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# RF TECHNIQUES FOR SPILL QUALITY IMPROVEMENT IN THE SPS

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*Abstract*

The CERN Super Proton Synchrotron (SPS) aims at providing stable proton spills of several seconds to the North Area (NA) fixed target experiments via third-integer resonant slow extraction. However, low-frequency power converter ripple (primarily at 50 and 100 Hz) and high-frequency structures (mainly at harmonics of the revolution frequency) modulate the extracted intensity, which can compromise the performance of the data acquisition systems of the NA experiments. In this contribution, the implementation of Radio Frequency (RF) techniques for spill quality improvement is explored, with particular focus on empty bucket channelling. It is shown that both the main RF systems (at 200 and 800 MHz) can be successfully exploited to improve the SPS slow extraction.

## INTRODUCTION

The CERN SPS provides spills of $T = 4.8$ s to the North Area via third-integer resonant slow extraction. The extraction is performed by ramping all magnets in the lattice, driving the horizontal betatron tune $Q_x$ of the beam into the resonant tune $Q_x = \frac{80}{3}$. However, undesired power converter noise at 50 and 100 Hz modulates the magnetic fields, compromising the uniformity of the extracted intensity $I(t)$. For a given spectral component $I(f_i)$, the impact on the spill can be quantified by its relative magnitude $\underline{I}(f_i)$ with respect to the total extracted intensity $I_0$:

$$\underline{I}(f_i) = \left|\frac{I(f_i)}{I_0}\right| = \left|\frac{\int_T I(t)\exp(-i2\pi f_i t)dt}{\int_T I(t)dt}\right| \tag{1}$$

For slow timescales, the spill $I$ during a chromatic extraction can be approximately related to machine parameters via,

$$I(t) = \frac{\partial n}{\partial t} = -\rho\frac{dQ_x}{dt} = -\rho[\dot{Q}_0 + \sum_i 2\pi f_i a_i \sin(2\pi f_i t + \phi_i)], \tag{2}$$

where $\rho = \frac{\partial n}{\partial Q_x}$ is the distribution of tunes in the ring, $\dot{Q}_0$ is the average tune speed across the boundary between stable and unstable betatron motion (separatrix) and $a_i$,$f_i$, $\phi_i$ are the i-th ripple amplitude, frequency and phase, respectively. The first term can be identified as the DC component $I_0$, while each oscillatory term corresponds to an AC component $I(f_i)$. Substituting $I(t)$ into Eq. 1 we obtain,

$$\underline{I}(f_i) = \frac{a_i \pi f_i}{\dot{Q}_0}, \tag{3}$$

showing that increasing $\dot{Q}_0$ will improve spill uniformity. However, if this were done naively by increasing the magnetic ramp speed, the spill would become shorter. This contribution explores two techniques to exploit this observation without compromising the spill length.

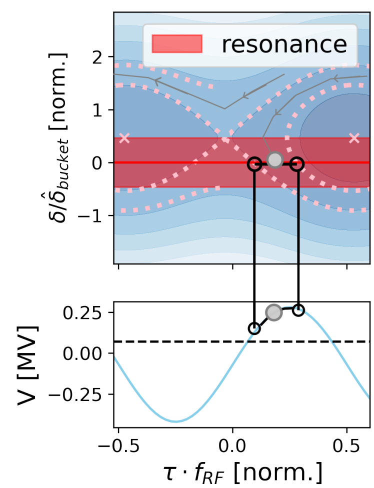


Figure 1: Illustration of the empty bucket channelling technique. Particles cross the resonance separatrix (top) while sampling the RF wave crest (bottom). The time of arrival $\tau$ and the relative momentum offset $\delta$ have been normalised by the RF frequency $f_{RF}$ and the bucket height $\hat{\delta}_{\text{bucket}}$, respectively.

## EMPTY BUCKET CHANNELLING

Empty bucket channelling was first implemented in the CERN PS in the 1980s [1] for spill quality improvement. An RF cavity of harmonic $h$ and frequency $f_{\text{RF}}$ is used to increase a particle's tune speed across the resonance boundary, as a longitudinal RF kick $V$ becomes a tune kick $\Delta Q_x$ via chromaticity $Q'$. Furthermore, one can restrict the speed-up to a localised region in momentum space, since only particles with revolution frequency $f_{\text{rev}}$ close to the RF resonance (i.e. small $|hf_{\text{rev}} - f_{\text{RF}}|$) are affected by these kicks in a coherent way. As shown in Fig. 1, one can exploit these two

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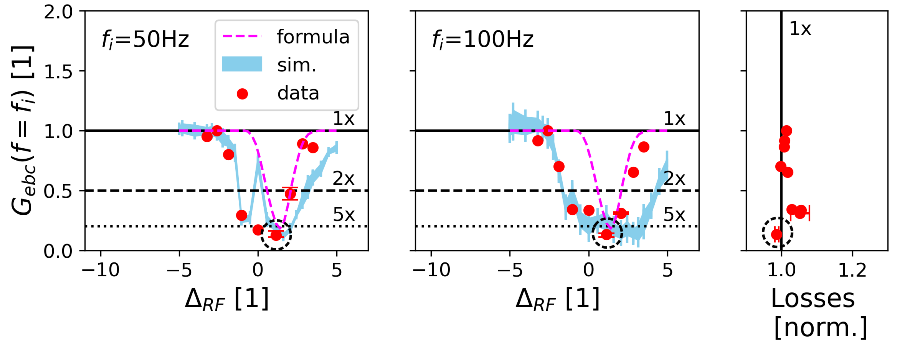
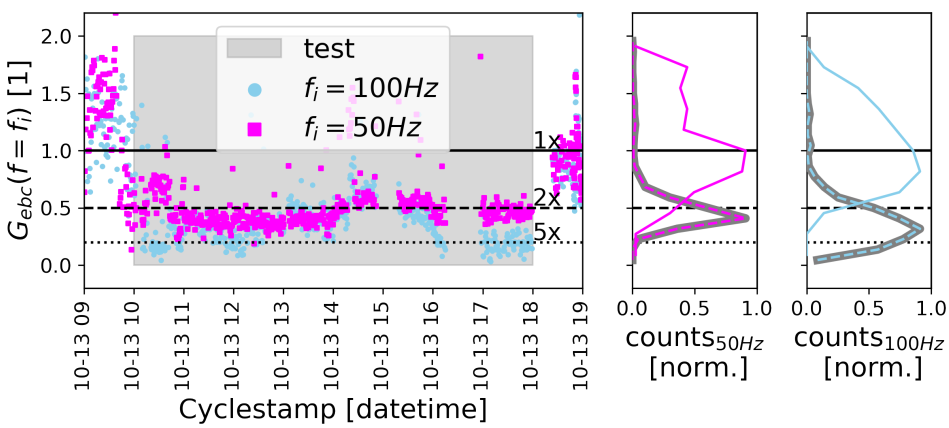



(a) Measured (data), simulated (sim.) and semi-analytical (formula) ripple magnitudes $G_{\text{ebc}}$ as a function of RF-frequency offset $\Delta_{RF}$. Beam loss data (right subplot) have been vertically aligned with their corresponding $G_{\text{ebc}}(f_i = 100\,\text{Hz})$.




(b) Cycle-by-cycle measurement of ripple magnitude $G_{\text{ebc}}$ with cycle timestamp 'month-day hour' in x-axis (left), and cumulative histograms (right). Plots show channelling at fixed optimised RF settings (grey filling) and RF off (no filling).

Figure 2: Normalised ripple magnitude $G_{\text{ebc}}$ of the 50 and 100 Hz spectral components present in the SPS spill. The horizontal black lines show the reduction factor w.r.t. RF off.

insights via the following setup: (i) the RF frequency is chosen such that an empty RF bucket is aligned with the resonant momentum; (ii) the reference momentum is gradually increased by ramping the bending magnetic field, forcing particles to pass through the channels between accelerating buckets; (iii) particles receive a net acceleration across the resonance boundary since they cluster near the RF crest (if the technique is well aligned). Overall, this procedure provides a speed-up factor $K$ ( $\dot{Q}_0 \to K\dot{Q}_0$), which suppresses a ripple $\underline{I}(f_i)$ by a factor $G_{\text{ebc}} = 1/K$ such that $\underline{I} \to G_{\text{ebc}} \cdot \underline{I}$.

### *Implementation in SPS*

Empty bucket channelling was implemented for the first time in the CERN SPS using the 800 MHz cavity system (harmonic $h = 18480$) powered at voltage $V = 0.1$ MV. During the test, the normalised RF frequency offset $\Delta_{\text{RF}} = (\delta_{\text{RF}} - \delta_{\text{res}})/\hat{\delta}_{\text{bucket}}$ was scanned from spill to spill, recording the improvement in 50 and 100 Hz ripple as shown in Fig. 2a. It can be seen that the best configuration (encircled) provides a factor ~ 5 suppression of the ripple with no increase in beam loss. Interestingly, the semi-analytical approximation from [2] is able to predict the maximum suppression accurately, but fails to capture the functional dependence on $\Delta_{\text{RF}}$. The latter is reasonably well traced by the simulation model, which generates rippled spills for each RF setting by performing 4D (horizontal-transverse + longitudinal) particle tracking with a sinusoidal perturbation of frequency $f_i = 50, 100$ Hz on the betatron tune [3].

Given the promising prospects, an operational test at full intensity was conducted, running with the best setting from the previous study. Figure 2b shows the ripple reduction before, during and after the test. By comparing the $G_{\text{ebc}}$ histograms on the right hand side subplots, one can identify a statistically significant average suppression factor of ~ 3-4, even though some scatter is present due to shot-to-shot power converter variation. The SPS experiments have expressed their interest in the improved spill and an operational implementation of empty bucket channelling might be pursued in 2023.

## PHASE-DISPLACEMENT BLOW-UP

Another strategy to increase $\dot{Q}_0$ is to enlarge the total relative momentum spread of the beam $\hat{\delta}_{\text{beam}}$. Since the total tune spread $\hat{\delta}Q = Q'\hat{\delta}_{\text{beam}}$ becomes larger, one must speed up the tune sweep to obtain the same spill length. This

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momentum blow-up is conventionally achieved via the phase jump RF gymnastics performed prior to extraction. However, such a technique is limited to providing $\hat{\delta}_{\text{beam}} \leq 2\hat{\delta}_{\text{bucket}}$ and is difficult to optimise in practice, since it inherently relies on unstable dynamics near the bucket separatrices. Here we propose an alternative that does not suffer from these limitations.

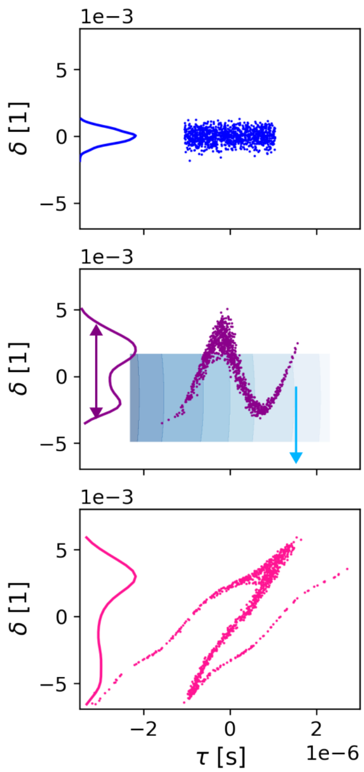


Figure 3: Simulation of phase displacement blow-up in the PS at $h = 1$. The momentum distribution is shown before (top), during (centre) and after (bottom) the manipulation, with the blue arrow and colour map (centre) showing the direction and location of the zero-area 'empty bucket', respectively.

In empty bucket channelling, the beam was swept through the bucket by ramping the magnetic field. Here the empty bucket will be swept through the beam by ramping $f_{\text{RF}}$. This manipulation, known as phase displacement, was used in the Intersecting Storage Rings (ISR) to accelerate the beam [4]. However, if the sweep is fast enough to eliminate the empty bucket area, the momentum distribution is blown-up with no mean displacement, as shown in Fig. 3. The blow-up, which was identified as a nuisance for acceleration in the ISR [5], is exploited in our application. Note that phase displacement is performed in a debunched beam and can thus be applied repeatedly on the same beam.

### *Implementation in PS*

Due the wider availability of machine time for studies, the technique was first tested as a proof-of-concept in the CERN Proton Synchrotron (PS) using the 10 MHz system operating in $h = 8$. Nevertheless, the lessons learnt remain relevant and applicable to the SPS, and the technique could be implemented using the SPS 200 MHz RF system's flexible control system. The RF program is shown in Fig. 4, where the frequency trim follows a half-sinusoidal function, sweeping twice through the circulating beam in opposite directions. This double-sweep approach improves the final distribution's symmetry.

The resulting momentum distribution is shown in Fig. 5. It can be seen that a significant momentum blow-up can be achieved, with the simulation output showing good agreement with the measurement. However, one of the main drawbacks is that the resulting distribution is far from uniform, showing a bell-like shape. It is likely that further customising the sweep function could help reshape the distribution.

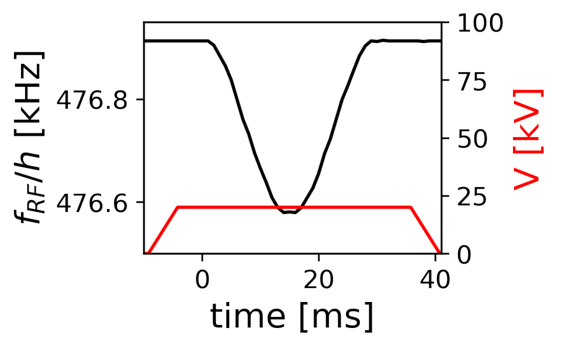


Figure 4: Phase-displacement blow-up program.

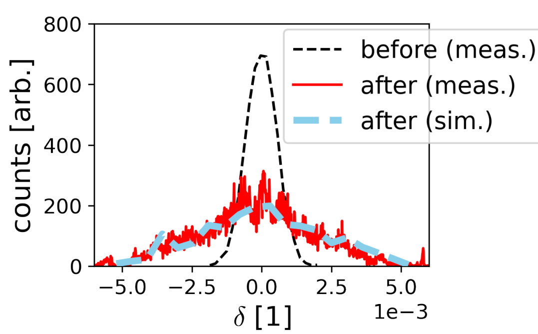


Figure 5: Beam-momentum distribution before and after phase-displacement blow-up.

## CONCLUSION

This contribution outlined two RF techniques that help improve spill quality by increasing the tune speed across the resonance. First, empty bucket channelling was successfully implemented in the SPS for the first time, demonstrating significant ripple suppression of the 50 and 100 Hz spill ripple. Secondly, a novel technique for beam momentum blow-up was presented and demonstrated in the PS, which could be ported to the SPS.

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