OBSERVATIONS OF SPACE CHARGE EFFECTS IN THE SPALLATION NEUTRON SOURCE ACCUMULATOR RING*

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Abstract

The Spallation Neutron Source accumulator ring was designed to allow independent control of the transverse beam distribution in each plane. However, at high beam intensities, nonlinear space charge forces can strongly influence the final beam distribution and compromise our ability to independently control the transverse distributions. In this study we investigate the evolution of the beam at intensities of up to ~8x10^{13} ppp through both simulation and experiment. Specifically, we analyze the evolution of the beam distribution for beams with different transverse aspect ratios and tune splits. We present preliminary results of simulations of our experiments.

INTRODUCTION

The SNS ring compresses a 1 ms beam of up to 1.5x10^{14} 1 GeV protons to a short 1 μs pulse for delivery to a liquid mercury target for neutron spallation [1]. Independent control of the transverse beam distributions is desired to facilitate meeting the operational requirements of the SNS liquid mercury target. The target design requirements are that the beam fill a 70 mm by 200 mm spot with a beam profile that is uniform in both transverse planes and has a peak density of less than of 2.6x10^{16} protons/m^2 for a 1.5 MW beam. It has been previously observed [2] that at high beam intensities the final accumulated beam distributions in each plane depend on the initial distribution in the alternate plane, such that independent control between the planes is lost. However, the effect is only intermittently observed. In other words, we observed space-charge-induced transverse beam coupling for certain beam configurations. We present here current results from experiments and simulations from ongoing efforts to understand transverse space charge coupling in the SNS Accumulator Ring. In this study we investigate the coupling dependence on intensity, tune split, and initial beam distribution for unpainted beams.

Experimental wire scan data was collected during beam development shifts over the past year for various beam configurations. The experimental data was processed and combined with simulations of the experiments using the ORBIT code [3]. In the first section of this paper, we present a summary of the experimental observations. Following this, we discuss our preliminary simulation results and future directions.

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EXPERIMENTAL PARAMETERS

To simplify the beam dynamics, experiments were conducted with flat-topped injection kickers, e.g., no injection painting. The skew quadrupoles throughout the ring were used to nullify any existing lattice coupling. While the nominal beam energy changed from shift to shift, the beam energy was typically on the order of 910 MeV. The nominal betatron production tune of the SNS Accumulator Ring is ν_x = 6.23 and ν_y = 6.20. For our experiments, both betatron tunes were varied between 6.15 and 6.25. The nominal production intensity is ~8x10^{13} protons per pulse (ppp) to target. The intensity was varied from ~2x10^{12} ppp to ~8x10^{13} ppp by decimating the beam such that the number of storage turns were the same for all intensities. Profiles were measured for the fully accumulated beam using four wire scanners in the Ring to Beam Target (RTBT) transport line. For our experiments, we formed two types of beams: those that were symmetric, equal aspect ratio, and those that were asymmetric as defined by the beam size at low intensity. Specifically, the symmetric beam had equal beam size in x and y. The asymmetric beams typically had a y distribution that was approximately half-sized compared to the symmetric distribution. The horizontal beam size remained fixed. Coupling was investigated by checking for profile changes in the horizontal plane when the beam distribution was altered in the vertical plane.

Dependence on Aspect Ratio and Intensity

In our experiments, we used decimation, the process of skipping injected pulses during accumulation to achieve a lower intensity beam, to maintain the same beam accumulation scenario while varying the beam intensity. By altering the injection kickers in the vertical plane, we were able to decrease the low intensity vertical beam size by half without changing the horizontal distribution. Figure 1 on the next page shows the horizontal profiles of the beam for the two different beam distributions at three different intensities. The horizontal beam profiles for both distributions are identical at low intensities. As the intensity increased, greater dilution is observed in the symmetric beam cases despite a higher beam density in the asymmetric cases. This is counter-intuitive since one would normally expect that beam density would play a larger role in dilution than beam shape. The fact that the lower density beam suffers more dilution points to another physical process, such as coupling. Furthermore, the observation of higher dilution in symmetric beams is particularly relevant since our production beam configuration is near symmetric, and therefore may also be in a region of high coupling.

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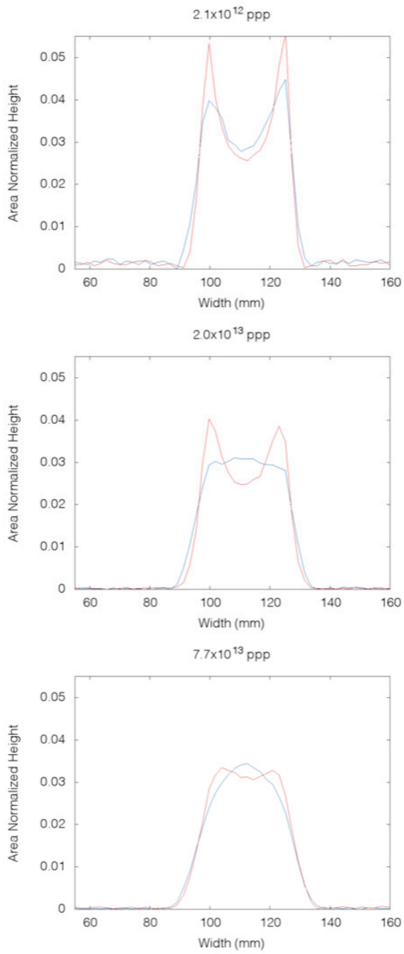

Figure 1: Horizontal beam profiles from wire scan data. The symmetric beams are blue and the asymmetric beams are red. These plots are for beams with $\nu_x = 6.22$ and $\nu_y = 6.17$ and intensities 2.1×10^{12} ppp, 2.0×10^{13} ppp, and 7.7×10^{13} ppp, respectively.

Tune Split

Using the Ring Optics Control and Setting (ROCS) application [4], we changed the betatron tunes in a wide range of settings. The betatron tunes for the beam distributions shown in Fig. 1 are $\nu_x = 6.22$ and $\nu_y = 6.17$. Figure 2, to the right, shows the same experiment as Fig. 1 with tunes now set to $\nu_x = 6.22$ and $\nu_y = 6.21$. By comparing Fig. 1 with Fig. 2, we can see that beam evolution has only a weak dependence on tune split. However, some recent data shows that the tune split can have some impact on beam evolution in certain circumstances. The appearance of some tune dependence might be due to the value of one or both tunes, or the magnitude of separation between the tunes. We do not currently understand why the tune split would have an effect in some cases and not in others.

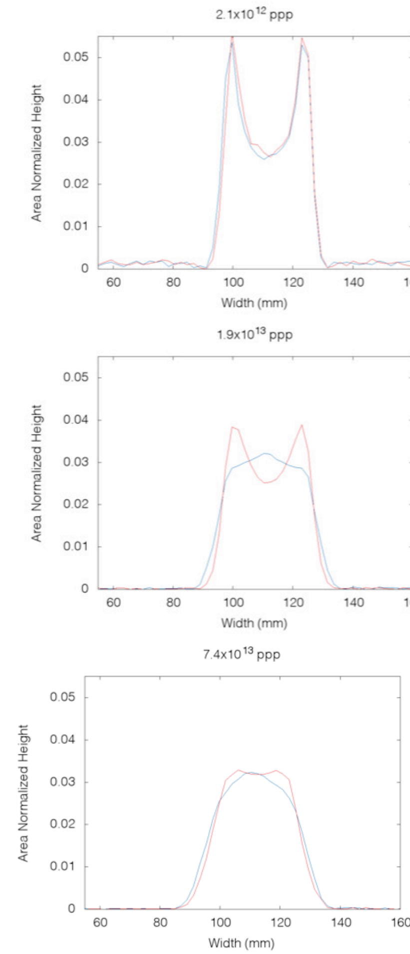

Figure 2: Horizontal beam profiles from wire scan data. The symmetric beams are blue and the asymmetric beams are red. These plots are for beams with $\nu_x = 6.22$ and $\nu_y = 6.21$ and intensities 2.1×10^{12} ppp, 1.9×10^{13} ppp, and 7.4×10^{13} ppp, respectively.

SIMULATION

Preliminary exploratory simulations of the experiments have been conducted using the ORBIT code. For all simulations, injected beams consisted of 430 macro particles per injected pulse, providing a total of 298,850 macro particles after a complete accumulation of 695 turns. This number of macro particles is sufficient for numerical convergence. The simulations include turn-by-turn injection, injection foil scattering, symplectic nonlinear tracking through the ring lattice, RF bunching, and longitudinal and transverse 2.5D space charge. Fringe field effects were not used.

Benchmark

For each experimental measurement, we configured the beam in the simulation to match the experimentally measured RMS emittance at low intensity where space charge effects are not significant. Additionally, the wire scan profiles were checked against the experimentally measured profiles. It should be noted that an exact agreement between the wire scan profiles was not

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expected and that our primary focus was that the shape of the profiles be similar. In future work, we intend to tighten this criterion to produce a stronger profile benchmark.

Beam Distributions

Results from simulations provide interesting insight into the possible causes of higher dilution of symmetric beams when compared to asymmetric beams. Figure 3 below shows the second order transverse moments, normalized to the beta function, for the simulation of the full beam accumulation for the experimental measurements shown in Figs. 1 and 2. The coupling is most pronounced in the symmetric beam with small tune split, shown in blue. For both symmetric beams, the transverse moments exchange amplitudes and beat against each other. However, the asymmetric beams show almost no coupling between the transverse moments during accumulation.

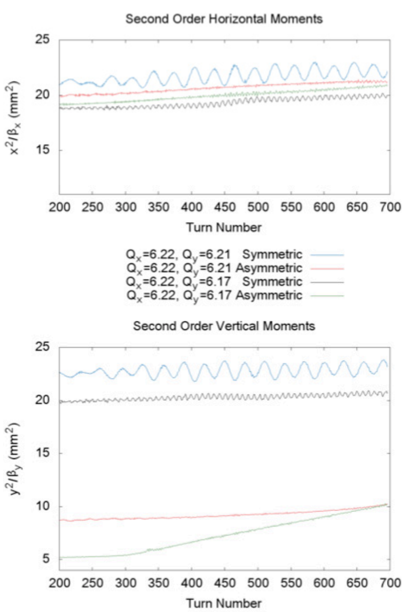

Figure 3: Simulated second order moments for ~7x10^{13} ppp intensity beams at a single location in the ring. The top plot is of the horizontal moments and the bottom plot is of the vertical moments. The scales of the vertical axes are similar though not exactly equivalent.

Figure 4 to the right shows the final transverse beam density corresponding to high intensity settings for Fig. 2. The asymmetric beam has maintained a relatively hollow shape despite high beam densities while the symmetric beam has become rounded and dilute. From animations of these beams throughout the later portion of accumulation, we can see a higher density region in the symmetric beam that rotates. While these effects have not been confirmed experimentally, this coupling would explain the quick dilution of the symmetric beams observed in the experiments.

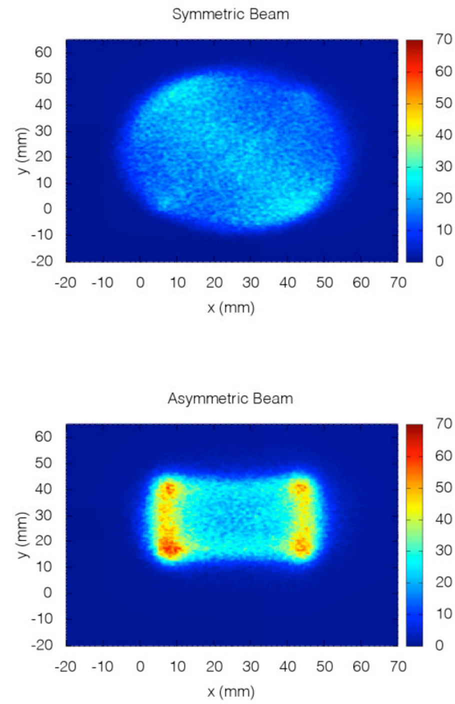

Figure 4: Simulated beam distributions of two 7.4x10^{13} ppp beams at turn 600 with ν_x = 6.22 and ν_y = 6.21. The top distribution is of a symmetric beam and the bottom plot is of an asymmetric beam. The color scales have been held constant to emphasize the difference in beam densities.

SUMMARY

A surprising result of our research so far is the discovery that symmetric beams will suffer from more intense coupling than asymmetric beams with higher beam densities. Further work is planned, including determining a better method of benchmarking our simulations to our experimental results, investigating a theory that describes these effects, performing experiments with zero chromaticity to help understand space charge tune shift dependence, and performing experiments with painted beam distributions to investigate the presence of coupling in beams that are more in keeping with production beams.

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