INSTABILITY OBSERVATIONS IN THE SPALLATION NEUTRON SOURCE ACCUMULATOR RING*

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Abstract

The 248 meter Spallation Neutron Source accumulator ring is designed to operate with a beam intensity of 1.5e14 ppp. A major concern for high intensity operation is the possibility of beam instabilities. Recently a series of experiments have been performed to systematically map out the instability parameter space. Beam instabilities have been measured versus betatron tune, beam intensity, and ring RF voltage. The results of these studies are presented here.

INTRODUCTION

The Spallation Neutron Source (SNS) accumulator ring is designed to compress a 1 ms long, 1 GeV H^- beam to a single 695 ns proton bunch for delivery to a liquid mercury target for neutron spallation. Full power operation will require 1.5e14 ppp to be accumulated in the ring at a repetition rate of 60 Hz, yielding 1.4 MW of beam power. A major concern for high intensity operation is the possibilities of beam loss due to electron-proton (e-p) instabilities [1]. Although simulations and calculations done during the design stages of the ring did not predict that e-p instabilities would be a concern for nominal full-power beam operation, a number of safeguards were installed in the ring to help ensure this result [2]. The majority of the vacuum chamber was coated in TiN to reduce secondary electron yields, solenoidal windings were placed in the drift section of the collimation region, electron clearing electrodes were installed near the injection stripper foil, a robust dual-harmonic RF system was incorporated to keep the beam gap clean, and finally the BPMs in the ring were built to be configurable as clearing electrodes through the use of an optional bias.

The SNS project is currently in the middle of an aggressive campaign to ramp the beam power to the 1.4 MW design value. To date, the SNS has operated with up to 540 MW of beam power during neutron production runs. For the present 890 MeV beam, this translates into routine 60 Hz operation with approximately 6e13 ppp of bunched beam in the ring and no limiting beam instabilities. During dedicated beam physics studies conducted at much lower repetition rates, up to 1.3e14 ppp of beam has been accumulated in the ring. Many of these experiments were conducted with off-nominal machine conditions, and a number of instabilities were observed, including e-p instabilities [3].

Prior to 2008, the majority of instability studies conducted were for a coasting beam configuration. Recently, the available beam intensity has become sufficient for inducing bunched beam instabilities, a state more relevant to SNS high power operations.

On three separate occasions in 2008, dedicated high intensity experiments were performed to systematically scan the parameter space for bunched beam e-p instabilities. In February of 2008, 20 uC (1.3e14 ppp) of beam was accumulated in the ring in 1000 turns. In April, 10 uC of beam was accumulated in 1000 turns, and the beam intensity and vertical betatron tune were scanned. Finally, in July, 8.5 uC was accumulated in 500 turns and then stored for 2000 turns. The first harmonic RF was varied to induce instabilities. The results of each of these studies are described in the section below. A comparison of the overall instability trends and discussion of possible issues is given in the last section.

EXPERIMENTAL RESULTS

February 2008 Dataset

In February 2008, the SNS linac was set up for a 1000 us long pulse train, and 1.3e14 ppp were accumulated in the ring in 1000 turns with a nominal painting scheme and optimized, dual harmonic RF settings. This is the highest bunched beam intensity achieved in the SNS ring to date.

During a normal production beam tune up, the machine configuration is carefully tuned to minimize beam loss. In contrast, the limited time available for high intensity beam studies demands a rapid alteration of the machine state with only minimal tuning, leading to very high beam loss in the ring. Thus although these studies are useful for inducing and studying instabilities, they are not in general a good measure of instability thresholds for cleanly-tuned production beams.

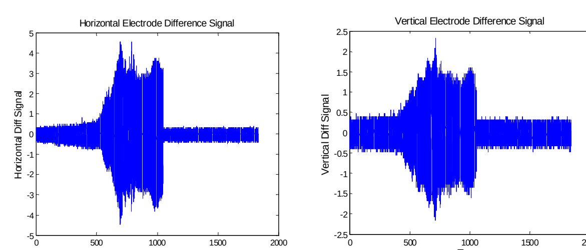

Figure 1: Raw BPM difference signal (arbitrary units) versus accumulation turn number.

Figure 1 shows raw BPM difference signals for the horizontal and vertical planes for the 20 uC beam state described above. Instabilities are clearly visible in both planes. As shown in the spectral waterfall plot of Figure 2, the instability has a frequency of 60 – 80 MHz and begins near 550 turns of accumulation in the vertical plane and 650 turns in the horizontal plane. This frequency range is characteristic of an e-p instability for the SNS ring [4].

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In order to provide a physical basis for comparing one experiment with another, it is useful to consider the amplitude of the instability oscillation. Figure 3 shows the BPM vertical difference signal for the 20 uC beam, in units of millimeters, at the peak of the instability activity around 700 turns. The gap region has been artificially set to a constant level in order to prevent dividing by zero in the BPM signal conversion. As seen in the figure, the instability occurs on the trailing edge of the beam and is about 2.5 mm in amplitude. The maximum amplitude of the instability oscillation is plotted over the accumulation time in Figure 4. The vertical instability proceeds the horizontal by about 100 turns, but ultimately the horizontal plane has a stronger instability and reaches a higher amplitude of oscillation.

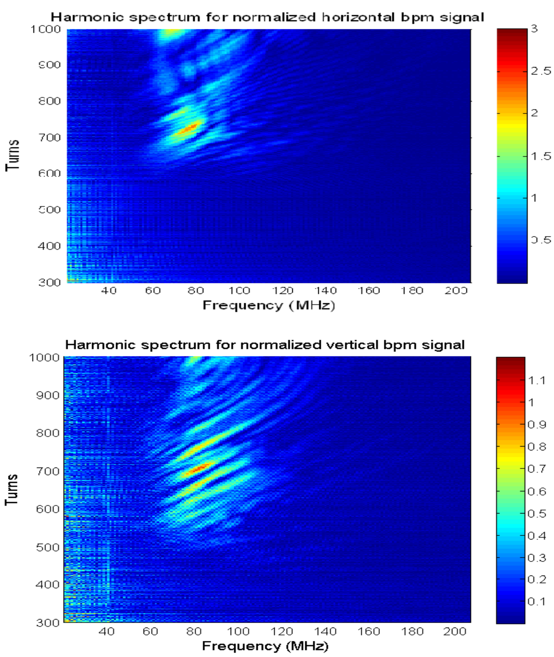

Figure 2: Turn by turn evolution of the frequency content of the instability for the horizontal plane (top) and the vertical plane (bottom).

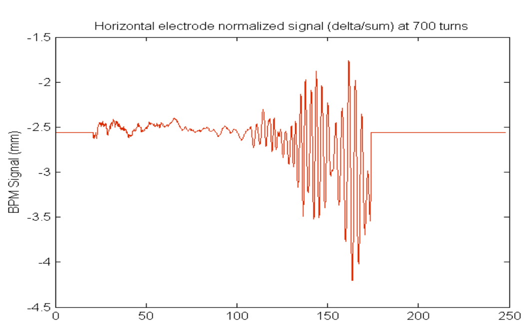

Figure 3: BPM difference signal in millimeters along the bunch length. The gap region of the beam has been set to a constant value.

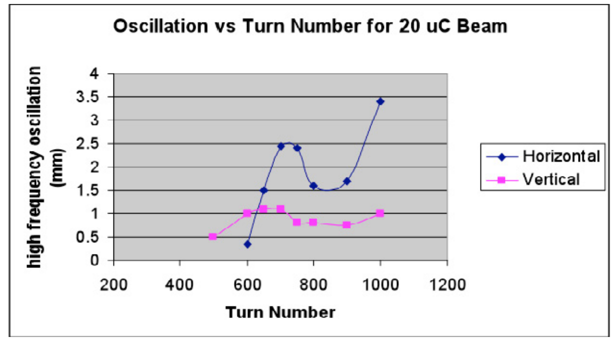

Figure 4: Maximum amplitude of the high frequency oscillation versus accumulation turn number.

April 2008 Dataset

In April 2008, a 10 uC beam was accumulated over 1000 turns, again with a nominal painting scheme and optimized RF settings. The vertical betatron tune was scanned from 6.24 to 6.16 while keeping the horizontal tune roughly constant at 6.19. The maximum amplitude of induced high frequency oscillations during the 1000 turn accumulation cycle versus the betatron tune is shown in Figure 5. No specific dependency of the instability on vertical tune is observed.

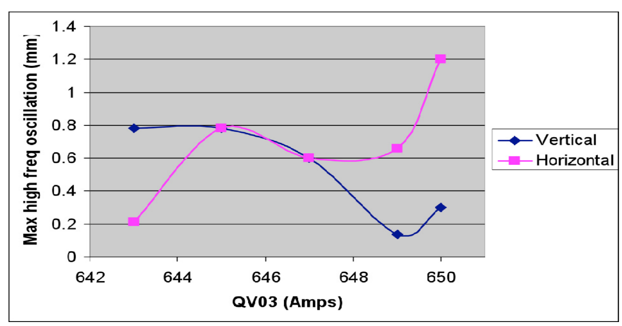

Figure 5: Amplitude of the maximum high frequency oscillation versus vertical betatron tune.

In another experiment, the dependence of the instability on beam intensity was studied. The beam intensity was varied by decimating the minipulses during 1000 turn accumulation cycle, therefore maintaining the same beam painting and RF configuration for all three intensities (10 uC, 5 uC, and 2.5 uC). Figure 6 below shows the vertical frequency spectrum for three different beam intensities, where the Fourier transform has been taken from the BPM signal in mm such that intensity effects are normalized out. The horizontal plane, not shown here, was similar in character but slightly weaker in strength. Interestingly, the frequency of instability activity does not change with intensity and is roughly 60 MHz for all three cases.

A plot of the evolution of the amplitude of the 60 MHz oscillation over the accumulation cycle for the three different intensities is shown in Figure 7. Surprisingly, for all three intensities, high frequency oscillations begin at around the same turn number in the accumulation cycle. The maximum oscillations are around 2 mm, which is similar to the February data set. This is perhaps due to beam loss which results in a relaxation of the instability. Unfortunately no turn-by-turn BLM data was recorded to confirm this theory.

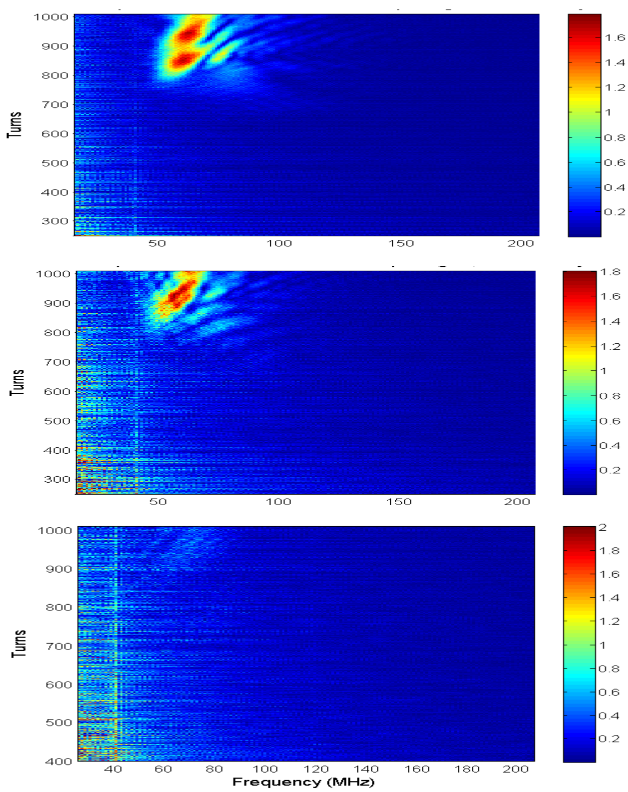

Figure 6: Turn by turn evolution of the frequency content of the instability for a 10 uC beam (top), a 5 uC beam (middle), and a 2.5 uC beam (bottom).

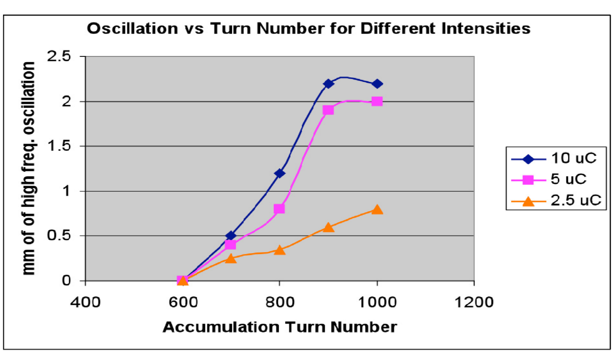

Figure 7: Amplitude of the high frequency oscillation versus accumulation turn number for the three different accumulated beam intensities.

It is clear from both Figures 5 and 6 that in this experiment the instability is present at beam intensities significantly lower than the current production run intensities. This point will be further addressed in the last section of this paper.

July 2008 Dataset

Unlike the previous two datasets, in the July experiment the machine was not reconfigured for high intensity physics studies. Rather, an 8.5 uC production run configuration with 500 turns of beam accumulation was used. The storage time of the beam in the ring was extended by 2000 turns after accumulation. The RF second harmonic was turned off and first harmonic was varied. Thus, the configuration of beam was quite different than the February and April data sets, mainly in that there were only 500 accumulation turns, and that the beam losses were well-tuned during the accumulation period. Additional loss tuning was not performed once the beam storage was extended, and losses did increase substantially in this step.

Since the SNS ring BLMs saturate at very low beam loss levels, they are not useful for indicating the presence of beam instabilities. Offline analysis of BPM data is usually required to identify and characterize an instability. In this experiment we were searching for the RF instability threshold for the 8.5 uC beam and a real-time indication of instability presence was necessary. A reliable signature of a substantial instability is a distinct drop in beam intensity, as measured by a beam current monitor in the ring. In order to induce such a signature, the first harmonic RF had to be dialed down to 4 kV or below; at this setting a discernable beam loss was observed on the ring BCM at around 1900 turns, as shown in Figure 8.

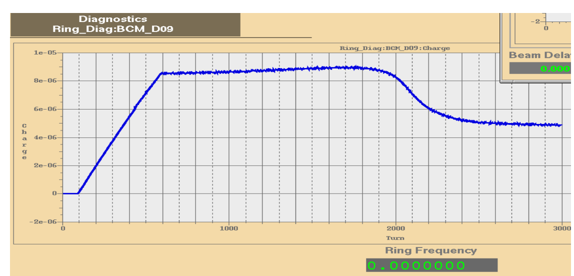

Figure 8: Ring BCM for 500 turns of accumulation and 2000 turns of beam storage, showing a major drop in beam current due to an instability. Note that the horizontal axis units on the plot are about 100 turns offset from the actually beam injection and storage.

Figure 9 shows the frequency content of the induced instability for an RF setting of 3 kV. The instability begins near the tail of the beam and works its way towards the front during the storage. Figure 10 shows the BPM difference signal in millimeters along the length of the bunch train at around 1900 turns, indicating that the lower frequency oscillations occur near the leading edge of the bunch. The amplitude of the oscillation is significantly larger than what was observed in the earlier studies, likely leading to the macroscopic drop in beam intensity in the ring.

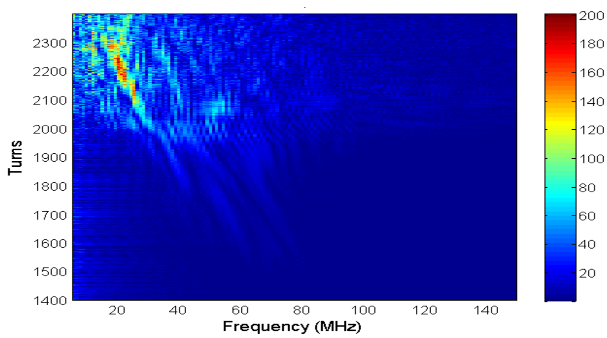

Figure 9: Turn by turn evolution of the frequency content of the instability for a first harmonic RF voltage of 3 kV.

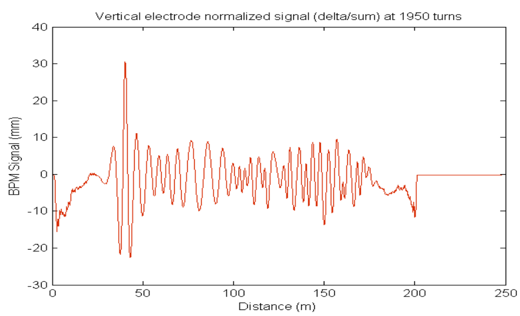

Figure 10: BPM difference signal in millimeters along the bunch length for an RF first harmonic voltage of 3 kV. The gap region of the beam has been set to a constant value.

In Figure 11, the evolution of the amplitude of oscillations is plotted for 4 different RF settings. The total available first harmonic RF voltage in the SNS ring is 60 kV, spread between 3 RF cavities. It is clear that the instability is very sensitive to the RF setting, and goes from a very strong instability at 3 kV to almost no instability by 11 kV. The typical total first harmonic voltage used during recent production runs is well above this level, near 20 kV.

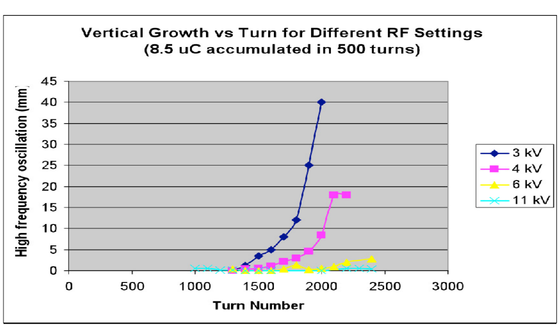

Figure 11: Amplitude of the high frequency oscillation versus turn number for four different first harmonic RF settings.

DISCUSSION OF INSTABILITY TRENDS

In order to identify instability trends and to pre-emptively address problems, it is useful to consider all of the datasets together on a common map. A good measure of the strength of the instability which is well-suited to this purpose is the amplitude of the high frequency oscillations. This parameter allows us to not only judge the strength of the instability from one case to the next, but also the location of the onset and first saturation.

Figure 12 below is a compilation of the amplitude data for the three datasets discussed in the previous section. Specifically, it shows the of the evolution of the amplitude of the high frequency oscillations for the February data (green lines), the April intensity scan data (blue lines), and finally the 11 kV July dataset (pink).

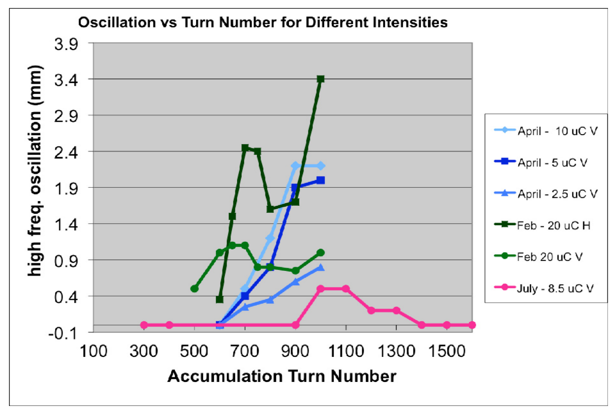

Figure 12: Amplitude of the high frequency oscillation versus accumulation turn number for February BPM data in both planes (green lines), April vertical BPM data (blue lines), and July BPM data (pink line). Note that in February and April, (blue and green), the beam accumulation ended at 1000 turns, whereas in July the accumulation ended at 500 turns and the beam was stored beyond this point.

This plot helps us identify an important feature: For the four different beam intensities that were accumulated in the February and April data sets (20 uC, 10 uC, 5 uC, and 2.5 uC), all instabilities began near 600 turns of accumulation, with the exception of a slightly earlier start in the vertical plane in February. In the July dataset, very little instability is seen at RF 1st harmonic levels greater than or equal to 11 kV. The RF for both the earlier datasets was well above this level, and thus was not the likely cause of the observed instabilities. The remaining distinguishing feature between the first two experiments and the more well-behaved July experiments was the number of minipulses accumulated in the ring: In both February and April the beam was accumulated over a 1000 turns cycle, but in July the beam was accumulated over only 500 turns. This points to an instability threshold related to accumulation turn number rather than the intensity level. The instability is likely a secondary effect, triggered by beam loss caused by an independent and yet unknown source.

Further evidence of this limit is found in two recent production beam tune-up efforts. In the first tune-up, a strong ion source gave 10 uC of beam in the 600 minipulses of beam which were available, with reasonable beam losses. In a subsequent production tune-up, the number of available minipulses was extended to 700 for the first time. However, only 640 minipulses could be used due to a sudden increase in beam loss beyond point. The total beam accumulated was only 9 uC, ten percent less than the previous case cited. This again points to an issue related to accumulation turn number rather than beam intensity. Unfortunately, due to time pressures for establishing a production beam configuration, the apparent beam loss limit was not explored, and no BPM data was taken for offline analysis and thus it is unknown if an instability was induced at this limit.

The SNS will not resume operations with more than 600 minipulses of beam until the spring of 2009. It is currently unclear if at this time a limit related to accumulation turn number will be observed. A plan is being formulated to help diagnose the issue if it occurs, and to look for the source of the beam loss which provides a trigger for the instability.

REFERENCES

[1] V. Danilov *et al*, Proceedings of the ICFA Workshop n High Intensity Hadron Beams in Rings, Upton (1999).

[2] J. Wei *et al*, PRST-AB **3**, 080101 (2000).

[3] V. Danilov *et al*, Proceedings of the ICFA HB 2006 Workshop, Tskuba (2006).

[4] S. Cousineau *et al*, Proceedings of the ECLOUD 2007 Workshop, Daegu (2007).