ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-TUPM094

INVESTIGATION OF MICRO SPILL IN RF KO EXTRACTION USING TAILORED EXCITATION SIGNALS*

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Abstract

Radio Frequency Knock Out (RF KO) extraction is used to extract stored particle beams from synchrotrons through transverse excitation, delivering spills of particles for experiments and medical therapy. Minimizing the fluctuations of spill intensity is vital to prevent detector pile-up and interlocks while making most efficient use of the extracted beam. To improve the spill quality, different excitation signals with characteristic frequency spectra are explored. Results of experimental studies at the Heidelberg Ion Beam Therapy Center (HIT) are presented. These demonstrate the possible improvements by tuning multi-band spectra at different harmonics. Particle tracking simulations of the slow extraction process at HIT are used to understand how different excitation signals influence the spill quality.

INTRODUCTION

Previous studies [1,2] have demonstrated, how the quality of spills from RF KO driven slow extraction can be improved by using multi-frequency excitation signals. Other studies [3, 4] showed, how synchrotron oscillations help to improve spill quality in bunched beam extraction. To expand on these findings, a dedicated experiment was carried out at HIT, where multi-frequency excitation signals were investigated in combination with bunched beam extraction.

EXPERIMENTAL STUDIES AT HIT

For the RF KO extraction, the emittance is controlled by a transverse electromagnetic RF field produced with a stripline kicker. A detailed description of the system is given in [5]. In this study, new RF signals from a recently implemented signal generator [6] are used. The device is capable of producing signals with up to three frequency bands, as shown in Fig. 1 and Table 1. Each band is generated by random binary phase-shift keying (RBPSK), a phase modulation technique in which a random binary sequence is encoded on the carrier frequency. The resulting signal is the sum of up to three sine waves with frequency $f_{\mathrm{ex},i} = Q_{\mathrm{ex},i} f_{\mathrm{rev}}$, which are inverted at random multiples of the phase flipping period $T_{\mathrm{flip}} = 1/\Delta f_{\mathrm{ex}}$. Here, $\Delta f_{\mathrm{ex}} = \Delta Q_{\mathrm{ex}} f_{\mathrm{rev}}$ is the -3 dB bandwidth and $f_{\mathrm{rev}} = 2.84$ MHz the revolution frequency. To maintain extraction under these varying excitation signals, the usage of the spill intensity feedback [5] is crucial.

* This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.
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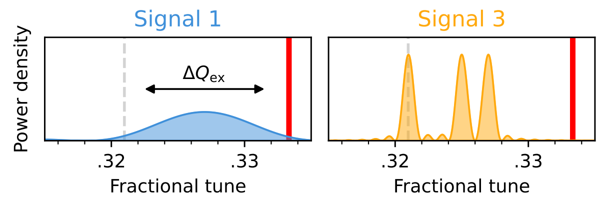

Figure 1: Spectra of excitation signals transformed to the baseband. The gray dashed line marks the machine tune $Q_x = 1.679\,02$ and the bold red line the resonance.

Table 1: Excitation Signals

No.	$Q_{\mathrm{ex},i}$	ΔQ_{ex}
1	0.327	0.009
2	0.321; 0.327; 1.327	0.009
3	0.321; 0.327; 1.325	0.001
4	2.321; 0.327; 1.325	0.001

The spills are recorded with an ionisation chamber (IC) at the end of the extraction channel. This particle detector has a time resolution of $\Delta t_{\mathrm{count}} = 50\,\mu$s. The quality of a spill is determined by the fluctuation in the number of particles N registered in each counting interval $\Delta t_{\mathrm{count}}$. To characterize a spill, two equivalent metrics are introduced; the coefficient of variation c_v and the spill duty factor F:

$$c_v = \frac{\sqrt{\mathrm{Var}\,N}}{\langle N\rangle} \qquad F = \frac{\langle N\rangle^2}{\langle N^2\rangle} = \frac{1}{1+c_v^2}.$$

Var denotes the variance and $\langle\rangle$ the mean over an evaluation interval $\Delta t_{\mathrm{evaluate}} \gg \Delta t_{\mathrm{count}}$. The achievable spill quality is limited by the Poisson statistics of independent events, for which $\mathrm{Var}\,N = \langle N\rangle$.

Spill of Multi-Band Signal Excitation

Compared to the broad single band excitation signal 1, the narrow multi-band excitation signal 3 greatly reduces the fluctuations in spill intensity (Fig. 2). The Fourier transform (Fig. 3) gives a more detailed insight into these fluctuations. For the non-optimized extraction (signal 1, coasting), noise up to the kHz region dominates the spectrum. Fluctuations below 100 Hz are suppressed by the spill intensity feedback [5]. For the optimized signal 3, the excitation bandwidth Δf_{ex} of the RBPSK band is small enough to become visible in the spill. The inversion of the excitation signal generates a sudden extraction of particles at multiples of

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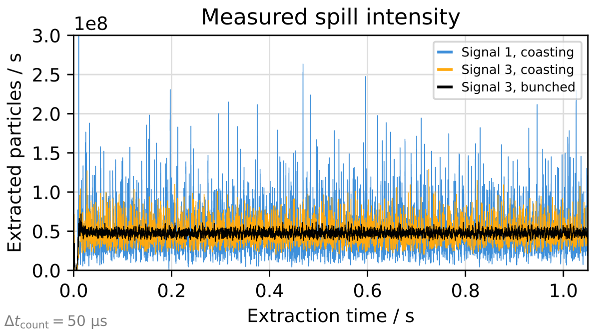

Figure 2: Spill intensity during the first second of extraction for two excitation signals, coasting and bunched beam.

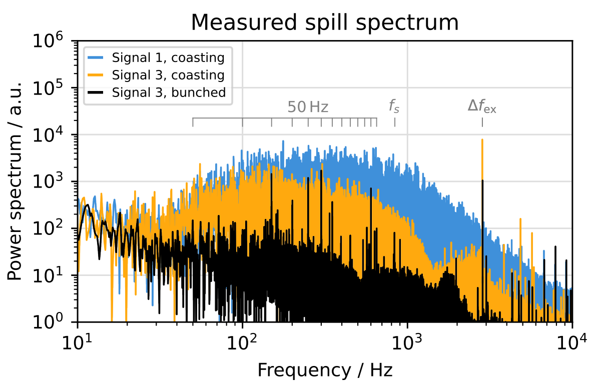

Figure 3: Frequency spectra of spill intensity for two excitation signals, coasting and bunched (factor 2.5) beam.

$T_{\mathrm{flip}} = 1/\Delta f_{\mathrm{ex}}$. At the same time, it reduces the kHz fluctuations. As a result, the spill quality is significantly improved, even for the case of coasting (unbunched) beam extraction.

Spill of Bunched Beam Extraction

Figure 4 summarizes the effect of the different excitation signals together with bunched beam extraction. A higher bunching factor corresponds to an increased gap voltage and is proportional to the frequency of synchrotron motion. In general, the multi-band excitation signals 2 and 3 deliver better spill quality than the single-band signal 1 in all cases. While for small bunching factors < 1 the bandwidth does not influence the spill quality when comparing signals 2 and 3, the smaller bandwidth is beneficial in the case of bunched beam extraction.

For all excitation signals, bunching improves the spill quality significantly compared to the coasting beam case. The synchrotron motion modulates the particle momentum and thus causes chromatic tune changes, which lead to fast oscillations of the size of the Kobayashi separatrix. As a consequence, the particles transition much faster across and remain much shorter in the vicinity of the separatrix [3]. This suppresses the influence of ripples and noise on the spill. There exists an optimal bunching factor at about 2.5 above which the synchrotron motion becomes so fast, that particles are re-captured before becoming unstable. The improvement due to bunching is also visible in Figs. 2 and 3,

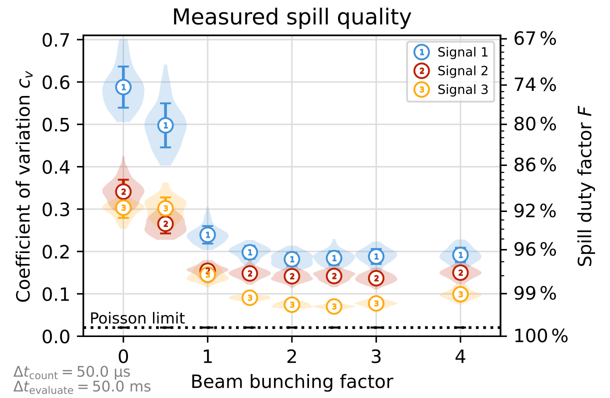

Figure 4: Spill quality for different excitation signals and bunching factors evaluated over $\Delta t_{\mathrm{evaluate}} = 50\,\mathrm{ms}$ intervals. The distribution at each setting is indicated by violin plots.

where the noise is suppressed by more than an order of magnitude, such that power supply ripples at multiples of 50 Hz become visible. The synchrotron frequency f_s modulating the separatrix size is also visible in the spill spectrum.

PARTICLE TRACKING SIMULATIONS

To improve the understanding of the RF KO extraction process, particle tracking simulations of the HIT synchrotron are carried out using the Xsuite thin lens tracking code [7]. The parameters of the simulation are matched to the experimental conditions, specifically the tune $Q_x = 1.679$, chromaticity $\xi_x = -1.589$, normalized sextupole strength $S = 27.894\,\mathrm{m}^{-1/2}$ and orbit bumps based on beam position measurements. The tracking is performed with a coasting beam of $^{12}\mathrm{C}^{6+}$ ions with specific energy $E_{\mathrm{kin}}/m = 251\,\mathrm{MeV/u}$, a momentum spread of $\delta = 10^{-3}$ and a normalized emittance of initially $\epsilon_{x,\mathrm{n}} = 1.5\,\mathrm{mm\,mrad}$.

While the experiment was performed with an extraction rate of 5×10^7 particles/s and a spill length of 5 s, the simulation uses only 10^6 particles extracted over 2 s. This is necessary due to the limited computational resources, resulting in runtimes of about 4 h per spill using GPUs on a high-performance computing cluster. The reduced statistics does not alter the general findings, but prevents absolute comparison of spill quality since the Poisson limits differ.

To model the beam excitation, a new exciter element was implemented and contributed to Xsuite. A spill intensity feedback similar to [5] controls the excitation signal amplitude, resulting in peak deflection angles of typically $|k_0 l(t)| \leq 0.2\,\mu\mathrm{rad}$. In addition, artificial power supply ripples at 100, 250 and 300 Hz [8] as well as low frequency noise below 10 kHz with a relative amplitude of 10^{-5} (peak and rms respectively) are added to the quadrupole magnets.

Comparison to Experiment

While the experimentally obtained Fourier transformation is limited to 10 kHz by the detector resolution (Fig. 3), the simulation based counterpart in Fig. 5 is not. There, not only the excitation bandwidth Δf_{ex} of the RBPSK signal, but also

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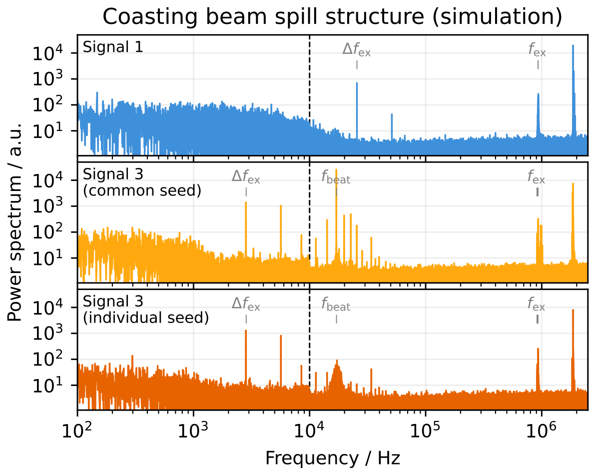

Figure 5: Frequency spectra of simulated spills for different excitation signals. Characteristic frequencies are labelled. The dashed line marks the limit of the spill detector.

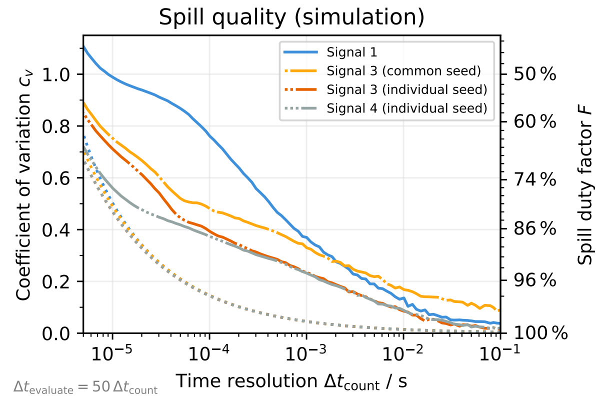

Figure 6: Spill quality as function of timescale for different excitation signals. The dotted lines indicate the Poisson limit of the simulation.

the excitation frequencies $f_{ex,i}$ and respective harmonics are imprinted onto the spill structure. Furthermore, a beating between the nearby carrier frequencies of the multi-band excitation signal 3 can be observed at $f_{beat} = \left|f_{ex,1} - f_{ex,2}\right|$ and degrades the spill quality on the respective timescale.

In the simulation, it is also possible to consider a perfect machine without power supply ripples and noise. However, the low frequency noise visible in Fig. 5 (top) remains for such cases. This means that it is in fact caused by the broadband excitation and the associated extraction mechanism itself. The reason is, that the excitation causes a periodic in- and decrease of single particle amplitude [9], which – taking the effect of all particles into account – has a similar effect as the fluctuations in separatrix size. The experiment showed, that this noise is usually dominant over the power supply ripples (see Fig. 3), so that the choice of excitation signal has a huge impact on the spill intensity fluctuations. This opens the possibility to further improve the spill quality by optimisation of the excitation waveform.

Further Optimization

The signal generator used in the experiment uses a common random seed for the RBPSK bands, such that the phase flipping occurs simultaneously for all three carrier frequencies. Figure 6 shows that the spill quality is further improved, if instead an individual random seed is used to generate the three bands of signal 3. It is important to note, that the amplitude spectrum of the excitation signal is identical in both cases; the difference lies only in the phase relation. The reason for this fundamentally different behaviour can be understood from the frequency spectrum of the spill (Fig. 5): For the case of a common random seed, the beating frequency dominates the spill spectrum. The usage of individual seeds interrupts this beating between the nearby carrier frequencies, as their phase flipping is no longer synchronized. As a result, the beating peak is smeared out and partly suppressed.

It is of course also possible to remove the beating altogether, by placing the carrier frequencies in three distinct sidebands (Signal 4 as in Table 1 and Fig. 6), which results in a further improvement of spill quality. However, the improvement happens on timescales smaller than the detector resolution of 50 µs and is thus not relevant for HIT.

CONCLUSION AND OUTLOOK

It is shown in experiment and simulation, that the excitation waveform used for RF KO slow extraction directly determines the frequency components present in the spill:

- The excitation frequencies $f_{ex,i}$ (and harmonics)
- The phase flipping frequency (bandwidth Δf_{ex}) of the RBPSK signals (and harmonics)
- The beating frequency f_{beat} of closely adjacent carrier frequencies in multi-band signals (and harmonics)
- Low frequency noise of broadband excitation signals

As a consequence, the spill quality can be improved by optimization of the excitation waveform. The presented narrow multi-band excitation signals reduce spill intensity fluctuations and thus increase spill quality for both, coasting and bunched beam extraction. The utilization of synchrotron motion in bunched beam extraction leads to an additional improvement, and the synchrotron frequency is likewise imprinted on the spill spectrum. Simulations show, that further improvement beyond the experimental results is possible even for coasting beam extraction.

The findings of this study are also important beyond medical applications, such as for example high rate physics experiments at GSI where time structures in the MHz regime are disturbing. Spill improvement by bunched beam extraction is not possible in this case, since the bunching frequency strongly dominates the spill structure. Instead, the presented methods of waveform optimization provide an opportunity to improve the spill quality also for coasting beams.

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