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SLOW EXTRACTION WITH OCTUPOLES AT CERN PROTON SYNCHROTRON TO IMPROVE EXTRACTION EFFICIENCY

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Abstract

The extraction inefficiency of the slow extraction process induces radioactivity in the area surrounding the electrostatic septum. Studies at the CERN Proton Synchrotron (PS) are investigating beam loss reduction techniques to improve the efficiency of the beams provided to the experiments of the East Area. Powering octupoles distorts the transverse phase-space of the extracted beam which can be exploited to maximize the number of particles in the field region of the septum with respect to the number lost on the septum. The effect of octupoles on the separatrices near the third-order resonance is simulated with MADX-PTC tools to observe phase space folding and to predict the multipole parameters needed to minimize beam loss. Experimental studies are performed to confirm the validity of the simulation models and to quantify the net benefit of using octupoles to improve the extraction efficiency.

INTRODUCTION

Slow extraction delivers a continuous spill of beam from synchrotrons on the order of 100 ms - 1 s, which is beneficial for applications such as radiation sensitivity testing of electronics [1]. The efficiency of this extraction method is limited by geometric restraints, whereby high-amplitude particles approaching the field-region of the extraction septa are lost and scattered on the electrodes.

Dynamics of high-amplitude particles near a resonance are strongly affected by higher-order multipoles. Octupolar fields of the correct strength and polarity can induce a decreased density of particles on the foil of the electrostatic septum [2], operationally achieving a reduction of beam loss, which can then be further optimised with increased spiral step via the sextupole fields.

The Proton Synchrotron (PS) at CERN receives beam from the Proton Synchrotron Booster (PSB), accelerates protons, and extracts beam to either the Super Proton Synchrotron (SPS) or to experimental areas such as the East Area. CHARM and IRRAD are electronic irradiation facilities located in the T8 beamline of the East Area which make use of the 24 GeV slow extracted proton beam from the PS [1].

In 2019, the SPS Losses & Activation Working Group applied this octupolar effect during slow extraction at the SPS and demonstrated over 40% reduction in beam loss [2], which could be used operationally with the high-intensity North Area upgrade, alongside crystal channelling techniques [3]. A dedicated study is required to apply the same procedure to the PS, due to the higher-order multipole components present in the Pole-Faced Windings (PFWs) of the PS Main Units, and the geometric constraints of the electrostatic septum (SEH23) and the two magnetic septa (SMH57, SMH61) that deflect the beam into the F61 extraction line. Simulations with MADX-PTC guided the initial selection of the operational LSA multipolar parameters. For each of these parameters, the proportion of lost particles in the ring was measured via the Beam Loss Monitors (BLMs). The total extracted intensity was inferred with the Beam Current Transformers (BCTs), and verified by the Secondary Emittion Chambers (XSEC) in the F61 extraction line. This method determined a relative improvement of the extraction inefficiency by over 20% compared to nominal operational settings.

PS Extraction Details

The horizontal tune is set below the horizontal third-integer resonance of $Q_x = 19/3$ with the QSE quadrupole, and driven by three XSE sextupoles. Particles that exceed the aperture of the septum foil enter the field region which provides a transverse kick towards the magnetic septa. The additional controllable octupolar field is provided with the chain of 10 ODN octupoles. The control of particle tune into the resonance is provided via COSE (constant-optics slow extraction), where the B-fields of the PS main units are linearly ramped with all other magnets [4]. The horizontal-tune knob of the PFWs is used for additional correction. For the purposes of this Machine Development (MD) study, the SMH61 septa directs the beam into the F61 beamline towards the East dump, rather than sent to an experimental beamline.

SIMULATIONS

Using octupoles to affect density of particles near the electrostatic septum runs the risk of rapidly collimating all of the beam onto the septum foil. To reduce this risk, simulations were performed prior to the study to determine which region of multipolar parameter-space should be investigated.

These were performed via MADX-PTC tracking, due to its understood and benchmarked optics repository. The cpymad module provides easy variation of the two main variables, XSE and ODN. The dynamic COSE extraction is difficult to reproduce in the static procedure of PTC, therefore the phase-space portrait during this extraction was produced by placing the tune exactly on resonance and tracking 10,000 particles

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within 500 turns. The distribution at the position of the electrostatic septum was observed throughout all turns, with particles considered lost if their trajectory overlapped with that of the thin anode foil or the cathode, and extracted if within the field region. Afterwards a negative kick of −0.39 mrad was applied in the x' coordinate, further PTC tracking traced these extracted particles to SMH57 and SMH61.

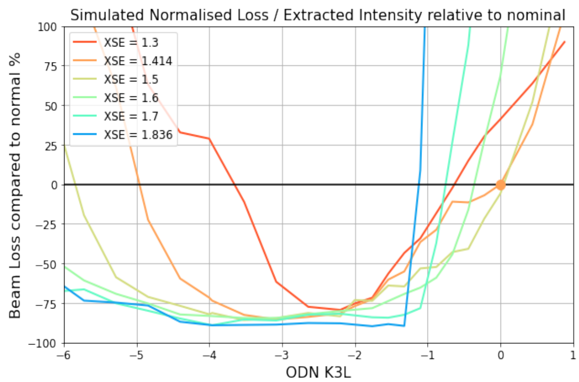

Figure 1: Simulations of relative beam loss reduction as a function of octupole strength and sextupole strength.

This simulation was repeated for a range of different multipole parameters, constrained by the nominal sextupole strength k_2(XSE)=1.414. The beam loss relative to nominal, shown by the orange dot and black line, is calculated for each multipole setting and represented in Figure 1. The trend shows that negative ODN polarity reduces relative beam loss for nominal XSE, with further improvements by increasing XSE strength. The functional dependence of Figure 1 is dependent on extraction bump BSW23, and the positions and kick strengths of the three extraction septa, which in operation are optimised manually. This gives varying differences between predicted relative beam loss for simulations and measurements. The track of an optimal particle distribution (k_2(XSE)=1.836, k_3(ODN)=-6.0) is represented in Figure 2 as it is traced through the SMH57 septum, the SMH61 septum and through the small window of Main Unit 63, where the beam is transformed under strong fringe-fields from the magnet. The evolution of the beam through the F61 transfer line was studied to determine the distorted shape of the final beam at the position of the BTV screen on the East dump. The distribution of horizontal position at each septa due to octupole folding is represented in Figure 3.

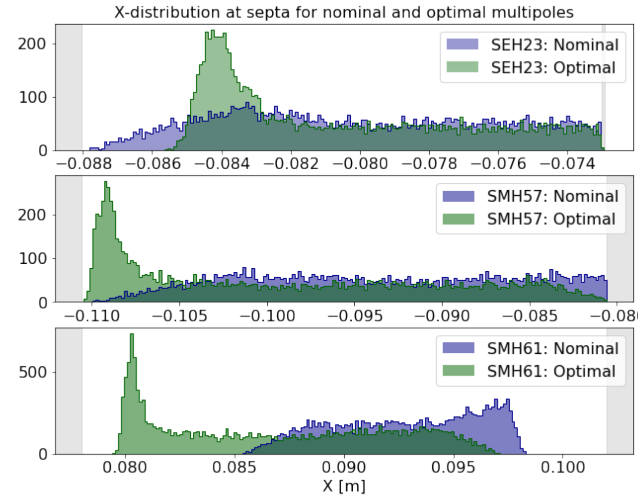

Figure 3: Simulations of particle distribution under octupole folding at the three septa, with aperture limits shaded in grey.

MACHINE DEVELOPMENT

The PS MD cycle consisted of a 24 GeV proton beam extracting to the T8 East beamline, diverted to the beam dump. The beam from the booster used the minimum possible intensity, shown in Table 1, to reduce radioactivity to the septa and to the East line.

Initially, a coasting beam with no XSE driven resonance was set-up to ensure that COSE B-field and PFW k_2 ramping settings were sufficient to cross the resonance. During flat-top, the XSE is ramped prior to the COSE ramp, and a constant extraction rate is verified via the linearly decreasing intensity measured with the BCTs. The ring BLMs, as pictured in Figure 4 observed a total evolution loss of 2200 units during this extraction time from 1200 ms to 1700 ms, of which ≈20% occurs at SEH23 and ≈40% is lost around the magnetic septa.

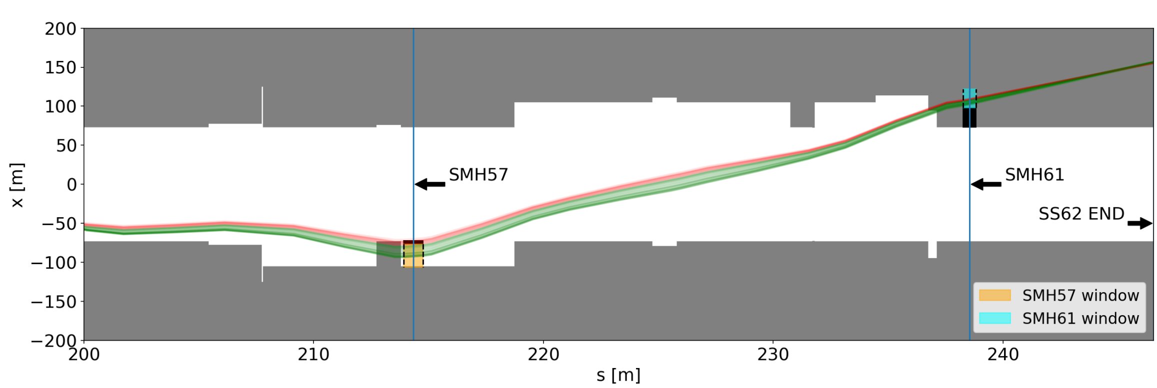

Figure 2: MADX-PTC tracking of beam throughout extraction from SMH57 to MU61.

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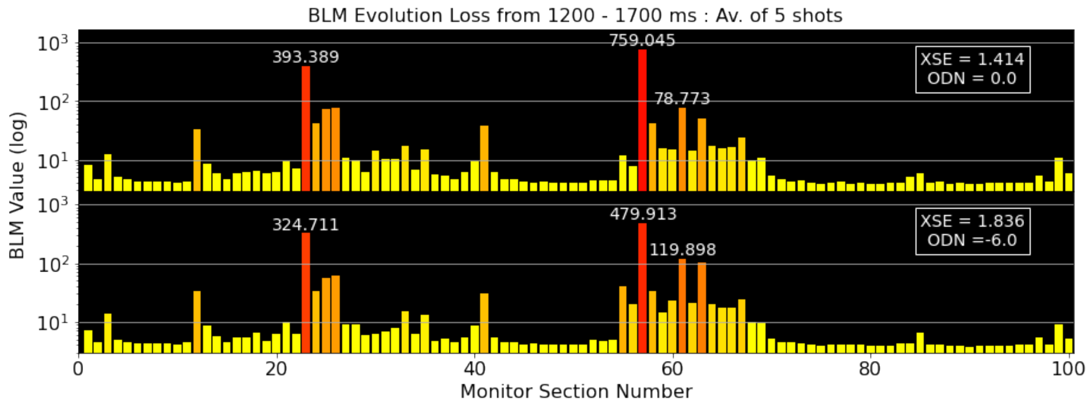

Figure 4: Comparison of BLM Signal during extraction.

Table 1: Parameters of MD5744

Parameter	Value	Parameter	Value
Energy [GeV]	24	Int. $[10^{10}]$	20
Emit. [um]	0.98	$\Delta p/p [10^{-3}]$	0.78
t_{ramp} [ms]	1200	t_{dump} [ms]	1730
Q_x Ramp	$6.29 \rightarrow 6\frac{1}{3}$	Q_y	6.173

All parameters were then kept constant, except for the k_2 strength of the XSE and the k_3L strength of the ODN, which were varied manually in LSA. Scans in ODN stopped once losses were measured to be increasing, to avoid unnecessary irradition. The introduction of octupole strength prompts an amplitude detuning effect, which results in the shifting of the beam away from the resonance. This causes incomplete extraction, seen by the BCT difference in intensity, which is the reason for normalising results with the XSEC measurement of extracted beam. For each setting of XSE and ODN strength, the response from the ring BLMs and the F61 XSEC were monitored.

Results

To calculate extraction efficiency improvement, the sum of all BLM losses is normalised by the total extracted intensity measured by the XSEC, for each XSE and ODN setting. Then the relative percentage difference is found with respect to the nominal setting of k_2(XSE)=1.414 and k_3L(ODN)=0. Within Figure 5, the nominal setting is represented as the orange dot at (0, 0). It is clear that by keeping the same sextupole strength and introducing a small negative octupole strength of k_3L(ODN) = -2, an extraction efficiency improvement of 15% can be achieved.

For further improvement, the XSE was increased incrementally until the maximum setting of 1.836, where an optimal extraction improvement of above 20% was achieved for k_3L(ODN)=−6.0. The loss distribution of Figure 5 is dominated by the function from the SMH57 which is parabolic with ODN, with a contribution from the losses at SEH23, which are uniform with ODN and decrease with XSE strength.

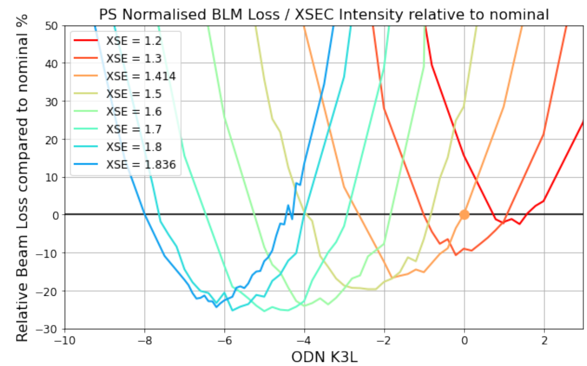

Figure 5: Measurements of relative beam loss reduction (y-axis) with octupole strength (x-axis) and sextupole strength (colour gradient), compared to nominal settings (orange dot).

CONCLUSION

The results from the MD imply a relative improvement in beam loss reduction in the PS with the addition of octupole folding effects in phase-space, providing a 25% difference compared to current operational multipole settings.

Simulations performed in MADX-PTC demonstrate a similar functional dependency on octupole strength and relative beam loss, and were used to observe spatial density differences at the positions of each septa, with and without the octupolar folding component. The results show that, of the proportion of beam that is extracted, a lower beam loss is measured. One additional consideration is that due to incomplete extraction intensities, the rate of extraction will need to be altered for each multipole setting to further demonstrate this effect and to apply it operationally. Simulations displaying beam transfer from the PS ring to the East Area via the F61 line helped to model the aperture limits from the septa to the East dump, which can translate to a comparable beam distribution from the dump BTVs.

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