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IMPLEMENTATION OF RF CHANNELING AT THE CERN PS FOR SPILL QUALITY IMPROVEMENTS

P. A. Arrutia Sota *[1, 2], P. N. Burrows[2], H. Damerau[1], M.A. Fraser[1], M. Vadai[1], and F.M. Velotti[1]

[1]CERN, Geneva, Switzerland
[2]University of Oxford, Oxford, UK

Abstract

Resonant slow extraction from synchrotrons aims at providing constant intensity spills over timescales much longer than the revolution period of the machine. However, the extracted intensity is undesirably modulated by noise on the machine's power converters with a frequency range of between 50 Hz and a few kHz. The impact of power converter noise can be suppressed by exploiting a Radio Frequency (RF) technique known as empty bucket channelling, which increases the speed at which particles cross the tune resonance boundary. In this contribution the implementation of empty bucket channelling in the CERN Proton Synchrotron (PS) is described via simulation and measurement. The technique was tested with both a resonant RF cavity and an inductive Finemet® cavity, which can produce non-sinusoidal waveforms, to significantly reduce the low frequency noise observed on the extracted spill.

INTRODUCTION

The CERN PS provides spills of 300 -400 ms to the East 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 $Q_x = \frac{19}{3}$ in a controlled fashion. The tune is ramped linearly, but undesired power converter noise at low frequencies (50 ,100 ,250 Hz...) modulates this ramp. This compromises the uniformity of the extracted intensity. To first approximation, the extracted spill $I = \frac{dn}{dt}$ can be expressed as,

$$I = \frac{dn}{dt} = \rho\frac{dQ_x}{dt} = \rho[\dot{Q}_0 + \sum_i 2\pi f_i a_i \sin(2\pi f_i t + \phi_i)], \quad (1)$$

where $\rho = \frac{dn}{dQ_x}$ 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, ϕ_i are the i-th ripple amplitude, frequency and phase, respectively. The goal is to minimise the impact of the oscillatory terms in the sum above.

In order to quantify the quality of a given spill, we define the duty factor $\mathcal{F}_T$ as the ratio of DC power to total power in a time window of length T:

$$\mathcal{F}_T = \frac{\langle I\rangle_T^2}{\langle I^2\rangle_T} \leq 1,$$

which can be expressed in terms of the tune by substituting I for Eq. 1 to obtain,

$$\mathcal{F} = \frac{1}{1+x}, \; x = \frac{\frac{1}{2}\sum_i (2\pi f_i)^2 a_i^2}{\dot{Q}_0^{\,2}}.$$

We can make x small by increasing $\dot{Q}_0$. However, if this was done by increasing the magnetic ramp speed, the spill would become shorter in time. This approach is incompatible with experimental constraints. In 1981, a technique known as empty bucket channelling [1] was developed that utilises an RF cavity to provide large $\dot{Q}_0$ near the resonance, while leaving the extraction time unaffected. In this contribution we explore this manipulation via simulation and experiment.

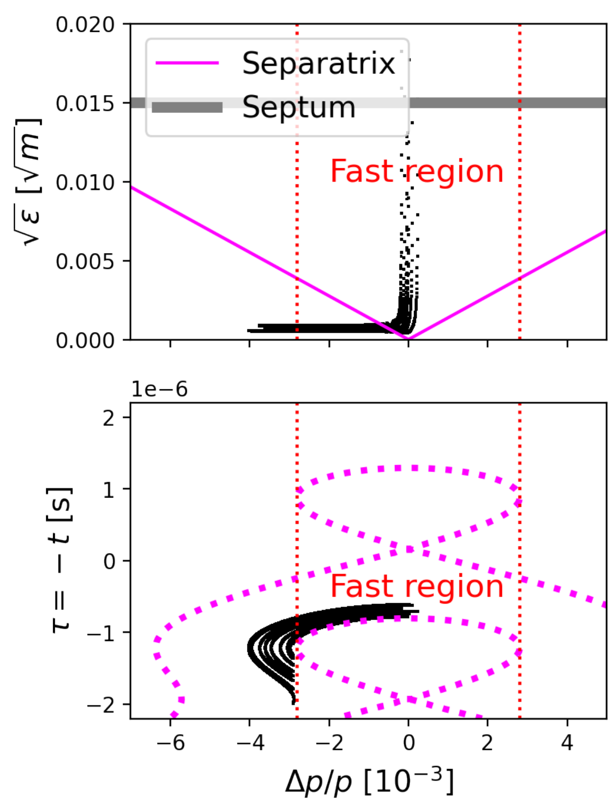

Figure 1: Illustration of the empty bucket channelling technique. Particles cross the resonance separatrix (top) while channelling between consecutive buckets (bottom).

* pablo.andreas.arrutia.sota@cern.ch

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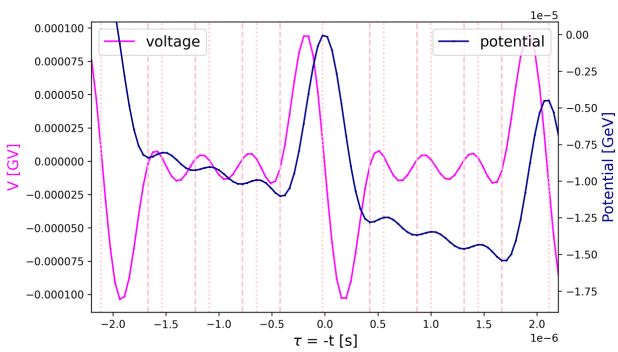
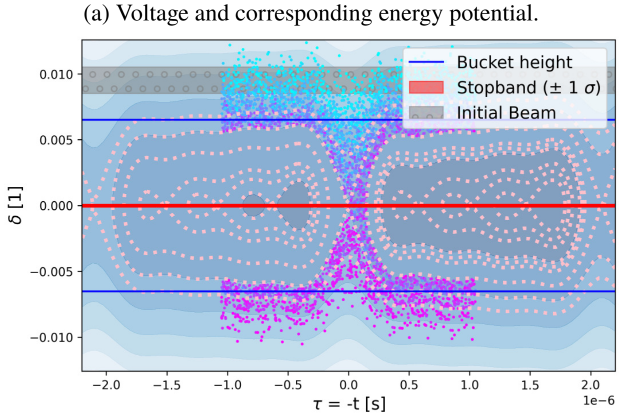
EMPTY BUCKET CHANNELLING

Empty bucket channelling creates two regions in tune space: a high $\dot{Q}_0$, low ρ region only near the resonance and a low $\dot{Q}_0$, high ρ region far from the resonance. The schematic of such a setup is shown in Fig. 1. The bulk of the beam waits in the slow region, with revolution frequencies far from the RF bucket frequency and drifting along the machine largely unperturbed. Particles are gradually pushed into the fast region, where their revolution frequency locks to the RF frequency, receiving kicks that add coherently. These particles cross the separatrix with high speed in the $\Delta p/p$ direction, which becomes high $\dot{Q}_0$ via chromaticity. Liouville's theorem provides an intuitive explanation for the speed-up: the buckets act as an obstruction and the incompressible phase space "volume" of the beam must increase in velocity to keep its density constant as it is forced through the narrow channel (like water forced through a pipe).



(a) Voltage and corresponding energy potential.



(b) Longitudinal phase space ($\tau = -t$, $\delta = \Delta p/p$) with particle tracking showing the channelling process. The blue to pink heatmap corresponds to different increasing turn number in the simulation.

Figure 2: Example of a periodic isolated sine wave pulse.

Non-Sinusoidal Waveforms

Standard RF cavities produce sinusoidal waves that generate buckets like the ones shown in Fig. 1. On the other hand, broadband inductive cavities allow to generate arbitrary voltage waveforms. The Finemet® cavity at CERN [2] can produce isolated sine pulses separated by (approximately) zero voltage regions, as shown in Fig. 2a. This can be exploited to create barrier buckets (long flat buckets) like the one shown in Fig. 2b. This extra degree of freedom provides more flexibility and is of particular interest when exploiting empty bucket channelling to deliberately bunch the extracted beam [3]. For example, one may generate channels that have the geometry of those of harmonic number $h = h_1$ (controlled by the isolated pulse-width) separated in time at the repetition number of harmonic number $h = h_2$ (with $h_2 < h_1 \in \mathbb{N}$).

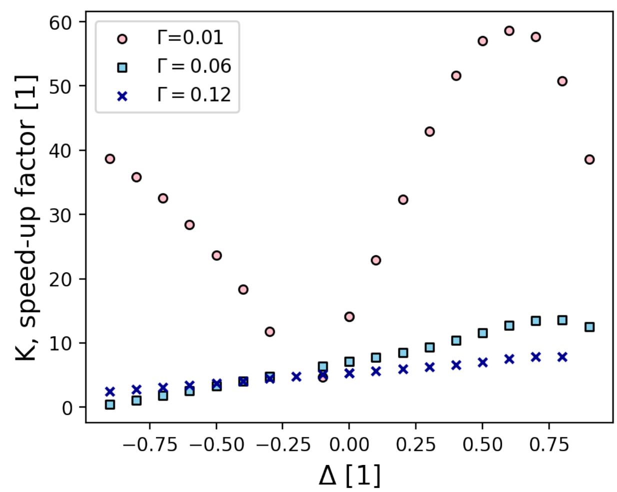


Figure 3: Simulation of average tune speed-up factor K vs. voltage $\Gamma \propto 1/V$ and normalised frequency offset Δ.

MEASUREMENTS AND SIMULATION RESULTS

Tune Speed-Up

A simple single particle tracking simulation was used to verify the speed-up effect caused by empty bucket channelling. Particles were tracked in the 4D phase space $(X, X', \tau, \Delta p/p)$, i.e. on the normalised horizontal trace space plus the longitudinal phase space. When extracted, their tune speed was recorded and an average was computed across all particles. Figure 3 shows the factor K, which measures the relative average speed-up compared to the nominal zero voltage extraction. $\Gamma = \sin\phi \propto 1/V$ is the sine of the unstable phase. Smaller Γ produces a narrower channel and thus larger K. Δ is the relative offset between the bucket centre and the resonance vertex ($\Delta p/p = 0$ in Fig. 1), normalised to the bucket height. Δ shifts the buckets in energy, changing the channel cross-section that is traversed by the particles just before extraction. It can be seen that K is a non-linear function of both Γ and Δ but, overall, large speed-ups can be consistently achieved.

Time Structure

The empty bucket channelling technique was set up with the help of the tomoscope in the ring. The tomoscope measures the one-turn time structure as a function of the cycle

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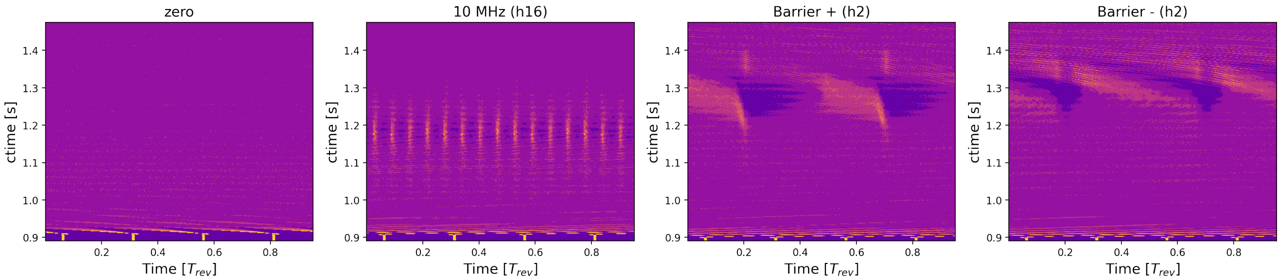
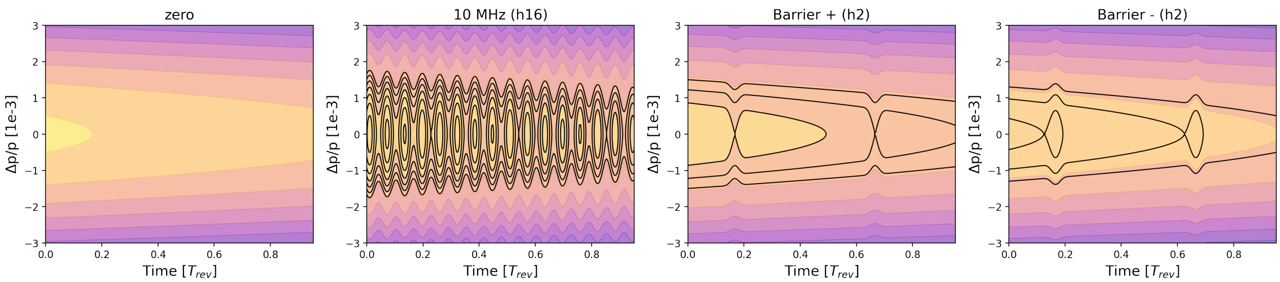


(a) Measured time profiles (tomoscope).



(b) Analytical longitudinal phase space.

Figure 4: Empty bucket channelling settings (left to right): (i) zero-voltage, (ii) main RF, $h = 16$, (iii) Finemet® , pulse-width $h = 8$, frequency $h = 2$, positive polarity and (iv) Finemet® , pulse-width $h = 8$, frequency $h = 2$, negative polarity.

time as shown in Fig. 4a. The beam can be observed (i) arriving at flattop in four buckets, (ii) debunching when the RF is turned off, (iii) rebunching later in the cycle when crossing the empty bucket channels. The underlying longitudinal phase spaces for each of the settings is shown in Fig. 4b. For the spill quality tests the main RF system and the positive Barrier for the Finemet® were used. The latter setting is often referred to as the isolated bucket configuration, which has stable motion inside the isolated sine pulse instead of between pulses. This is not ideal for speed-up since it creates wide channels in longitudinal phase space.

Spill Quality

The main RF system was set to a total voltage of 12 kV ($\Gamma = 0.04$) and the Finemet® system was set to its maximum possible voltage of 6 kV ($\Gamma = 0.07$). Then a scan in frequencies was performed, recording the spill at a 1 kHz sampling frequency for each configuration. Figure 5 shows the evolution of the duty factor $\mathcal{F}_{100m}$ along the cycle, computed by rolling a window of $T = 100$ ms across the entire spill. Both the main RF (dotted, yellow to red heatmap) and the Finemet® (solid, green to blue heatmap) produce an improvement with respect to the nominal spill (dashed black). The main RF obtained a larger improvement, with the best setting achieving an average flattop duty factor of $\langle\mathcal{F}_{100m}\rangle_{\text{flattop}} = 0.90$, as supposed to $\langle\mathcal{F}_{100m}\rangle_{\text{flattop}} = 0.70$ for the best ®Finemet setting, compared to $\langle\mathcal{F}_{100m}\rangle_{\text{flattop}} = 0.57$ for the nominal spill. We believe that larger voltages or wider pulses in the Finemet® would make both systems closer in performance. To achieve larger voltages in the Finemet® cavity, the current hardware would need to be upgraded. For both systems the largest improvements were achieved with negative frequency offsets, which correspond to $\Delta > 0$ in Fig. 3. This is consistent with the fact that $\Delta > 0$ produces larger speed-ups.

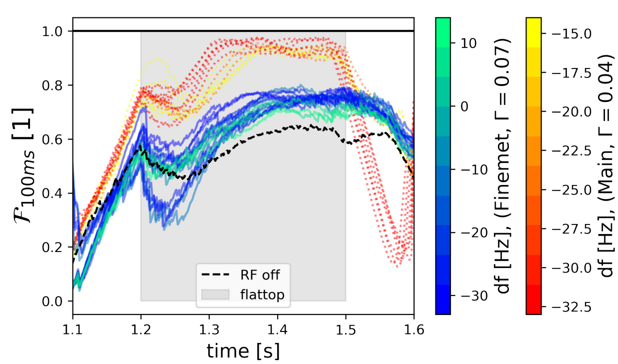


Figure 5: Measurement of evolution of $\mathcal{F}_{100ms}$ along the spill. The dotted (yellow to red heatmap) lines correspond to the main RF system, while the solid (green to blue heatmap) lines correspond to the Finemet®. The heatmaps indicate different RF frequency offsets.

CONCLUSION

Empty bucket channelling was successfully implemented in the CERN PS to improve spill quality in the low frequency range (< 1 kHz). The sinusoidal and barrier bucket settings were optimised by scanning the RF frequency to improve the spill duty factor from $\langle\mathcal{F}_{100ms}\rangle_{\text{flattop}} = 0.57$ to $\langle\mathcal{F}_{100ms}\rangle_{\text{flattop}} = 0.90$ and $\langle\mathcal{F}_{100ms}\rangle_{\text{flattop}} = 0.70$, respectively.

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