STUDIES WITH A PARTICLE TRACKING CODE FOR THE SIS100 RESONANT EXTRACTION SYSTEM

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Abstract

Several issues concerning the envisaged SIS100 resonant extraction at GSI can be resolved with a simulation-lead approach for which a particle tracking code was developed. Applications to date have included: design and testing of data supply algorithms for the accelerator control system; requirements analysis for the power converter ripple in the quadrupoles forming the doublet focusing; and verification of the RF Knock-Out exciter's performance.

INTRODUCTION

Nuclear instrumentation to be installed at the Facility for Antiproton and Ion Research (FAIR) will require smoothly varying beam currents at targets, at resolutions down to below 1 μs. Thus, a high fraction of the beam can be utilized; minimizing beam-induced reaction channel events missed during the dead-time of the data acquisition electronics. Another advantage is that the instrumentation can accept an average beam current which is close to the threshold for detector interlocks. The smoothness of a spill can be degraded by ripple stemming from power converter supplies to magnets. The measurement of power converter ripple in the spill current out of the SIS18 synchrotron at GSI, and its suppression by feedback to the power converter current by adding compensating frequencies, was proven to work in [1].

RF Knock-Out (RF-KO) is the preferred method for resonant extraction owing in part to its advantage of being able to offer a stable extracted beam spot at the target. The process involves a (horizontal) time varying electric field. All particles resonate simultaneously, driven by the excitation's spread spectrum from a Binary Phase Shift Key (BPSK) modulation. The bit-sequence in BPSK which governs the sudden shifting of the carrier-phase by 0° or 180° is determined by a Maximum Length Sequence from a Linear-Feedback Shift Register. The register size (16-bits) is large enough to provide a pseudo random sequence which repeats just 2-3 times during a typical spill. The SIS100, with its maximum magnetic rigidity at 100 Tm, is described in detail elsewhere [2].

PARTICLE TRACKING

RF Knock-Out simulations were carried out with the GSI code Hiukkas, which offers the following features:

- Thick and thin lens magnets.
- Excitation of a third-integer resonance.
- Transverse RF-KO band-limited noise.
- Extraction with quadrupole magnets.
- A stationary single frequency longitudinal RF cavity.
- Calculation of extraction efficiency.
- Spill feedback intensity control.

The code is partly based on the MICROMAP library [3] as concerns in particular ray-tracing through magnets.

SYSTEM DESIGN STUDY

The aim of this work is to find ways to reduce the frequencies in the spill current which matter the most, namely from DC to ~10 kHz. Momentum modulation using RF cavities, which can compensate the betatron tune modulation due to power converter ripple, introduces ripple in the spill at harmonics of the cavity's RF. These higher frequencies may cause problems for some experiments at FAIR and therefore DC beams are the preferred choice for these studies. The quadrupoles forming the doublets are one source of spill ripple. The tolerance on the ripple amplitude for these magnets will be determined in the following section. Spill frequencies contributing to the so-called macrostructure or spill-envelope, another concern, shall be discussed in the section on spill intensity control. These can be reduced with a predetermined feed-forward ramp for Amplitude Modulation (AM) of the RF-KO exciter, or using spill current measurement as a feed-back to the AM ramp, or both. The other sections detail the search for operating conditions which can optimally suppress coherent motion of the beam, and the RF-KO exciter's specification. All results presented are for $^{238}U^{28+}$ ions at the magnetic rigidity $B\rho = 100$ Tm.

Quadrupoles

Three SCR/SM power converters supply the two quadrupole families of the doublet lattice structure. One family focuses in the horizontal plane and is connected in series to a single power converter, while the other defocuses, also horizontally, and is grouped into two series circuits. Here the defocusing quadrupole in each doublet is downstream from the focusing quadrupole. These power converters produce the strongest ripple at 600 Hz with much smaller higher harmonics. In-phase ripple is assumed between circuits. This happens to produce a larger tune deviation than if anti-phased.

Extraction simulations were run with constant RF-KO exciter peak-peak amplitude at 10 kV, the maximum specified, and the same normalized sextupole gradients. The initial 6D beam phase space distribution was also fixed with only the quadrupole ripple-amplitude differing.

The runs produced a set of histograms of the arrival times of the extracted particles at the entrance to the first (electrostatic) septum, referred to hereafter as spill. The histogram bin size (10 turns) was small enough to sufficiently resolve the 600 Hz ripple. A region of interest in the spill was chosen where the average count per bin was large enough to obtain sufficient statistical certainty on the maximum counts per bin. The smoothness or "quality" of the spill was defined as the maximum counts per bin to the mean for a certain number of bins spanning a window in the histogram. The window size was chosen to be the same as the ripple period, ~1.7 ms. The region of interest was 130ms wide resulting in about 77 values of I_{max}/I_{mean} from which the minimum, maximum, mean, and RMS deviation were calculated and plotted in figure 1.

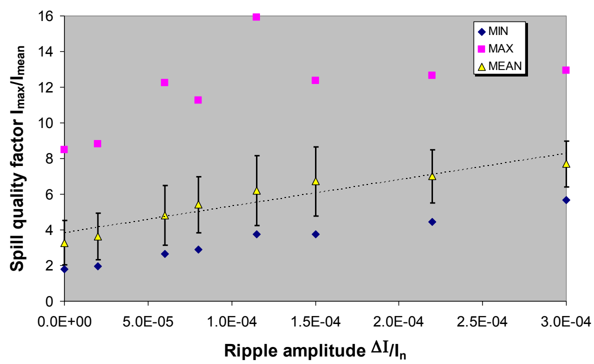

Figure 1: Spill quality is degraded by ripple from power converter currents in the main quadrupoles coils. The ±error bars are the ±RMS deviations. I_n = 8 kA.

A linear fit to the set of points representing the mean in I_{max}/I_{mean} in figure 1 sets the tolerance on the ripple's amplitude in the non-ramped power converter current to $\Delta I/I_n \leq \pm 2.6\cdot 10^{-5}$ for a 10% nominal increase in spill quality factor from that present without ripple, which represents the acceptable limit on spill microstructure degradation. This should be achievable during extraction down to approximately 22 Tm because the magnet's inductive coil and resistive connecting cables will attenuate the AC component of the current. The power converter has its 600Hz ripple at ±1% of its maximum 640V after its active filter stage. The LR circuit representing the magnets in series has a total effective L=29mH with negligible contribution at 600Hz from its resistance to the total impedance. This results in $\Delta I/I_n = \pm 6.2\cdot 10^{-5}$ at I_n=1 kA, and $\Delta I/I_n = \pm 7.5\cdot 10^{-6}$ at I_n=8 kA. Note that the nominated tolerance $\Delta I/I_n \leq \pm 2.6\cdot 10^{-5}$ holds for quadrupoles when not ramped, for DC currents in the range 1.7-8 kA corresponding to $B\rho$=22-100 Tm.

Effect of Momentum Spread on Spill Structure

A particle in a synchrotron in the presence of a driving frequency from a transverse RF voltage moves in a fashion similar to an undamped driven harmonic oscillator. Under such circumstances the oscillating particle's amplitude will oscillate with a 'beating' frequency equal to the difference between the driver and the eigenfrequency of the particle. Because excitation occurs at just one point in the beamline the excitation can in principle be tuned to either of the betatron sidebands which accompany the beam revolution harmonics.

For a bunch of particles, however, with their betatron tune spread due to the longitudinal momentum spread and chromaticity, the average motion in the second moments of the beam is reduced. Further reduction is possible by increasing the RF-KO excitation bandwidth. The result is a reduction of spill frequencies corresponding to this coherent motion.

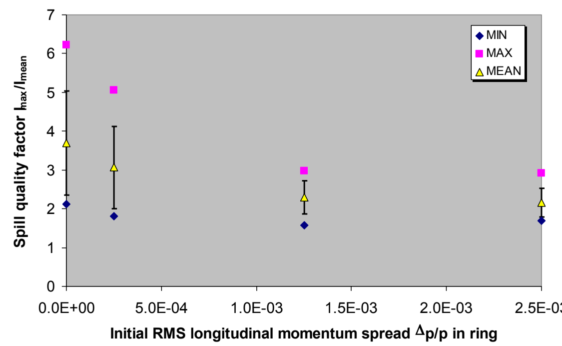

Figure 2: Increasing the longitudinal momentum spread has a smoothing effect on the spill. The conditions are the same as those for figure 3. Ripple neglected.

Therefore, one way to reduce coherence is to increase the momentum spread at the flattop prior to extraction, as shown in figure 2, avoiding excessive increase in the extracted emittance, and with it the spot size at the target.

Losses at the first septum will also inevitably increase with increased momentum spread. This is evident from figure 3 which plots septum loss normalized to the loss for $\Delta p/p$=0 and the horizontal extracted RMS emittance. Furthermore, it was found that the horizontal dynamic aperture became too small for a proper extraction of all particles if the longitudinal momentum spread exceeded $\Delta p/p \sim 7\cdot 10^{-4}$ RMS. All initial beams for figures 2 and 3 were DC coasting and Gaussian in $\Delta p/p$ up to $\pm 3\sigma$.

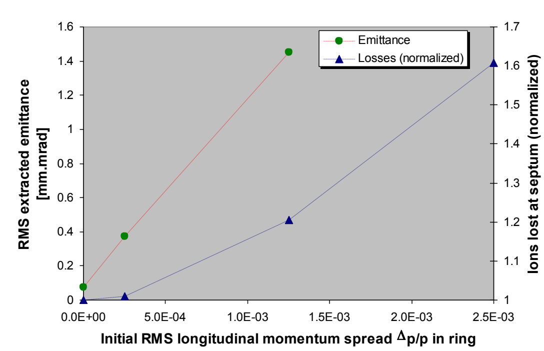

Figure 3: Increasing the longitudinal momentum spread and its influence on the extracted beam emittance and beam loss at the electrostatic extraction septum.

Specification for the RF Knock-Out

The RF-KO exciter, specified in [4], was simulated with the tracking code to verify if the beam could be extracted under realistic conditions with a sufficiently high transmission, within the beam user requirement of 1 second spill duration. Some parameters of the RF-KO system are specified in table 1. With a closed-loop control for the spill it was found that the intensity in the synchrotron could be made to fall by more than 90% (see Figure 4). The power amplifier (PA) output voltage in table 1 corresponds to a swing of 10 kV in the potential difference between the electrodes.

Table 1: Knock-Out System Specification

Component	**Specification**
Exciter electrodes	Horizontal excitation. Stripline geometry. Length 2500 mm. Separation 135 mm.
Power amplifier	Output 2.25 kV (peak) Bandwidth 10-100 kHz.
Linear feedback shift-register	10 kHz clock, 16-bit.

The PA voltage in table 1 can be reduced by making the currents through the electrodes flow opposite to each other thus creating a magnetic field which provides an additional horizontal Lorentz force to the ions [5].

Spill Intensity Control

It has been demonstrated in [6] that an analogue circuit based on the Proportional Integrator (PI) closed-loop control method for the spill intensity can be tuned to perform well at obtaining a flat spill envelope. Such feedback processes may be expressed as

$$V_{KO} = V_P\left(1 - \tfrac{IT}{N}\right) + \frac{V_I N t}{T}\left(\int_0^t I dt\right)^{-1} \quad (1)$$

For the AM of the exciter voltage, where: V_P and V_I are tuning parameters; I_0 is the set-spill current; and N is the initial beam intensity in the synchrotron to be extracted in a time T. The actual spill current I may be measured by a proportional pulse counting detector in the extraction channel such as an ionisation chamber. An initial attempt fully documented in [7] to tune a variant of the above algorithm resulted in figure 4. The term containing the integral in equation 1 was replaced with the actual intensity in the synchrotron normalized to the set intensity. This achieved a reduction in the number of ions in the synchrotron remaining after 1 second by causing the steepening rise in RF-KO amplitude towards the end of the extraction. Application of spill control to such systems is an area of continued interest.

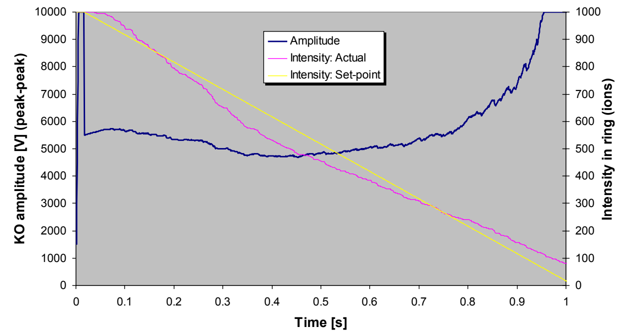

Figure 4: (Colour) Simulating the performance of a closed-loop spill intensity control.

CONCLUSIONS

The results presented are encouraging as concerns a RF Knock-Out system for SIS100. Magnet field errors were neglected. It is expected that these may have a significant effect on the extraction efficiency. Collective effects, so far not included, would add space charge tune shifts, increasing the required exciter voltage. Intensity control of the spill-macrostructure may be possible with a mixture of feedback and feedforward RF-KO AM in an iterative process, and shall be investigated. Longitudinal momentum spread can be increased for spill-smoothing by various means, e.g. via a jump in RF phase [8]. Longitudinal RF noise may also prove successful. Ripple in Closed Orbit (CO) distortions caused by main dipoles may produce significant tune ripple due to the varying CO offsets in the sextupole magnets. A well designed closed orbit correction system should therefore be undertaken.

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