (see Table 3). A 240 °C temperature rise was observed on the CfC, which is far below the material limits since it can withstand temperatures of 600 - 700 °C. Also the stresses induced in the second downstream (existing) units remain much lower than the material limits.

Table 2: TPSC4 and TPSG4 Dilution Sandwich

Parameters	Present	Upgraded
3D Carbon [m]		1.35
Graphite (CZ5) [m]	0.5	0.5
Carbon C/C [m]	1.7	1.7
Graphite (CZ5) [m]	0.3	0.3
Titanium (TiAl6V4) [m]	0.3	0.3
Inconel (Inco 718) [m]	0.3	0.3
Total dilution length [m]	3.1	4.45
Diluter width (mm)	21	19.3 - 21

Table 3: TPSG6 Dilution Sandwich

Parameters	Present	Upgraded
3D Carbon [m]		1.75
Carbon C/C [m]	1.75	1.75
Graphite (CZ5) [m]	0.85	0.85
Titanium (TiAl6V4) [m]	0.3	0.3
Inconel (Inco 718) [m]	0.6	0.6
Total dilution length [m]	3.5	5.25
Diluter width (mm)	6	6

MECHANICAL DESIGN

TPSC4 Conceptual Design

The main diluter elements (3D C/C) are incorporated in a vacuum vessel with an internal diameter of 444 mm and is mounted on a support that can be remotely adjusted in both angular and radial position. This displacement system consists of a series of crossed roller type slides which allow for a precise radial movement [18]. A park position is foreseen to retract the diluter out of the main SPS vacuum chamber aperture. The stainless steel vacuum vessel, with a length of 1802 mm from flange-to-flange, is equipped with vacuum ion pumps, vacuum gauges and a vent valve. To allow bake out of the porous 3D C/C before operation, an under vacuum heating element is installed on the diluter support.

Diluter Materials

The above mentioned simulations validated 3D C/C (density = 1.75 g/cm^3) as a suitable material for the TPSC4. The effective diluter length will be 1.350 m, composed of

8 blocks (7x 170 mm and 1x 160 mm). The thickness of the diluter blocks (as seen by the beam) is increased linearly along its length by stepping the width of the 8 blocks in units of 0.1 mm from 19.3 to 20.0 mm. A space of 1 mm is left between blocks to allow for thermal expansion/contraction. The diluter assembly, comprising 8 individual C/C blocks are clamped to a cooling tube in the arrangement to remove the heat deposited by the beam onto the diluter. The compression force is provided by a stack of compression washers which exert sufficient force on the assembly to assure optimum thermal contact between the diluter blocks and the cooling tube.

Alignment Accuracy

The accuracy of the horizontal positioning of the diluter with respect to the survey targets on the tank exterior is better than ±0.1 mm. Vertical and radial positioning accuracy is better than 0.2 mm with respect to the survey target. Two survey targets are positioned on machined surfaces on the upper reference surface of the vacuum tank. The targets are positioned above the SPS theoretical orbit.

CONCLUSION AND OUTLOOK

Due to the increased beam intensity and brightness, different studies have been performed on the TPSG4. These show that in case of a mis-steerd beam, a longer diluter is required in order to keep, the temperatures in the down-stream septa below the critical values. Due to the limited space in LSS4, a split-diluter configuration has been adopted, placing an additional diluter upstream of quadrupole 418 as a complement to the existing diluter downstream of this quadrupole. In the worst case scenario (1σ beam impact at the edge of the TPSC4 diluter blocks) the peak energy deposition, hence temperature rise, is located in the Inconel block, at the end of the diluter. The simulations show that the split-diluter configuration withstands full beam impact of the HL-LHC beam. No failure should occur of the diluter itself, and the downstream septa magnets will be properly protected. In LSS6 the integration of an additional diluter is feasible. By assuming the installation of 1 additional diluter containing 3D Carbon blocks upstream of the second existing TPSG6 tanks. The temperature peaks found on the high Z materials of the existing diluters remain below the acceptable limits, and they are even lower than the ones expected for the TPSC4/TPSG4. At the time of writing, the diluter in LSS6 has been upgraded and the construction of the TPSC4 is nearing completion. This additional diluter is foreseen to be installed in the SPS in autumn 2019.

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