OBSERVATIONS OF COUPLING DURING ACCUMULATION USING A NON-DESTRUCTIVE ELECTRON SCANNER IN THE SPALLATION NEUTRON SOURCE ACCUMULATOR RING*

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Abstract

An electron scanner has been installed in the accumulator ring of the Spallation Neutron Source (SNS). The non-destructive device permits turn-by-turn measurements of the horizontal and vertical profiles of the proton beam during accumulation with fine longitudinal resolution. In this study the device is used to investigate the source of transverse coupling in the SNS ring and to understand the impact of space charge on the evolution of the coupled beam. We present experimental observations of coupling dependent on tune, injected intensity, and accumulated intensity for a simplified accumulation scenario with no RF and no injection painting. We also investigate the effects of varying the skew quadrupoles and tune for beams with the SNS production-style ring injection and ring RF patterns.

INTRODUCTION

The SNS Accumulator Ring compresses up to 1050 turns of injected beam into a short 1 μs pulse containing up to 1.5×10^{14} protons. Once accumulated, this pulse is delivered to a liquid mercury target for neutron spallation by way of the Ring-to-Target Beam Transport (RTBT). The target has specific requirements for beam size and profile uniformity in both transverse planes. One primary requirement is that the peak on-target density remain less than 2.6×10^{16} protons/m^2 for a 1.5 MW beam. In order to achieve the on-target requirements, independent control of the transverse beam distributions is necessary. Previous studies have shown a loss of independent control between the planes. Initially this effect was only intermittently observed by accelerator operators during production shifts. In 2011 and 2012, it was shown that at high beam intensities the final accumulated beam distribution in each plane depended on the initial distribution in the alternate plane [1, 2]. Initially, the primary hypothesis was that the loss of control was due to space charge and could be related to the Montague Resonance [3] due to the small tune split of the coupled beam configurations. In 2015, it was shown that at low beam intensities the beam emittances could be caused to couple and fully exchange between the transverse planes by configuring a small tune split [4]. In this paper we present results of additional experiments from continuing efforts to understand the transverse coupling in the SNS Accumulator Ring. In previous studies, we have used traditional wire scanners to collect transverse beam profiles. This has proven to be a time prohibitive method to study beam oscillations. In this experiment we will use the Electron Scanner (ES), a novel diagnostic device recently developed in the SNS Accumulator Ring.

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ELECTRON SCANNER

The Electron Scanner obtains profiles by first passing an electron beam diagonally across the path of the accumulating proton beam. The electron beam is deflected in the presence of the electromagnetic field of the proton beam. The deflected path is then projected onto a fluorescent screen and an image is captured. The transverse profile is derived from the amount of the deflection along the projection [5]. The analysis, which can be run offline, slices through the center of the image and fits a gaussian peak to the pixel intensities along each slice to find the full set of (x, y) points. A spline curve is then fitted through the set of (x, y) points to calculate a smoother set of curve points so that a derivative can be taken to obtain a less noisy profile. The spline fit technique also allows the projection of the beam to be traced through the cutouts made by the electron scanner beam markers, which are used to provide a scale for the profile width. A derivative with respect to position is calculated from the difference of the spline curve with respect to the path of an undeflected electron beam.

The electron scanner has several advantages over traditional wire scanners. The first advantage is the non-destructive nature of the electron scanner, which allows us to collect data parasitically to regular production operations. This means that the electron scanner could become a useful diagnostics tool for regular use during operations in the future. Second, the electron scanner has the ability to capture 20 ns slices of the accumulating proton beam. When examining many slices together, this can provide a detailed longitudinal profile. This differs from the wire scanners which sum along the longitudinal profile of the beam. Additionally, a short scan time means that the transverse profiles can be studied across the length of the beam bunch. Finally, Fig. 1 shows the locations of the electron scanner compared to the wire scanners. Its position in the accumulator ring and a 1 Hz scan rate allow the electron scanner to collect large data sets quickly and without requiring operator interruption. It should be noted that each electron scanner profile represents the profile from within a certain point of a single proton beam, while a wire scanner profile represents

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numerous data points each from separate single proton beams. This can allow the electron scanner to more easily detect pulse-to-pulse variations, e.g. centroid jitter or profile variations. The main limiting factors of the electron scanner are the HV transformer, which arcs around 60 kV limiting the peak proton beam intensity that can be scanned, and the aperture sizes, which limit the maximum size of the proton beam that can be scanned [6].

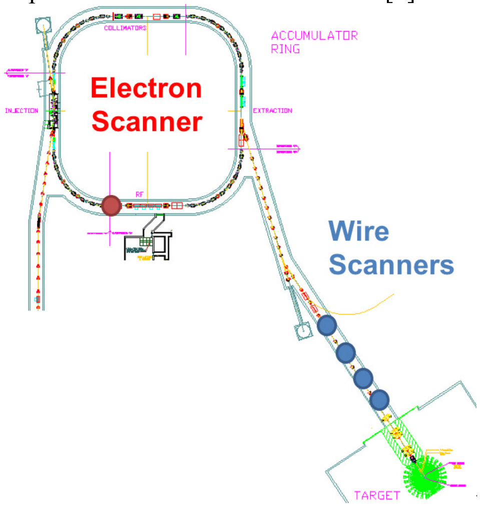

Figure 1: The Electron Scanner, red dot, is located in the SNS Accumulator Ring. The four wire scanners used in previous studies are located in the Ring-to-Target Beam Transport (RTBT), blue dots.

The electron scanner is capable of collecting 40 profiles within the longitudinal period of the accumulator ring. Figure 2 shows an example of how these can be combined to create a 3-dimensional profile of the beam. This 3D profile allows us to quickly see the consistency in transverse profile throughout the bunch. Additionally, the intentionally beamless gap in the ring can be seen as the pink-purple floor. We are able to quickly determine whether the beam has spread longitudinally with respect to other 3D profiles. Prior to examining our main results, an important part of our experiment was to reconfirm that the electron scanner would reasonably reproduce the wire scanner profiles. Figure 3 shows the electron scanner sum profile (left) and wire scanner profile (right) for the same data as shown in Fig. 2. The electron scanner sum profile is produced by summing the beam longitudinally. In this comparison, the profiles are of reasonable similarity in shape and some of the differences may be attributable to the differences in the rotation of the phase space. The horizontal Twiss parameters at the electron scanner are (α_x = 0.78, βx = 3.23) and at the wire scanner shown they are (α_x = 0.83, β_x =6.57). It should be noted that none of the wire scanners have vertical Twiss parameters similar to the electron scanner.

We will use these electron scanner sum profiles for two additional purposes. First, we will use this sum profile to calculate the RMS size. Second, we will assemble an evolution of the transverse beam profile over the duration of the experiment. Thus, each profile evolution will display the change in profile during both the accumulation and storage of the beam. However, the profile evolution will only present the sum of the bunch and will not show any longitudinal dynamics.

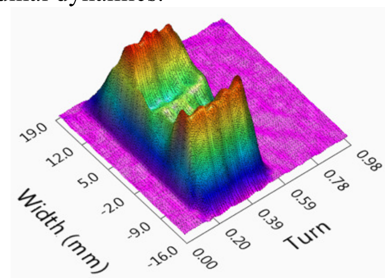

Figure 2: A 3-dimensional profile created from 40 separate horizontal profiles taken using the electron scanner. The horizontal profile width is shown in millimeters along the left axis, while the longitudinal position of the profile within a single turn is shown on the right axis.

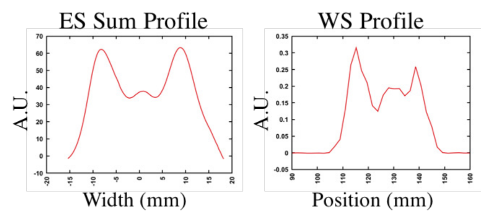

Figure 3: Comparison of an electron scanner sum profile (left) and wire scanner profile (right). The difference in profile could be attributed to the minor difference in Twiss parameters between the two diagnostics.

SIMPLIFIED ACCUMULATION EXPERIMENT

Our motivation is to create an experiment with a simplified accumulation and beam dynamics that will allow us to explore the effects of tune and intensity on coupling while using of the benefits of the Electron Scanner.

To simplify the beam dynamics, we make the following changes to the normal SNS configuration. First, we flat-top the injection kickers to remove the effects of injection painting. Next, we manually short the ring RF to remove any longitudinal effects. In order to make sure the beam remained clear of the extraction gap, the beam was injected to fill only 25/64ths of the ring, which is approximate half the production size. Next, we use the ring sextupoles to zero the chromaticity and better isolate the effects of space charge tune shift. Then, we use the skew quadrupoles located throughout the ring to eliminate any signs of transverse lattice coupling seen by monitoring the turn-by-turn centroid motion of a single bunch injected with offset. Finally, extending the storage period allows us to observe the beam evolution without the complication of added accumulation. Therefore, we set the beam accumulation to 100 turns and allow for 300 turns of storage. This provides us with the opportunity to see any effects during the early evolution of the beam and also study the beam without adding additional charge.

The nominal betatron tunes of the SNS Accumulator Ring are ν_x = 6.23 and ν_y = 6.20. The tune for the first

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configuration was ν = (6.2091, 6.1687), where $\Delta Q \approx$ 0.0404. We refer to this configuration as the "split tune" configuration. The tune for the second configuration was ν = (6.1994, 6.1978), where $\Delta Q \approx$ 0.0016. We refer to this configuration as the "equal tune" configuration.

During SNS production cycles, the size of the beam painted into the ring is optimized to reduce losses throughout the ring while matching the on-target beam requirements. During our experiment, we required a smaller beam size than the normal production size in order to fit the entire beam into the apertures of the electron scanner. The vertical aperture has tighter size limitations than the horizontal beam due to misalignment of the vacuum beam pipe and a larger betatron function, therefore we configured a smaller vertical beam size. The injection size for the split tune configuration was (17.3mm, 6.5mm). The injection size for the equal tune configuration was (17.9mm, 8.5mm). The MAD beta values at the injection spot are (β_x = 10.29, β_y = 11.06). The measured Twiss parameters at the electron scanner are (α_x = 0.78, β_x = 3.23, α_y = -0.72, β_y = 10.21).

The nominal beam energy during our experiment was 939.5 MeV. Due to the configuration of our experiments, our beam intensity is 7.5×10^{12} protons per pulse (ppp) or 1.2 μC. For the equal tune configuration, we also collected data for two lower intensities. In order to preserve the other configuration settings, we lowered the intensity by limiting the output from the H^- source. The two additional intensities are: "medium" intensity of 4.4×10^{12} ppp or 0.70μC, and "low" intensity of 2.5×10^{12} ppp or 0.35μC.

Effect of Tune

The top plot in Fig. 4 shows the evolution of the horizontal and vertical RMS beam sizes for the split tune configuration. Excluding the initial period of accumulation, the RMS sizes remain constant during beam storage from turn 100 to 400. When comparing the RMS sizes, it is important to remember that the betatron values at the location of the horizontal and vertical ES apertures are not equal, and the horizontal emittance of the beam is designed to be larger than the vertical emittance, as noted in the general experiment description. The left column of Fig. 5 shows the profile evolution for the same dataset.

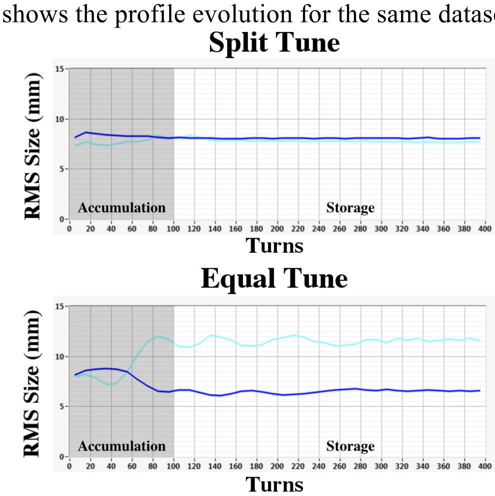

Figure 4: RMS size evolutions for the split tune (top) and equal tune (bottom) configurations for the simplified accumulation experiment. The horizontal RMS size is shown in dark blue and the vertical is shown in light blue.

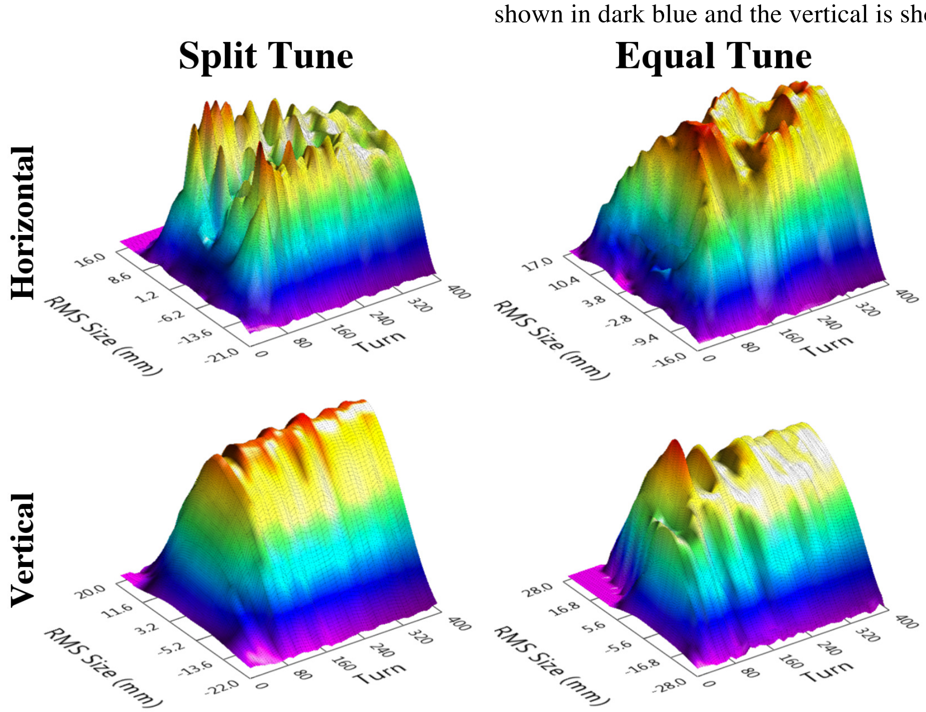

Figure 5: Profile evolutions constructed from electron scanner sum profiles for the simplified accumulation experiment. The horizontal evolutions are shown in the top row and the vertical evolutions are shown in the bottom row. The split tune configuration (left column) follows the expected evolution, while the evolution of the equal tune configuration (right column) displays coupling of the beam size and shape.

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During accumulation, the horizontal profile is hollow due to the injection pattern defined by the flat-topped injection kickers and the choice of betatron tune. While the beam is stored, space charge forces cause the horizontal profile to dilute and the profile becomes rounded. This overall behavior follows our understanding of a beam without coupling and provides a reference for our experiment.

The bottom plot in Fig. 4 shows the evolution of the horizontal and vertical RMS beam sizes for the equal tune configuration. We see an exchange between the two planes within the first 50 turns. By the time the beam accumulation has stopped at turn 100, we see a coupled oscillation between the planes. This oscillation dampens as the storage continues. The right column of Fig. 5 shows the profile evolution for the same dataset. These profiles show that the beam shape oscillates along with the beam RMS size. The horizontal profile becomes peaked midway through accumulation and proceeds to oscillate between peaked and hollow. The vertical profile, to a lesser extent due in part to its limited size, also oscillates. This evolution indicates beam dynamics that are significantly different from the split tune configuration. As mentioned before, the tune of the SNS beam is often changed during production setup to minimize losses in the ring while optimizing the beam size and shape on the target. These dynamics mean: 1) the beam no longer responds as expected to systematic changes in the injection kickers, and 2) the beam size and shape can change significantly if the extraction point is altered.

Effect of Intensity

Figure 6 shows the RMS size evolutions for the three equal tune configurations described in the general experiment description. The full intensity figure (bottom) represents the same case presented in the previous section. An exponentially-damped sinusoid has been fitted starting at turn 105, which is the first data point in the storage period. The profile evolutions, not shown, display oscillations in both planes matching those seen in the RMS size evolutions. The oscillation period for these fits decreases with increasing proton beam. This result shows that space charge forces damp the oscillation in the beam, contrary to our previous expectation.

SNS PRODUCTION-STYLE EXPERIMENT

Our motivation is to study the effects of tune and skew quadrupoles on beams configured with the same settings as the last nominal SNS production cycle. This is an important continuation of our research as the original motivation of our research was the understanding and reduction of coupling effects seen during the regular production operations. In this configuration, we will use the nominal SNS dual-plane injection painting. We will use a dual harmonic ring RF. We will have a natural beam chromaticity. Several of the skew quadrupoles have been turned on. As mentioned before, the skew quadrupoles are designed to allow the reduction of any lattice coupling that might be present and may have been used to reduce nominal beam losses. Finally, we will not store the beam.

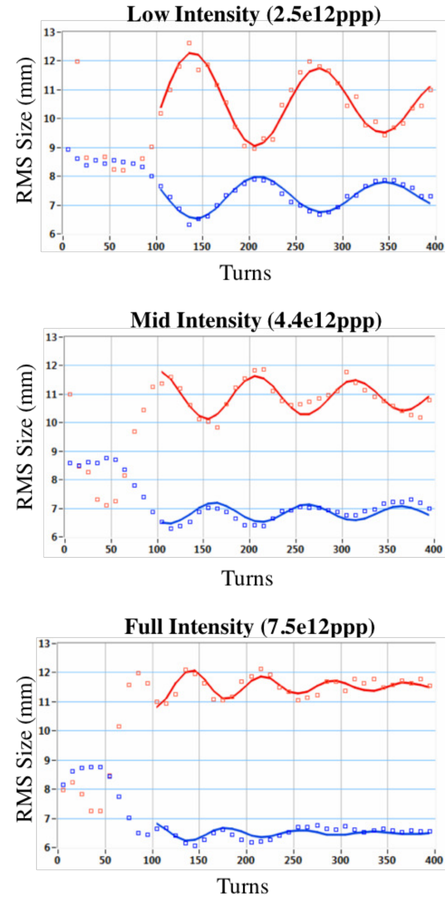

Figure 6: RMS size evolutions for the three equal tune cases of the simplified accumulation experiment: low intensity (top), mid intensity (middle), and full intensity (bottom). The electron scanner data is represented by points and the damped sinusoidal fit is represented by the solid lines. The horizontal RMS sizes are shown in blue and the vertical RMS sizes are shown in red.

The last production settings were for a betatron tune of ν = (6.2043, 6.1623), where $\Delta Q \approx 0.0420$. We refer to this configuration as the "production tune" configuration. The tune for the second configuration was selected to be ν = (6.1640, 6.1667), where $\Delta Q \approx 0.0027$. We refer to this configuration as the "equal tune" configuration. The last production settings were for an injection size of (17.5mm, 8.8mm). We expected the beam size to be symmetric and larger, however we continued with our original intention of using the last production configuration. The nominal beam energy during our experiment was 939.5 MeV. We used 878 turns of injected beam with 98 turns of beam ramping, which equates to a beam intensity of 9.0×10^{13} ppp or 14μC. Due to the larger beam size and intensity, and the restriction in the vertical aperture of the electron profile monitor device, the vertical electron scanner had trouble viewing the entire beam, especially in the last 100 turns. Therefore, only the horizontal data will be presented. However, any coupling effects seen in the horizontal

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RMS size and profile evolutions would be mirrored in the vertical data.

Effect of Tune

Figure 7 shows the RMS size evolution for the two tune configurations for the production style experiment. Both cases show an expected slow increase in RMS size during continued accumulation. Figure 8 shows the horizontal profile evolutions for the production and equal tune configurations, top and middle figures respectively. We can see that while the RMS size evolutions followed similar trends, the profile evolutions are not similar. The production tune profiles maintain some amount of hollowness even at the end of the evolution, however the equal tune profiles quickly become diluted.

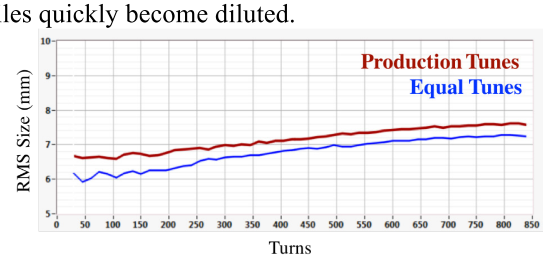

Figure 7: RMS beam sizes for the production tune (red) and equal tune (blue) configurations for the production style experiment.

Effect of Skew Quadrupoles

The skew quadrupoles are used in the production configuration in order to reduce any coupling present in the beam. This correction is done by monitoring the turn-by-turn oscillations of a single injected pulse and adjusting the skew quadrupole strengths. It was our expectation that using the skew quadrupoles would reduce the effects of coupling seen in the final distribution of the beam.

Figure 9 shows the RMS size evolution for the equal tune configurations with and without skew quadrupoles. While the general evolution of the RMS size is similar, the configuration with skew quadrupoles displays an additional level of coupling. By comparing the middle and bottom figures in Fig. 8, we can see that this additional coupling clearly appears as a rapid change in the shape and peak intensities of the profile evolution. Contrary to our expectations, the skew quadrupoles did not eliminate coupling and had a small effect on the beam evolution compared to the impact of the tune change.

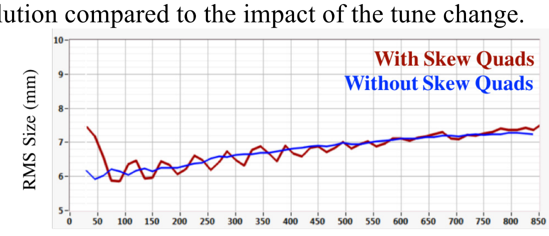

Figure 9: RMS beam sizes for the equal tune configuration with skew quadrupoles (red) and without skew quadrupoles (blue) for the production style experiment.

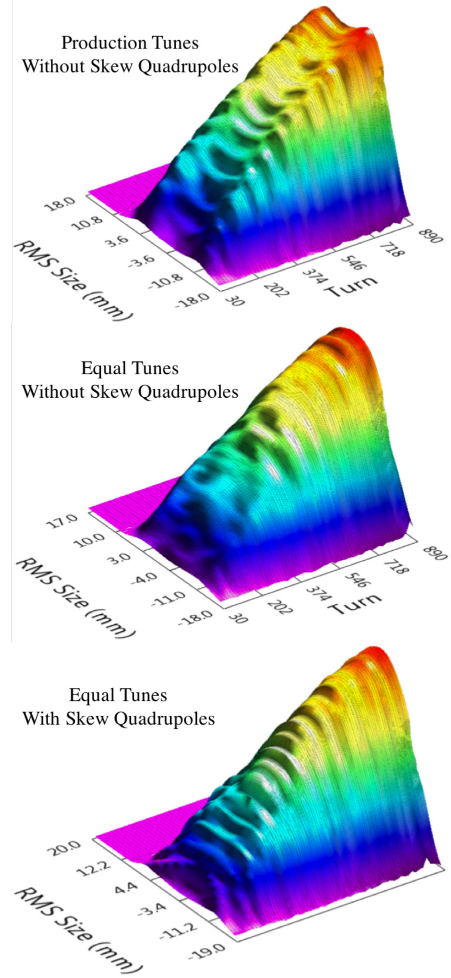

Figure 8: Horizontal profile evolutions are shown for the production style experiment.

CONCLUSION

We have presented the results of the first major physics study using the SNS Electron Scanner. We have demonstrated the following. First, an equal tune beam configuration produces coupling in RMS size and beam shape. Second, increased beam intensity dampened oscillations, instead of amplifying them as we expected. Finally, skew quadrupoles have been used to agitate the coupling, whereas we expected the effect to be the reduction of the coupling. Originally, we thought this was a Montague Resonance however these results imply an alternative source of coupling in the SNS Accumulator Ring, most likely linear lattice coupling.

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