ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK021

IMPROVEMENT OF SPILL QUALITY FOR SLOWLY EXTRACTED IONS AT GSI-SIS18 VIA TRANSVERSE EMITTANCE EXCHANGE

J. Yang*[,1], P. Forck, T. Giacomini, P. Niedermayer[1], R. Singh, S. Sorge,
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[1] also at Goethe Universität, Frankfurt am Main, Germany

Abstract

The temporal beam stabilization of slowly extracted beams from the synchrotron within several seconds is crucial for fulfilling the demands of fix-target experiments. Results from previous investigations suggest that the transit time spread can be increased by reducing the beam emittance in the plane of extraction. Increased transit time spread is known to cut-off high frequency noise introduced by magnet power supplies. A pilot experiment was performed at SIS18 at GSI to introduce transverse emittance exchange, resulting in the circulating beam's smaller horizontal beam size. The improvement of the spill micro structure is reported in this contribution.

INTRODUCTION

The quality of slowly extracted beams from GSI synchrotron SIS18 within 100 µs scale is required by fixed target experiments. The basic procedure of slow extraction consists of exciting the resonance and feeding the resonance [1]. Sextupoles are used for the excitation of the third-order resonance, leading to the formation of a triangular phase space area of stable betatron motion in the extraction plane. Its boundary is defined by separatrix [2, 3].

This contribution focuses on the slow extraction in the heavy-ion synchrotron SIS18 at GSI, which has a circumference of 216.72 m and a beam rigidity up to 18 Tm. Tune swept slow extraction is regularly performed in SIS18. The resonance is fed by executing the tune sweep by increasing the strength of two fast quadrupoles. The extracted beam, referred to as a spill, has a temporal variation on time scales of micro to milli seconds which is caused by the power supply ripples. It is called in the following spill micro structure. The mitigation of the spill micro structure is of high importance for fixed target experiments at GSI.

Previous investigations suggest that the horizontal beam size (emittance) influences the spill micro structure and decreasing the horizontal emittance would result in an improvement in spill quality. Thus, methods that reduce the beam size may result in an improvement of the spill micro structure [4]. There are several possibilities of reducing emittance, 1) less number of injected turns, 2) beam cooling using the electron cooler. However, less number of injected turns reduces the intensity and electron cooling needs time. Transverse emittance exchange allows a fast emittance exchange without reduction of intensity. The disadvantage might be transmission losses in the beamline due to larger vertical beam size. Transverse emittance exchange [5] is executed by utilizing linear horizontal-vertical betatron coupling while Q_x is crossing the second integer coupling resonance in a short time. The resonance in SIS18 is defined by $Q_x = Q_y + 1$. The amount of the emittance exchange is determined by the interplane coupling strengths and the speed of moving the tune across the coupling resonance [5].

Previous observations of transverse emittance exchange at SIS18 are described in [6]. For this paper, the improvement of the spill micro structure is studied by performing slow extraction measurements with and without utilizing transverse emittance exchange and comparing the results.

EXPERIMENTS

The measurements were performed using an Ar^{18+} beam injected at $E = 8.49$ MeV/u in 11 revolutions by horizontal multi-turn injection resulting in a horizontal emittance significantly larger than the vertical emittance. Afterwards, the beam was accelerated to 300 MeV/u.

In the first step, the transverse emittance exchange was performed to reduce the horizontal beam size just before the start of the extraction process. This was done by utilizing linear horizontal-vertical betatron coupling during a tune crossing in a short time caused by residual skew quadrupolar components in the SIS18. In the second step, the slow extraction was performed. The vertical tune was kept constant at $Q_y = 3.24$ during both steps of the spill measurement.

The transverse emittance exchange was performed by moving a horizontal tune from 4.17 to 4.2995 within 40 ms resulting in horizontal emittance reduction and vertical emittance increase. The beam profiles were simultaneously measured by an Ionization Profile Monitor (IPM) installed in SIS18 [7]. The profile readout period is 10 ms. The emittances exchanged at the time of 660 ms after the begin of the cycle. As shown in Fig. 1, after emittance exchange, the horizontal beam size (1σ) shrunk from 4.90 mm to 3.10 mm while the vertical beam size (1σ) increased from 2.83 to 5.18 mm.

The slow extraction was performed by sweeping the horizontal tune in 1.5 s by changing the strength of two fast quadrupoles, which was varying as a third polynomial function of time. The set value of the tune changing range in the control panel was from 4.3275 to 4.3345. The maximum sextupole strength was $k_2 L = 0.05\ \mathrm{m}^{-2}$.

Spill Characterization

The spills were measured with a plastic scintillator (BC400) installed inside the transfer line with up to several 10^6 particles per second. The detected signal was recorded

* Jia.Yang@gsi.de

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-WEPOTK021

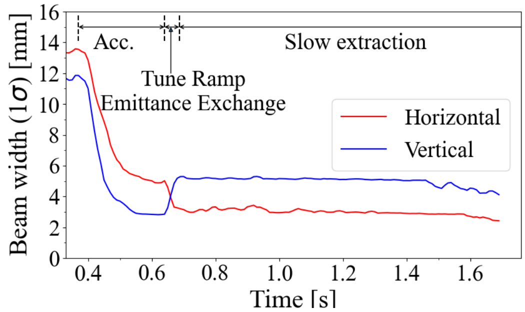

Figure 1: Beam sizes evolution at horizontal and vertical plane in one acceleration cycle when emittance exchange was executed.

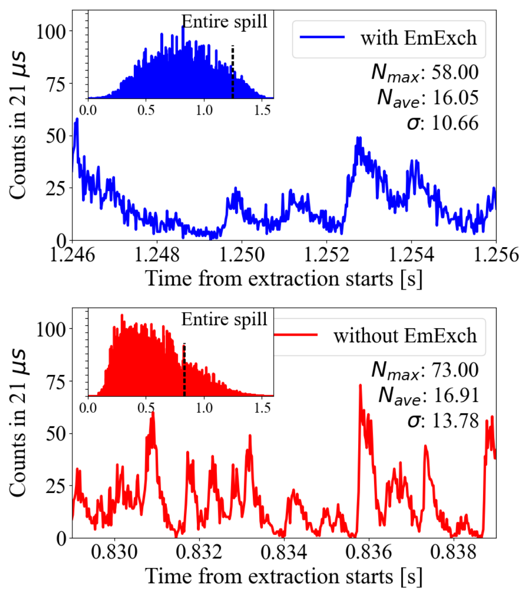

Figure 2: The micro spill structure in 10 ms for the typical spills in two cases, with and without using emittance exchange.

with a read time of 21 μs by a scaler data acquisition system. Major advantages of the scintillator are that there is no noise background, and the signal could be directly compared with simulations. Spills extracted without exchanging transverse emittances were also measured for comparison.

The spill characteristics was evaluated in time and frequency domains. Figure 2 shows an example of the micro spill structure measured for an average count rate of ≃ 0.8 μs^{-1} within a 10 ms time window. It can be seen that spill with utilizing the emittance exchange has broader spikes, with lower standard deviation with same average counts.

In time domain, quantities in terms of spill duty factor $F(t)$ with its upper Poisson limits $F_{Poisson}(t)$, and max-average ratio $R_{max-ave}(t)$ were calculated as [8]:

$$F(t) = \frac{N_{ave}(t)^2}{N_{ave}(t)^2 + N_{std}(t)^2}, \tag{1}$$

$$F_{Poisson}(t) = \frac{N_{ave}(t)}{N_{ave}(t) + 1}, \tag{2}$$

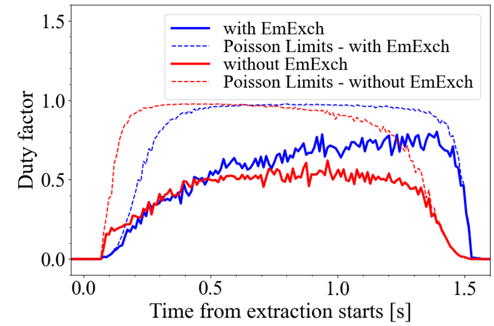

Figure 3: Duty factor and the Poisson limits as functions of time for both cases, with and without emittance exchange.

$$R_{max-ave}(t) = \frac{N_{max}(t)}{N_{ave}(t)}, \tag{3}$$

where N_{ave} is the average counts, N_{std} is the standard deviation of the counts, and N_{max} is the maximum counts in the evaluation length. The evaluation length is 10.5 ms and contains 500 data points. A higher duty factor and lower max-average ratio indicate better micro spill structure.

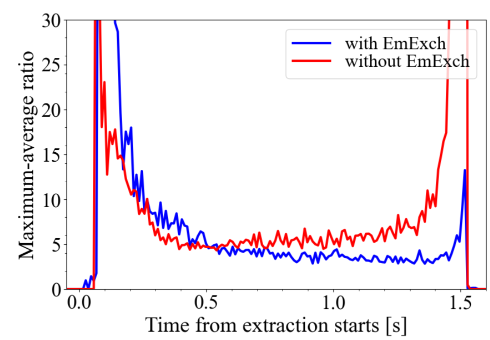

Figure 4: The maximum-average ratio as a function of time for both cases, with and without emittance exchange.

Figures 3 and 4 show the duty factor and maximum-average ratio as functions of the time in both cases: with and without introducing emittance exchange. The duty factor and max-average ratio (blue lines) show that the spill quality was improved after reducing the beam size. In addition, Fig. 3 shows that the increase of the time dependent duty factor as well as its Poisson limit achieved by the emittance exchange occur preferentially towards the end of the extraction when the tune is closer to the resonance. Tune values closer to the resonance implies a larger average and spread of the transit times for the circulating beam to the extraction channel. That agrees with the expectation that the spill quality is improved if the spread of these transit times are increased [9]. The maximum-average ratio also indicated the same results.

The entire spill is characterized by time independent quantities weighted duty factor and weighted maximum-average ratio [8], defined by

$$F_{weighted} = \frac{\sum N_{ave}(t)F(t)}{\sum N_{ave}(t)}, \tag{4}$$

$$R_{max-ave,weighted} = \frac{\sum N_{ave}(t) R_{max-ave}(t)}{\sum N_{ave}(t)}. \quad (5)$$

The weighted duty factor is increased from 0.47 to 0.64 by the emittance exchange. Correspondingly, the corresponding weighted max-average ratio is reduced from 5.70 to 4.11, which proves the improvement in spill quality.

In frequency domain, Fourier transformation (FFT) of the spills in both cases were executed using different bin widths, as shown in Fig. 5: in the upper figure, the FFT spectrum with smaller bin width Δf=1.45 Hz shows more frequency information, and the frequency spikes of 50 Hz, 100 Hz, 150 Hz, 300 Hz and 600 Hz are evident; in the lower figure, larger bin width Δf=14.53 Hz was used for better estimation of the cut-off frequency f_{cut}, which can be used for the spill quality evaluation due to the lower pass filtering effect of the slow extraction process [4]. The cut-off frequency is determined by the condition that it has the half-height of the flattop for frequencies below 500 Hz. A lower cut-off frequency indicates a larger transit time spread and better spill micro structure.

As depicted in the lower figure of Fig. 5, FFT analysis of the spills for both cases suggest an improvement in the micro structure of the spill extracted after introducing the transverse emittance exchange, with a lower estimated cut-off frequency of ≃ 1.8 kHz (in blue). The cut-off frequency obtained without introducing emittance exchange is ≃ 3.1 kHz (in red).

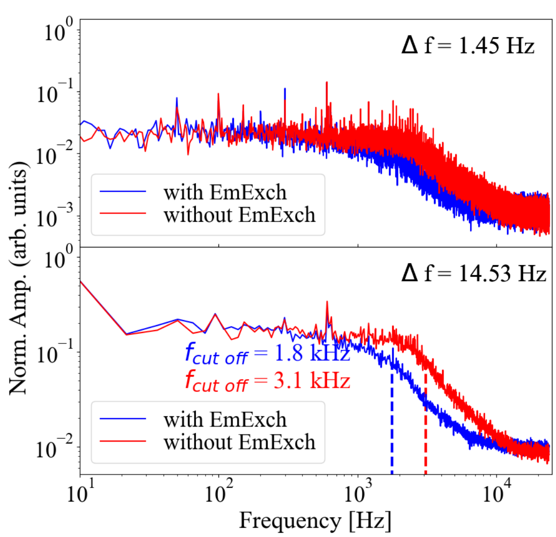

Figure 5: Fourier transformation of the spills for both cases, with and without emittance exchange.

CONCLUSION

This contribution shows the improvement in the micro spill structure of slowly extracted particle beams by reducing the horizontal beam size with transverse emittance exchange. These results will be confirmed with simulation work to obtain better operational parameters for introducing transverse emittance exchange into slow extraction in SIS18.

ACKNOWLEDGEMENTS

The authors wish to thank SIS colleagues and the beam operation team at SIS18 for their great support in carrying out the measurement. This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under GA No 101004730.

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, p. 044076, 2020. doi:10.1103/PhysRevApplied.13.044076

[2] Y. Kobayashi, "Theory of the resonanct beam ejection from synchrotrons", *Nucl. Instr. Meth.*, vol. 83, pp. 77-87, 1970. doi:10.1016/0029-554X(70)90537-9

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

[4] R. Singh, P. Forck, T. Milosic, S. Sorge, and J. Yang, "Spill Microstructure Investigations at GSI", in *ICFA Mini-Workshop on Slow Extraction*, Tokyo, Japan, Jan. 2022.

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

[6] R. Singh, P. Forck, G. Franchetti, T. Giacomini and P. Kowina, "Observation of dynamic transverse emittance exchange in SIS-18", Darmstadt : GSI Helmholtzzentrum für Schwerionenforschung, Rep. GSI Report 2015-1, p. 488. 2014. doi:10.15120/GR-2015-1-FG-SIS18-02

[7] T. Giacomini, P. Forck, J. G. De Villiers, J. Dietrich, and D. A. Liakin, "Ionization Profile Monitors - IPM @ GSI", in *Proc. DIPAC'11*, Hamburg, Germany, May 2011, paper TUPD51, pp. 419–421.

[8] 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

[9] 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