

# SLOW EXTRACTION SPILL CHARACTERIZATION FROM MICRO TO MILLI-SECOND SCALE

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## Abstract

This contribution deals with the topic of slow extraction spill quality characterization based on the measurements performed at GSI SIS-18. The sensitivity of the spill to power supply ripples are studied by introducing external ripples. An estimate of sources of inherent power supply ripples along with ripple magnitude are thus obtained. Spill characterization in time and frequency domain are discussed and exemplified by a typical spill and the differences from an ideal or Poisson spill. An appropriate spill characterization aims to provide a suitable abstraction for communication about the spill quality requirements between accelerator operations and users.

## INTRODUCTION

Slowly extracted beam from GSI SIS-18 is required by users for a variety of experiments. SIS-18 has two operational modes of slow extraction based on the controlled excitation of a third order resonance. The third order resonance is excited by means of sextupolar fields which couples the particle betatron amplitude  $x$  and its betatron oscillation (tune) frequency denoted by  $Q$ , enabling the particles to enter resonance as a function of their betatron amplitude [1]. In the first method which is referred to as resonant slow extraction, the betatron tune of the synchrotron is moved into the resonance by means of "fast" quadrupoles. The characteristics of tune progression curve defines the length and uniformity of extraction. The other method is the knock-out (KO) extraction method, where the machine tune is brought to a certain distance (in tune space) from resonance, following which the beam size is transversely "blown-up" by means of transverse electrical stripline exciters. The uniformity and length of extraction is governed by distance from resonance, sextupole strength and strength of KO excitation. Figure 1 shows the Steinbach diagrams for a qualitative description of both excitation methods. The horizontal axis represents the horizontal tune, and vertical axis is betatron amplitude of the particle. The slope of the curve separating the region between unstable (shaded) and stable (unshaded) region is proportional to the sextupole field gradient. An arbitrary betatron amplitude and tune distribution of stored particles is depicted by the red shaded blob.

## SPILL MEASUREMENT AND CHARACTERIZATION

The main spill characteristics are extraction efficiency, spill uniformity also referred to as macro-spill or coarse spill, and micro-spill or the fine spill structure. Extraction efficiency is the ratio of extracted particles to the particles accelerated in the synchrotron. It is determined by extraction

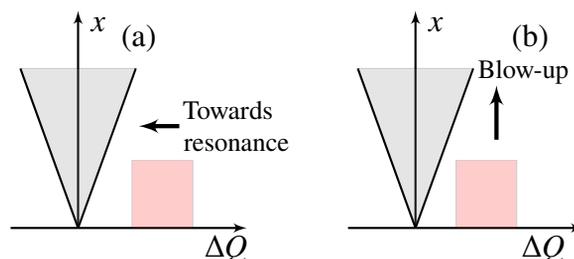


Figure 1: Steinbach diagram illustration of (a) resonant and (b) KO extraction processes.

lattice settings, e.g. extraction bump which ensures that septum is the aperture limitation, sextupole strength determines the spiral step of the resonant (unstable) particles which in turn affect the probability of particle hit on the septum wires and thus extraction efficiency. The spill uniformity or coarse spill is related to the appropriate choice of amplitude and speed of quadrupole strength scan in the resonant extraction and knock out exciter power scan for a given beam amplitude and tune distribution. The time scale  $T_c$  for calculation of coarse spill is chosen to reflect those aspects of spill. Fine spill structure describes everything below the coarse spill time scale ranging from millisecond to nanosecond scale. It is typically the most difficult to optimize, measure and characterize and will be the focus of this contribution.

## Measurement Constraints

The suitability of a certain detector for spill measurement primarily depends on the rate of particle extraction and in some cases, also the beam energy. Particle counting detectors are used for spill characterization when extraction rate is below  $10^7$  particles / s. They are practically noiseless due to direct counting of particles in their range of operation and the temporal resolution is  $\approx 10$  ns. For rates higher than that, indirect methods such Ionization Chambers (ICs) or secondary electron monitors (SEMs) are used and their typical resolution is  $\approx 10 \mu\text{s}$ . Non-invasive detectors such as Cryogenic Current Comparators (CCC) are only available for higher intensities  $> 10^9$  / s extraction rate, and have low temporal resolution ( $\approx 0.1$  ms) at highest sensitivity [2]. Further details on spill detectors can be found in [3].

## Histogram, Duty Factor and Spill spectra

It is important to define the different "time scales" relevant for the fine spill characterization. The first is the length of spill or time of extraction given by  $T_{spill}$ . Following that is the measurement resolution of the spill diagnostic system denoted here by  $T_m$ . The users are typically interested in knowing about the spill at the temporal resolution  $T_d$  given by the specifics of the physics investigations and technology

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of their experimental system. Spill characterization should ideally be performed with  $T_d$ . The simplest characterization of the spill is the histogram i.e. the plot of particle counts per time bin ( $T_m$ ) against the number of bin counts over the time  $T_{spill}$ . It shows the fluctuations in the spill in terms of the ratio between empty bins and spiky (overfilled) bins. As discussed earlier, the spill itself is a transient process, and the properties of spill are expected to change over the time  $T_{spill}$ . Therefore, many histograms by different binning times  $T < T_{spill}$  would be needed for full spill characterization. A quantitative measure of the spill is the duty factor ( $F$ ) typically calculated over the same time bin  $T_c$  as the coarse spill. It compresses the properties of the histogram, mean ( $\mu$ ) and variance ( $\sigma^2$ ) into a single quantity and helps a better visualization of spill quality over time. If  $N$  is the number of particle counts per time bin  $T_m$ , duty factor is given as the ratio of square of mean count against mean of count squares using  $M = T_c/T_m$  measurement samples,

$$F = \frac{\langle N \rangle^2}{\langle N^2 \rangle} = \frac{\mu^2}{\mu^2 + \sigma^2} \quad (1)$$

While the duty factor highlights the variation/fluctuations in the spill at time scale  $T_m$ , it does not expose the source of these variations. For understanding the source of these fluctuations, spill spectra should be calculated which show the temporal correlations and their frequencies. It also allows to ascertain, if the characterization at measurement bin  $T_m$  is suitable for the detection system with  $T_d < T_m$ . If the spectrum is clear of frequencies above a certain frequency  $f_{cut}$ , no information is lost in characterization of a spill with  $T_m = 1/f_{cut}$  even if  $T_d \ll T_m$ . Third important outcome is the hint for an appropriate time bin  $T_c$  for duty factor and coarse spill calculation.

### Poisson Limit

A charged particle source is typically modelled by a Poisson process to account for discrete nature of measured quantity (i.e. particle counts). The duty factor of a Poisson process is only a function of the mean particle count in the calculation time bin and the expression in Eq. 1 is reduced to,

$$F_{Poisson} = \frac{\langle N \rangle}{\langle N \rangle + 1} \quad (2)$$

For  $N > 10$ , Poisson distribution approaches a Gaussian distribution whose mean is equal to the variance. It should be noted, that it is also the distribution of the shot noise and is characterized by large "dc" component and a flat spectrum in frequency domain.

### Typical Spill

Figure 2 shows a typical slow extraction spill of a coasting beam from GSI SIS-18 measured with  $T_m = 10 \mu s$  and average extraction rate of  $2 \cdot 10^6$  particles / s. The rebinned spill for  $T_c = 10$  ms normalized to the number of bins ( $M$ ), which represents the coarse spill discussed earlier is

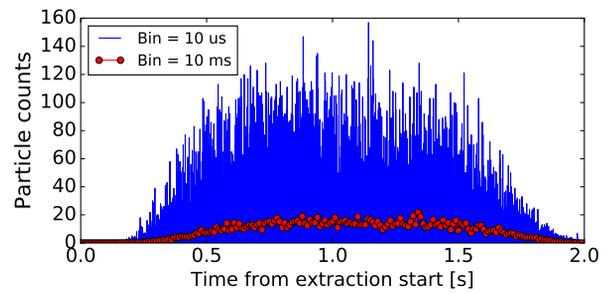


Figure 2: Example of a typical spill at SIS-18 measured with  $T_m = 10 \mu s$ . The red markers denote the mean counts on a 10 ms timescale.

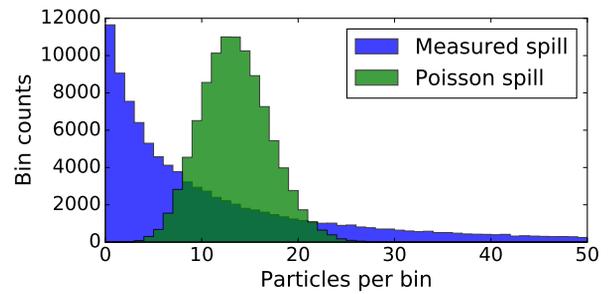


Figure 3: Histogram of a typical spill and equivalent Poisson spill.

also indicated. Figure 3 shows the histogram of this spill along with a "simulated" Poisson spill with an equivalent extraction rate. The simulation was performed by drawing particle counts from a Poisson distribution at each time bin  $T_m$ . Further, the duty factor of the spill is shown along with the Poisson limit in Fig. 4. Two observations can be made, spill quality has large variations during the spill at measurement resolution of  $T_m = 10 \mu s$ , and duty factor is  $\approx 50\%$  of the corresponding Poisson limit. Figure 5 shows the frequency spectrum of the aforementioned spill, and the spectrum is normalized to the power at the zeroth frequency bin. There are peaks at harmonics of 300 Hz and generally a higher noise floor until 5 kHz compared to the one expected from the spill governed by a Poisson process. It is evident, that the spill is modulated with both coherent and incoherent components until  $\approx 5$  kHz. The main suspects are magnet power supplies and its effect on spill modulation is well discussed in literature [1]. A theoretical estimate of the duty factor for a resonant extraction with machine tune approaching the resonance at the rate  $\dot{Q}$  due to a ripple causing a tune modulation of  $\delta Q$  at a fixed frequency  $\omega$  is given by [1],

$$F_\omega = \frac{1}{1 + \frac{(\omega \delta Q)^2}{2\dot{Q}^2}} \quad (3)$$

for  $N > 10$ . When  $\omega \delta Q = \dot{Q}$  the duty factor  $F = 0.67$ , and the spill is said to be 100% modulated, which means half of the bins are expected to be empty and others overfilled if

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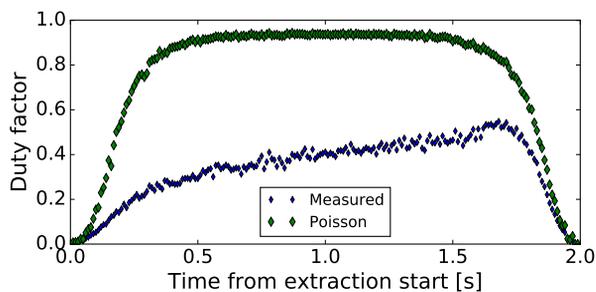


Figure 4: Duty factor of a typical spill and equivalent Poisson spill with  $T_m = 11 \mu s$  and  $T_c = 10 ms$ .

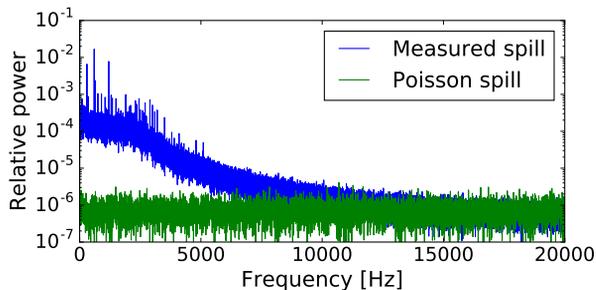


Figure 5: Spectrum of the given spill and equivalent Poisson spill over the complete spill time,  $T_{spill} = 2 s$ .

$T_m = 2\pi/\omega$ . Our example case with  $F = 0.4$  is equivalent to  $\omega\delta Q = 2\dot{Q}$ , the spill is on average  $\approx 200\%$  modulated.

## POWER SUPPLY RIPPLES AND EFFECT ON SPILL

In order to investigate the source and magnitude of the power supply ripples affecting the spill, external ripples were introduced in the dipole and quadrupole power supplies at increasing magnitudes and the ripple transfer to the spill was measured [4]. The experimental set-up for ripple transfer measurement is shown in Fig. 6. Power supplies

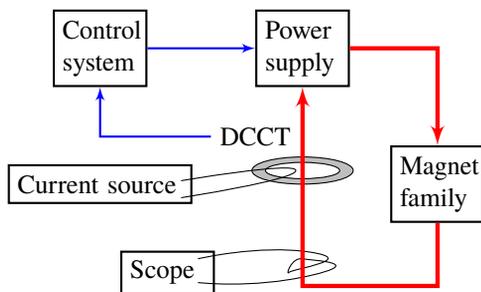


Figure 6: Experimental set-up of power supply ripple measurements.

are equipped with a regulation loop to provide stable current to the magnets. The regulation loop consists of DC current transformer (DCCT), which provides a feedback to the control regulation circuit. Currents in the range of  $\Delta I/I_{nom} = 10^{-5}$  to  $10^{-4}$  at 177 Hz were coupled through

the DCCT using an extra loop. The power supply regulation introduces a ripple with opposite phase into the current loop to compensate the introduced perturbations. An external ripple at 177 Hz of magnitude  $\Delta I/I_{nom}$  of  $2 \cdot 10^{-5}$  introduced in the quadrupole showed the same peak amplitude as the inherent ripple present at 600 Hz in the spill spectra. Therefore, it was ascertained that the maximum inherent ripple at 600 Hz is  $2 \cdot 10^{-5}$  relative to nominal current of 1.5 kA. Even though the individual ripples at power supply harmonics seem to be narrow, the "incoherent" noise floor till 5 kHz is most likely caused by them due to mixing of particle transit times. The effect of ripples introduced in the dipoles was an order of magnitude lower than quadrupoles.

## Ripple Mitigation

Mitigation of power supply ripple has been a topic of interest since the advent of slow extraction, with the early efforts focused on increasing the resonance entering velocity ( $\dot{Q}$  in Eq. 3) of the particles by means of longitudinal dynamics either by introducing noise in  $rf$  cavity [5],  $rf$  channelling [6] or beam bunching [7] at  $f_{rf}$  frequency or some combinations of them. These methods show significant improvements for detectors with  $T_d > 1/f_{rf}$  however their performance for  $T_d < 1/f_{rf}$  was either not demonstrated or shown to be ineffective. Another approach shown to be effective in simulations at medium to high frequencies is referred to as amplitude-momentum extraction in [1] was recently demonstrated in measurements at SIS-18 [8]. Basically, the spread in transit time of different particles getting into resonance at the same instant acts as a low pass filter for high frequency ripples [8,9].

## SPILL COMMUNICATION

The default slow extraction set in SIS-18 is typically optimized for transmission efficiency. However, that may not mean a Poisson spill at the required time scale. In addition to beam energy, beam intensity and spill length, a specification of desired fine-spill structure characteristics in relation to Poisson limit along with the required time scale would allow better optimization of the fine spill structure. For instance, the tracking experiments at NUSTAR [10] have expected extraction rates in the range 100 Hz to  $10^6$  Hz. While the Poisson limit can be reached for experiments with rate below  $10^4$  Hz by beam bunching, experiments with higher rate can be further deteriorated due to bunching by SIS-18 acceleration cavity.

As far as characterization of spill on the accelerator side is concerned, if the experimental system is interested in a time scale  $T_d = 10 ns$  for a resonant extraction, duty factor calculated with coasting beam with  $T_m = 10 \mu s$  is appropriate if frequencies above  $1/T_m$  are not visible as is the case for SIS-18. However, bunching introduces frequencies  $f_{rf} \approx 5 MHz$  and its harmonics, and even though the duty factor for  $T_m = 10 \mu s$  approaches Poisson limit, a suitable characterization is only possible by a system with higher time resolution such that  $T_m \approx T_d$ .

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