ORBIT BENCHMARK OF EXTRACTION KICKER INSTABILITY OBSERVED IN SNS*

J.A. Holmes, S. Cousineau, V. Danilov, ORNL, Oak Ridge, TN, 37830, USA
Z. Liu, Indiana University, Bloomington, Indiana 47405, USA

Abstract

During one of the high beam intensity runs in SNS, a coasting beam instability was observed in the ring when the beam was stored for 10000 turns. This instability was observed at an intensity of about 12 microcoulombs and was characterized by a frequency spectrum peaking at about 6 MHz. A likely cause of the instability is the impedance of the ring extraction kickers. We carry out here a detailed benchmark of the observed instability, uniting an analysis of the experimental data, a precise ORBIT Code tracking simulation, and a theoretical estimate of the observed beam instability.

INTRODUCTION

During the past three years, several SNS accelerator physics shifts have been set aside for the study of high intensity ring stability issues. Under normal operating conditions, stable beams have been achieved in excess of 1.3×10^{14} protons, or 21 μC. These stable beams are obtained using RF bunching, and previous simulations predicted that bunched beams of this intensity would indeed be stable [1, 2]. In order to induce instabilities, a number of measures have been taken. The ring RF buncher voltages have been modified, or turned off altogether, so that coasting beams are accumulated, and the chromatic sextupoles have been activated in order to zero the ring chromaticity. In such cases, three independent instabilities have been observed. The frequency signatures of these instabilities strongly suggest 1) a broad e-p instability in the 20→100 MHz range, 2) a narrower transverse (extraction kicker) impedance-induced instability in the 4→10 MHz range, and 3) a low frequency resistive wall instability at ~100 kHz. The observations of these instabilities have been discussed in Refs. [3] and [4], and preliminary simulation results have been shown in Refs. [5] and [6]. The present paper refines the results of Refs. [5] and [6] for the extraction kicker instability by presenting a simulation in which the actual accumulation and storage conditions are carefully matched to those in the experiment. Future work will deal with the e-p instability.

BACKGROUND

The Spallation Neutron Source accumulator ring was designed and constructed to be stable at the full intensity of 1.5×10^{14} protons. Because early estimates predicted that the extraction kickers would present the dominant ring impedance, they were carefully designed to minimize that impedance. As a result, stability calculations for the extraction kicker impedance showed longitudinal stability up to 8×10^{14} protons, while transverse stability at 1.5×10^{14} protons was predicted for up to 3 to 4 times the known impedance [1]. These results were obtained computationally for bunched beams using the ORBIT code [7]. However, for coasting beams in SNS, analytic and ORBIT calculations for mode number $n = 10$ and 1.5×10^{14} protons predict vertical instability when $\mathrm{Re}(Z) > 0$ kΩ/m at zero chromaticity and when $\mathrm{Re}(Z) \geq 250$ kΩ/m at natural chromaticity. The measured impedance of the extraction kickers in the vicinity of $n = 10$ is $\mathrm{Re}(Z) \sim 25$-30 kΩ/m. It is therefore appropriate to use coasting beams and corrected chromaticity to look for this instability.

The extraction kicker instability has been observed in the course of high intensity beam studies. The scenario was the following: The ring tunes were set at $Q_x = 6.23$ and $Q_y = 6.20$. The chromaticity was corrected to zero and the RF buncher cavities were turned off. The choppers were also turned off so that a continuous coasting beam was accumulated. An 860 MeV beam of 7.7×10^{13} protons, more than 12 μC, was injected for 850 turns and subsequently stored until the beam was lost in the ring. The evolution of the beam was followed for 10000 turns. The observed instability began at about 1200 turns and saturated somewhat beyond 4000 turns. It was active in the transverse vertical direction with dominant harmonic at 6 MHz and noticeable excitation in the 4→10 MHz range. 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 unstable mode numbers from the extraction kicker impedance.

The experimental results for this case have been presented in Ref. [3], and the growth rate of the 6 MHz ($n = 12$) harmonic was use to theoretically infer the extraction kicker impedance at that frequency. The resulting prediction of 28 kΩ/m is in excellent agreement with the laboratory-measured impedance of 25 kΩ/m. The intent of this paper is to precisely simulate this case, using ORBIT, and to match all known experimental details as closely as possible. The parameters in the earlier simulations, presented in Refs. [5] and [6], differ somewhat from those of the experiment, so that quantitative comparison is not appropriate for those cases.

RESULTS

The present simulation was carried out using the ORBIT code [7]. We used the actual ring settings with $Q_x = 6.23$ and $Q_y = 6.20$ and zero chromaticity. The ring

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

RF cavities were turned off and a continuous coasting beam of 7.7×10^{13} protons at 860 MeV was injected for 850 turns and stored up to 10000 turns. The injected beam RMS energy spread was taken to be 0.5 MeV, consistent with observation, and the nominal SNS transverse injection painting was employed. Tracking was carried out using symplectic single particle transport, the laboratory-measured longitudinal and transverse impedances for the extraction kickers, and the 3D space charge model. In addition, the ORBIT foil scattering model was activated and a complete set of apertures was included to incorporate beam losses during accumulation and storage. The number of macroparticles in the simulation was 4.25 million.

One of the more impressive results presented in Ref. [3] was the agreement between the extraction kicker impedance calculated from the growth rate of the instability and that measured in the laboratory. The relationship between the impedance and the growth rate is

$$\mathrm{Re}(Z) = \frac{2\gamma\beta^2 E_0}{\tau\beta_{twiss} I_{avg}} \tag{1}$$

where Z is the impedance in Ω/m, γ and β are the relativistic factors, E_0 is the proton mass in eV, τ is the growth time in turns, β_{twiss} is the beta function at the location of the impedance, and I_{avg} is the average beam current. There are 14 extraction kickers distributed over a length of about 10 m in the SNS ring. The vertical beta function at the kickers varies from a minimum of 6.4 m to a maximum value of 13.5 m, with an average value of 9.3 m. The measurement gave an experimental growth time of 1036 turns. In estimating the value of 28 kΩ/m using Eq. (1), a value $\beta_{twiss} = 7$ m was assumed. If, instead, the average value of $\beta_{twiss} = 9.3$ m is used, the estimated impedance is 21 kΩ/m, a bit lower than the lab value of 25 kΩ/m. However, Eq. (1) was derived under the assumptions that we are far from threshold and that the energy distribution is a delta function, thus ignoring Landau damping. Both these assumptions overestimate the growth of a real beam with energy spread. Therefore, the experimental growth time should be longer than that from Eq. (1), and its use in Eq. (1) should result in an impedance prediction that is somewhat lower than the actual value.

The ORBIT simulation was carried out with a single extraction kicker impedance node located at a central position among the extraction kickers. The local value of the vertical beta function at the node was $\beta_{twiss} = 12.9$ m and, as shown in Fig. 1, the exponential growth time is about 800 turns. Although this is a shorter time than that observed experimentally, the impedance in the calculation was placed at a location of higher beta function. Using the value $\beta_{twiss} = 12.9$ m and the growth time of 800 turns in Eq. (1), we obtain the value Re(Z) = 20 kΩ/m, which is within 5% of the experimental value of Re(Z) = 21 kΩ/m when the average $\beta_{twiss} = 9.3$ m is used. However, an impedance is required by ORBIT in order to perform the calculation, and the impedance assumed by ORBIT for the n = 12 harmonic was Re(Z) = 25 kΩ/m. Using this in Eq. (1), the observed growth time should be 640 turns, rather than 800 turns. The injected beam in the simulation has an energy spread of RMS value 0.5 MeV and total energy deviation up to ±1 MeV, so due to Landau damping and the threshold effect, we expect to observe slower growth than predicted by Eq. (1). The impressive result here is the agreement between the simulation and the experiment.

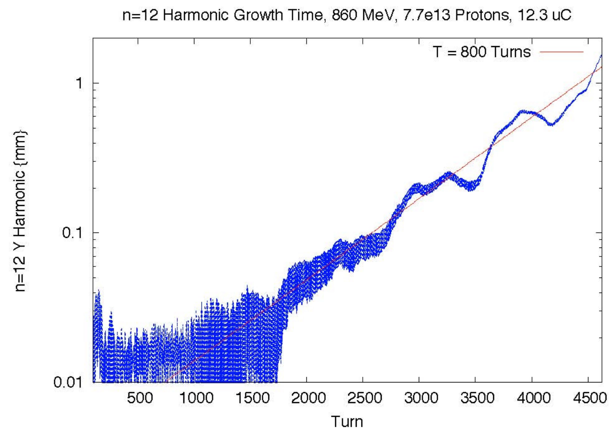

Figure 1: Vertical n=12 harmonic versus turn number in ORBIT extraction kicker instability simulation.

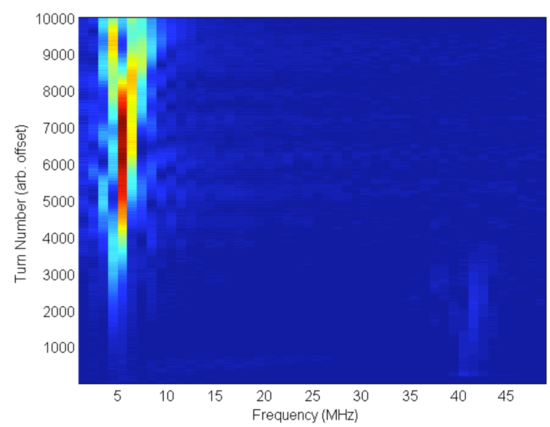

Figure 2: Evolution of experimental vertical harmonic spectrum of the extraction kicker instability.

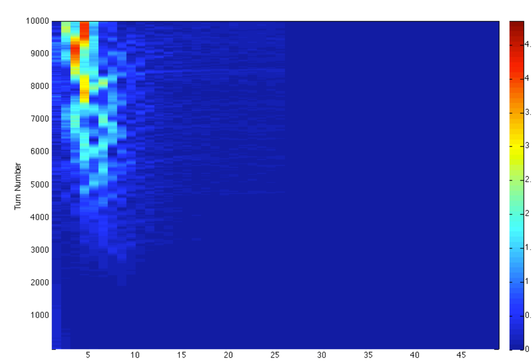

Figure 3: Evolution of simulated vertical harmonic spectrum of the extraction kicker instability.

At this time, the present calculation has been carried out to 4600 turns, and completion to 10000 turns is ongoing. We have completed a slightly different calculation to 10000 turns. The differences between the completed calculation and the present one are two: an old and higher set of impedances for the extraction kickers was employed and a chopped, rather than continuous, beam was injected into the ring. Although chopped, the beam was allowed to debunch with zero ring RF.

Although this latter simulated case is for somewhat different conditions than the experimental measurement, the evolution of the modal spectrum shown in Fig. 3 shows activity over essentially the same range of modes as the experimental spectrum shown in Fig.2. Following completion of the present calculation, a similar comparison will be prepared. As a next step, we intend to repeat the present calculation with the impedance node located at $\beta_{twiss} = 9.3$ m, as this will give us the closest match to experiment that we can achieve. In this case, we will compare the growth times of the experiment and the simulation and hope to achieve good agreement.

CONCLUSIONS

As we ramp to full power operation in SNS, we dedicate some time to the study of high intensity beams. Some of this work involves the inducement and analysis of instabilities in the accumulator ring. In this paper we presented a careful comparison of an ongoing calculation of the extraction kicker impedance instability, and found that the growth rate predicts a value of the impedance within 5% of the experimentally predicted value. Comparison of the spectral evolution of the experiment and simulation out to 10000 turns was shown for slightly different cases, with qualitatively similar results. However, we have yet to compare the spectral evolutions of identical cases. Finally, we need to repeat the simulation with one minor change: the impedance node must be relocated to a position at which the beta function satisfies $\beta_{twiss} = 9.3$ m.

REFERENCES

[1] J. A. Holmes, V. Danilov, and L. Jain, "Transverse Stability Studies of the SNS Ring," PAC'05, Knoxville, June 2005, TPAT032, (2005).

[2] A. Shishlo, S. Cousineau, V. Danilov, S. Henderson, J. Holmes, M. Plum, "Electron Cloud Self-Consistent Simulation for the SNS Ring," EPAC'06, Edinburgh, (2006).

[3] V. Danilov, S. Cousineau, A. Aleksandrov, S. Assadi, W. Blokland, C. Deibele, S. Henderson, J. Holmes, M. Plum, and A. Shishlo, "Accumulation of High Intensity Beam and Observations of First Instabilities in the SNS Accumulator Ring," in *Proceedings of the 41st ICFA Advanced Beam Dynamics Workshop on High-Intensity, High-Brightness Hadron Beams (HB2006)*, Tsukuba, Japan, May, 2006.

[4] S. Cousineau, "Instability Observations in the SNS Accumulator Ring," in *Proceedings of the 42nd ICFA Advanced Beam Dynamics Workshop on High-Intensity, High-Brightness Hadron Beams (HB2008)*, Nashville, August, 2008.

[5] J. A. Holmes, S. Cousineau, V. Danilov, and A. Shishlo, "Computational Beam Dynamics Studies of Collective Instabilities Observed in SNS," *in Proceedings of the European Particle Accelerator Conference (EPAC08),* Genoa, Italy, 2008.

[6] J. A. Holmes, S. Cousineau, V. Danilov, M. Plum, and A. Shishlo, "High Intensity Effects in the SNS Accumulator Ring," *in Proceedings of the 42nd ICFA Advanced Beam Dynamics Workshop on High-Intensity, High-Brightness Hadron Beams,* Nashville, 2008.

[7] J.A. Holmes, S. Cousineau, V.V. Danilov, S. Henderson, A. Shishlo, Y. Sato, W. Chou, L. Michelotti, and F. Ostiguy, *in The ICFA Beam Dynamics Newsletter*, Vol. 30, 2003.