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BEAM CHARACTERIZATION OF SLOW EXTRACTION MEASUREMENT AT GSI-SIS18 FOR TRANSVERSE EMITTANCE EXCHANGE EXPERIMENTS

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Abstract

The quality of slowly, typically several seconds, extracted beams from the GSI synchrotron SIS18 is characterized with respect to the temporal spill stability, the so-called spill micro structure on the 100 µs scale. A pilot experiment was performed utilizing transverse emittance exchange to reduce the beam size in the extraction plane, and the improvement of spill micro structure was found. Important beam instrumentation comprises an Ionization Profile Monitor for beam profile measurement inside the synchrotron and a plastic scintillator at the external transfer line for ion counting with up to several 10^6 particles per second and 20 µs time slices. The performant data acquisition systems, including a scaler and a fast Time-to-Digital Converter (TDC), allow for determining the spill quality. The application of the TDC in the measurements and related MAD-X simulations are discussed.

INTRODUCTION

Temporary beam stability within 100 µs of the slowly extracted beam from the GSI SIS18 synchrotron is crucial for fixed-target experiments. Beam instrumentation plays an essential role in the slow extraction investigation into searching for better methods that could mitigate the spill micro structure.

SIS18 has a circumference of 216.72 m and a beam rigidity of up to 18 Tm. Tune-swept slow extraction is regularly performed. The third-order resonance excited by the sextupolar field is fed 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-milliseconds, which is also called spill micro structure [1]. The reason is related to the power supply ripples which act on the quadrupole magnet, leading to the unintended variation of the machine tune [2]. The spill micro structures are mitigated if the machine tune during the extraction is set closer to the resonance tune, which results in a larger spread of the transit times [3]. That can be achieved not only by proper lattice settings, e.g. lower sextupole strengths but also by reducing the beam size (emittance) in the extraction plane. The latter is applied for this study. Since the beam is injected into the synchrotron by horizontal multi-turn injection, the horizontal emittance is significantly larger than the vertical emittance. One of the possible techniques to get a smaller beam is to benefit from the transverse emittance exchange effect to reduce the beam size at the extraction plane under a suitable emittance exchange condition [4]. The emittance exchange effect has already been successfully observed at SIS18 due to residual skew quadrupole components, described in [5]. It was executed by utilizing linear horizontal-vertical betatron coupling while the horizontal tune Q_x crosses the coupling resonance in a short time. The resonance in SIS18 is defined by $Q_x = Q_y + 1$. Tune-swept slow extraction measurement with transverse emittance exchange was performed using a $E = 300$ MeV/u Ar^{18+} coasting beam [6]. By performing emittance exchange, beam size at the extraction plane was reduced, and the improvement of the spill micro structure was found.

Essential beam instrumentation was used for different purposes in the slow extraction experiment utilizing emittance exchange: firstly, an Ionization Profile Monitor (IPM) [7] was used for the observation and measurement of the beam profiles during the transverse emittance exchange; secondly, a plastic scintillator [8] was used for particle counting while performing slow extraction; moreover, data acquisition systems were used to characterize the spill signals, including a scaler [9] and a fast Time-to-Digital Converter (TDC) [10].

This contribution will present the application example of the above-mentioned beam instrumentation used in the recent slow extraction investigation utilizing transverse emittance exchange. The experiment results concerning spill characterization and related simulations are discussed in detail.

MEASUREMENTS

Beam Profile

The online observation of the transverse emittance exchange effect is essential in the investigation and ensures the beam size condition for the following slow extraction.

During the emittance exchange process, tune crossing was executed by moving the horizontal tune from 4.17 to 4.2995 within 40 ms; meanwhile, the vertical tune was kept constant at 3.24. The resultant horizontal emittance reduction and vertical emittance increase were observed by the IPM [7], which is installed inside the SIS18 synchrotron ring for beam profile measurement. The profile readout period of the IPM is 10 ms. The signals from the detector within 50 µs were integrated and formed one profile data. By calculating the widths of beam profiles, beam size evolution along with the time in one acceleration cycle was obtained. The emittance exchange effect was evidently demonstrated in Fig. 1. It

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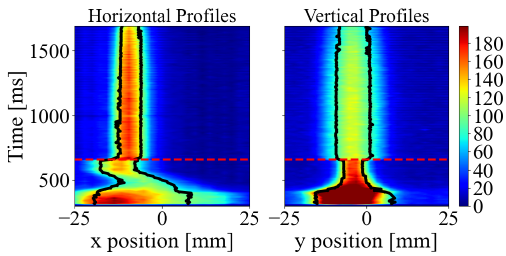

Figure 1: Beam size evolution at horizontal and vertical plane in one acceleration cycle when emittance exchange was executed. The black lines represent the standard deviation of the beam profiles with respect to the beam centers.

could be estimated that by utilizing transverse emittance exchange, the horizontal beam size (1σ) shrunk approximately from 4.9 mm to 3.1 mm, while the vertical beam size (1σ) increased approximately from 2.8 to 5.2 mm. The estimated horizontal RMS emittance reduced from 1.9 mm·mrad to 0.75 mm·mrad, while the vertical emittance increased from 1.04 mm·mrad to 3.37 mm·mrad. In addition, the time of the emittance exchange was around 660 ms (marked as a red dashed line) after the start of the acceleration cycle.

Spill Measurement

Detector and DAQs The choice of detectors to be used in the spill measurement depends on particle extraction rate and beam energy [1]. In this measurement, the extracted particles were counted by a plastic scintillator inside the transfer line with an extraction rate of up to several 10^6 particles per second [8]. The scintillator is made of BC400, with a square area of 75×75 mm^2 and a thickness of 1 mm. The advantages of the plastic scintillator are that single particle counting can be achieved, and there is no noise in the detected signals; therefore, the signal could be directly compared with simulations [11]. Particle signals were discriminated by the 300 MHz discriminator that connected to the scintillator [11].

There are two alternative data acquisition electronics systems to characterize the data. The counts from the discriminator were read out by either a scaler counting system with a minimum readout time of 10 µs [9] or TDC with the RMS time resolution of 35 ps per input channel [10]. Besides the information that the scaler counting system can provide, the TDC provides high-resolution time structure information, including the particles' arrival time with respect to the ring RF cavity frequency and particle interval distribution with respect to the subsequent particle. This information can be observed in an online display tool for operation and measurement, and can also be reconstructed from the recorded binary data using a TDC exporter with user-defined settings in offline data analysis [10].

Spill Time Structure from TDC In order to demonstrate the data information which could only be provided by the TDC, an example of a bunched beam slow extraction is given below. Figure 2 shows the particle interval distribution (a) and particle arrival distribution with respect to the ring RF cavity frequency (b) of the same spill. In this case, the displayed time structure was limited within the user-defined particle intervals range of 2 µs. Both subfigures' horizontal and vertical bin sizes are 1 ns and 0.05 s. In both subfigures, projections of 2-dimensional data were depicted in the left and upper side plots. In subfigure (a), the horizontal axis is the particle intervals, while in subfigure (b), it is the particle arrival time with respect to the ring RF cavity frequency; the vertical axes in both subfigures are the extraction time. The left projections in both subfigures show the total particle counts in a user-defined bin length along with the extraction time. Moreover, the top projections show the total distributions of particle arrival time with respect to the subsequent particle (a) or ring RF cavity frequency over the full extraction time (b).

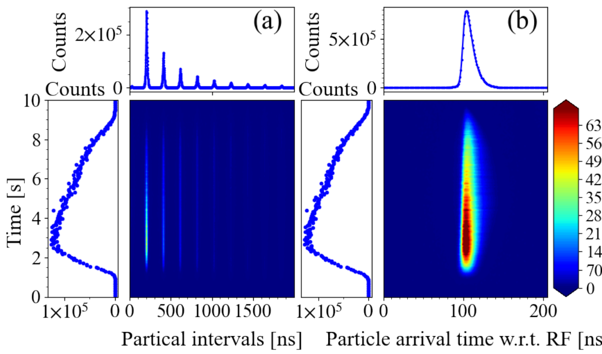

Figure 2: Particle interval distribution and particle arrival distribution of spills extracted in bunched beam slow extraction (RF voltage = 505 V).

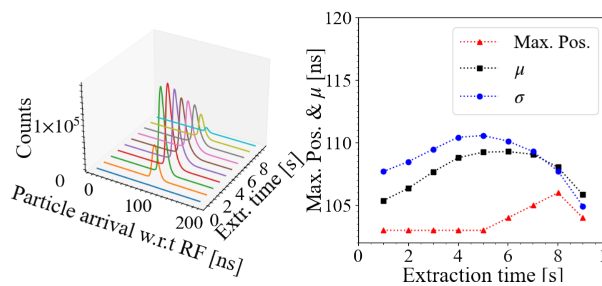

Figure 3: Time structures of spill slices in a bunched beam slow extraction (RF voltage = 505 V), obtained from TDC.

The time structures of the spills in different time slices during the extraction were also evaluated. The 3-dimensional plot of the particle arrival distributions of the same spill in 10 different time slices is shown in left subfigure of Fig. 3, while the right subfigure depicts the position of maximum counts, mean value and standard deviation of the corresponding distributions; for different spill slices, the position of the maximum, the center and the width of the particle arrival time with respect to the ring RF cavity frequency vary along the extraction time. The same evaluations were executed for the spills extracted with different RF voltages. Figure 4

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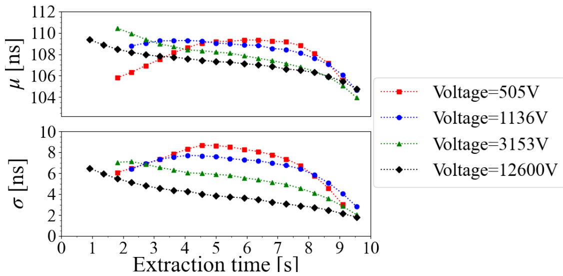

Figure 4: Comparison of the statistical moments of spill slices in bunched beam slow extractions with different RF voltages.

demonstrates the mean values and standard deviations of the particle arrival distributions of the spill slices from bunched beam slow extractions using different RF voltages: 505, 1136, 3153 and 12600 V. The time structures of the spills extracted with different RF voltages have different variation behaviors during extraction.

SPILL CHARACTERIZATION

The performant data acquisition system and data analysis tools offer evaluation for both the time and frequency domain. Details of spill characterization can be found in [1], definitions of time-dependent quantities such as standard deviation, duty factor, and maximum-average ratio were described. A higher duty factor and lower max-average ratio indicate better micro spill structure. The quality of the entire spill is characterized by weighted duty factors and weighted maximum-average ratios [12]. In this measurement, spill data was recorded using both data acquisition systems discussed in the previous section. Data obtained by the scaler system with the readout time of 21 µs was evaluated, and depicted in [6]. The statistical moments of every 500 data points were evaluated and formed one evaluation interval, equivalent to 10.5 ms in time. The improvement of the spill quality was found by using transverse emittance exchange.

TDC data The TDC system provides more information. As shown in Fig. 5 for the coasting beam slow extraction, particle interval distribution evolution of the spills extracted with (a) and without (b) utilizing emittance exchange were measured by using the TDC application. The horizontal and vertical bin sizes for both cases are 5 ns and 21 µs. Particle interval distributions in different time slices were evaluated as well, as shown in Fig. 6. The corresponding times were marked out in Fig. 5 with white dashed lines.

Spill quality characterization in terms of duty factor and spill particle interval distribution was executed. The TDC data was converted with a readout time of 21 µs for duty factor evaluation, the same as the scaler system settings of this measurement. The evaluation interval is 31.5 ms. Figure 7 depicts the time-dependent duty factor evaluations, which shows better spill micro structures in the second half of the spill extracted with emittance exchange. Weighted duty factors were evaluated to characterize the quality of the

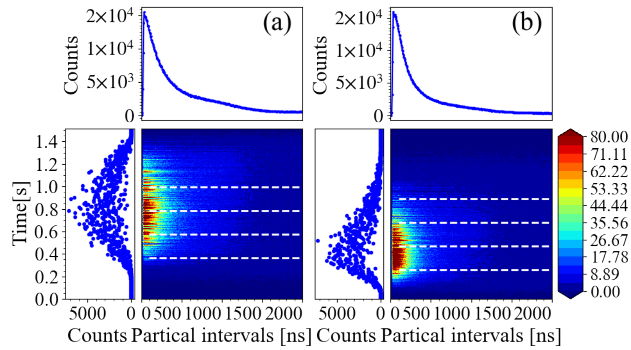

Figure 5: Particle interval distributions of spills extracted with (a) and without (b) transverse emittance exchange.

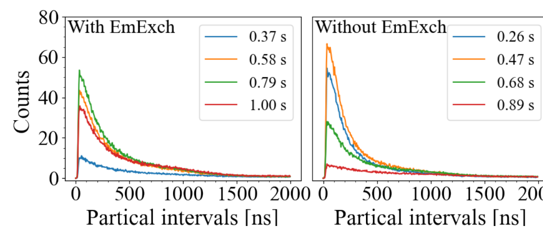

Figure 6: Particle interval distributions in different time slices of spills extracted with and without transverse emittance exchange.

entire spills for both cases. It increased from 0.49 to 0.64 after introducing the transverse emittance exchange.

The particle interval distributions in a selected extraction time window of 0.315 s duration in a high count rate region were evaluated and compared to their corresponding hypothetical Poisson distributions (dashed lines) calculated from the average count rate in the same time window length, shown in Fig. 8. The vertical axis is the counts normalized by the total spill counts in the selected duration; the mean particle intervals of the Poisson distributions for both cases were marked with corresponding colors. As depicted in the figure, a smaller distance between the particle interval distribution and its corresponding Poisson distribution suggests a smoother spill. The differences between measured particle interval distributions and corresponding Poisson distributions are consistent with the distances between the time-dependent duty factor evaluation results and corresponding Poisson distribution limits (shown in Fig. 7).

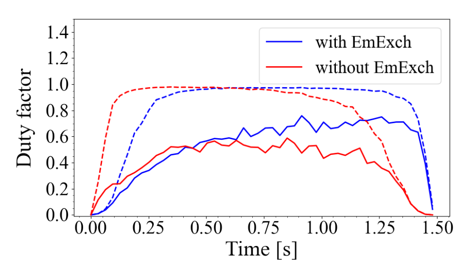

Figure 7: Comparison of measured time-dependent duty factors with corresponding Poisson limits (dashed lines) of spills obtained with and without emittance exchange.

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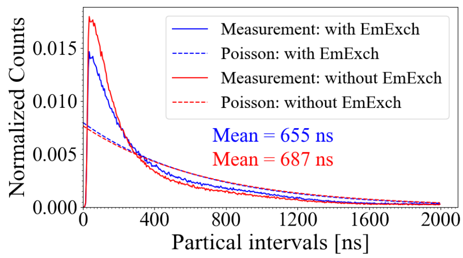

Figure 8: Comparison of measured particle interval distributions of spills in a selected extraction duration with corresponding hypothetical Poisson distributions obtained with and without emittance exchange.

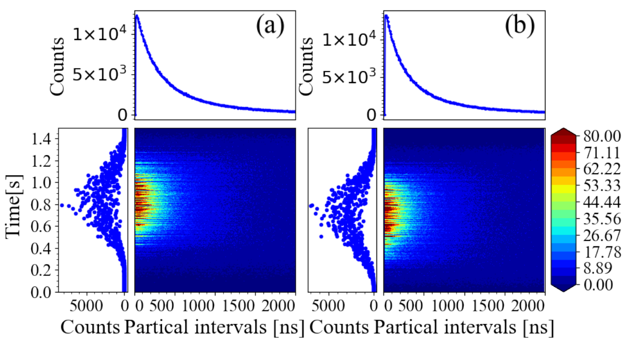

Figure 9: Simulated particle interval distributions of spills extracted with (a, beam size = 3.1 mm) and without (b, beam size = 4.9 mm) emittance exchange.

SIMULATION

The validity of the method for spill quality improvement by reducing the beam size on the extraction plane was verified by particle tracking simulations using the thin-lens tracking module in MAD-X [13] within the Python environment [14]. 1.2×10^6 particles with the kinetic energy of 300 MeV/u were tracked over 1354071 revolution turns for a 1.5 s extraction time. The momentum spread of the beam was set as 5×10^{-4} as the maximum length for Gaussian distribution truncated at $\pm 2\sigma$ [3]. Power supply ripples were introduced to quadrupoles as sine waves consisting of a few frequency components (50, 100,150, 300 and 600 Hz) with different ratios: 0.25, 0.3, 0.2, 0.3, 0.7; the amplitude of the ripples was normalized to 0.35×10^{-5}. A bandwidth (0-20 kHz) limited white noise signal was applied. The parameters of the power supply ripples were adjusted to adapt to the measurement. Simulations for different horizontal beam sizes were executed with the same power supply ripples input, but the tune ramps were modified.

The particle interval distributions were constructed with the simulated particle tracking data, shown in Fig. 9. Particle intervals below 20 ns are ignored, corresponding to the dead time of the scintillator electronics. The comparison of the particle interval distributions in a selected extraction duration within a high count rate region with corresponding hypothetical Poisson distribution was shown in Fig. 10, the tendency of which is consistent with the measurement

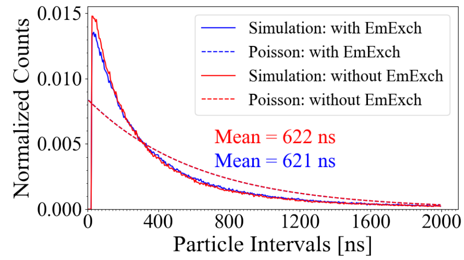

Figure 10: Comparison of simulated particle interval distributions of spills in a selected extraction duration with corresponding hypothetical Poisson distributions obtained with and without emittance exchange.

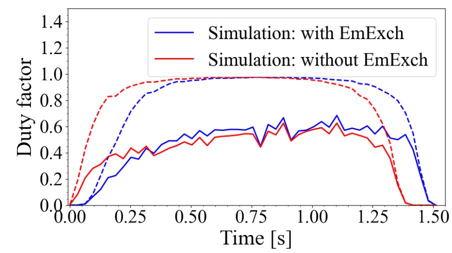

Figure 11: Comparison of simulated time-dependent duty factors with corresponding Poisson limits (dashed lines) of spills extracted with and without emittance exchange.

results shown in Fig. 8. Figure 11 shows the simulated time-dependent duty factor with an evaluation interval of 31.5 ms. The weighted duty factor of the spill extracted from the larger beam (0.51) is lower than it (0.56) from the smaller beam. Characterization of the simulated spills agrees with the measurement that a spill extracted from a horizontally narrower beam has a better micro spill structure.

CONCLUSION

This contribution presented the application of the beam instrumentation in the slow extraction measurement via transverse emittance exchange performed at SIS18. The beam instrumentation consists of Ionization Profile Monitor, Scintillator, and two data acquisition systems (scaler, fast Time-Digital-Converter) were used in the measurement. Analysis of the data acquired from TDC was discussed. Particle tracking simulations were performed to reproduce the measurement results obtained from TDC, and the TDC-like data were achieved in the simulation. Both experimental results and simulations agree with the fact that a horizontally narrow beam leads to a better spill micro structure.

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REFERENCES

[1] 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

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

[3] 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

[4] 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

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

[6] 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

[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] P. Forck, "Lecture Notes on Beam Instrumentation and Diagnostics", in *Joint University Accelerator School*, 2021, pp. 31–35.

[9] T. Hoffmann, P. Forck, D. A. Liakin, "New Spill Structure Analysis Tools for the VME Based Data Acquisition System ABLASS at GSI", *AIP Conf. Proc.*, vol. 868, p. 343, 2006. doi:10.1063/1.2401422

[10] T. Milosic, P. Forck, and R. Singh, "Sub-ns Single-Particle Spill Characterization for Slow Extraction", in *Proc. IBIC'21*, Pohang, Rep. of Korea, May 2021, pp. 438–442. doi:10.18429/JACoW-IBIC2021-WEPP28

[11] P. Forck *et al.*, "Measuement of the spill structure on a wide time range at GSI", in *Proc. ARIES Slow Extraction Workshop 2017*, CERN, Geneva, Switzerland, Nov. 2017.

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

[13] W. Herr and F. Schmidt, "A MAD-X Primer", CERN, Geneva, Switzerland, Rep. CERN-AB-2004-027-ABP, 2004.

[14] 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.