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ALTERNATIVE MATERIAL CHOICES TO REDUCE ACTIVATION OF EXTRACTION EQUIPMENT

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Abstract

At CERN, the Super Proton Synchrotron (SPS) is equipped with a resonant slow extraction system in Long Straight Section 2 (LSS2) towards the fixed target (FT) beam lines in the North Area. The extraction region provides the physics experiments with a quasi-DC flux of high-energy protons over a few seconds, which corresponds to tens of thousands of turns. The resonant slow extraction process provokes beam losses and is therefore the origin of radiation damage and the production of induced radioactivity in this region of the machine. This induced radioactivity imposed high constraints on the equipment design to be reliable to minimise the radiation exposure to personnel during machine maintenance. A detailed FLUKA model was developed in order to better understand the beam loss patterns, activation of the machine and to identify equipment components that could be optimised to reduce the residual dose related hazards. Simulations identified multiple alternative materials for extraction equipment components as well as shielding locations, which implementation could reduce residual activation hazards.

INTRODUCTION

The SPS is currently providing the North Area fixed target experiments with protons and heavy ions by the third-integer slow extraction process. The circulating beam is extracted by exciting the beam particles in the horizontal plane by moving the machine tune toward the third-integer resonance. The tune sweeps over the chromatic tune spread of the circulating beam until all particles, from lowest to highest momentum, have migrated across the electrostatic septa (ZS) into the high-field region of the extraction channel. This process provokes beam losses at locations where the beam aperture is restricted from the septa that separates the circulating beam aperture to the electric- or magnetic field regions of the extraction channel. These beam losses jeopardise machine availability as they are the origin of both radiation damage and induced radioactivity of the machine. Demand for even higher beam intensities to the proposed SHiP [1] experiment motivates all efforts of the multidisciplinary SPS Losses and Activation Working Group (SLAWG) [2, 3] at CERN to reduce losses and activation in the machine for a safer working environment for intervening personnel.

The SPS extraction channel (Fig. 1) spans three periods between quadrupoles 216 and 219, which stretches approximately 100 meters. It includes five consecutive electrostatic septa ZS, a subsequent extraction protection element TPST upstream of three thin magnetic MST septa, followed by 5 thick magnetic MSE septa.

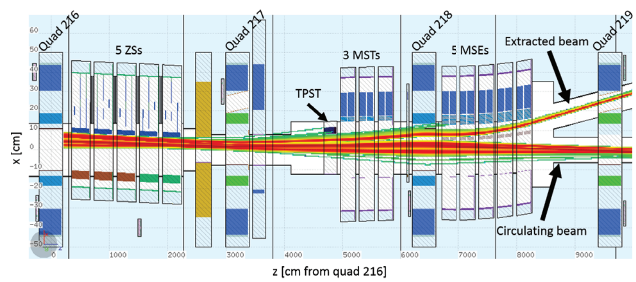

Figure 1: Horizontal view of LSS2 extraction region rendered in FLAIR [10]. The image is showing the horizontal aperture, relevant extraction equipment and the paths of the circulating and extracted beams.

The extraction beam line will be the most radioactive accessible part of the SPS machine as of 2021 when its synchrotron beam dump system is upgraded for HL-LHC era [4]. Figure 2 shows the residual ambient dose equivalent rate profile of the extraction region measured 30 h after beam stop 1 metre from beam axis at the end of the 2018 proton run. The measured dose rate profile highlights that the most critical elements for residual activation hazard of the extraction beamline are the ZS tanks, the TPST, the MST tanks and the area just upstream of quad 218.

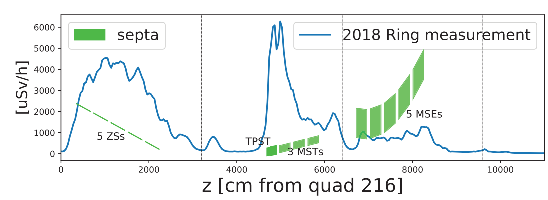

Figure 2: Residual dose rate profile of LSS2 measured at 1 meter distance from beam axis 30 hours after beam stop on November 13th, 2018.

FLUKA MODEL

The newly developed LSS2 FLUKA model [5–9] has been used to evaluate alternative materials and shielding locations of the extraction equipment, while taking into account both the spatial complexity of the extraction beamline and the specific radiation fields produced during and after the extraction process.

Each primary proton of the FLUKA source term is sampled from a MAD-X tracking distribution, which considers the last four turns of any primary particle being extracted,

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hitting the vacuum chamber or lost in nuclear interactions in the ZS septa [11]. Particles scattered off the ZS septa are considered in the source distribution through the linking of pycollimate [12] to the MAD-X tracking simulation.

ZS Anode Wire Septa Modelling

The approximately 2080 individual tungsten-rhenium (WRe) wires that make up the anode wire septa of each the five ZS modules are each modelled as a slightly wider continuous ribbon with the collective mass of all wires averaged over the full volume of the ribbon. A dedicated MAD-X inter-model comparison study determined that this simplification incorporates the horizontal position uncertainty of the individual wires by accurately reproducing the phase space of particles scattered from the ZS septa. The same simplification was given further credibility by correctly reproducing the loss and activation profiles throughout the beamline [6].

ALTERNATIVE MATERIAL ASSESSMENT

This section presents the material exchanges that were found to reduce residual dose related hazards of the radioactive elements of the extraction beamline. The materials with lower atomic number Z suggestions of Table 1 have been found to be radiologically advantageous through both the FLUKA and Actiwiz codes [13, 14]. The latter code utilises fluence spectra obtained with the LSS2 FLUKA model to be used as input. The reduction of residual ambient dose equivalent rate for each of the material exchanges are plotted along the beamline in Fig. 3.

Table 1: Radiological Beneficial Component Material Exchanges for Extraction Equipment

Element	Component	Current material	Beneficial material
ZS	Anode wires	Tungsten/ Rhenium	Titanium or Graphite
ZS	Anode support	Stainless steel or Invar	Titanium
ZS, TPST, MST, MSE	Vacuum tanks	Stainless steel	Al6061
	Beam pipe	Stainless steel	Al6061

Electrostatic Septa (ZS) Material Exchange

Constructing the ZS anode wire septa with a lower-Z material will both reduce its radiological contribution at 1 meter distance by a factor of 0.001 - 0.1 [14] and drastically reduce activation throughout the extraction beamline, as seen in Figures 3 and 4. The implementation of Carbon Nano Tubes (CNT) septa was simulated as graphite for the first

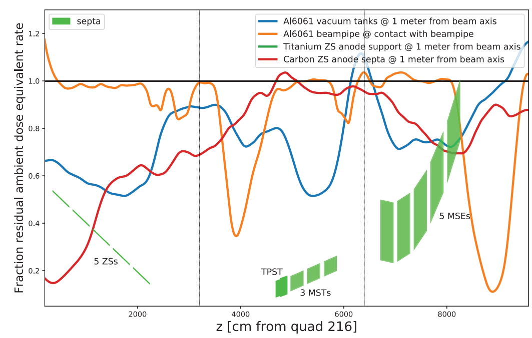

Figure 3: Reduction factors along beamline of residual ambient dose equivalent rate from material exchanges listed in Table 1 after 1 week of cool down. Sampled 1 meter distance from beam axis or upon contact with beam pipe.

two tanks, ZS1 and ZS2, with the same source distribution as for the reference case with WRe wires. The reduction in activation follows from reduced beam loss during extraction, as a result of the reduced probability of hadronic interactions between the beam particles and the nuclei of the lower-Z wire septa. The resulting production of secondary particles from nuclear interactions will be of decreased number and variety and therefore less likely to further activate the machine. The reduced probability of losing particles in the ZS septa also suggests that exchanging the septa to a lower-Z material could reduce degradation of the machine due to radiation damage.

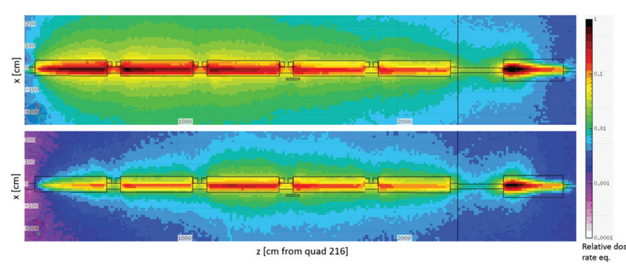

Figure 4: FLUKA residual dose rate comparison after 30h of cool down for the ZS tanks of the current setup (top) to a carbon nanotube wires setup (bottom), simulated as graphite, in tanks ZS1 and ZS2.

ADDITIONAL SHIELDING

Two locations, the TPST and quadrupole 218, would benefit from additional shielding as an effective alternative to the limitation in possibility of exchanging materials of the equipment itself. The extraction protection element TPST is currently protecting the downstream magnetic septa from stray particle showers provoked by scattering or interactions with the upstream ZS anode wires. The number of hadronic interactions with the TPST blade are sufficient to make this protection element the hottest part of the extraction beamline. Additionally, stray particle showers also activate quadrupole

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218 and the upstream orbit corrector to such a degree that it contributes more to the residual dose rate hazard than two of the MSTs. Figure 5 shows that shielding the TPST within a 20 cm marble encasement and the quadrupole 218 behind a 15 cm marble wall can reduce the residual dose rate 1 metre from beam axis by a factor of 10 after 1 week of cool down. Shielding the highly activated TPST addresses the most radioactive part of the extraction region.

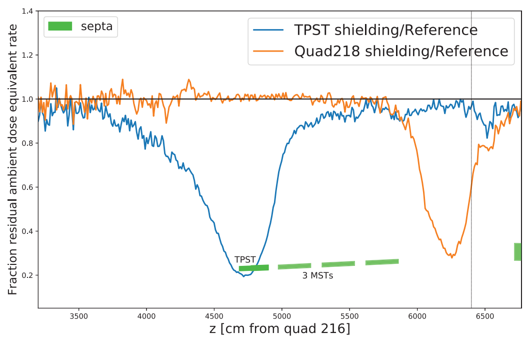

Figure 5: Reduction of residual ambient dose equivalent rate by the implementation of marble shielding for the TPST and for Quadrupole 218. Sampled 1 meter from beam axis after 1 week of cool down after beam stop.

IMPLEMENTATION FEASIBILITY

The use of low-density materials for the ZS wires will need to be validated before they can be deployed instead of the present WRe wires. Titanium wires could potentially suffer from lower operating temperatures and CNT have not yet been demonstrated to be compatible with high electric fields due to reduced surface smoothness. Where the presently used WRe wires are polished before use, the surface of the CNT wires will be less smooth because the Ø 100 µm wires are composed of strands of Ø 7 µm CNTs. Although the CNT wires appear attractive due to their high tensile strength and resistance to high temperatures. Tests are currently being prepared at CERN to validate CNT wires as cathode material.

Further studies and tests will be needed to assess the behaviour of titanium as anode support under operating conditions, especially in view of it being a poor heat conductor and also rather elastic. Before deploying a titanium anode support it needs be demonstrated that it remains thermally stable during operation, and that the wire array remains straight.

Constructing the MST and MSE vacuum tanks out of the aluminum alloy Al6061 requires that they can maintain their mechanical integrity at the bake out temperature of 150 °C which assures a good vacuum. The ZSs do not suffer from this limitation as they are not baked anymore. Large 'Suchet' style flanges need to be developed for this technology to be viable for the large vacuum tanks of about Ø 600 mm. Implementing an aluminum beam pipe in between the accelerator elements and inside the quadrupoles and correctors is expected to be easily implemented based on experience from previous applications.

Concerning the proposed shielding of both the TPST as well as the quad 218, there are no major challenges identified if the shielding can be design to easily be removable if required.

The feasibility to implement each measure before the next Long Shutdown 3 (LS3), when all the equipment can be accessed again, is shown in Table 2. It also compares the integrated dose rate over the extraction length of the residual dose rate profile of Fig. 2 by first multiplying it with the local reduction factor obtained from the solution options brought forth in this study. Finally a figure of merit (F.o.M.) is obtained from the saved residual dose rate exposure, by subtracting the reduced integrated dose rate from the integrated dose rate of the reference case, and then dividing by its cost, seen in column 5 of Table 2.

Table 2: Cost Benefit Aanalysis of the Different Measures Using a Figure of Merit (F.o.M., see text)

Solution Option	Feasibility before LS3	Cost [A.U.]	Ratio of integrated dose rate eq.	F.o.M.
CNT wires	Tbc.	500	0.676	924
Al Tanks	Tbc.	1000	0.769	329
TPST shielding	Yes	100	0.897	1476
Al beampipe	Tbc.	300	0.988	33
Ti anode support	Tbc.	500	0.988	52
Quad218 shielding	Yes	175	0.972	225

CONCLUSION AND OUTLOOK

The reduced radiation hazard from material exchanges and proposed shielding designs looks promising for the future. Implementing these improvements could allow the SPS to increase beam intensities delivered to the North Area without losing availability from increased activation of the machine. In particular, exchanging the ZS wires to CNT has the potential to drastically reduce activation throughout the beamline. The implementation of marble shielding for the TPST and quad 218 together with the exchange of the vacuum tanks to Al6061 could directly address some of the hottest elements of the SPS machine. Implementing the same aluminum alloy for the beam pipe could substantially reduce the radiation dose to personnel at locations of frequent interventions in close proximity to the beam pipe. The radiologically advantageous property of the Al6061 alloy is believed to remain favourable over stainless steel at radiation facilities exposed to hadronic radiation fields.

For the immediate future, it is of high interest to research the implementation feasibility of the CNT wire septa and Al6061 for the vacuum tanks.

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