STUDY ON SPILL QUALITY AND TRANSIT TIMES FOR SLOW EXTRACTION FROM SIS18*

J. Yang†,1, P. Forck, R. Singh, S. Sorge
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
1 also at Goethe Universität, Frankfurt am Main, Germany

Abstract

Slowly extracted beams from a synchrotron have temporal fluctuations, the so-called spill micro structure. The reason is related to power supply ripples that act on the quadrupole magnets, leading to unintended tune fluctuations during extraction. Related simulations regarding the dependency of spill quality on the power supply ripples are executed with varying excitation levels of the sinusoidal ripples and bandwidth-limited white noise. In addition, transit time spread is simulated, a few simulation approaches are proposed, and related data analysis procedures and preliminary results are described.

INTRODUCTION

The temporal quality of slowly extracted beams from GSI heavy ion synchrotron SIS18 is crucial for fixed-target experiments. Ripples of the magnet power supplies can lead to unintended tune variations, affecting the uniformity of the extracted beam or spill. This results in a temporal variation of the spill on a micro-to-millisecond timescale [1, 2] referred to as spill micro structure. Experimental studies have shown that the spill micro structure is smoothed while extracting the lower emittance beams [3,4]. The reduction of the horizontal emittance of the circulating beam was achieved by the emittance exchange between the horizontal and vertical plane by crossing a coupling resonance [5]. Simulation investigation of power supply ripples is crucial for understanding their impact as the primary source of spill micro structures. In addition, the physics behind the improvement of spill quality can be investigated by studying the transit time spread, which refers to the time interval when the particle reaches resonance and becomes unstable until the moment when the particle is extracted by the septum [1, 6–8]. Transit time is a key quantity in the slow extraction process, a good understanding of transit time benefits the explorations of novel methods for mitigating the micro structure.

Motivated by the above considerations, simulation investigations were performed and classified into two main areas: investigating the impact of power supply ripples on the spill quality for two circulating beams with different beam sizes and the simulations of transit time and its spread. Simulation methods for estimating the transit time are proposed and described, and the results are presented.

SIMULATIONS OF TUNE RIPPLES

Spill Quality with Power Supply Ripples

Particle tracking simulations of SIS18 were executed using the Xtrack tracking code of Xsuite [9], a collection of Python packages capable of using CPUs and GPUs to simulate particle accelerators. The lattice is imported from MAD-X using cpymad [10]. Six sextupoles ($k_2 l_\mathrm{max} = 0.05\ \mathrm{m}^{-2}$) were used in the simulation. The distance between the septum and the beam for the reference orbit is 55 mm. It was modified by a closed orbit bump of 18 mm. The slow extraction is driven by linearly moving the machine tune towards the resonance during particle tracking.

Power supply ripples were introduced by sinusoidal frequency components and bandwidth-limited white noise (0–20 kHz). The sinusoidal ripples were generated based on a measured FFT spectrum, with the following frequencies and weights of 50 Hz (0.25), 100 Hz (0.3), 150 Hz (0.1), 300 Hz (0.25) and 600 Hz (0.35), and normalized to 10^{-5} of the quadrupole strength. Additionally, bandwidth-limited white noise signals were generated separately for focusing and defocusing quadrupoles.

Coasting proton beams with a kinetic energy of 300 MeV/u were tracked for 5.1×10^5 turns. The momentum spread was described by a 2σ-truncated Gaussian distribution, with the maximum deviation of 5×10^{-4}.

The particle's arrival time was estimated based on the turn numbers at which particles were lost at the septum. The spill quality was evaluated in terms of duty factor and Fourier Transformation (FFT). The full spill characterization was achieved by evaluating the weighted duty factor [11] characterizing the fluctuations normalized to the mean value for the extracted particles. Figure 1 shows the weighted duty factors of different ripple settings variation with the noise excitation levels. For simulations with each ripple setting, particles were tracked from circulating beams with two different beam sizes, depicted in the same color but different line styles: the solid line with dot markers represents the narrower circulating beam, whereas the dashed line with triangle markers represents the broader beam.

Emittance In all simulations with the same ripple setting, the larger weighted duty factor of a spill extracted from a narrower beam suggests better spill quality.

Ripples Scenarios with sinusoidal ripples of different amplitudes and bandwidth-limited white noise are examined. The resulting weighted duty factors are shown for different sinusoidal ripple amplitudes as a function of the amplitude of the white noise signal in Figure 1. It turned out that a higher

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† Jia.Yang@gsi.de

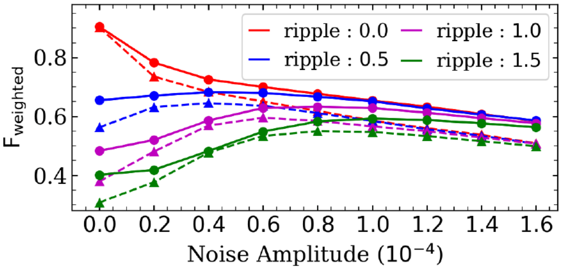

Figure 1: Simulated weighted duty factor as a function of sinusoidal ripple amplitude and bandwidth-limited white noise amplitude. The ripple amplitudes shown by the labels in the legend should be multiplied by $10^{-5}\times$ quadrupole strength. The dot markers denote the simulations for the narrower circulating beam, whereas the triangle markers represent the broader beam.

amplitude of the sinusoidal ripples always reduces the spill quality, whereas an increase of the noise amplitude leads to a maximum of the duty factor at intermediate noise amplitudes. When exceeding this noise amplitude, the spill quality is reduced. However, that effect is visible only if the sinusoidal ripples are sufficiently strong. This observation suggests that introducing noise into the power supply feedback system can have a spill-smoothing effect, especially for machines with large sinusoidal ripples, as the noise can help to reduce their impact.

Suitable Ripple Parameters

Suitable ripple parameters are determined by comparing the FFT spectra of the simulated and measured spills. To find suitable ripple parameters, simulations with more circulating particles were performed for some ripple parameter settings, showing a comparable tendency with the measurements. 10^6 particles were tracked over 1.34×10^6 turns, corresponding to 1.5 s. The ripple amplitude is 1.0×10^{-5}, and noise amplitude is 0.6×10^{-4}. Figure 2 shows the simulated and measured FFT spectra, with the amplitude normalized to the DC level. The simulated FFT is comparable to the measurements, suggesting it is a realistic parameter setting. Due to data binning, the narrow 50 Hz harmonics are smoothed.

Moreover, the diminishing of high-frequency contributions indicates a better spill quality in the second half of the spill. Meanwhile, comparing the results for different emittances, it is evident that the particles extracted from a lower emittance circulating beam have better spill quality.

TRANSIT TIME SIMULATION

Approach Description

The transit time is a vital quantity in spill micro structure mitigation. A major problem of transit time determination is to find the beginning of a particle's transit. We have defined two categories to order the methods to deal with this problem.

Category I The transit time of a single particle can be estimated by the variation of either its amplitude or its tune at the extraction plane; this is executed by recording particle amplitude and tune of every turn during the particle tracking process. There are three possibilities.

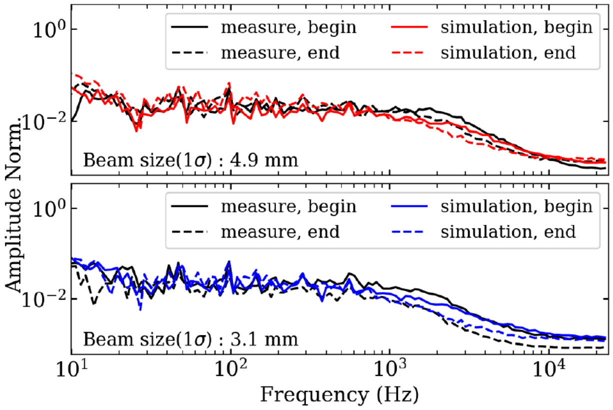

Figure 2: Comparison of simulated Fourier transformation spectrum for beams with different beam sizes to the measured results; ripple amplitude = 1.0×10^{-5}, noise amplitude = 0.6×10^{-4}; 'begin' and 'end' denotes the first and second half of the spill.

1) Tune Crossing Particle's fractional tune is determined during tracking, and the transit time starts from the turn when the tune reaches third-order resonance until the turn when the particle is extracted. Notably, in realistic simulations that consider power supply ripples, particles may reach resonance multiple times, making it challenging to determine the precise starting turn of the transit time.

2) Amplitude Variation The transit time is estimated as the interval during which the particle's amplitude continuously increases until it is extracted, but the start condition of transit time is defined using two different approaches.

I. The transit time is calculated by the turn duration of the complete amplitude increasing range;
II. Within the turn duration defined in the approach I, the transit time start from the time when the particle's amplitude is larger than the maximum amplitude it ever reached in previous turns.

The determination of the transit time of a single on-momentum particle using the above 3 methods is depicted in Fig. 3. The off-momentum particles have comparable tune and amplitude variation behaviours. The oscillation's minimum and maximum ratio depends on the particles' horizontal offset. Every 6 data points are averaged to obtain a smooth curve to determine the start point of transit time precisely.

Category II A specially designed stepped tune ramp was utilized during slow extraction; the tune is changed in multiple steps with a short step length. The tune remains constant at each step and increases instantly to the next. This sudden tune change clearly defines the starting instant of the transit of particles. The tune steps are achieved by varying the strengths of two quadrupoles installed in the lattice. A suitable step length is essential in this method. If the step

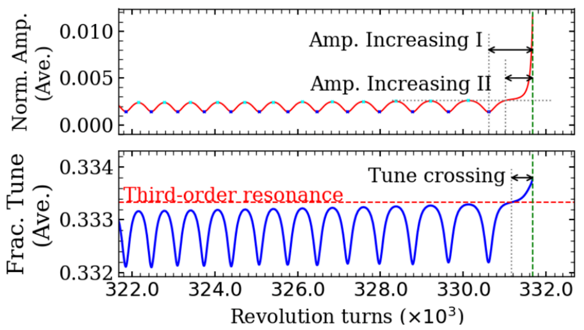

Figure 3: Transit time determination using amplitude and tune information for a single particle. The upper figure is the variation of the particle amplitudes along the time or revolution turns, while the lower figure shows the variation of the particle's fractional tune; the red dashed line is the third-order resonant border.

length is too short, the arrival time of the particles at the current tune step would be at the next step and refers to a wrong start point for transit time estimation. If the step length is too long, the transit time estimation time resolution will reduce. The spill duration in this paper is 0.5 s with a step length of 10 ms, corresponding to 5.1×10^5 and 10^4 revolution turns, respectively. A major disadvantage of the method of Category II is that the tune change must occur within a time span which is significantly shorter than the average transit time. The typical average transit time for our example is shorter than 1000 turns, shown in Figure 4. Hence, the rise time of the magnets should not exceed 100 turns in order to be at least an order of magnitude less than the transit time. It is difficult to achieve that with real magnets in experiments.

Data Analysis Procedure

In Category I simulations, particles' coordinates and tune information are computed and stored in cache memory every turn, leading to heavy computational loads, which limit achievable simulation statistics. While in category II simulations, the transit time is determined by only the particles' arrival time. In addition, in Category I simulations, outliers arise due to the possible errors in estimating the starting transit time (depicted in Fig. 3) and challenge to accurate analysis. Hence, data is refined in the following steps:

Firstly, removal of the low statistics area: The first and last 5% of the spill duration were excluded. The remaining 90% particles were divided into 6 parts according to arrival time, and the transit time and its spread in each part were evaluated to illustrate its time dependency.

Secondly, removal of the outliers: The sigma-clipping algorithm was applied, identifying and removing data points outside a certain multiple of standard deviations from the mean in an iterative process. The clipping value was set to 3.5σ, which needs about 10 effective converging iterations, and roughly 5% of total data were removed; further iterations did not affect the results. These steps were crucial in mitigating the impact of poor statistics and ensuring reliable and robust simulations.

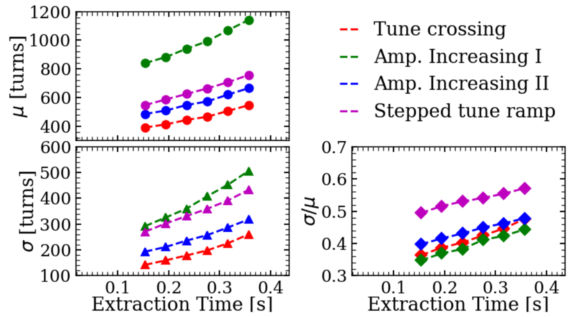

Figure 4: The statistic moments of the estimated transit time vary with the extraction time for four different approaches.

Simulation Results

The circulating beam has the same properties for all transit time spread simulations. The kinetic energy of the circulating beam is 500 MeV/u, with a maximum momentum spread of 5×10^{-4} (corresponding to 2σ). The horizontal tune change range is 4.3285 – 4.337. 10^4 particles were tracked for the simulations in category I, and 2×10^5 particles were tracked for simulation in category II. Note that power supply ripples were not applied.

The simulation results are compared in Fig. 4, which displays the mean and standard deviation of transit time in the upper and lower left figures, respectively, while the σ / μ ratio is shown in the lower right figure. The horizontal axis in each sub-figure represents the extraction time. It is evident that the average transit time has an increasing tendency for all simulation methods. This is related to the increasing distance from the separatrix to the septum, as the separatrix shrinks during extraction. Additionally, the transit time estimation from method 'Amp. Increasing I' line is expected to be larger by the half-period shown in Fig. 3. Moreover, the transit time spread (σ) and relative spread (σ / μ ratio) increase, indicating that the spill gets smoother towards the end of the extraction.

The same tendency among results from all methods suggests that transit time simulation adopting a stepped tune ramp with a step length of 10 ms is a valid approximation in transit time simulation and can be used for fast calculations.

CONCLUSIONS AND OUTLOOK

The simulations using different power supply ripple settings show that introducing white noise positively affects the spill quality for machines with large sinusoidal ripples. Besides, different transit time simulation methods were proposed and discussed, suggesting that the spill gets smoother towards the end of the extraction. Transit time simulations with introducing power supply ripples are ongoing.

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REFERENCES

[1] R. Singh, P. Forck, and S. Sorge, "Reducing fluctuations in slow-extraction beam spill using transit-time-dependent tune modulation", *Phys. Rev. Applied*, vol. 13, pp. 044076, 2020. `doi:10.1103/PhysRevApplied.13.044076`

[2] S. Sorge, P. Forck, and R. Singh, "Spill ripple mitigation by bunched beam extraction with high frequency synchrotron motion", *Phys. Rev. Accel. Beams*, vol. 26, no. 1, p. 014402, Jan. 2023. `doi:10.1103/PhysRevAccelBeams.26.014402`.

[3] J. Yang, P. Forck, T. Giacomini, P. J. Niedermayer, R. Singh, and S. Sorge, "Improvement of Spill Quality for Slowly Extracted Ions at GSI-SIS18 via Transverse Emittance Exchange", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 2093–2095. `doi:10.18429/JACoW-IPAC2022-WEPOTK021`

[4] J. Yang, P. Boutachkov, P. Forck, T. Milosic, R. Singh, and S. Sorge, "Beam Characterization of Slow Extraction Measurement at GSI-SIS18 for Transverse Emittance Exchange Experiments", in *Proc. 11th Int. Beam Instrum. Conf. (IBIC'22)*, Kraków, Poland, Sep. 2022, pp. 318–322. `doi:10.18429/JACoW-IBIC2022-TUP36`

[5] A. Franchi, E. Métral, and R. Tomás, "Emittance sharing and exchange driven by linear betatron coupling in circular accelerators", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 10, p. 064003, 2007. `doi:10.1103/PhysRevSTAB.10.064003`

[6] L. Badano *et al.*, "Proton-Ion Medical Machine Study (PIMMS), 1", CERN, Geneva, Switzerland, Rep. CERN/PS 99-010, 1999.

[7] M. Pullia, "Transit time for third order resonance extraction", Geneva CERN, Rep. CERN-PS-96-036-DI, 1996. `https://cds.cern.ch/record/313678`

[8] S. Sorge, P. Forck, and R. Singh, "Measurements and Simulations of the Spill Quality of Slowly Extracted Beams from the SIS-18 Synchrotron", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 924–926. `doi:10.18429/JACoW-IPAC2018-TUPAF081`

[9] Xsuite, `xsuite.web.cern.ch`

[10] K. Fuchsberger and Y. I. Levinsen, "PYMAD – Integration of MADX in PYTHON", in *Proc. IPAC'11*, San Sebastian, Spain, Sep. 2011, paper WEPC119, pp. 2289–2291.

[11] R. Singh, P. Boutachkov, P. Forck, S. Sorge, and H. Welker, "Slow Extraction Spill Characterization From Micro to Milli-Second Scale", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 2095–2098. `doi:10.18429/JACoW-IPAC2018-WEPAK007`