# COMPUTATIONAL BEAM DYNAMICS FOR A HIGH INTENSITY RING: BENCHMARKING WITH EXPERIMENT IN THE SNS*

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## *Abstract*

As the Spallation Neutron Source (SNS) continues to ramp toward full intensity, we are acquiring a wealth of experimental data. Much effort is being applied to understand the details of the beam accumulation process under a variety of experimental conditions. An important part of this effort is the computational benchmarking of the experimental observations. In order to obtain quantitative agreement between the calculations and the observations, and hence a full understanding of the machine, a great deal of care must be taken to incorporate all the relevant experimental parameters into the calculation. These vary from case to case, depending upon what is being studied. In some of these cases, the benchmarks have been critical in unearthing flaws in the machine and in guiding their mitigation. In this paper, we present the results of benchmarks with a variety of experiments, including coupling in beam distributions at low intensities, space charge effects at moderate intensities, and a transverse instability driven by the impedance of the ring extraction kickers.

## INTRODUCTION

The Spallation Neutron Source continues to make impressive progress toward its full operating power of 1.44 MW. In the most recent run, SNS operated at a sustained power of 865 kW during production. At the current applied energy of 930 MeV, this corresponds to nearly $10^{14}$ protons on target per pulse. In recent dedicated high intensity studies, $1.55\times10^{14}$ protons (24.8 μC) were injected stably into the ring, extracted, and transported to the target. This is the first time the SNS ring has exceeded its design beam intensity of $1.5\times10^{14}$ protons per pulse. Although we are able to operate in production mode at 865 kW with acceptably low losses ($< 10^{-3}$ total beam loss and $10^{-4}$ uncontrolled beam loss), losses in the high intensity studies are much higher. In order to achieve acceptable losses as we continue to increase the beam intensity, we must gain a detailed understanding of the underlying beam dynamics.

Another reason to thoroughly understand the SNS ring beam dynamics is to avoid instabilities. In several studies, including the one that achieved the record beam intensity, we found that we can easily induce instabilities in the ring. In order to do so, a number of measures are typically taken. These include various combinations of the following: ring RF buncher voltages are modified, or turned off altogether, so that coasting beams are accumulated; the choppers may be turned off to provide continuous beam with no gap; the chromatic sextupoles are activated in order to zero the ring chromaticity; and the ring tunes may be altered to induce the resistive wall instability. So far, three independent instabilities have been observed. The frequency signatures of these instabilities strongly suggest 1) a low frequency resistive wall instability at ~100 kHz, 2) a transverse (extraction kicker) impedance-induced instability in the 4→10 MHz range, and 3) a broad e-p instability in the 20→100 MHz range. The slow-growing resistive wall instability occurs only when the tunes are set below integer values, such as $5.8 < \nu_{x,y} < 6$. Because SNS is operated nominally with $\nu_x = 6.23$ and $\nu_y = 6.20$, the resistive wall instability will not be a problem. The extraction kicker instability has been observed only for a continuous coasting beam under the condition of zero chromaticity and with the beam stored for several milliseconds. It is not expected to be a problem for SNS as currently designed, but it could arise at the higher powers being considered for an SNS upgrade. The e-p instability has been observed the most frequently and under a wide variety of conditions. It is likely to present the greatest challenge as we push the intensity frontier. The observations of these instabilities have been discussed in Refs. [1,2], and preliminary simulation results have been shown in Refs. [3-5].

In order to gain a quantitative understanding of the beam dynamics in the SNS ring, it is necessary to apply careful numerical simulation. We carry this out using the ORBIT Code [6], which was written with high intensity rings and transfer lines in mind. We now present the results of benchmarks with a variety of experiments, including coupling in beam distributions at low intensities, space charge effects at moderate intensities, and the transverse instability driven by the impedance of the ring extraction kickers. We begin with a low-intensity study that revealed the presence of x-y coupling in the extraction septum magnet and follow this work through to its present state of benchmarking with low and intermediate intensity beams with injection painting. We then present the results of a careful study of the observed extraction kicker induced instability. Lacking from this paper will be any results of e-p instability simulation. We are actively pursuing this work on a number of fronts, but have not yet obtained results beyond those previously presented [3,4]. Throughout this paper we stress the necessity of attention to detail as well as the interplay between theory, experiment, and computation required for successful and accurate simulation.

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## ACCUMULATION

One of the first benchmarks attempted for the SNS ring was to simulate the accumulation process. The object of the benchmark was to compare measured wire scanner profiles of the extracted beam in the Ring to Target Beam Transport (RTBT) line with corresponding profiles from the simulations. The simulations meticulously matched the parameters used in the experiments. These included the injection stripper foil position and incident beam emittances, position, and angles; the painting waveforms of the injection kickers; the ring lattice settings and tunes; and the applied ring RF focusing. The runs were carried out using ORBIT's foil scattering model, a complete set of apertures and collimators, symplectic tracking, 1D longitudinal space charge, and 2.5D transverse space charge.

The initial tracking studies were conducted at low intensities, and were thus designed to test the accuracy of our single particle model of the ring, rather than collective effects. The simulation results bore no similarity to the measured profiles, which changed shape significantly, in both planes, over the several wire scanners in the RTBT. This, together with an unexplained tilt of the beam at the target view screen, suggested that there was x-y coupling somewhere upstream of the wire scanners. Because care had been taken to correct x-y coupling in the ring using the available skew quadrupole magnets, we focused on the large and complicated extraction septum magnet, which simultaneously bends the beam vertically down and horizontally left from the ring into the RTBT. J.G. Wang then modeled this magnet using the OPERA 3D Code [7]. He found many higher order multipoles, including strong sextupole components [8].

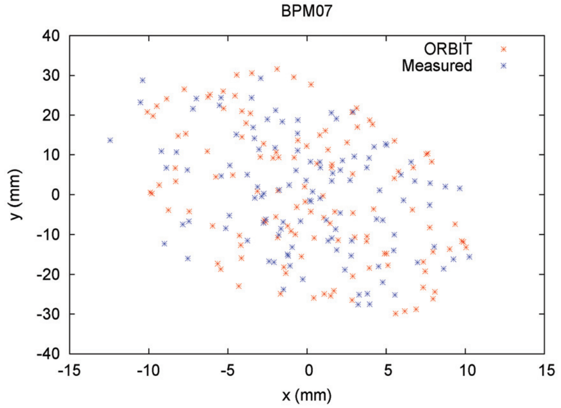

Figure 1. Measured and simulated distributions of single turn injected pulses stored for varying times.

These calculated multipoles were then included in the ORBIT simulation, and a careful experiment was performed. Experimentally, single turn injection was carried out and the pulses were stored for various durations up to 120 turns. They were then extracted and their positions were recorded on the several beam position monitors (BPMs) in the RTBT. In this way, the signals from the single pulses were used to build up a distribution at each BPM. The resulting experimental distributions were then compared with one from an ORBIT simulation in which a single macroparticle was injected each turn for 120 turns. Figure 1 shows a comparison between the experimental and simulation results at BPM07 in the RTBT. Both distributions have substantially the same size, shape, and orientation, thus confirming both the presence of coupling and the extraction septum magnet as its source. Without the coupling multipoles, the distribution is a rectangle without tilt in the x-y plane. Similar results were found at BPMs throughout the RTBT. As a result of this initial benchmark, the extraction septum magnet was modified to remove the higher order multipoles and the consequent coupling [8]. This illustrates the value of careful benchmarking in finding and diagnosing problems with real machine components.

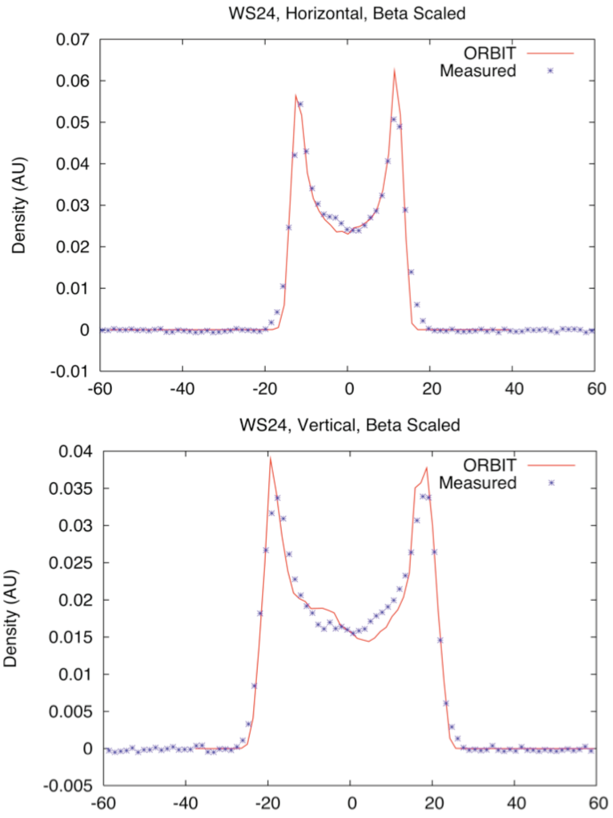

Figure 2. Measured and calculated horizontal and vertical beam profiles at wire scanner WS24 in the RTBT for a low intensity beam of 8.6×$10^{12}$ protons per pulse.

After the modification of the extraction septum, the benchmark of the injection process was repeated. The simplest cases used flat-topped injection kicker waveforms, so that the painting was constant. In both the experiments and the benchmarks the injected beam spot at the stripper foil was 18 mm, both horizontally and vertically, from the closed orbit of the circulating beam. Beams were accumulated in the ring for various times, ranging from 80 to 460 turns, and corresponding intensities, ranging from $8.6\times10^{12}$ to $5.3\times10^{13}$ protons per pulse. Thus, these benchmarks were carried out at low to moderate beam intensity. The beams were extracted after two turns of storage and then measured in the RTBT. Figure 2 shows a comparison of the measured and calculated horizontal and vertical beam profiles at the low intensity of $8.6\times10^{12}$ protons per pulse taken at wire scanner WS24 in the RTBT. The agreement is very good, with ORBIT matching the widths and hollow shape, due to off-axis injection, of the actual profiles. Minor observed differences include slight tails on the experimental data and slightly different density fluctuations in the profiles at the beam center. Comparably good agreement was obtained at the other wire scanners in the RTBT.

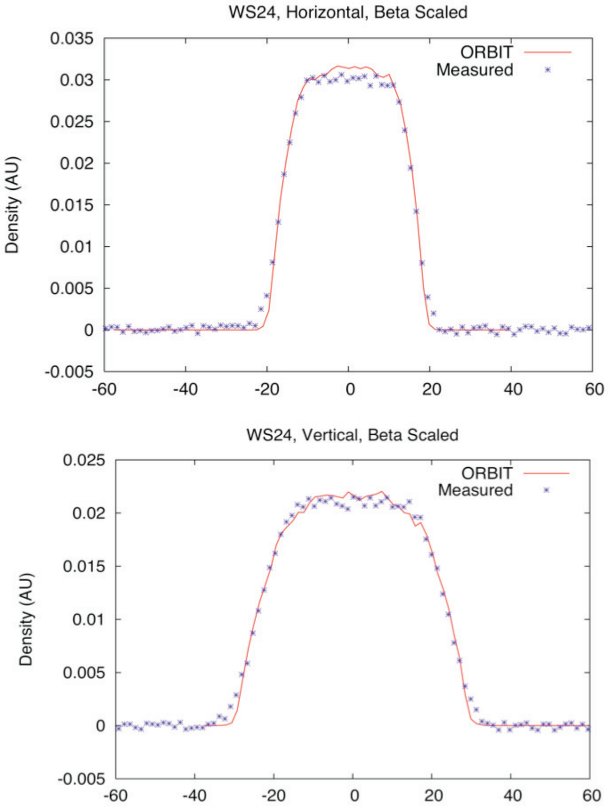

Figure 3. Measured and calculated horizontal and vertical beam profiles at wire scanner WS24 in the RTBT for a moderate intensity beam of $5.3\times10^{13}$ protons per pulse.

Good agreement between experiment and simulation was found over the entire range of intensities. Figure 3 shows the comparison of measured and calculated beam profiles at wire scanner WS24 for $5.3\times10^{13}$ protons per pulse. In comparison with the low intensity profiles, accumulated over 80 turns, the moderate intensity profiles, accumulated for 460 turns, fill in the centers and broaden slightly due primarily to space charge. The broadening is not substantial, however, because the maximum incoherent space charge tune shifts, estimated using ORBIT, are only about 0.07, so the coherent tune shift is perhaps 0.04. With the bare tunes of the ring set at $\nu_x = 6.23$ and $\nu_y = 6.20$, there is not sufficient space charge in the beam to activate the half integer resonance at $\nu = 6$ [9]. In addition to profiles, measurements were also taken of the RMS emittances of the beams. These are compared with the calculated RMS emittances from the simulations in Table 1, in units of millimeter-milliradians. As with the beam profiles, the agreement is quite good, falling within 5% for all cases. It is interesting that, in spite of the different shapes of the low and high intensity beams, the RMS emittances change little with intensity.

Table 1: RMS Emittances, Experiment and Simulation

| Case | Expmnt (H,V) | ORBIT (H,V) |
|---|---|---|
| 80 Turns | (13.3,13.1) | (13.7,12.6) |
| 460 Turns | (13.8,13.1) | (13.2,12.5) |

The studies for injection with painting were carried out in a somewhat different fashion than those with flat-topped injection kickers. In all cases with painting, 640 turns of beam accumulation and two turns of storage were performed prior to extraction. The intensity was varied by beam decimation, in which pulses are injected only on a fraction of available turns. In this way, intensities ranging from $8.2\times10^{12}$ to $7.5\times10^{13}$ protons per pulse were obtained. As in the flat top case, these benchmarks are still in the range of low to moderate intensity. The initial results showed less agreement between experiment and simulation than for the flat-topped case, especially at low beam intensity, where the simulated case resulted in more hollow and slightly narrower profiles than the experimental case. At moderate intensity, the agreement was better, but the disagreement at low intensity was a cause for concern. Because the agreement in the flat top injection cases was so good, we focused on the injection kicker waveforms. The simulations faithfully implemented the programmed waveforms from the control room, so an experiment was carried out to test the experimental waveforms. Single turn injection was carried out with varying delay times between the initiation of the injection kickers and the injected pulse. Then the BPMs were used to measure the displacement between the injected pulse and the closed orbit in the ring at the time of injection. In this way, the actual injection waveforms were determined. Not surprisingly, these did not match the programmed waveforms. The reason turned out to be that the timings of the injection kickers were not synchronized with each other or with the beam, resulting in delays of as many as 60 turns. This problem is now being rectified. Once again, careful benchmarking provided guidance in finding and diagnosing faulty hardware performance.

In order to "close the loop" on this injection benchmark, the painting experiment was repeated, but this time the actual measured kicker waveforms were used in the simulations. Figure 4 shows the resulting profiles in the vertical direction at wire scanner WS24, both for low and moderate intensities. The moderate intensity results are good, with the measured profiles just slightly broader than the calculations. At low intensity the agreement, although better than before (compare red and green curves with blue experimental data), is not yet perfect. As we continue to improve these injection benchmarks, our next efforts will be to repeat the painting experiment after the injection kickers have been corrected, and also to repeat the flat top experiment with different kicker amplitudes.

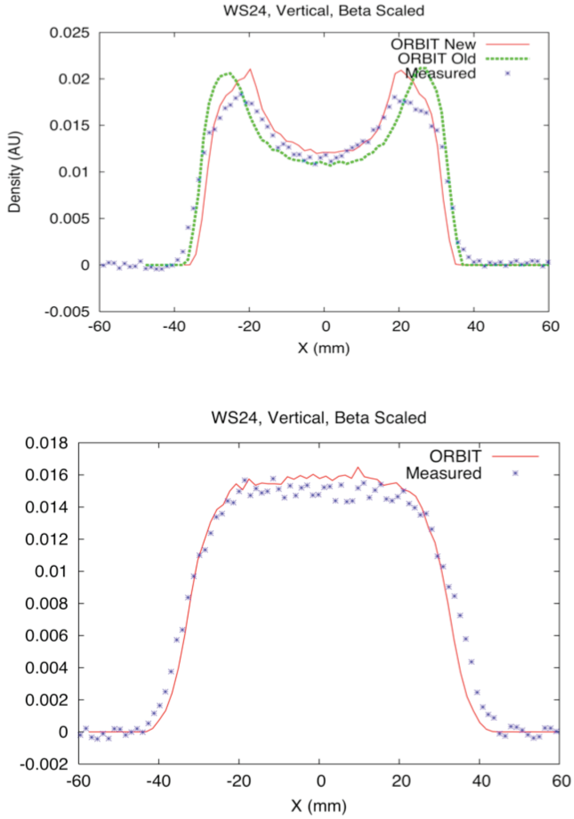

Figure 4. Measured and calculated vertical beam profiles at wire scanner WS24 in the RTBT for low ($8.2\times10^{12}$ protons per pulse) and moderate ($7.5\times10^{13}$ protons per pulse) intensity beams.

Before leaving this subject, we again remark on the difference between the low and moderate intensity beam profiles. Calculation of the incoherent space charge tune shifts using ORBIT shows maximum shifts of about 0.07 for the moderate intensity case. As in the flat top injection, this is insufficient to excite the half integer resonance. Accordingly, we see neither substantial beam broadening nor an increase in emittances with increasing intensity. Rather, space charge tends to “smooth out “ the profiles by filling in the hollow center and adding slightly to the width. As we push to higher intensities and greater tune shifts, we expect to see broadening of the profiles due to space charge [9].

## EXTRACTION KICKER INSTABILITY

The Spallation Neutron Source accumulator ring was designed and constructed to be stable at the full intensity of $1.5\times10^{14}$ 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 $8\times10^{14}$ protons, while transverse stability at $1.5\times10^{14}$ protons was predicted for up to 3 to 4 times the known impedance [10]. These results were obtained computationally for bunched beams using ORBIT. However, for coasting beams in SNS, analytic and ORBIT calculations for mode number $n = 10$ and $1.5\times10^{14}$ 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 $7.7\times10^{13}$ 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. [1], 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 used in the earlier simulations, presented in Refs. [3-5], differ somewhat from those of the experiment, so that quantitative comparison is not appropriate for those cases.

The present simulation was carried out using the ORBIT code [6]. We used the actual ring settings with $Q_x = 6.23$ and $Q_y = 6.20$ and zero chromaticity. The ring RF cavities were turned off and a continuous coasting beam of $7.7\times10^{13}$ 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. [1] 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

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

where $Z$ is the impedance in Ω/m, $\gamma$ and $\beta$ are the relativistic factors, $E_0$ is the proton mass in eV, $\tau$ is the growth time in turns, $\beta_{\mathrm{twiss}}$ is the beta function at the location of the impedance, and $I_{\mathrm{avg}}$ 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 $\beta_{\mathrm{twiss}} = 7$ m, close to the average beta of the ring, was assumed. If, instead, the average value of $\beta_{\mathrm{twiss}} = 9.3$ m for the kickers 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.

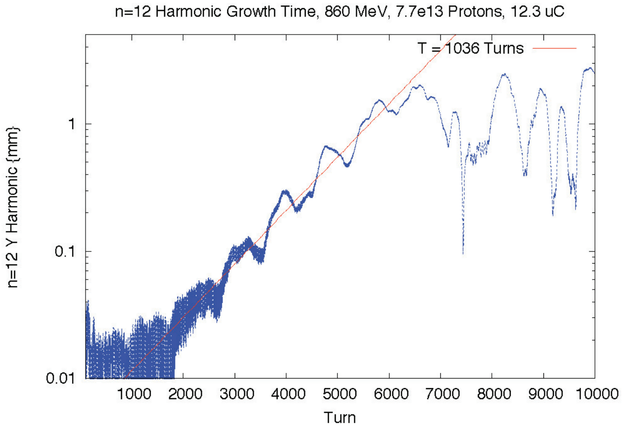

Figure 4. Vertical n=12 harmonic versus turn number in ORBIT extraction kicker instability simulation.

The ORBIT simulation was carried out with a single extraction kicker impedance node using the experimentally measured impedance values and placed at a position among the extraction kickers where the beta function satisfies $\beta_{\mathrm{twiss}} = 9.3$ m. The result, shown in Fig. 4, is an exponential growth time for the n=12 harmonic that is completely consistent with the measured time of 1036 turns. This impressive result is an important testimony to the necessity of getting all the details correct when performing a quantitative comparison between experiment and simulation. In reaching the result of this simulation, we made a number of false starts [3-5]. Erroneous assumptions included the use of chopped beams, the use of (too large) impedances from a previous design of the extraction kickers, and the placement of the impedance node at the geometric center of the extraction kickers rather than at a location with the average beta function. With hindsight, mistakes such as these appear to be foolish. However, in simulating a complicated particle accelerator, there are many details, each of which can affect the results. As each of these errors was rectified, the simulation improved, until we now achieve the correct growth rate for the instability.

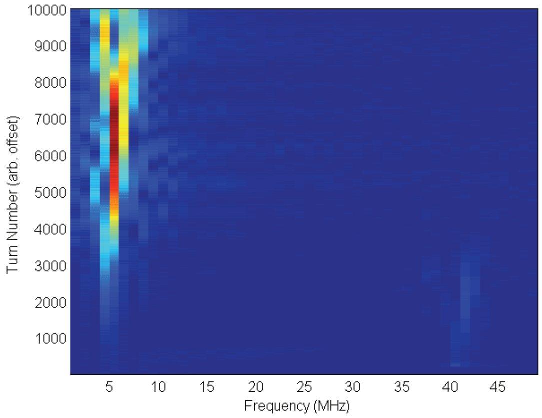

Figure 5. Evolution of experimental turn-by-turn vertical harmonic spectrum of the extraction kicker instability.

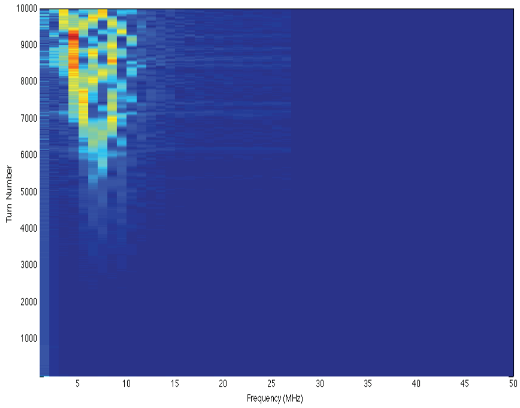

Figure 6. Evolution of simulated turn-by-turn vertical harmonic spectrum of the extraction kicker instability.

We have now completed the calculation to 10000 turns. The evolution of the simulated turn-by-turn spectrum shown in Fig. 6 displays activity over a similar range of frequencies as the experimental spectrum shown in Fig. 5, although the simulation shows somewhat more spreading than the experiment. Also, most of the activity occurs after 5000 turns, which is after the completion of the linear growth. Should we wish to pursue this comparison of the nonlinear stage further, there are a few uncertainties we will need to address. The experimental signals were extracted from an FFT of high bandwidth BPM data. The simulated signals are harmonics of the beam centroid oscillations, in millimeters. Are they directly comparable? We will also need to compare the beam loss over 10000 turns in the experiment, which can vary from shot to shot, with that in the simulations, which is calculated using ORBIT's aperture and collimator routines. These are possibilities for future work.

## CONCLUSIONS

As we ramp to full power operation in SNS, we are simulating much experimental data in order to gain a thorough understanding of the machine's beam dynamical behavior and to diagnose problems when they arise. Benchmarking has already allowed us to identify significant x-y coupling in the original ring extraction septum magnet and also improper performance of the injection kicker painting waveforms. Significantly, we are obtaining good agreement between simulated and experimental results. Thus far, our benchmarks of the ring injection process have been limited to low and medium intensities. In these cases, the main effect of space charge is to fill in the hollow central region of the beam. So far, the space charge tune shifts are insufficient to cause beam broadening through the half integer resonance. We have also completed a careful benchmark of the extraction kicker impedance instability, and have found that the calculated and experimental growth rates are in perfect agreement. Comparison of the spectral evolution of the experiment and simulation out to 10000 turns shows qualitatively similar results. However, the detailed evolution in the nonlinear stage of the instability after 5000 turns is somewhat different. Finally, although not presented here, we have begun simulation of a wealth of e-p instability data acquired during dedicated high intensity shifts. This data includes systematic variation of e-p activity with longitudinal beam profile, controlled by varying the relative phases of the ring RF cavities.

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