INVESTIGATING BEAM LOSS REDUCTION WITH OCTUPOLES DURING SLOW EXTRACTION IN THE CERN SPS

L. S. Stoel*[1], M. Benedikt, M. A. Fraser, B. Goddard, CERN, Geneva, Switzerland
K. A. Brown, BNL, Upton, New York
[1]also at Vienna University of Technology, Vienna, Austria

Abstract

Several different methods for reducing beam loss during resonant slow extraction at the CERN Super Proton Synchrotron (SPS) are being studied. One of these methods is the use of multipoles to manipulate the separatrices in order to reduce the fraction of protons hitting the thin wires of the electrostatic extraction septum (ES). In this paper the potential of using octupoles for this purpose is explored. Beam dynamics simulations using both a simplified model and full 6D tracking in MAD-X are presented. The performance reach of such a concept at the SPS is evaluated and the potential of future machine development studies using the octupoles already installed is discussed.

INTRODUCTION

At the CERN SPS a sextupole-driven slow extraction at 1/3-integer tune is used to provide a continuous extracted beam of several seconds long to the fixed target experiments in the North Area. The beam has a momentum spread $\Delta p/p_0 \approx \pm 1.5\mathrm{E}{-3}$ and the extraction takes place at a normalized chromaticity of -1, so there is a large tune spread. The machine tune setting starts below the resonant tune and is then slowly swept upwards by ramping the main quadrupoles so that particles of higher momenta become resonant and are extracted as time progresses.

Due to the continuous amplitude growth in this extraction, some particles inevitably hit the anode wires of the ES, causing radio-activation. The activation of extraction equipment is expected to limit the availability of the machine at the intensity requested by proposed future experiments, hence several methods of slow extraction loss reduction are being investigated [1].

It was shown in [2,3] that higher-order multipoles can fold the extracted beam in phase space, so that the ratio of the beam intensity hitting the ES wires to the intensity extracted through the ES aperture can be lowered. In [4] a preliminary study of the possible loss reduction at the SPS with decapoles was presented. In this paper the loss reduction with octupoles will be explored. The clear advantage of octupoles over decapoles is that there are already many octupoles installed in SPS.

HAMILTONIAN

The 2-dimensional phase space dynamics near a 1/3-integer resonance can be well approximated using the Kobayashi Hamiltonian [5]

$$H = \frac{\epsilon}{2}\left(X^2+P^2\right) + \frac{1}{4}K_2\left(X^3-3XP^2\right) + \frac{9}{32}K_3\left(X^2+P^2\right)^2,$$

or equivalently

$$H = \frac{\epsilon}{2}A^2 + \frac{1}{4}K_2A^3\cos(3\theta) + \frac{9}{32}K_3A^4.$$

Here $\epsilon = 6\pi\left(Q - Q_{\mathrm{res}}\right)$ is a measure of the tune distance from the resonance, X and P are the normalised phase space coordinates, (A,θ) are the polar coordinates for (X,P) and

$$K_n = \frac{1}{n!}\frac{L}{B\rho}\left[\frac{\partial^n B_y}{\partial x^n}\right]_{x=y=0}\beta_x^{(n+1)/2}$$

are the normalised multipole strengths, assuming a single thin lens of effective length L. For an accelerator with several sextupoles and octupoles the parameters of an equivalent virtual sextupole and octupole, which may replace the original multipoles in a first-order approximation, can be calculated in order to apply the Hamiltonian theory.

When we apply the coordinate transformation $(\hat{X},\hat{P}) = K_2\cdot(X,P)$, as proposed in [6], it becomes clear that the shape of the levelsets of the Hamiltonian is purely determined by the parameter $\kappa = K_3/K_2^2$. Similarly, when we apply the same transformation to the thin lens multipole kick

$$\begin{pmatrix}X\\P\end{pmatrix} \mapsto \begin{pmatrix}X\\P+K_2X^2+K_4X^4\end{pmatrix},$$

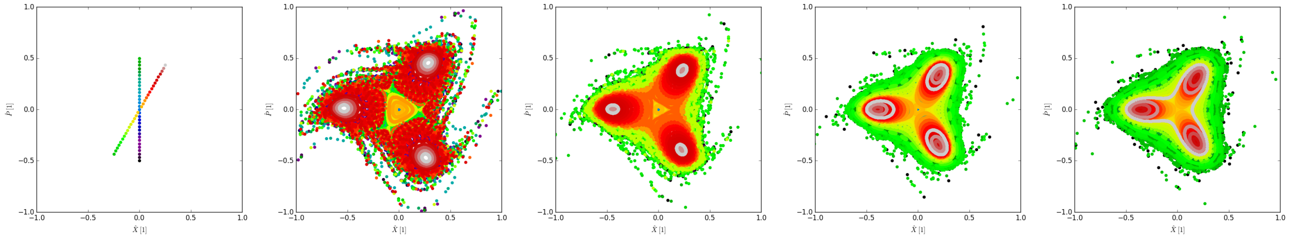
$$\begin{pmatrix}\hat{X}\\\hat{P}\end{pmatrix} \mapsto \begin{pmatrix}\hat{X}\\\hat{P}+\hat{X}^2+\kappa\hat{X}^4\end{pmatrix},$$

we see that the dynamics is fixed by κ while K_2 merely takes the role of a scaling parameter.

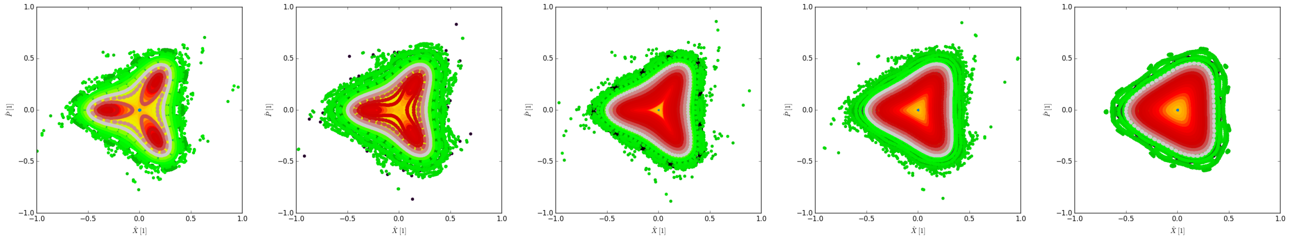
When $\kappa\epsilon > 1/8$ the Hamiltonian has only a single stable point at $(0,0)$ and all motion is stable. When $\kappa\epsilon < 1/8$ there are six additional stable points at $K_2A = \frac{1\pm\sqrt{1-8\kappa\epsilon}}{3|\kappa|}$. The three stable points at the smaller amplitude define a rounded stable triangle around the origin. Just outside of this stable triangle we find motion that is useful for extraction, even though the motion is mathematically stable. Particles in this phase space region will grow in amplitude and then turn around the stable points at larger amplitude before decreasing in amplitude again. If the ES wires are well-positioned, this allows the extraction of a beam that is folded in phase-space during the last turns before extraction.

---

* linda.susanne.stoel@cern.ch



(a) Initial condition. (b) $\epsilon = -1/4$. (c) $\epsilon = -1/8$. (d) $\epsilon = -1/16$. (e) $\epsilon = -1/32$.



(f) $\epsilon = 0$. (g) $\epsilon = 1/32$. (h) $\epsilon = 1/16$. (i) $\epsilon = 1/8$. (j) $\epsilon = 1/4$.

Figure 1: Normalised phase space $(\hat{X}, \hat{P})$ at the first multipole for $\kappa = 2$ and several values of ϵ, crossing the resonance. Particles are initialised according to the first figure and tracked in a simple ring with three multipoles for 1000 turns.

SIMPLE SIMULATIONS

A 2D tracking code was written in python, applying phase-space rotations to model the linear parts of the machine and non-linear thin lens kicks to model the multipoles, similar to the algorithm described in [4]. In order to compare the tracking model and the Hamiltonian theory, a simple ring was modelled, with 3 multipoles at $2\pi/3$ phase advance from each other and a tune of 5/3. Each of the multipoles has a sextupole component as well as an octupole component. Tracking results from this simple model are shown in Fig. 1. These results agree well with the Hamiltonian model. We see the expected stable points and the trajectories that grow in amplitude and bend around the stable points.

SCALED OPTICS

The simple python model was extended to simulate slow extraction from the SPS, using the optics parameters calculated by MAD-X as an input to define the lattice including dispersion and chromaticity, but otherwise using only phase-space rotations between multipoles and thin lens multipoles. The code was extensively benchmarked to MAD-X.

Presently, the SPS slow extraction is driven by ramping only the quadrupoles to sweep the machine tune through the chromatic tune spread of the beam. As a result of the edge-focusing effect of the main dipoles, which are not ramped, the optics seen by the resonant particles at extraction changes throughout the spill.

It was demonstrated in simulation that simply by changing the main dipole field along with the quadrupoles and following the momentum spread, most of the negative effects of the optics mismatch can be eliminated. Figure 2 shows the extracted beam as simulated in MAD-X under nominal conditions compared to the extracted beam using a scaled main dipole field. The invariance of the extraction optics with momentum makes it easier to discern the effects of strong higher-order multipole fields, so a scaled extraction optics is used as the reference in this paper. Assuming an effective ES thickness of 200 um, simulations predict a 15 % loss reduction due to the reduced angular spread the scaled optics presents to the ES, as shown in Fig. 2.

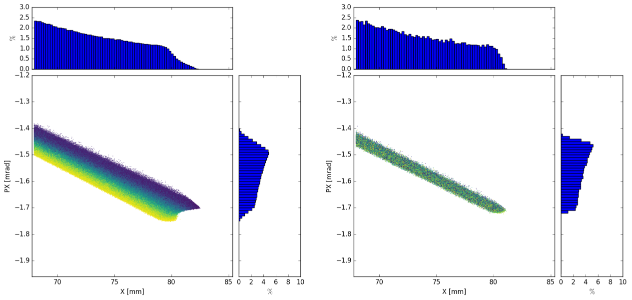


Figure 2: Horizontal phase space of the extracted beam at the ES entrance for the operational extraction scheme (left) and with the scaled optics (right). Particles are colored based on their momentum deviation, from low (purple) to high (yellow) and the ES wires are at 68 mm.

OCTUPOLES IN SPS

Three families of octupoles are already installed in the SPS. One of these families is installed at locations with low β_x (20–25 m), while the other two are at high β_x (85–105 m). Since the normalized octupole strength is proportional to β_x^2, only the latter two families were considered for this study. These two families contain 40 octupoles in total, of which 25 are currently connected to their power supplies. They are assumed to have a maximum integrated field of 1320 T/m^2 each.

Loss Improvement Potential

In order to assess the loss improvement potential of this method an initial study was carried out using all 40 octupoles installed at high β_x locations, at their maximum strength, with the scaled extraction optics. The sextupole strength was then varied and set such that the horizontal extracted beam size is similar to the nominal case shown in Fig. 2 (right). By setting the octupoles to the maximum positive or negative strength, the extracted separatrix is bent downward or upward. The resulting extracted beams at the upstream end of the ES are shown in Fig. 3.

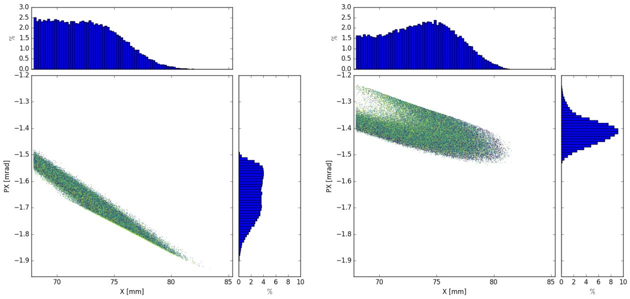


Figure 3: Optimum extracted beams at the ES entrance for maximum positive (left) or negative (right) octupole strength with all 40 relevant SPS octupoles. The ES wires are at 68 mm.

The geometry and optics of the SPS is such that, for the desired horizontal beam size and given octupole strength, bending upward is more effective. A higher sextupole field can be used and the phase space is truly folded. The values applied in the simulation are almost a factor 2 higher than presently available in the SPS. The possibilities of increasing the effective sextupole strength in the SPS have yet to be studied.

Since the separatrix is bent, the average angle of particles at the ES wires is changed and the ES girder needs to be realigned in the simulations before an accurate prediction of the extraction efficiency can be made. A scan of the position of the downstream end of the ES girder was performed in order to determine the new optimal alignments. For more information on this alignment procedure see [7, 8].

Compared to the nominal extraction with scaled optics, the downward bent beam shown in Fig. 3 (left) has a slightly increased particle density at the wires and a 36 % increase in angular spread, so it will have higher losses. The upward bent beam on the other hand has a 32 % reduction in density, but a doubled angular spread. When realigning the ES girder to the moved average angle of the beam, simulations predict a 17 % reduction of losses at the ES compared the the nominal scaled optics case.

Potential for Tests in 2018

The possible loss reduction using only the sextupoles and octupoles that are already connected to their power supplies was also studied. For this study the sextupole strength was set to maximum and the octupole strength was varied to obtain a similar horizontal beam size. The beam at extraction is shown in Fig. 4, for an octupole strength at 92 % of the maximum strength available.

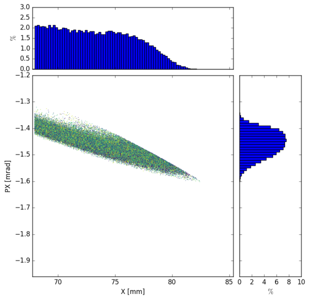


Figure 4: Optimum extracted beam at the ES entrance with the 25 octupoles presently available for use in SPS. The ES wires are at 68 mm.

In this simulation the density at the wires is reduced by 12 % compared to the nominal case with scaled optics, while the angular spread is increased by 44 %. After re-aligning the ES girder to the changed angle, this gives a 4 % loss reduction.

CONCLUSION & OUTLOOK

Two possible scenarios for loss reduction using the SPS octupoles were presented. A case that would be possible in SPS today, reducing beam loss by 4 % and one that would require some changes to the SPS multipoles for a 17 % loss reduction. These are still preliminary results, and further research is needed before pursuing tests in SPS this year. Future simulations will have to take the scattering of particles on the ES wires into account.

Next to adding this improved realism to the simulations, there are also some parameters that have not yet been varied and optimized. In particular, the extraction bump may be used to increase the distance between the circulating beam and the end of the spiral step, so that less octupole strength would be required for the same bending effect. One would then have to take care not to hit any other aperture limits in the SPS ring. Additionally, different chromaticity settings may be used to change the resonance width, and perhaps to obtain a Hardt-like condition, so that the angular spread is much reduced for all scenarios.

REFERENCES

[1] M. A. Fraser *et al.*, “SPS Slow Extraction Losses and Activation: Challenges and Possibilities for Improvement”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May 2017, paper MOPIK045, pp. 611-614.

[2] N. N. Alexeev, S. L. Bereznitsky, and A. E. Bolshakov, “Perturbation of relevant resonance for slow extraction efficiency increase”, in *Proceedings of the 1997 Particle Accelerator Conference*.

[3] K. A. Brown, V. Schoefer, and M. Tomizawa, “Improving Extraction Efficiency of Third Integer Resonant Extraction

using Higher Order Multipoles", BNL technical note, United States, Mar. 2017.

[4] L. S. Stoel *et al.*, "Phase Space Folding Studies for Beam Loss Reduction During Resonant Slow Extraction at the CERN SPS", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, paper MOPIK046, pp. 611-614.

[5] Y. Kobayashi and H. Takahashi, "Improvement of the emittance in the resonant ejection", in *Proc. VIth Int. Conf. on High Energy Accelerators*, Cambridge, Massachusetts, 1967, pp. 347–51.

[6] R. Cappi and M. Giovannozzi, "Multiturn extraction: performance analysis of old and new approaches", *Nucl. Instr. Meth. A*, vol. 519, pp. 442–452, 2004.

[7] J.P. Prieto *et al.*, "Effects of Electrostatic Septum Alignment on Particle Loss During Slow Extraction at CERN SPS", presented at the 9th Int. Particle Accelerator Conf. (IPAC'18), Vancouver, Canada, May 2018, paper TUPAF052, this conference.

[8] L.S. Stoel *et al.*, "Progress Toward a Dynamic Extraction Bump for Slow Extraction in the CERN SPS", presented at the 9th Int. Particle Accelerator Conf. (IPAC'18), Vancouver, Canada, May 2018, paper TUPAF055, this conference.