TECHNIQUES FOR MEASUREMENT AND CORRECTION OF THE SNS ACCUMULATOR RING OPTICS*

S. Henderson, P. Chu, S. Cousineau, V. Danilov, J. Holmes, T. Pelaia, M. Plum, Spallation Neutron Source Project, Oak Ridge National Laboratory, Oak Ridge, TN, USA

Abstract

The Spallation Neutron Source (SNS) Accumulator Ring will reach peak intensities of $1.5\text{x}10^{14}$ protons/pulse through multi-turn charge-exchange injection. Accumulation of these unprecedented beam intensities must be accomplished while maintaining extremely low losses (less than 1 W/m). It is anticipated that the understanding and control of the ring optics will be important for achieving these low loss rates. We describe our plans for measuring and correcting the optical functions of the accumulator ring lattice.

INTRODUCTION

At full design intensity, the SNS accumulator ring will reach peak intensities of $1.5\text{x}10^{14}$ protons/pulse. The 1-msec long linac beam pulse is accumulated in the ring over 1060 turns via charge-exchange multi-turn injection using a stripping foil. In order to allow hands-on maintenance of beamline components, a stringent loss criterion of less than 1 W/m has been established. It is anticipated that good understanding and control of the ring optics will be important for achieving these low loss rates.

The SNS accumulator ring lattice is a hybrid lattice with FODO cells in the achromatic arcs and doublets in the four long straight sections [1]. The ring is composed of 52 quadupole magnets, powered in six strings. All quadrupoles are outfitted with trim correction coils, powered in 16 families. The optical functions for one quadrant of the ring for the $Q_x = 6.40$, $Q_y = 6.30$ working point are shown in Figure 1.

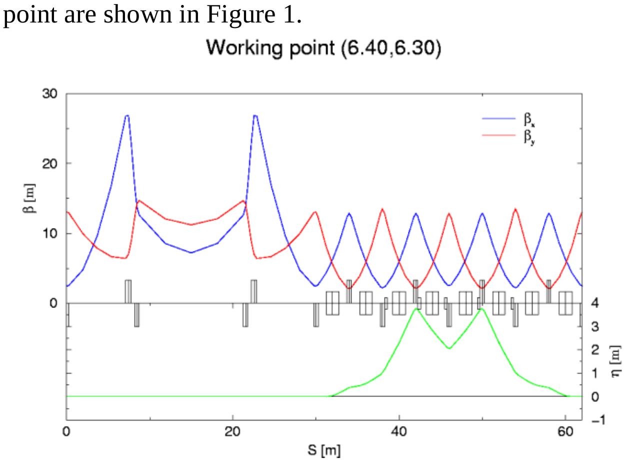

Figure 1: Horizontal and vertical beta-functions (top) and dispersion (bottom) in one quadrant of the ring.

* SNS is managed by UT-Battelle, LLC, under contract DE-AC05-00OR22725 for the U.S. Department of Energy. SNS is a partnership of six national laboratories: Argonne, Brookhaven, Jefferson, Lawrence Berkeley, Los Alamos and Oak Ridge.

In normal operation of the accumulator ring, a 1-msec long, chopped, linac beam pulse is “stacked” over 1060 turns, so that the instantaneous beam current increases from 26 mA to 26 Amps during accumulation. For the purposes of measuring the ring optical functions, low-intensity beams, ranging from a single “mini-pulse” (one turn of accumulated charge providing 26 mA current) to several tens of “mini-pulses” may be used.

While many beam optical measurement techniques have been developed and utilized at storage rings [2,3] utilization of those methods in a pulsed accumulator ring requires some modification.

The purpose of this paper is to outline the techniques that may be used to measure the ring’s optical functions during initial accumulator ring commissioning (presently scheduled to begin in January 2006) as well as later during routine operations.

DIAGNOSTIC CAPABILITIES

The accumulator ring beam position monitor system [4] forms the heart of optics measurement capability. The ring is equipped with 44 beam position monitors, each of which has turn-by-turn measurement capability for beam current ranging from 10 mA (less than a single minipulse) to 52 A. The techniques envisioned for ring optics measurement all rely in one way or another on the turn-by-turn measurement capability of the BPM system to provide betatron tunes, betatron phase advances, coupling parameters, as well as the closed-orbit.

The BPM readout electronics provide sensitivity at the linac microbunch frequency (402.5 MHz) as well as at baseband (the ring revolution frequency of 1 MHz). Since the linac microbunch structure decoheres rapidly [5], we anticipate relying on the baseband system to record the turn-by-turn beam positions at all BPMs for a beam with large betatron oscillation amplitude, which is obtained in one of two ways. Since the SNS ring aperture has been designed for multi-turn injection, very large displacements of the injected beam from the closed-orbit are readily accommodated. In the most straightforward scenario, a single mini-pulse is injected into the ring with a sizeable injection offset, readily obtained with a set of injection kicker magnets. Alternatively, an accumulated beam of several tens of minipulses could be kicked in a single turn, although this capability will not exist at the time of beam commissioning.

Figure 2 shows the betatron phase measurement resolution obtained from sinusoidal fits to simulated turn-by-turn data as a function of oscillation amplitude divided by BPM position resolution (signal to noise). For signal to noise of 10 and for 256 turns of useful coherent signal, a betatron phase resolution of one degree is expected.

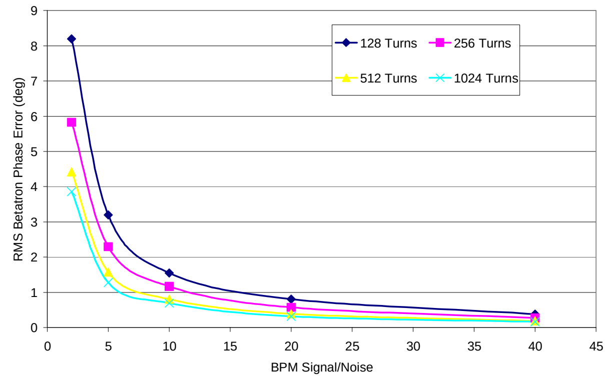

Figure 2: Betatron phase measurement resolution as a function of the ratio of oscillation amplitude to BPM resolution for varying numbers of turns of coherent betatron motion.

Figure 3 shows the results of simulations of the turn-by-turn baseband BPM signals expected from single minipulse injection calculated by the ORBIT code [6] for zero chromaticities. A BPM turn-by-turn resolution of 2 mm, obtained from bench measurements, was assumed. The expected tune resolution and betatron phase resolution for single mini-pulse injection at zero chromaticity is 0.0001 and 1.5 degree, respectively. For natural chromaticity we expect the coherent motion to decohere in about 50 turns, giving resolutions of 0.0007 and 4.0 degrees respectively.

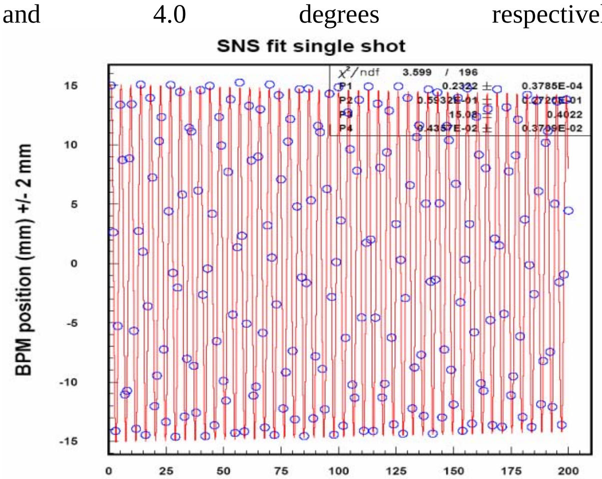

Figure 3: Simulated turn-by-turn beam position from single-turn injection of a linac pulse train into the accumulator ring with chromaticities set to zero.

BETATRON PHASE-ADVANCE MEASUREMENT AND CORRECTION

The betatron phase advance from BPM to BPM may be obtained from turn-by-turn analysis of the BPM signals. This powerful method has been used successfully at several storage rings [1] for measurement and correction of the linear optics. This method may be applied to the SNS accumulator ring optics by recording the turn-by-turn BPM positions and fitting the turn-by-turn data, as in Figure 3, for the initial phase. The difference in initial phases from BPM to BPM is the betatron phase advance. A model-based fit may then be used to adjust quadrupole strengths to match the measured data and to allow subsequent correction.

Two types of quadrupole errors are anticipated. First, quadrupole string setpoint errors may arise from a variety of sources, including power supply calibration errors, hysteresis, energy errors, or field errors due to the proximity of adjacent magnets [7]. Secondly, for quadrupoles on the same power supply string, magnet to magnet variations may arise, although the measured variations are quite small (less that $2x10^{-4}$ measured variation in integral transfer function [8]). Nevertheless, this method provides the capability to diagnose and correct both types of errors.

Quadrupole setpoint errors are determined using a model-based fitting procedure. In this procedure a merit-function consisting of the sum-squared deviations of the horizontal and vertical betatron phases from their design values is minimized.

Figure 4 shows the results of 100 simulation runs in which the six main quadrupole strings are set about their design value with 1.5% rms uncertainty.

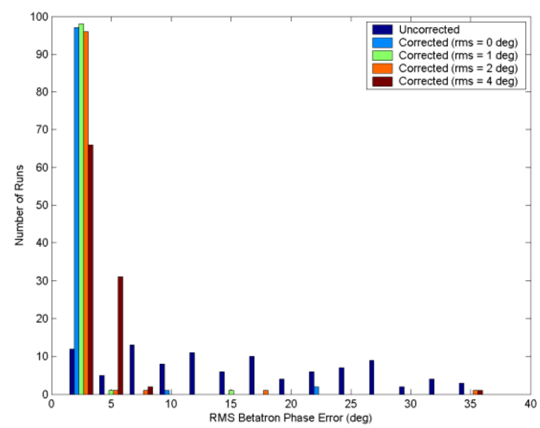

Figure 4: Histograms of RMS betatron phase errors for 100 simulated measurement and correction operations before and after correction for varying betatron phase measurement resolutions.

In each case a given resolution is applied to the simulated betatron phase data, which is then fit to determine the quadrupole setpoints. Figure 4 shows the initial rms betatron phase error before correction, and the resulting phase errors after correction for varying betatron phase measurement resolutions. We see that the resulting betatron phase is corrected to the level of the input measurement resolution, as expected. A particular example in the horizontal plane is shown in Figure 5. In this case we see that the predicted betatron phase error after correction is reduced to the level of the assumed betatron phase measurement resolution, as is expected. Even for the largest betatron phase resolution considered here, the beta functions are corrected to with 2% of their

0-7803-8859-3/05/$20.00 ©2005 IEEE

design values. These examples demonstrate that we expect adequate measurement resolution to correct the optics to the desired level.

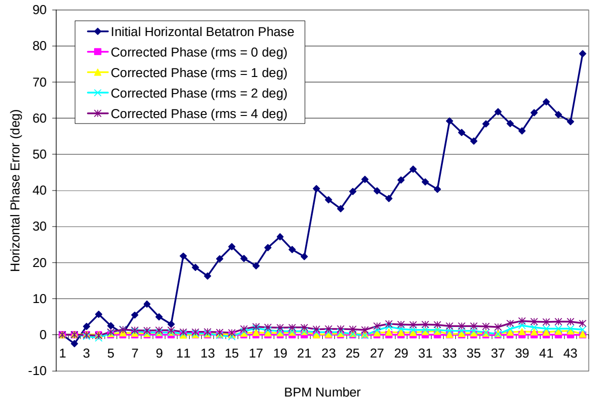

Figure 5: The initial horizontal betatron phase error is shown for a particular error set. The resulting corrected betatron phase errors are shown for varying phase measurement resolutions.

ORBIT BASED CORRECTION

Various orbit-based optics correction methods have been developed [2] and applied to a variety of rings and can be applied to the SNS ring. A simple example is presented here. We simulate a correction scheme in which one horizontal and one vertical dipole corrector are powered to measure a difference orbit. The two corrector strengths and six quadrupole string strengths are determined from a combined fit using a model-based fitting procedure. Figure 6 shows a simulated example of this approach. Two curves show the starting betatron phase errors in each plane and the subsequent errors following correction, assuming a (pessimistic) closed-orbit position resolution of 0.5mm.

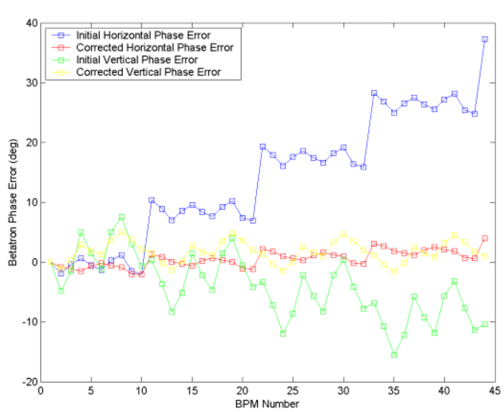

Figure 6: Betatron phase errors before and after correction using a simple orbit-based technique.

This technique is a simpler alternative to the correction based on betatron phase measurement, but it provides somewhat less accurate correction as implemented in this example. The simple technique shown here has been extended at other labs to make use of multiple measured orbit differences, with the addition of BPM gains to the set of fit parameters. While this technique is far superior to the simpler one described here, it is also time-consuming and cumbersome, and therefore somewhat beyond the scope of the initial SNS ring beam commissioning.

BETA FUNCTION MEASUREMENT

The classic beta-function measurement in which the tunes are recorded as a quadrupole is modulated works well for individually powered quadrupoles. Application of this approach to the SNS ring where the quadrupoles are powered in six strings is still useful, but the method then provides the average of the beta-functions at all quadrupoles in the string. Given that the string configuration adheres to the four-fold symmetry in the ring, string setpoint errors also produce four-fold symmetric beta function errors, and may be diagnosed by this simple measurement. Figure 7 shows the anticipated beta-function measurement resolution for the six main quadrupole strings for varying tune measurement resolution. For anticipated measurement resolution less than 0.001, average beta-functions can be determined at the 10% level.

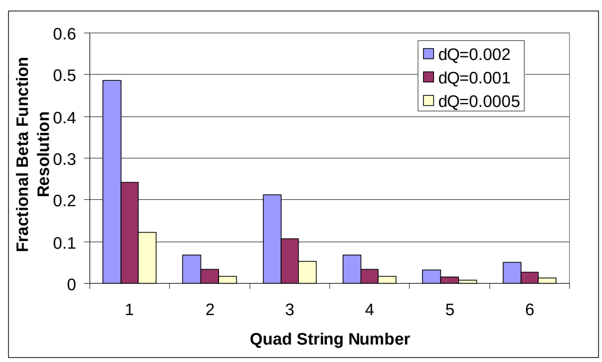

Figure 7: Beta function measurement resolution obtained from a statistical analysis of simulated data for various tune measurement resolutions.

REFERENCES

[1] J. Wei et. al., Proc. EPAC 2000, p. 978.
[2] D. Sagan, PRST-AB 3, 102801 (2000).
[3] J. Safranek, BNL note 63382 (1996). For a recent example see C. Steier et. al., Proc. EPAC 2004, p. 1488.
[4] P. Cameron et. al., Proc. PAC 2003, p. 2444.
[5] J. Holmes et. al., Proc. EPAC 2004, p. 1530.
[6] ICFA Beam Dynamics Newsletter 30 (2003) 100.
[7] J.G. Wang et. al., these proceedings.
[8] D. Raparia et. al., Proc. EPAC 2004, p. 1574.