ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPR61

MEASUREMENTS OF THE TIME-STRUCTURE OF THE CURRENT TO A SINGLE INJECTION KICKER MODULE AND SIMULATION OF ITS EFFECT ON THE TRANSVERSE BEAM DYNAMICS IN THE SIS100 SYNCHROTRON

M. Kirk[1], I. Petzenhauser[1], M. Osemann[2], D. Ondreka[1], P. Spiller[1]
[1]GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[2]RI Research Instruments GmbH, Dortmund, Germany

Abstract

Distortions in the SIS100 injection kicker's pulse timeform gives rise to beam emittance increase in the horizontal plane. Particle tracking simulations of the primary beam were carried out to try to predict the emittance at the end of the injection process for the modes of operation for antiproton ($\bar{p}$) and Radioactive Ion Beam (RIB) production. The RIB cycle's beam grew to just beyond the acceptance of the slow extraction separatrix at 27 Tm. During $\bar{p}$ mode with the longitudinal RF cavities set to bunch the beam at the 5th harmonic of the beam revolution frequency instead of the originally planned 10th harmonic, the beam emittance increase was considerably reduced, resulting in -at most- negligible beam loss at the halo collimator.

INTRODUCTION

The 1083.6 m circumference SIS100 synchrotron to be built at GSI as part of the FAIR facility will receive bunched beam from the existing SIS18 synchrotron. The bunches have to be deflected onto the optical axis as they enter SIS100. Deflection is caused by a set of pulsed dipole magnetic fields produced by a row of 6 identical kicker magnet modules spanning $\approx$2.7 m in SIS100 collectively referred to as the kicker. The magnetic field rises from zero to a certain field strength before the beam to be injected arrives at the first module. The field then stays as close to constant strength as possible while the beam is deflected onto the optical axis before falling back down to zero field strength. Particle tracking simulations were undertaken to estimate the effect on the beam from imperfections of the kicker's magnetic flux density (B-field) pulse. Two cases were studied; the RIB and $\bar{p}$ cycles. The beam is accumulated at injection energy in a 'stacking' process. In RIB mode four batches of two $^{238}U^{28+}$ bunches each from SIS18 are injected every 355 ms into SIS100, filling 8 out of 10 neighbouring RF 'buckets'. Likewise, in $\bar{p}$ mode a single proton bunch is injected every 371 ms.

KICKER-CURRENT TIME STRUCTURE

The concept and overall design of the kicker was defined at GSI. The detailed engineering was done at Research Instruments (RI) and Danfysik where the systems are currently built. Measurement of the time-form of a module's pulse in terms of the current through its coil –before, during, and after a main pulse– were carried out at RI. Measured pulse data was 'fed' into a transverse beam dynamics simulation. The pulse of length suited for RIB mode is shown on the left in Fig. 1, and in Fig. 2. The overshoot at the start of the pulse's 'plateau' was reproduced in a simulation with SPICE, the brief 'ringing' at the start of the rising flank –thought to be a measurement artefact caused by the current transformer of the measurement system– was however not. A small fraction of the beam is present in this part of the pulse for the RIB mode with RF harmonic h=10 whereas for $\bar{p}$ with h=5 there is no beam there. Additional ringing comes after the main pulse. It is caused by reflections resulting from impedance mismatches between the cable used as pulse forming line and transfer cable, the kicker magnet inductance and the stray inductance of the pulse generators. All these distortions may cause 'dilution' to the beam's horizontal phase space distribution.

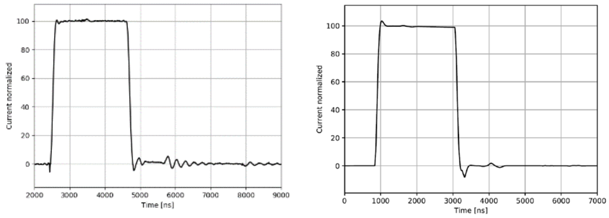

Figure 1: Normalized current $\propto$ B-field vs. time: left, measured first of series kicker module, and right, simulated effective kicker current $\propto$ kick deflection angle. Measurement taken 20th July 2022.

The overall distortion may be reduced by optimising the storage and transmission cable lengths for each module, allowing time delays between module pulses, resulting in partial mutual cancellation of distortions between modules. This was demonstrated with SPICE. The kicker's deflection angle vs. time, thus obtained, is on the right in Fig. 1. The ringing after the pulse has clearly been diminished.

SIMULATION

Depending on the task, different codes were used to simulate the beam-kicker interaction. For the initial conditions in longitudinal phase space the ESME code (ver. 2003) [1] or the BLonD library (ver. 1.19) [2] was used to 'paint' uniform density bunches. The transverse beam dynamics was simulated with an in-house computer program which tracked the beam-particles' phase space coordinates with a single turn map representing the linear lattice of SIS100. The initial beam phase space distribution in the horizontal plane, twiss parameters, and chromaticities for the map were calculated with Micromap [3]. Chromaticity was represented to lowest order in the single turn map as linear perturbations to the matrix elements. The kicker was represented as a ‘thin’ element. Kicks to the particles were given at the middle of the kicker. The beam distribution in the transverse phase space was a waterbag distorted slightly by dispersion and chromaticity. Particle motion in the transverse planes was assumed decoupled.

LONGITUDINAL PHASE SPACE

The kicker’s magnetic field rise-time has to be short enough to avoid kicking the trailing edge of a circulating bunch on the lower part of the rising flank, or over or under kicking parts of the bunch being injected caused by the overshoot and the upper part of the rising flank. A circulating bunch should pass by the kicker before the kickers’ field rises significantly. The bunch’s longitudinal phase space was chosen to have a uniform density with the 70% design RF bucket fill factor, space charge neglected. ESME was used to determine the ends of the bunch current-time profiles, thereby allowing the bunch gap to be determined; the gap in the beam, in this case that between beam in 2 neighbouring RF buckets, specifically a circulating bunch and the bunch being injected. From the current-time profiles, the bunching factor was determined, which could be used to obtain the peak transverse betatron tune shifts. The rise-time of the kicker is defined as the time it takes for the B-field to rise from 2 to 98% of a reference height on the plateau of the pulse where the current was closest to constant. Measurements show the rise-time to be 141-161 ns for a ≈2 μs long pulse plateau, used during RIB mode with the RF harmonic at *h*=10, and 152 ns for a ≈0.5 μs long pulse plateau used during $\overline{\mathrm{p}}$ mode with the RF at *h*=5. It was found that bunches during $\overline{\mathrm{p}}$ mode at the original design value *h*=10 will incur beam phase space increase in the horizontal from the rising edge of the kicker pulse at the trailing end of the bunch. The transverse beam dynamics simulations in the next section help quantify how much beam emittance increase may occur when RIB with *h*=10 and $\overline{\mathrm{p}}$ with *h*=5 are in operation. As mentioned, it is proposed to inject during $\overline{\mathrm{p}}$ mode with *h*=5. Injecting proton bunches with the same emittance as that in the original design into a lower harmonic bucket provides a longer bunch gap thereby accommodating the rise-time, consequently avoiding transverse emittance increase. Batch compression [4, 5] before the 1st bunch merging at injection rigidity would get the beam into 4 of the 10 RF buckets required at the start of merging in the original scheme. A suitable choice would be to inject into buckets at *h*=5 since there is adequate bunch gap (462 ns) for accommodating the rise-time (152 ns). An ESME simulation with direct space charge showed that batch compression with beam remaining in the RF buckets was possible over 350 ms with Δ*h*=1. Changing from *h*=10 to *h*=5, we increase the bunching factor in the absence of the beam’s collective effects from 0.20 to 0.23 thereby slightly reducing transverse space charge tune shifts. The original design fill factor of 70% in a single harmonic RF bucket RIB mode scenario provided a bunch gap of ~200 ns > 161 ns, the measured rise-time of the 2 μs long single module pulse.

TRANSVERSE PHASE SPACE

Injection for $\overline{\mathrm{p}}$ and RIB cycles, and slow extraction during the RIB cycle at the lowest foreseen rigidity of 27 Tm were considered. A nominal beam deflection of 7 mrad from the pulse plateau was used which was close to the deflection angles found in all operational scenarios. Single particle phase space trajectories were simulated with ELEGANT [6] to determine the separatrix’s form. The separatrix encloses a 24π μm area. Therefore, the total emittance after any kicker-induced beam emittance dilution should be < 24 μm. Scaling with adiabatic damping from 27 Tm to 18 Tm at injection, we get an acceptance of 36 μm, slightly larger than the nominal 100%-beam emittance of 35 μm which is slightly greater than the design value 34 μm. We therefore expect only intentional losses at the start of slow extraction at 27 Tm if the kicker pulse were ideal. In reality, however, there will be kicker induced emittance ‘blow-up’. The synchrotron motion of a particle in an RF bucket must be considered because it modulates a particle’s longitudinal position in the bunch resulting in the particle receiving a different kick strength from one pulse distortion to the next even if the distortions were approximately the same. Therefore, a detailed tracking was necessary with coupling between the longitudinal and transverse dynamics due to chromaticity and dispersion while taking into account the time-form of the pulse distortions. To assess the effect of the kicker-pulse on the beam’s phase space distribution, all pulse distortions encountered by a bunch during stacking must be considered, as shown in Fig. 2 for the RIB mode.

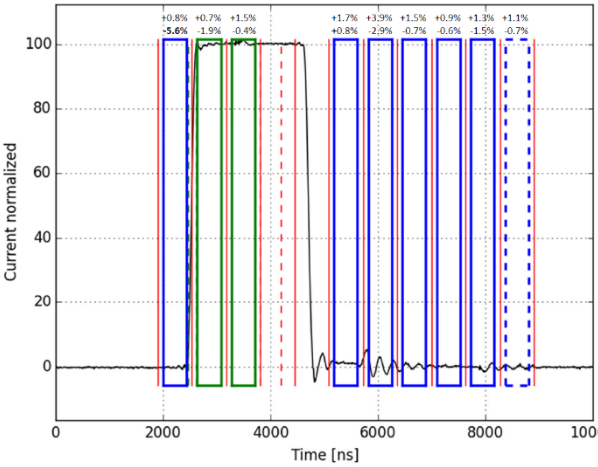

Figure 2: Normalized current vs. time of measured kicker module coil current on the left in Fig. 1. Widths in time of the boxes represent bunches at various times during stacking. + and -% values are the max. and min. relative deviations from the ideal module current (i.e., rectangular pulse) respectively.

The 1st injected bunch-pair during RIB mode receive a distorted kick on the pulse plateau, i.e., in the 2nd and 3rd RF periods. Later, during the 2nd injected batch, these same bunches –which have now been circulating for 355 ms– experience pulse distortion in the 1st and 10th RF periods. One beam revolution period later, the leading bunch of the bunch-pair receives a distorted kick in the 11th RF period.

The trailing bunch of the bunch-pair does receive kicks in the 12th RF period but these are negligible. Upon the 3rd batch injection kicks are in the 8th and 9th RF periods. During the final batch, injection kicks are received in the 6th and 7th RF periods. Figure 3 shows how the horizontal emittance of the 1st injected batch develops during stacking.

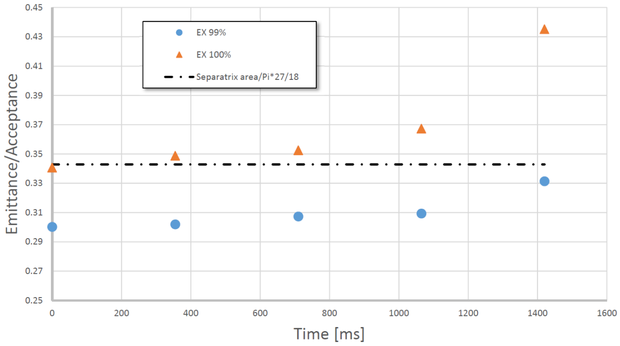

Figure 3: RIB cycle during stacking. Horizontal 99 & 100%-beam emittances of 1st injected bunch-pair, normalized to the 105π µm halo collimator acceptance.

All bunches should be considered however. Thus, the final 100%-beam emittance normalized to the halo collimator acceptance of 105π µm was ≈0.44 which lies within the dashed acceptance ellipse in Fig. 4. In such a case, however, there would be losses at the start of slow extraction at 27 Tm because the emittance exceeds the 36 µm at 18 Tm governed by the separatrix's acceptance. 17 particles were lost, corresponding to ≈0.19% of the initial beam. This was determined by counting the particles outside the aforementioned scaled separatrix ellipse's 36 µm area. Assessment of the measured kicker module pulse and its effect on the beam during injection during a $\bar{p}$ cycle was carried out in the same fashion. The 100%-beam emittance 371 ms after the final bunch is injected occupies ≈97% of the acceptance set by the collimator. It can be however that a small fraction of the beam will be 'scraped' away by the collimator because the beam's periphery is close to the acceptance and the momentum of the particles are modulated by the RF cavities leading to some particles moving transversally away from the central orbit due to dispersion. These losses are expected to be << 1% of the beam since the 99%-beam emittance occupies just 49% of the acceptance.

It should be noted that the above stated values actually overestimate emittance growth, since the reduction of ringing by optimizing cable lengths was not taken into account. Therefore, the study provides a worst-case upper bound on expected emittance growth.

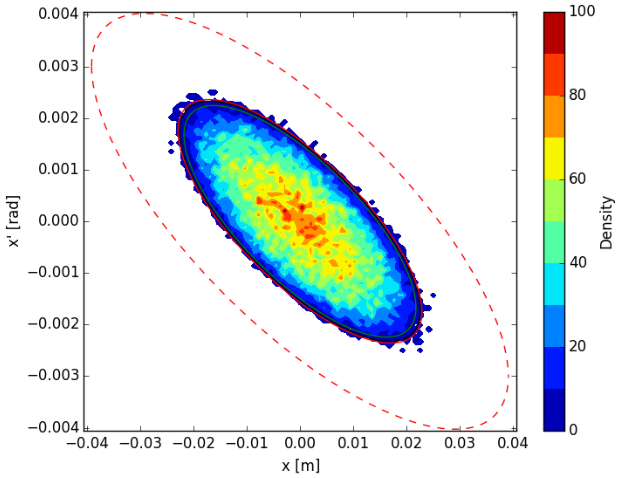

Figure 4: RIB cycle. Horizontal beam phase space density distribution at middle of kicker after stacking.

SUMMARY

The transverse dynamics simulation for the RIB cycle revealed that the beam at the end of injection stacking grew in horizontal phase space but was still well within the halo collimator acceptance. However, losses of ~0.2% of the beam at the start of third-integer slow extraction at 27 Tm may be expected. Longitudinal dynamics simulations reveal that h=5 in the design of the $\bar{p}$ cycle's injection stacking while keeping the longitudinal bunch emittance unchanged from the original design value allows a sufficient gap between bunches for the rise-time of the injection kicker. A kicker module's measured pulse for the $\bar{p}$ cycle, caused the horizontal 100%-beam phase space area to come close to the halo collimator acceptance during the stacking when simulated with the same code as used for the RIB scenario.

REFERENCES

[1] J. MacLachlan, "Fundamentals of particle tracking for longitudinal projection of beam phasespace in Synchrotrons", FermiLab note FN-0481, April 1998.

[2] CERN Beam Longitudinal Dynamics code BLonD, `http://blond.web.cern.ch`

[3] G. Franchetti, I. Hofmann, G. Turchetti, "Micromap approach to space charge in a synchrotron", in AIP Proc. of Workshop on Space Charge Physics in High Intensity Hadron Rings, 448, 233–244 (1998). `doi:10.1063/1.56776`

[4] R. Garoby. "RF gymnastics in synchrotrons," in Proc. of CERN Accelerator School, Seeheim, Germany, 2000, CERN-2005-003, p. 301. `doi:10.48550/arXiv.1112.3232`

[5] A.W. Chao and M. Tigner, *Handbook of Accelerator Physics and Engineering*. Singapore: World Scientific, 1999. `doi:10.1142/3818`

[6] M. Borland, "Elegant: A Flexible SDDS-Compliant Code for Accelerator Simulation", in Proc. 6th International Computational Accelerator Physics Conf. (ICAP 2000), Darmstadt, Germany, September 2000. `doi:10.2172/761`