COMPUTATIONAL BEAM DYNAMICS STUDIES OF COLLECTIVE INSTABILITIES OBSERVED IN SNS*

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Abstract

During the commissioning and early operation of the Spallation Neutron Source, some physics shifts were set aside for high intensity stability studies. Under certain, especially contrived conditions, a number of beam instabilities were induced. These included both electron cloud and ring impedance driven phenomena. We are now applying both simple analytic models and the ORBIT Code to the description and simulation of these observed instabilities.

INTRODUCTION

On three separate occasions, September 2007, February 2008, and April 2008, SNS accelerator physics shifts have been set aside for the study of high intensity stability issues. In the September 2007 run, as many as 1.1×10^{14} protons were extracted from the SNS ring without instability. These stable beams were subject to RF bunching, and previous simulations predicted that bunched beams of this intensity would be stable [1,2]. In an attempt to induce instabilities, the ring RF buncher voltages were turned off, so that coasting beams were accumulated. In this case, three independent instabilities were observed. The frequency signatures of these instabilities strongly suggest 1) a broad e-p instability in the 20→100 MHz range, 2) a narrower (extraction kicker) impedance-induced instability in the 4→10 MHz range, and 3) a low frequency resistive wall instability at ~100 kHz. In the February 2008 run, 1.3×10^{14} protons were accumulated, but with high losses, and the electron cloud instability was observed for a bunched beam. Finally, in the April 2008 run, both e-p and resistive wall instabilities were observed for a range of ring tune settings. Most of this data is so new that it is only now being analyzed, but we discuss here the present status of this work.

RESULTS

The Spallation Neutron Source accumulator ring was designed and constructed to be stable at full intensity of 1.5×10^{14} protons. The beam pipe was coated with TIN to reduce electron multipacting for mitigation of electron cloud effects [3]. The magnetic field configuration at the primary stripper foil was designed for the collection of the stripped electrons. The extraction kickers were carefully designed to minimize their dominant ring impedance. The operating point tunes of $(Q_x,Q_y) = (6.23,6.20)$ were chosen away from resonances. Calculations for the dominant extraction kicker impedance showed longitudinal stability up to 8×10^{14} protons [4], while transverse stability at 1.5×10^{14} protons was predicted for up to 3 to 4 times the known impedance [1]. Electron cloud calculations predict that the full intensity SNS beam should be quite stable [2]. Finally, SNS will be stable with respect to the resistive wall impedance unless the tunes are changed to sub-integer values.

September 2007 Results

The observations of September 2007 were made with at most 1.1×10^{14} protons and operating tunes set at $(Q_x,Q_y) = (6.23,6.21)$, except for the resistive wall instability, for which the tunes were set below integer values $(Q_x,Q_y) \sim (5.9,5.9)$. To induce instabilities, the ring RF cavities were turned off to provide coasting beams. The electron cloud instability initially develops toward the first half of the proton beam and extends toward the rear as the instability grows (Figure 1). Analysis of experimental BPM data places the onsets of instability at 3.4×10^{13} protons in the horizontal plane and at 5.8×10^{13} protons vertically. However, higher intensities are obtained in the vertical direction.

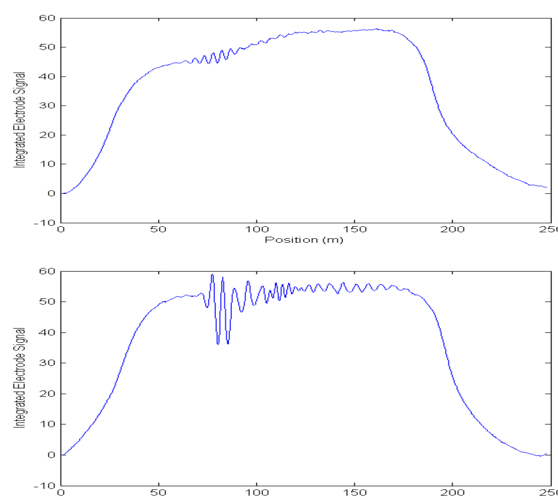

Figure 1: e-p instability as seen in coasting beam current profile shortly after its inception (top) and 100 turns later (bottom).

The observed e-p instability was simulated for the experimental operating parameters using the ORBIT code [5] electron cloud model [6]. The instability is seen in the simulations, as shown in the vertical frequency spectra in Fig.2, but the range and extent of the simulation frequency spectrum are somewhat lower and smaller than observed experimentally. Both the measured and

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simulated spectra drift toward lower frequencies as the instability evolves. Thus, the simulation agrees qualitatively with reality, but there are quantitative differences. These may be due to the position and localization of the electron cloud nodes in the simulations.

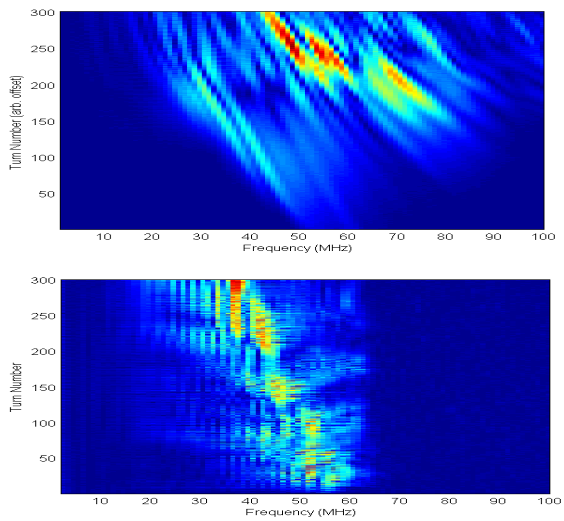

Figure 2: Turn-by-turn vertical frequency spectrum of the coasting beam e-p instability seen in SNS in September 2007. Top: measured results. Bottom: ORBIT simulation.

Also observed during the September 2007 run was a transverse instability in the vertical direction with dominant harmonic at 6 MHz and noticeable excitation in the 4→10 MHz range for a stored coasting beam. Interpreting this to be a "slow" mode, the frequency is consistent with dominant harmonic n = 12, and excitation in the range $10 \leq n \leq 16$. This agrees well with the predicted range of dominant mode numbers for instability from the extraction kicker impedance. The spectral evolution of this instability is shown in Fig. 3.

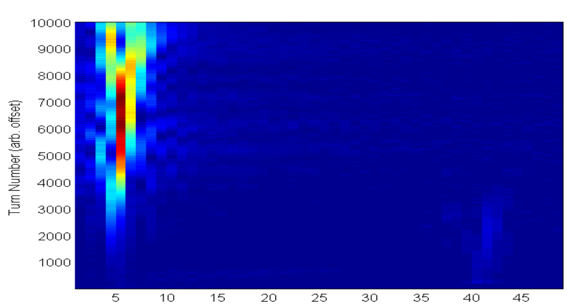

Figure 3: Turn-by-turn frequency spectrum of the coasting beam extraction-kicker-induced instability seen in SNS in September 2007.

Previous analytic and ORBIT calculations of coasting beam instabilities in SNS for n = 10 and 1.5×10^{14} protons predict vertical instability at Re(Z) > 0 kΩ/m at zero chromaticity and at Re(Z) ≥ 250 kΩ/m at natural chromaticity [1]. The measured impedance of the extraction kickers in the appropriate range of n is Re(Z) ~ 30 kΩ/m. The experimental observation of the instability was made at natural chromaticity with only 1.5×10^{14} protons in the ring, so there is a discrepancy in that the previous calculations indicate that this case should be stable. We are now repeating the ORBIT calculations for assumptions that carefully match the experimental conditions: details of injection painting, lattice configuration and settings, and stored turns are included in the new calculations.

A third instability, at ~ 100 kHz, was observed at settings $Q_{x,y} < 6.0$. This instability has the signature of the resistive wall instability, the largest contributors to which are the injection kickers. Previous analytic calculations indicate that the resistive wall instability has a lower threshold for zero chromaticity than for natural chromaticity, but we have not yet performed detailed calculations for the specific observed cases.

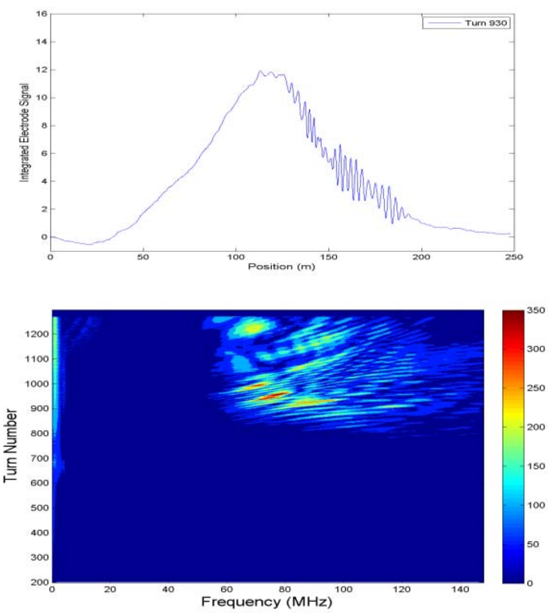

Figure 4: Beam current profile and horizontal turn-by-turn spectrum for e-p instability observed in February 2008.

February 2008 Results

The second dedicated high intensity beam shift occurred in February 2008. Beam intensities as high as 1.3×10^{14} protons were accumulated, although losses were very high. In this run, instabilities were observed for bunched beams, although the relative RF buncher cavity phase settings were not standard and resulted in mismatched longitudinal distributions and peaked current profiles. The frequency spectra were broad, ranging from 40→150 MHz with additional low frequency activity, and peaking at about 75 MHz. The instability onsets were observed at 7.2×10^{13} protons in the horizontal direction and 6.0×10^{13} protons vertically. The dominant intensities were found to be in the horizontal direction. Current profiles obtained from the integrated left-right BPM signals show the instability to be located between the beam peak intensity and the trailing edge (Fig. 4). Figure 4 also shows the horizontal turn-by-turn spectrum. Simulation of the February results is underway, but is incomplete at this time. By using the control room settings, we have been able to reconstruct the observed beam intensities and current profiles. We are now running these through ORBIT's electron cloud module to determine the stability properties.

April 2008 Results

The most recent high intensity measurements were conducted in April 2008. This run constitutes the broadest range of high intensity instability data taken to date. Studies included scans of the horizontal tune around the design operating point and further resistive wall observations for tunes in the $5.8 \leq Q_{x,y} \leq 5.95$ range.

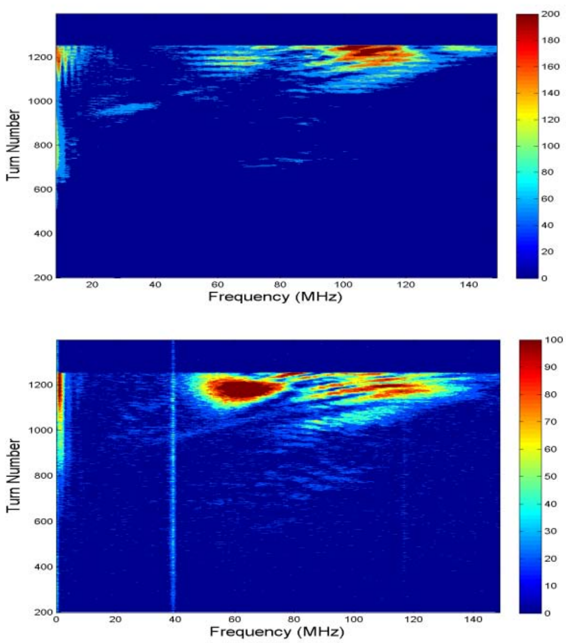

Figure 5: Turn-by-turn horizontal and vertical spectral from a typical April 2008 instability measurement.

The results show a broad range of high frequency activity between 40→150 MHz in both horizontal and vertical planes, together with low frequency excitation below ~20 MHz. Peaks in the high frequency spectra appear to be at about 60 MHz and 110 MHz. The onset of activity is at 5.0×10^{13} protons in the horizontal plane and at 4.7×10^{13} protons in the vertical plane. We also see a strong line at 39 MHz in the vertical plane. We believe that this is an artifact of the diagnostic equipment, rather than a physical signal. When we change the oscilloscope resolution, this line shifts in frequency, while the rest of the image remains unchanged. Figure 5 shows typical horizontal and vertical turn-by-turn spectra from the April 2008 run. As this data is very recent, it is still undergoing basic analysis, and we have not begun to perform simulations.

CONCLUSIONS

In preparation for full power operation, we have begun to perform high intensity studies at SNS. In the process, we have extracted 1.3×10^{14} protons from the ring. However, this has been achieved at the expense of high losses, and the three different classes of instability have been observed: high frequency e-p instability, intermediate frequency instability driven by the extraction kicker impedance, and low frequency resistive wall instability. The simulation of these instabilities has begun using detailed assumptions that attempt to match the actual conditions under which the experiments were conducted. Thus far, results are not quantitatively successful and further work will be required to understand the conditions, and perhaps to adjust the models to explain the observations.

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