

BEAM DYNAMICS SIMULATIONS OF THE EFFECT OF POWER CONVERTER RIPPLE ON SLOW EXTRACTION AT THE CERN SPS

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Abstract

The SPS provides slowly extracted protons at 400 GeV/c to CERN's North Area Fixed Target experiments over spills of duration from 1-10 seconds. Low frequency ripple on the current in the main magnets originating from their power converters is a common issue that degrades the slow-extracted spill quality. In order to better understand how the stability of the power converters affects losses, beam emittance and spill quality, particle tracking simulations were carried out using MAD-X and compared to measurements, with the impact of each magnet circuit investigated systematically. The implications for the performance of the SPS slow extraction are discussed.

INTRODUCTION

The extraction scheme at the SPS for 400 GeV/c protons uses a sextupole-driven 1/3-integer resonant excitation with non-zero chromaticity. The resonant tune of the machine is swept through the tune spread of the beam by ramping the strength of the main quadrupoles. The non-zero chromaticity allows for the control of the tune spread. Particles that become unstable in the horizontal plane jump into the high field region of an electrostatic septum (ES) and are deflected into the transfer line. A small fraction of particles (~2%) inevitably hit the wires of the ES anode, which delimits the low and high field regions, making this extraction scheme inherently lossy.

The challenges posed by the experiments requesting slow-extracted beams are twofold. On the one hand, future experiments in the context of the Physics Beyond Colliders project will require an unparalleled number of 4×10^{19} POT/year. To facilitate this request an extraction loss mitigation scheme needs to be put in place to avoid increasing the radio-activation of the SPS Long Straight Section 2 (LSS2) to unacceptable levels. On the other hand, experiments require uniform spills free from rate fluctuations in order to maximise their data-taking capability. This means that any undesired time structure in the spill needs to be accounted for and corrected. On top of that, the beam is presently debunched during the extraction, but some experiments have expressed their interest in having a MHz time structure for gating and suppressing certain background processes [1]. Provision of slow-extracted beams with MHz time structure will require a modification to the present extraction scheme to suppress the coupling of the synchrotron motion to the transverse plane during the extraction and the resulting high losses.

In the present work, we present several studies investigating the effect of power converter (PC) ripple in the slow

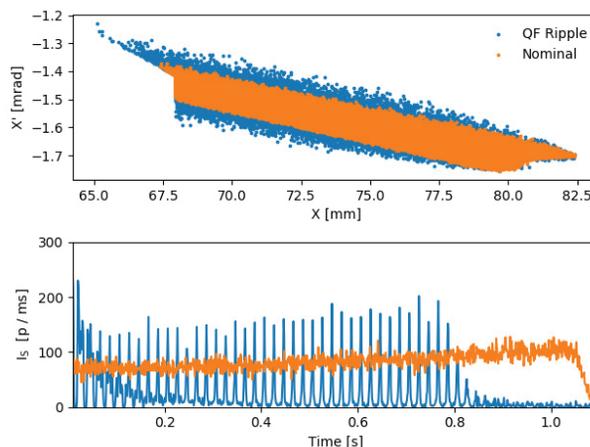


Figure 1: Comparison between extraction with nominal settings and QF ripple ($A = 2000$ ppm, $f = 50$ Hz). Top: Phase space plot of particles lost or extracted at the ES. Bottom: Spill rate.

extraction process. First, we aim to characterise the impact of PC ripple on several figures of merit, namely losses, emittance and spill quality, in order to specify the level of stability required on the PC's to meet the aforementioned requirements. Secondly, we aim at understanding the role of beam dynamics in the transfer function between power supply and spill. Finally, we investigate the suitability of the present extraction scheme with the radiofrequency (RF) system switched on to deliver slow-extracted, bunched beams.

POWER CONVERTER RIPPLE

PC ripple is a common source of low frequency noise observed on the slow-extracted spill. Imperfections in the AC to DC conversion make harmonics of the grid frequency leak into the current feeding the magnets. In the SPS, the ripple in the magnet currents is constantly monitored. It has a relative amplitude of $\sim 10^{-5}$ and a base frequency of 50 Hz. The 12-phase rectifier induces a dominant 600 Hz [2] line in the rectified current, but the impact on the magnetic field is strongly damped for frequencies higher than about 200 Hz. This is at least in part due to eddy current shielding provided by the vacuum chamber in the machine. The relationship between the noise spectra measured on the current, voltage or spill can be characterised by linear transfer functions [3].

In this work, the effect of power converter ripple on each magnet circuit was studied systematically. MAD-X simulations were carried out and a sinusoidal component in the magnet strengths introduced with the desired amplitude, frequency and phase. In each simulation, 10^5 particles were

initialised with an isotropic Gaussian distribution in normalised transverse phase space and tracked for 50,000 turns. Lost particles were post-processed to determine whether they were extracted or impinged the ES wires. In the latter case, they were automatically tagged as lost, disregarding any scattering effects. This approximation over-estimates the total loss but provides a reliable figure of merit for extraction efficiency independent of the ripple parameters.

The main effect of ripple in the quadrupole magnets is an oscillation in the tune distance from resonance

$$\delta Q = Q - Q_{\text{res}} \quad (1)$$

In the context of a chromatic 1/3-integer resonant slow extraction at SPS, the stop-band is pushed into and out of the waiting stack of particles with higher momenta. In addition, the triangular region of stability for any given particle will beat with the ripple. As a consequence, the intensity of the spill is modulated with the same frequency as the ripple applied to the magnets. Furthermore, particles that become resonant and start growing in amplitude can become stable again depending on the amplitude and frequency of the ripple. In simulation it is observed that particles coming in and out of resonance do not follow clean trajectories close to the separatrix arm. As shown in Fig. 1, the angular spread of the beam is increased at the extraction point, which increases the losses downstream on the ES wires, from both the circulating and extracted sides.

The edge-focusing of the main bends contribute to the tune of the machine and so any ripple on the PC is also seen on the spill. Ripple in the extraction sextupoles has a similar effect, which can be understood by noting that the area of the stable triangle is proportional to $\frac{\delta Q}{S}$ [4], therefore:

$$\frac{\Delta J(\Delta S)}{J} \simeq -\frac{\Delta S}{S} \quad (2)$$

where J is the stable area and S is the sextupole strength. The same reasoning applied to the quadrupoles yields

$$\frac{\Delta J(\Delta Q)}{J} = \frac{\Delta Q}{\delta Q} = \frac{\Delta Q}{Q} \left(1 + \frac{Q_{\text{res}}}{\delta Q} \right) \quad (3)$$

The main difference between the two is the presence of the factor $\frac{Q_{\text{res}}}{\delta Q}$ in the latter case. Given that $Q_{\text{res}} \gg \delta Q$, the effect of quadrupole ripple will be noticeably bigger than that of sextupole ripple.

Losses and Emittance

As shown in Fig. 2, no significant increases in losses or emittance were observed for ripple amplitudes within the range of 10 - 100 ppm. This result is in line with observation during MDs last year, when ripple of up to 100 ppm in amplitude was artificially injected in the power supply circuits and no increase in losses was detected [3]. An increase in the emittance of the extracted beam is observed in simulation only when high amplitude (10^3 - 10^4 ppm) ripple is injected in the main quadrupoles and main bends. This higher emittance is accompanied by increased losses at the

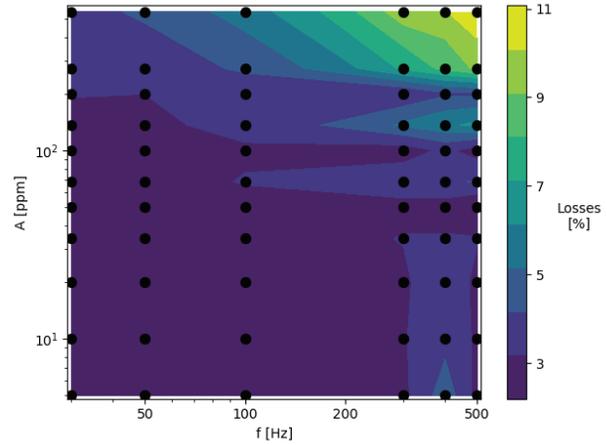


Figure 2: Losses at the ES due to ripple in the focusing quadrupoles for different amplitudes and frequencies.

ES, due to particles with high angular spread impinging on the anode wires downstream of the extraction point. No significant effect of this sort is observed when adding ripple to the extraction sextupoles, even for high amplitudes.

Overall, these results suggest that the SPS currently operates in a regime where ripple has no discernible impact on losses or emittance.

Spill Quality

The injected ripple frequency is observed as a modulation in the extracted intensity (I_S) for every magnet circuit. Multiples of the base frequency are also present for amplitudes higher than 100 ppm. Even harmonics can be explained by noticing that the intensity is a rectified signal (since it cannot take on negative values). Odd harmonics however are likely to come from transient behaviour at the beginning of the spill (see Fig. 1 (bottom)).

Spill quality, as measured by the duty factor $F = \frac{\langle I_S \rangle^2}{\langle I_S^2 \rangle}$, is reduced by PC ripple. This drop in spill quality however is mediated by frequency, with higher frequencies showing less degradation for the same amplitude. This can be understood in terms of the transfer function introduced in the next section.

Transfer function

The transfer function characterises the response of a system with input $X(t)$ and output $Y(t)$ as

$$H(i\omega) = \frac{\hat{Y}(i\omega)}{\hat{X}(i\omega)} \quad (4)$$

where \hat{X} and \hat{Y} are the Fourier transforms of the signals.

The transfer function from magnet currents to extracted spill intensity has been measured in the machine [3, 5]. To estimate the contribution to this transfer function from the dynamics of the beam, simulations were performed and the transfer function computed as,

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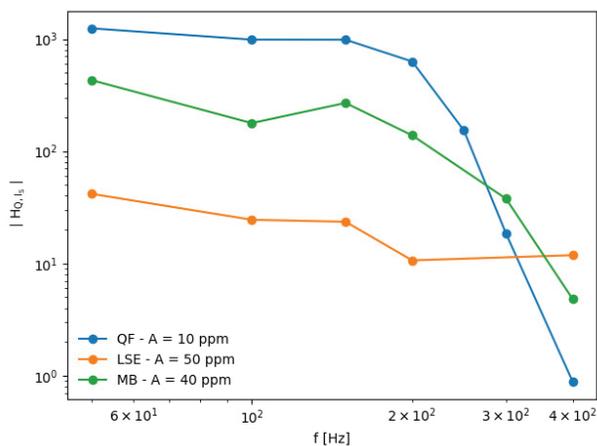


Figure 3: Transfer function for focusing quadrupoles (blue), extraction sextupoles (orange) and main bends (green).

$$H_{Q,I_S}(\omega_0) = \frac{|\text{FFT}[I_S](\omega_0)|}{A_0} \quad (5)$$

where ω_0 and A_0 are the ripple frequency and amplitude, respectively. The results shown in Fig. 3 are in good agreement with measurement and previous theoretical considerations [2]. Frequencies higher than ~ 200 Hz are strongly suppressed. This suggests that beam dynamics and not eddy currents in the shielding of the vacuum chamber account for most of the overall low-pass filter behaviour measured in [3]. Furthermore, the spill is more sensitive to PC ripple in the quadrupoles and main bends, followed by the extraction sextupoles, as expected from equations 2 and 3.

EXTRACTION WITH BUNCHED BEAM

In order to provide slow-extracted beams with a time structure on the order 10 - 100 of MHz, the RF system of the SPS must remain on to keep the beam bunched during the extraction. Due to the non-zero chromaticity used in the present extraction scheme, the resulting synchrotron motion induces a tune modulation in a way similar to that of a current ripple. The difference in this case is that the tune modulation is not coherent; the modulation frequency and phase of each particle depend on its initial location in the bunch (longitudinal action and angle).

Extraction efficiency, extracted beam emittance and spill quality were analyzed for an RF voltage of 7 MV, shown in Fig. 4. A threefold increase in losses was observed. This can be attributed to the higher angular spread of the extracted beam. As in the case of ripple, this can be explained because particles coming in and out of resonance don't follow clean trajectories along the separatrix.

Spill quality was also extremely poor, with a duty factor of $F = 0.55$, and the spill length was effectively halved. This is due to the fact that particles undergoing synchrotron motion visit the lower half of the bucket every $1/\Omega_{synch} \sim 40$ turns. As the tune sweep progresses in momentum from the lower tip to the centre of the bucket, virtually every particle

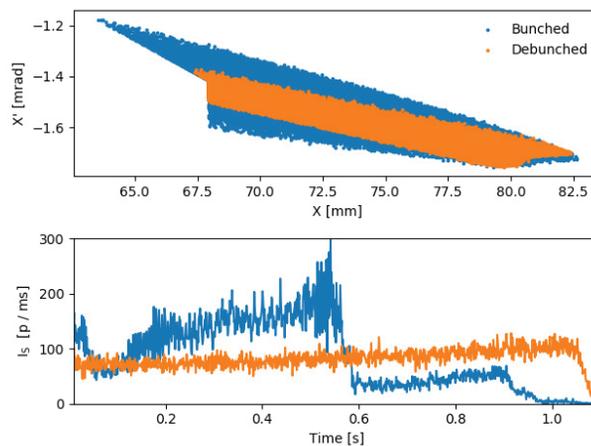


Figure 4: Comparison of debunched and bunched ($V_{RF} = 7$ MV) chromatic extraction. Top: horizontal phase space at the extraction point. Bottom: Spill rate.

will have the chance to become resonant and be extracted. Thus, when the sweep reaches half-way and matches on-momentum particles, the extracted intensity drops as all particles have been pushed through resonance by their synchrotron motion.

This result highlights the need to fundamentally rethink the extraction scheme in the face of experimental requests for beam with a MHz time structure. Other extraction schemes are a matter of ongoing study, but they have their own shortcomings. For instance, a similar scheme with near zero chromaticity has been shown to reduce the angular spread of the extracted beam, however, this comes at the expense of having to make a slower sweep, thus increasing the sensitivity to ripple. Possibilities of smoothing the spill with zero chromaticity by applying transverse and/or longitudinal RF noise are being investigated. Finally, another extraction scheme in which the strengths of the main bends and the extraction sextupoles scale with the quadrupole sweep has shown very promising preliminary results for loss mitigation and spill stability [6]. The impact of PC ripple in this case is yet to be investigated.

CONCLUSIONS

Power converter ripple during slow extraction at the CERN SPS was studied systematically for every magnet family. Losses and emittance are largely unaffected for typical values of 10-100 ppm. On the other hand, spill quality is significantly diminished. The magnet circuits accounting for most of this effect are the focusing quadrupoles. However, high frequency (≥ 200 Hz) ripple is strongly suppressed, in agreement with measurement and theory [2, 3]. Ripple-like dynamics arising from the coupling of synchrotron and betatron motion by longitudinal RF have a severe impact on losses and spill quality, highlighting the need for extraction schemes with low chromaticity when the extracted beam needs to be bunched.

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