STATUS OF HIGH INTENSITY EFFECTS IN THE SPALLATION NEUTRON SOURCE ACCUMULATOR RING*

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Abstract

The 248 meter Spallation Neutron Source accumulator ring has accumulated up to 1.55e14 protons. At this intensity, collective effects contribute significantly to the beam dynamics. Here we present recent observations of collective effects in the SNS ring, with emphasis on space charge effects and e-p instabilities.

INTRODUCTION

The Spallation Neutron Source ring was designed to accommodate a high intensity proton beam on the order of 1.5e14 ppp. In this intensity regime collective effects strongly influence the beam dynamics. These effects were extensively studied during the design phase of the ring and measures were taken to ensure that they would not threaten high intensity production beam operations [1]. Specifically, the ring is equipped with a two-stage collimation system, titanium nitride coating on most vacuum chambers, one section of solenoidal windings, and most recently, a transverse feedback system.

The SNS accelerator is routinely operated with beam intensities on the order of 1.2e14 ppp to support 1 MW production beam operations. Up to 1.55e14 ppp (1.5 MW equivalent) has been demonstrated during dedicated high intensities studies. Collective effects did not limit the beam intensity in either case. In practice the beam intensity in the ring is limited by more mundane issues, such as equipment limitations or the facility mission which prioritizes availability over beam power.

Though they are not intensity limiting phenomena at present, a multitude of collective effects do exist in the ring, both during routine operation and during dedicated high intensity studies. Some of these effects were anticipated, and some were not. In this manuscript we describe the most recent observations of collective effects and discuss the impact, if any, on production beam operation. The first section of the manuscript reports on space charge effects, while the second is focused on e-p instabilities. Finally, we end with an update on the status of simulation work.

SPACE CHARGE EFFECTS

In the first few years following the commissioning of the ring in 2006, the thrust of the accelerator physics effort was aimed at ramping up the beam power and troubleshoot key equipment issues [2]. Only recently has the focus shifted to investigating the beam dynamics. Because of the limited availability of beam physics shifts, much of the data presented in this section was taken for purposes other than to study space charge; therefore machine conditions may not have always been ideal. Nonetheless, the data still serves as a good foundation for understanding the impact of space charge on the beam. In the last several months a few dedicated space charge experiments have been executed, and we present those as well.

For a full intensity beam of 1.5e14 ppp, the incoherent space charge tune shift is ~0.15. The design tune of the machine is ν_x=6.23, ν_y=6.20, which places the high intensity beam safely away from the ν=6.0 half integer resonance. In practice, the bare tune of the lattice is often changed during routine loss tuning, and production beams have been operated with various tune points in the range of 6.16 to 6.24.

In order to minimize foil hits, the injected beam is painted in both planes in an uncorrelated fashion with a waveform that varies as the square root of the turns. This yields a hollow beam profile at low beam intensities.

Profile Dilution

At high beam intensities, space charge dilutes the beam, resulting in flatter profile distributions. This effect is expected and even desired, since flat profile is more ideally suited for the beam target. The beam evolution during the accumulation of a 1 MW production beam is shown in Fig. 1. This data was taken using the ring electron profile scanner [3], a non-interceptive profile measurement device with very fine time resolution. In the Fig., profiles are shown every 100th turn between turns 200 and 800, with a 25ns time resolution. The profiles begin hollow, but significant profile dilution is observed already by turn 300, which corresponds to ~2.0e13 ppp.

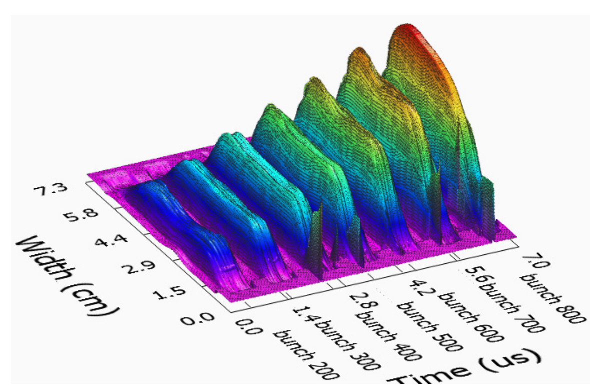

Figure 1: Evolution of a 1e14 ppp beam during beam accumulation. Beam is shown for turns 200, 300, 400, 500, 600, 700, and 800, with a 25ns time resolution within a turn.

To isolate the space charge effect, it is useful to fix the injection painting scheme and vary the beam intensity by

* ORNL/SNS is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725

decimation. Profile measurements taken in this fashion are shown in Fig. 2. As expected, at low beam intensity the profiles are hollow, and at high beam intensities they are flat or even Gaussian. More surprising is the amount of dilution observed at intensities as low as ~2e13 ppp. This is consistent with the observations from Fig. 1. The space charge effect has significant influence over the beam distribution at intensities a full order of magnitude lower than the design intensity.

No extended tails are seen on the wirescan data, though it's possible that they exist and fall below the noise level of the device.

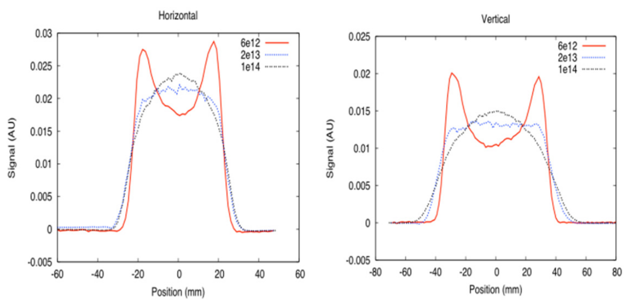

Figure 2: Horizontal and vertical profiles of the beam after extraction from the ring for three different beam intensities but the same painting scheme.

A four wire scanner station near the end of the Ring to Beam Transport (RTBT) line allows rms emittance measurements of the ring beam. The result of this measurement for the experiment shown in Fig. 2 indicates that the emittance is nearly the same for all intensities. This is not a surprising result since the space charge dilution amounts to a re-distribution of particles, which does not necessarily affect rms quantities. For the SNS beam, the raw profiles are often a better measure of space charge effects than derived rms quantities.

Intensity Dependent Transverse Coupling

Recently, an intensity-dependent transverse coupling has been identified in the ring beam profiles. The phenomena was serendipitously observed while trying to adjust the horizontal beam size on the target. The injection kickers were changed in the horizontal plane, and a change in profile was observed in both horizontal and vertical planes. After lowering the beam intensity by decimation, the coupling vanished and the profiles were independently adjustable. At a later date, the coupling was observed for a 5e13 ppp beam, but vanished when the betatron tune split between planes was increased. This case is shown Fig. 3. The top plots show the horizontal and vertical profile response of the beam when the tune split was 0.10, and the bottom plots shows the response when the tune split was 0.03.

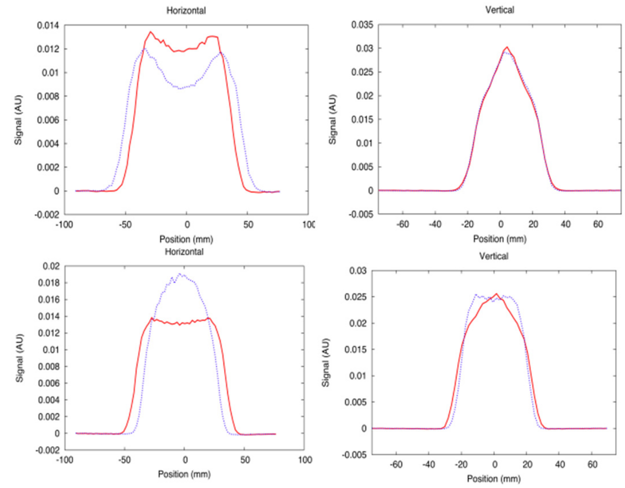

Figure 3: Horizontal and vertical profiles (top) for two different horizontal injection kicker settings. The corresponding profiles when the tune split was 0.1 (top) and 0.03 (bottom).

Following these initial observations, an effort was made to map out the region of coupling with the same technique of varying the injection configuration in one plane and looking for a profile change in the alternate plane. Fig. 4 and 5 show the results of these experiments, which took place in June 2010 and March 2011, respectively. In the first experiment, the coupling was demonstrated to depend on both tune split and intensity. Unfortunately due to time limitations only a small set of data points were taken. In an effort to produce a more complete data set, the experiment was repeated in March of 2011. However, for this case the character of the coupling had changed, and only a intensity dependence was observed. Why the behavior shifted between experiments is unclear. The only identifiable difference between the experiments was the closed orbit in the injection region. Both the strength of the dipole magnet fields and the trajectory through those fields had changed, indicating that the beam would have sampled the fields differently. The chicane magnets are known to have large multipole components which perhaps can drive resonances when the intensity is high enough. This phenomena will be further explored in the future.

It is clear that production beam operations have at times ensued with a coupled beam state. The coupling has never limited beam operations, nor has it caused noticeable complications with tuning. However, the loss of independent control between the transverse planes is not ideal.

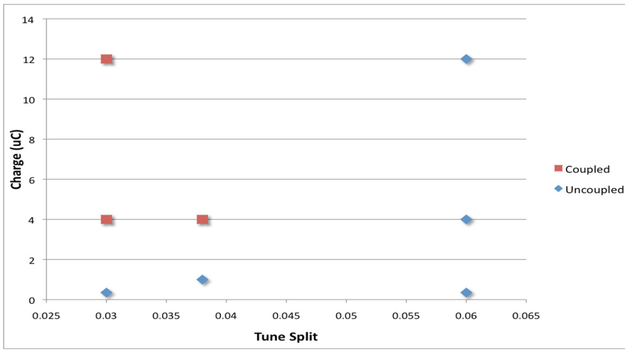

Figure 4: Distribution of coupled and uncoupled states of the beam, versus tune split and accumulated beam charge. Data from June 2010.

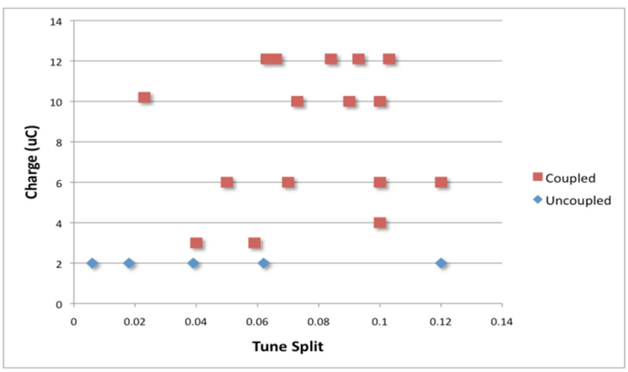

Figure 5: Distribution of coupled and uncoupled states of the beam, versus tune split and accumulated beam charge. Data from March 2011.

Half-Integer Resonance Experiments

Another dedicated space charge experiment that has been executed explored the affect of approaching the vertical half integer resonance at ν_y=6.0. In this experiment, profiles were recorded for a 1.2e14 ppp, production style beam with tunes ν_x=6.20, ν_y=6.16, and with tunes ν_x=6.20, ν_y=6.10. Because the effect of the integer closed orbit resonance is strong within the vicinity of ν_y=6.0, care was taken to ensure that the closed orbit at the injection foil and thus the painting scheme was identical for both cases. The profiles were recorded using an RTBT wire scanner, set to high gain and low gain to ensure that any extended tails above the noise floor would be revealed. No such tails were produced. However, as shown in Fig. 6, significant core beam broadening is observed in the vertical plane at the lower tune value. The horizontal profiles did not change, indicating that there was no coupling in this configuration.

Future experiments are being planned to further explore this resonance.

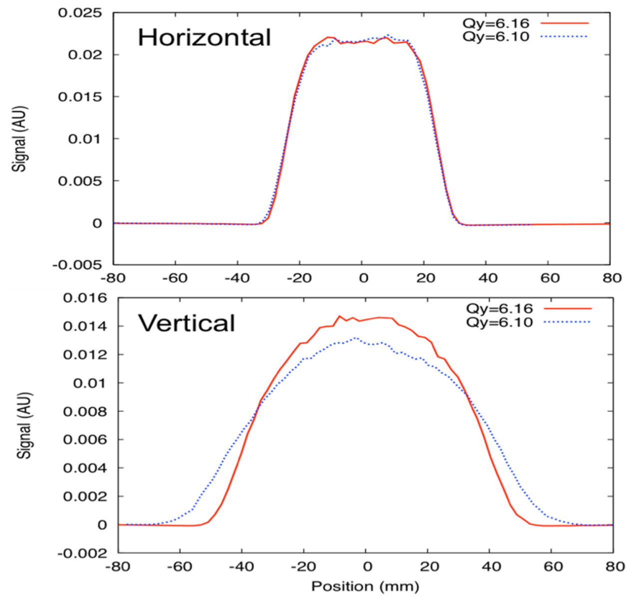

Figure 6: RTBT wirescanner profiles, for a 1.2e14 ppp beam with vertical tunes Qy=6.16, and Qy=6.10. The horizontal tune was fixed at Qx=6.20. top.

INSTABILITIES

The majority of instabilities seen in the SNS ring have been observed during dedicated instability studies, where a high intensity beam is accumulated in the ring for off-nominal conditions. In total, three types of instabilities have been observed: 1) e-p instability (20 – 100 MHz), 2) transverse instability from extraction kicker impedance (~6 MHz), and a resistive wall instability (~200 kHz). Recently work has focused on the e-p instability. Information on the other two instabilities can be found in previously published work [4].

e-p Instability in the SNS Ring

To date, the e-p instability does not limit the production beam intensity in the SNS ring. All major e-p instabilities have occurred during dedicated studies where the instability is intentionally excited. A typical instability has a frequency in the range of 20 – 100 MHz. Other parameters of the instability are not as well defined. Specifically, the location of the instability within the bunch (leading or trailing edge), the plane in which it occurs (horizontal or vertical), and the threshold intensity all vary on a case by case basis. It is difficult to identify a repeatable, one-to-one relationship between the instability threshold and the machine control parameters, including the ring RF system. Furthermore, the instability is not generally consistent with a Landau damping law, as demonstrated Fig. 7. In this experiment, the instability threshold was measured against the first harmonic RF amplitude and no correlation was found. Correlations have been observed in other experiments, but the nature of the relationship varies from one case to the next.

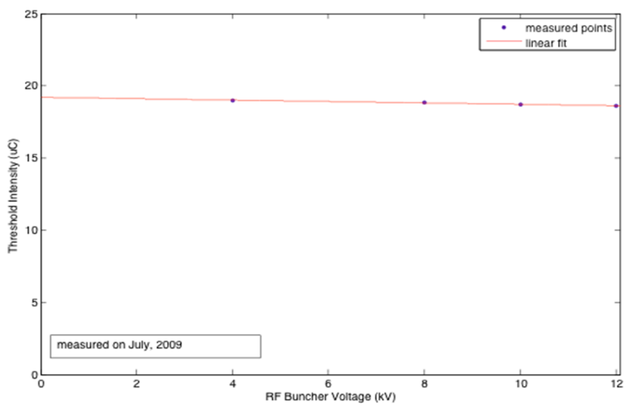

Figure 7: e-p instability threshold versus RF 1st harmonic amplitude.

Though the instability is not well-correlated with any single machine parameter, it is consistently sensitive to the bunch profile of the beam. Multiple experiments have demonstrated that a flat bunch shape is advantageous for suppressing the instability, and a peaked profile with long trailing edges encourages the instability. As an example, Fig. 8 shows a case where the 2nd harmonic RF was varied to flatten the bunch profile. The instability which had been present disappeared. In other cases, not shown here, the 1st harmonic RF was lowered to flatten the bunch profile, and the instability again vanished [5].

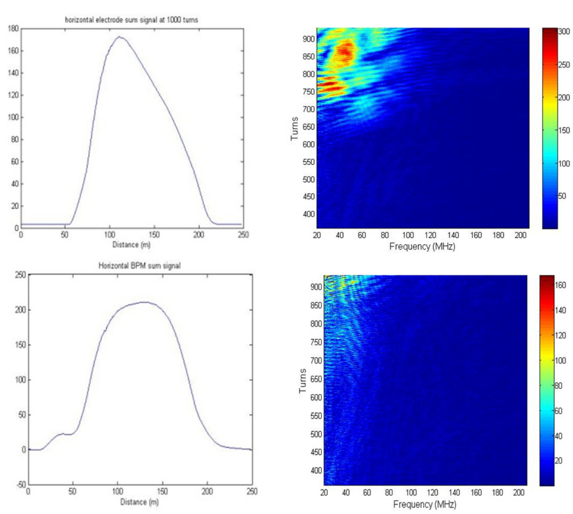

Figure 8: The bunch shape and corresponding frequency spectrum for two beams with a 35 degree difference in the 2nd harmonic RF phase.

For the ring dual harmonic RF system, there are four parameters in play when adjusting the bunch shape: the 1st harmonic RF amplitude and phase, and the 2nd harmonic RF amplitude and phase. Various combinations can be used to increase or decrease the bunch flatness, and hence the relationship between the instability and any one parameter varies from one machine configuration to the next. Thus far, it has always been possible to extinguish the instability using the RF system. Since the first harmonic is generally used to keep the beam gap clean, the second harmonic is a good candidate for suppressing the instability, should it ever become problematic.

Trace levels of e-p activity have been observed during production beam operation. The activity is very low level and does not interfere with beam operations. Fig. 9 shows the BPM signals versus turn for a March 2011 production beam with 9e13 ppp. As seen in the Fig., there is activity near the end of accumulation in the typical e-p frequency range. Fig. 10 shows BPM signals for a portion of a single turn of beam near the end of the accumulation cycle. The top plot in the Fig. shows the bunch intensity, and the bottom plot is the beam position in units of mm. As shown, the induced oscillation is less than 0.5 mm. The activity could be suppressed with the RF system. However, the RF is tuned to minimize the ring losses in a global sense without regard to specific phenomena. If the optimized loss state includes low level e-p activity, then this is considered acceptable for production beam operation.

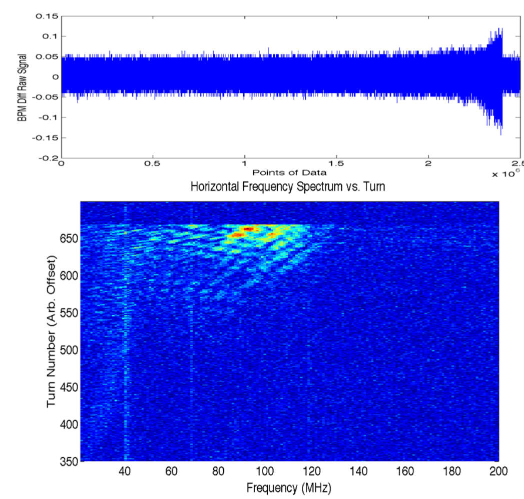

Figure 9: Raw BPM data (top) and the processed data for frequency versus turn.

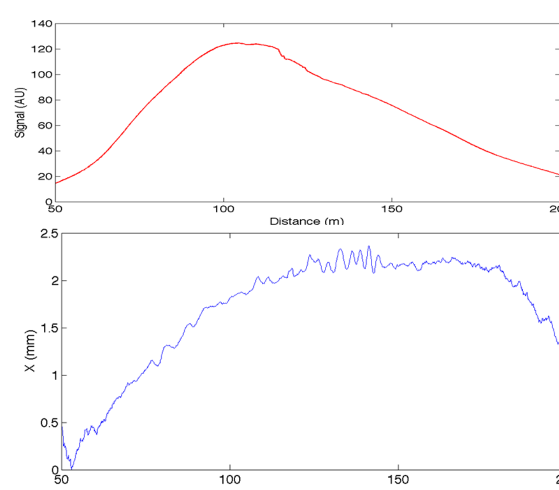

Figure 10: Bunch intensity and position for a portion of a single turn of beam near the end of the accumulation cycle for the beam shown in Fig. 9.

A promising future candidate for suppressing the e-p instability is the newly configured transverse feedback system in the ring. The system has recently demonstrated success in suppressing a low-level instability which occurred during production [6]. Fig. 11 shows the instability before and after feedback. Studies to test the effectiveness of the feedback system on larger instabilities are forthcoming.

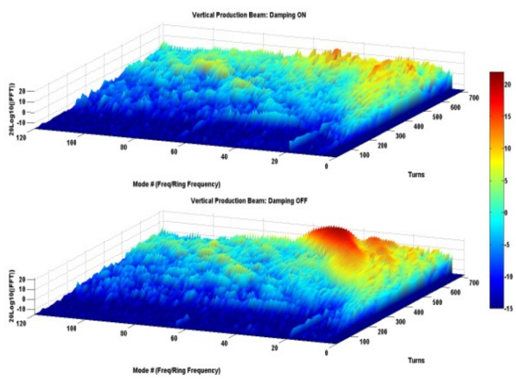

Figure 11: Data for a Feb 2011 production beam, showing the vertical plane frequency space during accumulation for beam with (top) and without (bottom) the transverse feed back system on.

BENCHMARK EFFORTS

Simulations are an important aspect of the high intensity research effort, enabling a more detailed view of the physics than can be realized from experiments. The initial goal of the ring simulations effort is to benchmark the code against machine data to ensure reliability of the models. The ORBIT code [7] has been used to benchmark ring beam profiles for various machine configurations, and also to simulate the extraction kicker transverse impedance. Both efforts have been successful. The extraction kicker benchmark is discussed in detail in reference [8]. Shown below in Fig. 12 is an example of a typical profile benchmark for painted beam at both low and high intensity. There is good general agreement and the code reproduces the profile dilution at high intensity, though it underestimates the effect somewhat. The benchmark is certainly sufficient to qualify the ORBIT code for use in studying space charge effects in the ring.

SUMMARY

The high intensity SNS ring beam exhibits several interesting collective effects. Presently these effects do not limit the beam intensity of the ring. Table 1 below gives a summary of the collective effects observed in the SNS ring, and the impact, if any, on production beam operations.

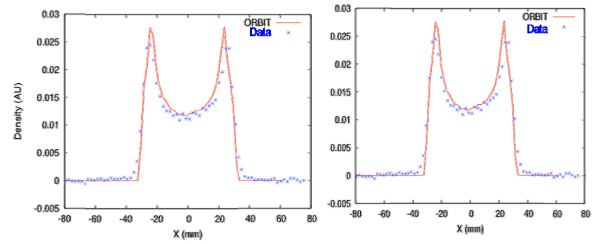

Figure 12: Benchmark of horizontal beam profiles for a painted beam with 2.2e12 ppp (left) and 7.5e13 ppp (right). The red line is the simulation, and the blue dots are the measurement.

Table 1: Summary of Collective Effects

Phenomena	**During Production?**	**Impact**
Profile dilution	Yes	Results in flatter beam on target
Transverse coupling	Sometimes	Loss of independent control between planes.
Resonance broadening	No	N/A
e-p	Yes (trace levels)	No impact
Extraction kicker instability	No	N/A
Resistive wall instability	No	N/A

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