

SIS-18 RF KNOCK-OUT OPTIMISATION STUDIES

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Abstract

The extraction efficiency of the SIS-18 heavy ion synchrotron and temporal structure of its spill are part of the upgrades to the GSI accelerator complex. Losses to the extraction septum can be minimised through implementation of the Hardt condition resulting however in a poorer quality of the spill microstructure at resolutions of a few μs due to lowering of the horizontal chromaticity from its ‘natural’ value. Ways to improve the extraction efficiency and spill microstructure are investigated with a tracking code. One possibility for improvement may be to use an alternative modulation applied to the RF knock-out exciter.

INTRODUCTION

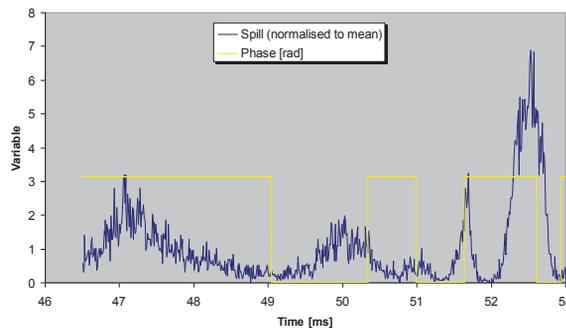
As demands from spill users increase for better spill quality, most notably those from the HADES experiment, means should be found to improve operation. Spill quality degradation has many causes. Power converter ripple and RF knock-out signal time-structure are identified as possible areas of improvement for SIS-18. This work concentrates on the RF knock-out extraction scheme which, in contrast to tune driven extraction, can offer optimum beam-spot stability at the target as well as higher operating stability of the power converters for the magnets, since they do not have to be ramped during extraction. A theoretical study is presented involving an in-house particle tracking code which has been used to resolve SIS-100 design issues [1]. Results presented here concern the extraction of DC circulating beams. Though RF-bunched beam operation can suppress tune modulations from magnet ripple at frequencies on the order of the synchrotron frequency, which can be $\sim 100\text{ Hz} - 1\text{ kHz}$ [2], due to upgrade of the HADES DAQ system, the presence of the RF-bunch frequency, typically a few MHz, at the 4th harmonic of the beam revolution frequency creates problems when it comes to the spill variation at resolutions of a few ns.

RF EXCITER VOLTAGE

Originally SIS-18 used RF Knock-Out for particle therapy. Now its potential is being investigated for the remaining beam users for the above mentioned reasons. Present day operation uses BPSK with a PRN bit-train from a Galois sequence implemented as a 16-bit Linear Feedback Shift Register to phase-modulate the carrier frequency for transverse (horizontal) RF excitation of the beam. Instead, for the simulations, a different random number generator was arbitrarily chosen with the ability

to allow the phase to remain at 0 or 180° for longer than 15 bit-periods which is a seldom. The difference therefore to the qualitative form of the microstructure is expected to be negligible. The RF exciter consists of two parallel stripline electrodes each 750 mm long and 200 mm apart. They provide the horizontal transverse electric field. It provides the maximum effective voltage $U_{\text{eff}} \sim 1.3\text{ kV}$, i.e. maximum E-field strength \times length. The third integer resonance at $Q_h = 13/3$ is powered with sextupoles while maintaining the original ‘natural’ chromaticities of the linear focusing lattice. The nominal working point tunes were $Q_h = 4.296$ and $Q_v = 3.27$ giving a suitable separatrix when powering the resonance with the sextupole amplitude $K_2L = 0.03\text{ m}^{-2}$. Without power converter ripple, one may expect the spill to resemble that in Fig. 1a which is for a carrier frequency equidistant to the (horizontal) working point and resonance, and for a width of the centre lobe in the $\text{Sinc}^2(f)$ power spectrum $\sim 2 \times$ the working point-resonance bandwidth. This was found to provide a sufficiently short extraction time. The (pseudo) random occurrence of the jumps in phase of the carrier produces the random time structure of the spill ‘packets’.

a) BPSK: $U_{\text{eff}} = 1.3\text{ kV}$



b) Dual FM: $U_{\text{eff}} = 4.5\text{ kV}$

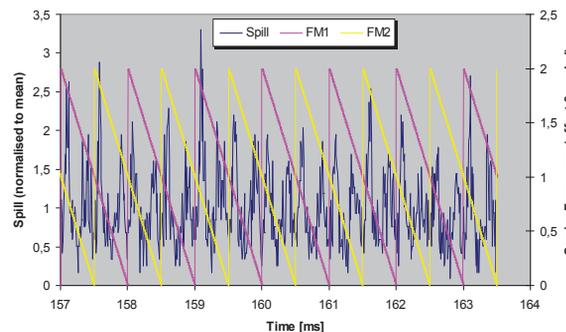


Figure 1: (Colour) Spill with a) BPSK and b) Dual FM. Horizontal chromaticity $Q_h' = -6.94$ ($=\Delta v/\delta$), unadjusted from natural value. Bin size 10 μs (ca. 10 turns), $^{12}\text{C}^{6+}$, 6.35 Tm.

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Applying instead the Dual FM technique, also originally developed for particle therapy [3], one can considerably reduce the spill roughness as demonstrated in Fig. 1b. The mean extraction currents over the regions shown are approximately the same, as should be for a meaningful comparison of the two methods; Important is that the ‘global’ spill forms (bin size ~ 10 ms) are the same. The corresponding roughness parameter in Fig. 2 – defined as the peak to mean spill (MAX/AVG) over a region (window) of interest– is distributed over a significantly lower range than for BPSK. Just a few spikes exceeding for example 6 times the mean in a 1 second spill may cause problems for experiments which have beam-sensitive detectors with interlocks which when triggered can stop the experiment for minutes before reaching their operating conditions again. Dual FM has the disadvantage of requiring more voltage to get the same global spill form as BPSK. Increasing the BPSK bandwidth by increasing the frequency of the phase-jumps has been shown to reduce spill breaks but with the overall smoothness being marginally increased from that in Fig. 1a. Note that the signal form will not converge to that of noise in the limit of infinite bandwidth. As concerns Dual FM, switching one FM off and adjusting the peak voltage to regain the original global spill form, provides approximately the same roughness as with Dual FM albeit with half the repetition rate in the spill.

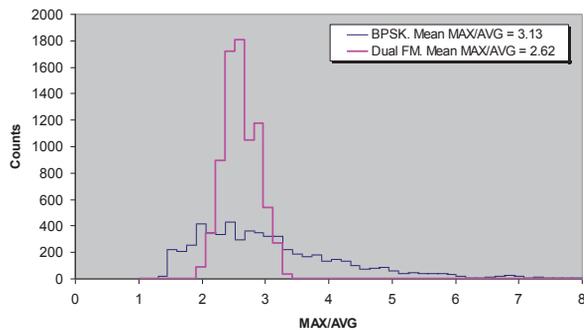
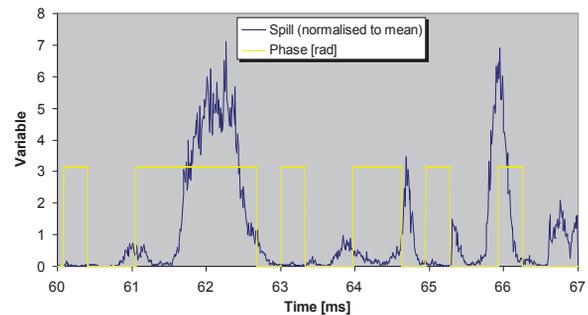


Figure 2: (Colour) Roughness parameter distribution. Beam/machine parameters same as Fig. 1. Histograms formed with ‘sliding’ window 1ms (100 spill-bins) in size.

Another demand from users is higher beam intensity. With this comes the need to reduce radiation load on and around the septa. A well established condition by Hardt [4] for achieving minimal losses on the first extraction septum can reduce the septum losses from the ‘standard’ operating value at $\sim 10\%$ down to $\sim 1\%$ for a longitudinal circulating beam momentum spread HW (Gaussian cut at $\pm 2\sigma$) of $\Delta p/p \sim 0.04\%$. Reduction is achieved by the effect of dispersion counter acting that from chromaticity such that particles of different momentum enter the septum with the same angle with respect to the design orbit. The downside to all this is the requirement –set by the SIS-18 layout and limitation on the sextupole strengths– that the chromaticity in the extraction plane (horizontal) be much

lower than its unadjusted (natural) value. Consequently for Dual FM the (horizontal) tune spread will be reduced, resulting in a faster sequential excitation through the betatron frequencies for the same: ‘saw-tooth’ sweep rate (1 kHz) on each FM; centre carrier frequency (301 kHz); and full sweep-range (27 kHz), as was for the standard operation. This results in the taller and sharper peaks in the Dual FM spill shown in Fig. 3 (See also Fig. 4 and compare against Figs. 1 & 2.) BPSK also yields under these conditions a rougher spill with the reason due to coherent non-damped beating (transient term solution of a driven SHM system) of the betatron amplitudes by the driver frequency (KO exciter), which for low chromaticity and moderate momentum spread can be quite pronounced.

a) BPSK: $U_{\text{eff}} = 1.1$ kV



b) Dual FM: $U_{\text{eff}} = 5.3$ kV

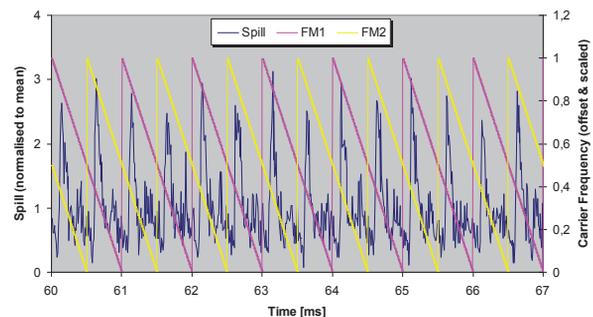


Figure 3: (Colour) Spill with a) BPSK and b) Dual FM. Low chromaticity $Q_h' = -0.29$ for the Hardt condition. Bin-size $10\mu\text{s}$ (ca. 10 turns). Beam ions: $^{12}\text{C}^{6+}$, rigidity 6.35 Tm.

Spills were also simulated for band-limited white noise that had been initially band-pass filtered with a rectangular ‘hard-edge’ function in frequency domain. Such signals are termed ‘coloured noise’. The resulting excitation range was approximately matched to the working point-resonance band. The microstructure appears qualitatively very similar to that obtained with BPSK under the same conditions. The distributions of MAX/AVG in Fig. 4 (and Fig. 2) for white noise, Dual FM and BPSK, reveal the performance of each modulation with better clarity than inspection of the time structure over a small section of spill. Pure white noise is included for reference as it provides the ideal benchmark.

This infinite-band noise has a Gaussian voltage distribution cut at $\pm 3\sigma$ with (maximum) $U_{\text{eff}} = 5.5$ kV.

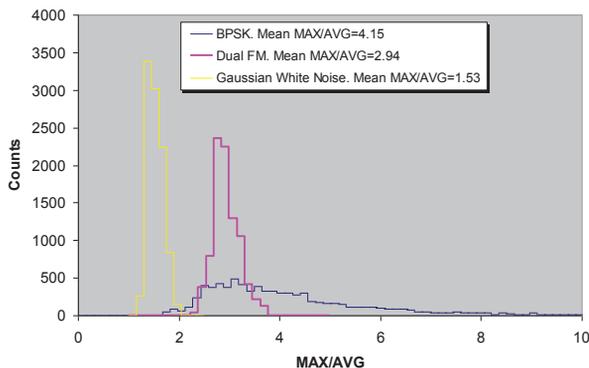


Figure 4: (Colour) Roughness parameter distributions. Beam/machine parameters same as Fig. 3. Histograms formed with ‘sliding’ window 1ms (100 spill-bins) in size.

POWER CONVERTER STABILITY

The main dipoles are series connected to a power converter and supplied with current to better than $\Delta I/I_n = \pm 2.5 \cdot 10^{-5}$ according to the design specification. Measurements were made of the frequency spectrum of the power converter current with an oscilloscope using a built-in FFT to check the specification because of unexpected observations of strong 150 Hz in the spill during November 2012. Peaks were found in the region ~ 0.1 – 1 kHz. A maximum deviation of the actual current from the set DC current (~ 1.2 kA) of approximately $\pm 1.8 \cdot 10^{-5}$ was found. The DC current provided 6 Tm of magnetic rigidity which is for knock-out extraction of $^{12}\text{C}^{6+}$ at ~ 360 MeV/u. A reconstruction is in Fig. 5. Note the 150Hz beat.

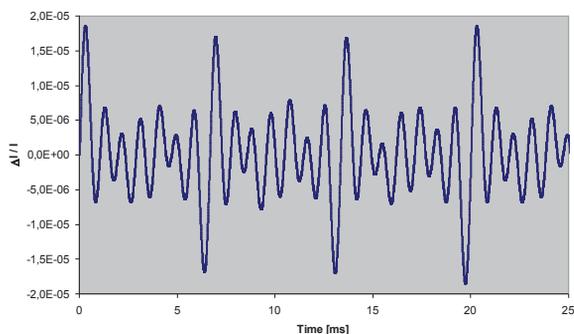


Figure 5: Measured ripple in the main dipoles. $I = 1190$ A.

Spill under these conditions was simulated by treating the ripple as perturbations to the main dipoles’ bending angle produced by an infinitesimally long dipole in the middle of each main dipole. Results from the tracking code did not reveal visible ripple in the spill even after increasing the current deviations by a factor of 10. It is therefore still uncertain as to the cause of the strong 150Hz spill-ripple. Degradation in the form of blow-up of the extracted beam phasespace distribution was however evident for the exaggerated ripple. (A few % increase in RMS emittance in both transverse planes.) It is nonetheless important to reduce other causes of spill ripple if one is to successfully reduce the overall spill roughness with an improved knock-out signal form.

CONCLUSIONS

It has been shown that changing operation from BPSK to Dual FM for RF Knock-Out can considerably improve smoothness in the spill at temporal resolutions of a few μs . This is particularly important when the lattice is set to a low chromaticity such as would be necessary for maximising the extraction efficiency á la Hardt. Dual FM and wide-band noise would require more effective voltage from the exciter. This could be achieved by increasing the exciter’s length, reducing the gap between the electrodes and/or, most likely, increasing the peak (and RMS) voltage capability of the knock-out system.

ACKNOWLEDGMENT

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