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SLOW EXTRACTION LOSS REDUCTION WITH OCTUPOLES AT THE CERN SPS

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Abstract

The powering of octupoles during third-integer resonant slow extraction has been studied and recently tested with beam at the CERN Super Proton Synchrotron (SPS) in order to increase the extraction efficiency and reduce the induced radioactivity of the extraction straight. The octupoles distort the particle trajectories in phase space in such a way that the extracted separatrix is folded, which decreases the particle density impinging the wires of the extraction septum at the expense of increasing the extracted beam emittance. During experimental SPS machine studies a reduction of over 40 % in the specific (per extracted proton) beam loss measured at the extraction septum was demonstrated. In this paper, the prerequisite studies needed to safely but efficiently deploy the new extraction scheme in a limited time-frame are described, the experimental results are presented and an outlook is given towards the next steps to bring slow extraction with octupoles into routine operation.

INTRODUCTION

The application of higher-order multipole fields to manipulate the spatial density of the beam presented to the extraction septum is one of many slow extraction beam loss reduction techniques pursued at CERN in recent years [1–3]. In the present operational scenario four extraction sextupoles (LSE) are used to drive the third-integer resonance and increase the amplitude of particles on outward spiralling separatrices, which closely resemble straight lines in phase space. In this scenario, the spatial density of the beam at the extraction septum located in Long Straight Section (LSS) 2 drops off quadratically with amplitude. When strong higher-order multipole fields are added, one can curve the phase space separatrix presented to the septum and manipulate it such that, after optimisation and at the expense of a larger extracted beam emittance, the spatial density projection of the extracted beam is peaked inside the extraction channel rather than at the wires of the electrostatic septum that shield the circulating beam from its high electric field. The lower density at the septum wires reduces the number of protons interacting with them during extraction, reducing the overall beam loss and induced radioactivation. A full discussion on the technique of applying higher-order multipoles, including both octupoles and decapoles, to third-integer slow extraction can be found in [4].

OCTUPOLES IN THE SPS

The large number of octupoles installed in the lattice of the CERN SPS make it an ideal test-bed for applying higher-order fields to slow extraction. The SPS is equipped with two octupole families (LOF and LOD) for mitigating transverse instabilities through Landau damping. The LOF magnets are installed near focusing quadrupoles where the horizontal β-function is large and typically 85 - 105 m. There are 24 LOF magnets in the machine powered by a single power converter in series and, even though 6 are cabled with an inverted polarity, there is adequate normalised strength for the scope of this study. Only the LOF family were considered because they have an order of magnitude larger normalised strength than the LOD family, which are located near defocusing quadrupoles.

PROCEDURE & MACHINE PROTECTION

As the powering of octupoles during slow extraction has potentially serious machine protection implications for the delicate wire arrays in the electrostatic septum, a detailed procedure [5] was prepared and approved to establish safe limits for the machine parameters used. The main risk was identified as accidentally trapping the beam in the machine at large amplitudes with relatively strong octupole fields, which could increase the beam density close to the electrostatic septum wires with the potential to collimate the beam directly onto them. In order to mitigate the risk, a low intensity beam of $1 - 5 \times 10^{11}$ protons was specially prepared in the CERN injectors. Conversely, concerns were also raised of accidentally increasing the extracted beam size at the septum and striking the cathode on the outside of the extraction aperture, nominally spaced at 20 mm from the wires on the grounded anode. A fortuitously-located LHC-type collimator (TCSM) in LSS5 was used to safely define and restrict the aperture to protect the cathode.

The tests with beam were split into two parts. The effective strength of the LSE and LOF circuits were first safely checked with the extraction bump in LSS2 turned off and the beam slow-extracted instead onto the TCSM aligned with the beam at the same aperture as the wires of the extraction septum. The onset of trapping could be observed and safe machine parameters identified. The second part proceeded using the pre-determined safe limits on the multipole strengths to extract the beam through LSS2 with the extraction bump on and with the TCSM retracted to shadow the cathode of the septum. The main objective of the procedure was to demonstrate a prompt extraction beam loss reduction at the electrostatic extraction septum with carefully chosen LSE and LOF strengths.

The beam tests were performed over two mornings and totalled no more than 8 h due to the reduced availability of the injector chain on those days. It was therefore absolutely

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critical to use detailed beam dynamics tracking simulations to guide the settings applied in the machine.

BEAM DYNAMICS ASPECTS

A derivation of the Kobayashi Hamiltonian including arbitrary multipoles in modern notation can be found in [4]. Assuming a single effective multipole magnet of length L with arbitrary normalised multipole components, one can express the normalised and integrated multipole strength as,

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

where the effective multipole is situated at a location in the lattice with β_x. Using non-dimensionalised polar coordinates and assuming $K_2 \neq 0$, the Hamiltonian can be written in the case of octupoles as,

$$\hat{\mathcal{H}} = \frac{\epsilon}{2}\hat{A}^2 + \frac{1}{4}\hat{A}^3\cos 3\hat{\theta} + \frac{9}{32}\kappa_3\hat{A}^4, \tag{2}$$

where the polar coordinates $(\hat{A}, \hat{\theta})$ are defined by,

$$\hat{X} = \hat{A}\cos\hat{\theta} \quad \text{and} \quad \hat{P} = \hat{A}\sin\hat{\theta}, \tag{3}$$

and X and P are the normalised phase space coordinates re-expressed in non-dimensionalised coordinates as,

$$(\hat{X}, \hat{P}) = K_2 \cdot (X, P). \tag{4}$$

The tune distance from resonance is $\epsilon = 6\pi(Q - Q_{\text{res}})$ and $\kappa_3 = K_3/K_2^2$.

The number of fixed points of the Hamiltonian motion, as well as the shape of the Hamiltonian flows, are essentially determined by the parameter κ_3, with K_2 playing the role of a scaling parameter. The number of stable points is determined by $\kappa_3\epsilon$. For non-zero κ_3 the motion is always bounded, regardless of initial conditions. The motion for $\kappa_3\epsilon > 1/8$ is uninteresting with regard to extraction. For $\kappa_3\epsilon < 1/8$ the three fixed points at larger amplitude are stable, while the three fixed points at smaller amplitude are unstable but define a separatrix on which the motion is useful for extraction as shown in Fig. 1. Particles near this separatrix can grow in amplitude and then turn around the stable fixed points before decreasing in amplitude again, allowing the extraction of a beam that is folded in phase space.

A simple tracking code was written to understand the behaviour of the extraction scheme in a simplified lattice, before detailed and more time-consuming simulations were carried out using MAD-X and the realistic SPS lattice. The separatrix can be bent downward by using positive LOF strengths, or upward with negative values. For optimal performance the LSE strength is increased and the horizontal extent of the extracted beam maintained by bending back the separatrix as far as possible without touching the wires again, and respecting the acceptance of the extraction aperture. The optimised result of the MAD-X simulation effort is shown in comparison to the reference case in Fig. 2, where the horizontal phase space is presented on the high-field side of the extraction septum at its upstream end. The LSE strength could be ramped by over a factor of 2 with the LOF circuit powered. The reduction of the spatial density of the beam at the septum wires located at $x = 68$ mm along the vertical axis is evident with very little change in the angular spread of the impacting protons. The ratio of protons lost on the septum wires to those extracted is reduced by 43 % for an effective septum thickness of 200 µm.

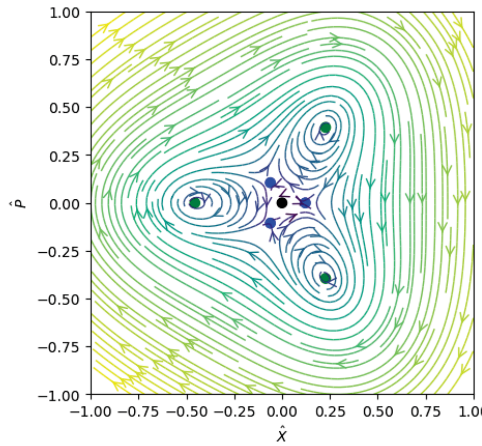

Figure 1: Hamiltonian flow in non-dimensionalised phase space for $\kappa_3 = 2$ and $\kappa_3\epsilon = -1/4$ with stable (green) and unstable (blue) fixed points.

ROTATING THE SEPARATRIX ARMS

The amplitude detuning introduced as the octupoles are powered changes the angle at which the extracted separatrix arm strikes the septum. During the first beam tests it quickly became apparent that this effect needed to be compensated due to the inhibitive beam loss in LSS2, localised mainly on the protection device located in front of the magnetic septa downstream of the electrostatic septum. The mechanical realignment of all the extraction septa in LSS2 was ruled out as prohibitively time-consuming and impractical. Instead, the phase of the resonant (sextupole) driving term was rotated by using two other independent and orthogonal groups of extraction sextupoles, which remain in the SPS for historical reasons. Rotating the phase of the resonant driving term has the effect of rotating the angle of the separatrix arm presented to the septum. The ability to rotate the presentation of the separatrix arms to the electrostatic septum allowed the machine tests to progress without realigning the extraction channel.

EXTRACTION WITH OCTUPOLES

As time was limited only a few combinations of multipole strengths, which performed well in simulation, were tested. For each setting, the resonant driving term was rotated and a scan performed in order to minimise the sum of the specific beam loss at the Beam Loss Monitors (BLMs) at the electrostatic septum. For the tested configurations with negative LOF strengths, the relative loss reduction was similar on all

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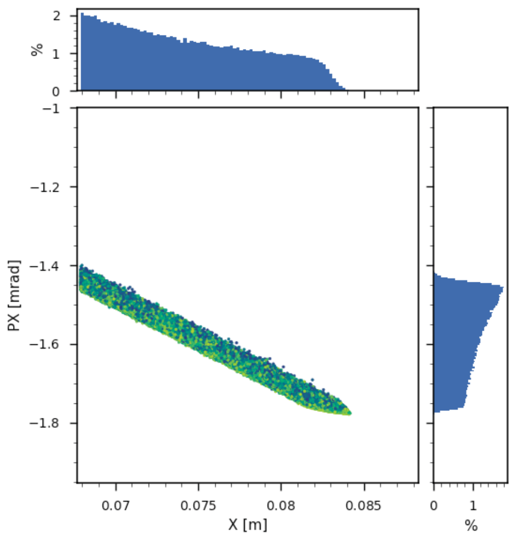
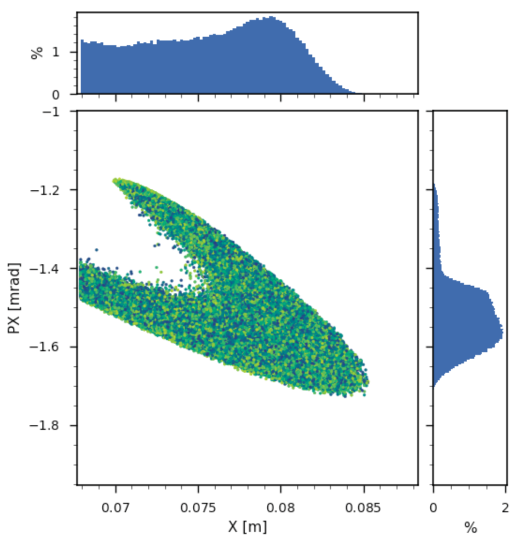


(a) Octupoles OFF and $K_{2,\mathrm{LSE}} = K_{2,\mathrm{LSE,nominal}}$ (reference).



(b) Octupoles ON and $K_{2,\mathrm{LSE}} = 2.1K_{2,\mathrm{LSE,nominal}}$.

Figure 2: Simulated extracted phase space distribution on the high-field side upstream of the extraction septum, impacting wires located on the vertical axis at $x = 68$ mm.

units of the ZS and in the best case reduced the beam loss by 42 %, equivalent to the simulation presented in Fig. 2(b). The measured beam density distribution at the entrance to the extraction septum is shown compared to the reference case in Fig. 3, where a clear reduction in the beam density close to the estimated wire location of the septum is seen along with an increased density at large amplitude inside the extraction aperture. For this case, the loss signal increased on a BLM located ~ 100 m downstream of the electrostatic septum at an enlarged aperture quadrupole where the extracted beam leaves the synchrotron. The most likely cause, supported by beam profile measurements on a grid located inside the magnetic septa, was the extracted beam scraping on the outside of the downstream end of the final magnetic septum. Due to the limited time available it was not possible to attempt to reduce the observed hotspot by steering or realigning the extraction channel.

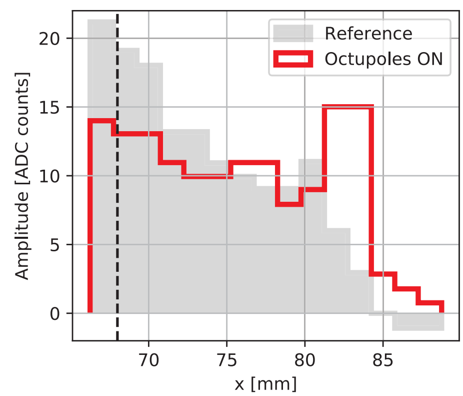


Figure 3: Extracted beam profile measured at the upstream end of the extraction septum with octupoles powered along with the estimated wire location at $x = 68$ mm.

CONCLUSION AND OUTLOOK

First tests at the SPS have successfully demonstrated the feasibility of using octupole fields to manipulate the phase space density of a slow extracted beam to reduce beam loss on the extraction septum by up to 42 %. The tests also validated the simulation tools used to design the extraction scheme. To implement the scheme in operation, further study and optimisation, e.g. steering and alignment of extraction septa in LSS2 etc., will be needed after the SPS restarts from Long Shutdown 2 in 2021 to ensure that the increased horizontal transverse emittance can be transported out of LSS2, split and transported to the production targets. In addition, the machine protection aspects of an operational implementation will need careful consideration.

Slow extraction with octupoles was also successfully tested in combination with a thin, bent crystal shadowing the wires of the extraction septum [6], demonstrating a loss reduction factor of over 3 as presented in [3]. This important result demonstrates that different techniques can be combined in the quest for the factor of 4 - 5 reduction in the specific beam loss needed to welcome the proposed Beam Dump Facility [7] at CERN, which is requesting far higher extracted proton fluxes in the future [8].

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