ORBIT SIMULATIONS OF THE SNS ACCUMULATOR RING*

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Abstract

As SNS undergoes construction, many detailed questions arise concerning strategies for commissioning and operating the accumulator ring. The ORBIT Code is proving to be an indispensable tool for addressing these questions and for providing guidance to the physicists and decision makers as operation draws near. This paper shows the application of ORBIT to a number of ring issues including exclusion of the HEBT RF cavities during commissioning, the detailed effect of the injection chicane magnets on the beam, the effects and correction of magnet alignment errors, decorrelation of the linac 402.5 MHz beam signature and its impact on tune measurement, the injection of self consistent uniform beam configurations, and initial electron cloud simulations.

INTRODUCTION

As SNS construction and commissioning proceeds and the ring moves closer to operation, many detailed issues regarding ring physics and operation are being addressed using the ORBIT code [1]. ORBIT has been developed with a broad range of physics, engineering, and diagnostic modules that allow the simulation of a broad range of scientific and practical issues. In the studies presented here for SNS, we use the following ORBIT capabilities: For single particle motion we assume symplectic tracking, including hard edge fringe fields. Collective effects include space charge and dominant ring impedances. We assume a 1 GeV proton beam. We model the SNS ring lattice assuming tunes of $\nu_x = 6.23$, $\nu_y = 6.20$ and natural chromaticity, unless stated otherwise. The ring magnets are organized into chosen families, including dipole and quadrupole correctors. We consider magnet errors and correction as appropriate. Correction is carried out using the signals from the 44 horizontal and vertical BPMs, placed at their correct locations. We consider a detailed model for the injection chicane when appropriate. The injection painting scheme is carefully represented and foil hits tabulated with proton/foil interactions calculated. Dual harmonic longitudinal RF focusing is calculated with four cavities at their correct locations. Collimators and apertures for the entire ring are included with correct sizes and locations to ascertain for proton losses. We apply these models to the investigation of several ring issues including exclusion of the HEBT RF cavities during commissioning, the detailed effect of the injection chicane magnets on the beam, the effects and correction of magnet alignment errors, decorrelation of the linac 402.5 MHz beam signature and its impact on tune measurement, the injection of self consistent uniform beam configurations, and initial electron cloud simulations.

APPLICATIONS TO SNS RING ISSUES

We will now consider the application of ORBIT to a number of SNS ring issues.

Exclusion of HEBT RF Cavities

The HEBT RF cavities consist of an energy corrector cavity, whose purpose is to remove the energy jitter coming from the linac, and an energy spreader cavity, which paints a controlled ±4 MeV energy spread into the ring. The decision was made to postpone the installation of these two cavities until after commissioning. Although this would not be expected to affect operations during commissioning, one of the requirements is that the SNS configuration at commissioning be capable of 1 MW operation. ORBIT simulations were conducted to determine if this requirement can be met. The main effect of the cavities is on the energy and longitudinal distributions, indicating possible impedance and/or bunch factor effects. We considered six scenarios corresponding to different assumed beam energy distributions at injection. In all cases, the beam remained stable with respect to impedances at 1 MW, but space charge effects led to slightly more peaking and beam tail some cases. Concentrating on the worst (monoenergetic beam at foil) case, it was found that losses in the ring remain negligible ($<10^{-4}$) and the beam distribution on target satisfies requirements, as shown in Fig. (1). Hence, the ORBIT simulations indicate that 1 MW operation is possible even with the omission of the HEBT RF cavities.

Table 1. Beam Transport to Target

Case	Window Loss (%)	Beam Reaching Target (%)	Beam in Footprint (%)	Average Current Density (mA/cm^2)	Peak Current Density (mA/cm^2)
Case 1	2.52	96.5	93.0	37.4	154.1
Case 2	2.43	96.5	93.1	37.4	151.1
Case 3	2.52	96.5	93.0	37.4	155.6
Case 4	2.41	96.6	93.3	37.4	161.3
Case 5	2.40	96.6	93.1	37.4	156.8
Case 6	2.38	96.6	93.3	37.5	153.0

Figure 1. Data for beam transport to the target for the six cases considered.

Effect of Injection Chicane

ORBIT simulations have been carried out to calculate the effects of the field distributions in the injection chicane magnets on the ring beam accumulation. This issue is deemed worth studying because one of the chicane magnets, the one at the injection foil, is shaped at the exit pole tips to introduce a field configuration suitable to direct the electrons created by stripping at the injection foil to the electron collector plate. As a first approach, beam accumulation calculations were carried out with chicane magnets modeled using just the basic field components plus edge-focusing with hard-edge fringe fields. No significant effect on the beam was observed. In a second approach, ORBIT simulations were performed with measured integrated multipole field data for the two interior chicane magnets, which include the magnet with the shaped pole tips. Again, the resulting beam growth was observed to be small, and no significant losses occurred. The machinery is now being developed to carry out a third and final approach that will use a 3D field map from TOSCA and track particles through the actual fields.

Magnet Alignment Errors and Correction

Recently, we concluded a thorough study of the effects of misalignments and strength errors in the SNS ring, and their correction. ORBIT was the primary tool used in this study. Various errors were considered individually and also in conjunction with other errors via random generation using uniform distributions. The errors included displacements and rotations of all magnets as well as errors in the field strengths. The magnitude of the errors was always taken to be greater than or equal to the SNS tolerance. The closed orbit was corrected by adjusting dipole corrector strengths to minimize BPM signals. Two methods were employed, least square minimization and the 3-bump method, with nearly identical results. BPM signal errors were also assumed, and were generated randomly according to a Gaussian distribution with σ_{rms}=1.0 mm, σ_{cutoff}=2.0 mm. Quadrupole field strength errors were corrected using phase advance information calculated using MAD [2]. For the purpose of field error correction, phase advances at specific BPMs were assumed to be obtainable to within ±3.6° with a uniform distribution. Quadrupole and dipole roll errors were not corrected because they were found to have no significant effect on beam. In addition to studying the effects of individual errors, cases were considered with all errors simultaneously activated. Without correction, the worst case beam loss is 49%, with losses starting before 400 turns of the 1060 turn injection. With orbit and phase correction, assuming no BPM errors, losses are less than 10^{-4}. Even with random BPM signal uncertainties, losses are still only 1.7×10^{-4}. These results have been found to hold in general for cases considered thus far.

Decorrelation of the Linac Beam Signature

In SNS, BPMs will be used to measure both the betatron tune and phase advance around the ring. The BPMs have both base-band (a few MHz) and narrow-band (402.5 MHz, the injected linac bunch frequency) capability. The 402.5 MHz band has higher resolution at low intensity, so that we need to assess the lifetime of the 402.5 MHz structure in the ring. This is done using two models: an analytic model and ORBIT simulations. For the analytic model, we consider an ellipsoidal beam with uniform density in a transverse uniform focusing channel and with free expansion in the longitudinal direction. For the initial condition, we used the expected transverse emittances, longitudinal, and energy distributions at the end of the superconducting linac. This model predicts that all space charge effects occur in approximately the first 250 meters, after which the bunch expansion proceeds based on the energy spread developed during that time. According to this analytic model, the microbunches reach inter-bunch spacing in about 9 turns. The ORBIT simulation model tracks the distribution of a single linac microbunch through the ring. Initial conditions were taken to be the expected transverse emittances, longitudinal, and energy distributions at the injection foil. Calculations were carried out using both the full 3D space charge model and, for comparison, the simple longitudinal space charge model. The ORBIT simulations show decoherence of the 402.5 MHz signal in about 5 turns, as shown in Fig. (2), which is in fair agreement with the analytic model prediction. The implication of these calculations is that, with 5-10 turns of data, single shot narrow-band BPM signals can be used for tune calculations, but we should expect errors due to the low number of turns. It should be mentioned that ORBIT has been benchmarked against experimental single turn data from PSR, which has a 201 MHz linac signature. The data shows decoherence of the 201 MHz structure in about 30 turns followed by the reappearance of the structure about 1000 turns (one half synchrotron period) later. ORBIT simulations show the same longitudinal dynamics, including the 30 turn decoherence and the reappearance 1000 turns later.

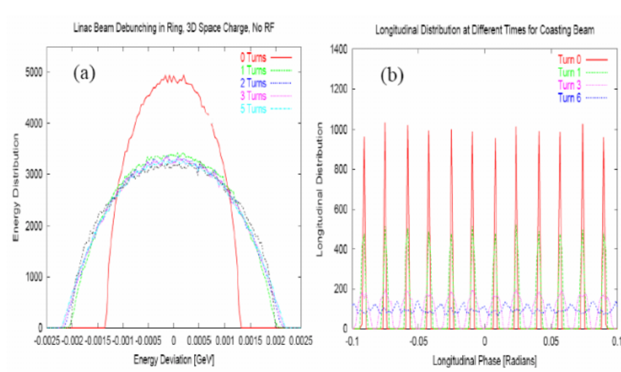

Figure 2. a) Longitudinal energy distribution at 0, 1, 2, 3, and 5, turns and b) longitudinal current distribution at 0, 1, 3, and 6 turns.

Tune Measurement

Single turn BPM data were simulated with ORBIT, post-processed, and then fit with a CERN Lib fitting program to obtain the horizontal betatron tune. The bare tune was known to be $\nu_x = 6.23$. Both narrow band (402.5 MHz) and base band signals were used. As shown in the previous section, narrow band data are available for about 5-10 turns. Base band data is available for about 50 turns before chromatic effects cause it to decohere. Random BPM errors of 1.0 mm were assumed for narrow band fitting and 2.0 mm for the less sensitive base band fitting. Results for the fractional tunes were the following: For the narrow band fit we obtained $\nu_x = 0.2324 \pm 0.0044$, while the base band fit gave $\nu_x = 0.2325 \pm 0.00065$.

ORBIT was also used to study tune calculation due to kicking an accumulated beam. The chosen scenario was to accumulate a beam for 50 turns, then allow it coast up to 300 turns, at which time it is given a kick of 1.5 mradians. The kicked beam was then followed until decoherence, approximately 50 more turns, and the BPM signals analyzed to obtain the fractional tune. In this case, a BPM error of 1.0 mm was assumed for fitting, which is smaller than for the single-shot measurement because of the higher beam intensity. In this case the fitted tune was found to be $\nu_x = 0.2381 \pm 0.00034$, as shown in Fig. (3). Figure (3) also shows that, when the sextupoles are used to zero the chromaticity, the signal lasts much longer, thus allowing very precise tune calculations. In the example shown here, the precision of the zero chromaticity measurement is about an order of magnitude better than the case with chromaticity.

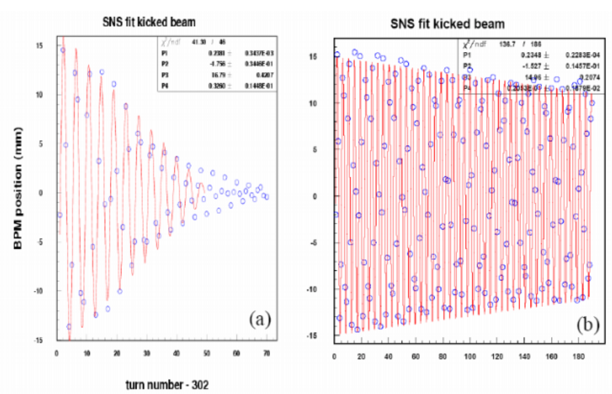

Figure 3. a) BPM signal and fit for kicked beam and b) BPM signal and fit for kicked beam with zero chromaticity.

Self Consistent Beam Configurations

We have demonstrated [3] that there are an infinite number of uniform density elliptical KV-like beams that retain their uniformity and ellipticity under all linear transformations. Such distributions could provide advantages for SNS: Uniform density is desirable from the standpoint of target requirements and uniform distributions have lower space charge tune shifts. We have demonstrated a painting scheme to create a uniform beam in SNS. The scheme requires painting in x′ and y′ as well as in x and y. Specifically, it is required to use nearly equal horizontal and vertical betatron tunes, to paint with linearly increasing (in time) emittances $\varepsilon_x = \varepsilon_y = \varepsilon_f * t / t_f$, and to paint with 90° phase difference between the x-x′ and y-y′ planes. By including two solenoids in one of the straight sections, the eigenvalues can be separated and the scheme can be made more robust. In this case, the painting is carried out to one of the elliptical eigenfunctions of the lattice with solenoids.

Electron Cloud Simulations

A new electron cloud module has been integrated into the ORBIT simulation code. It includes: an adaptation of the surface emission model (SEY) of Pivi and Furman [4] as well as the full proton bunch and electron cloud dynamics, including the interactions between them. Benchmarking of the secondary electron emission model is completed as are the electron tracking and electron cloud formation process in bunched cold proton beams. We are just starting the application of the ORBIT electron cloud model to PSR, but benchmarking ORBIT to an analytic coasting beam model [5] with uniform charge distributions shows agreement of growth rates to within about 15%.

CONCLUSIONS

Using a number of examples, we have demonstrated that the ORBIT Code is a valuable tool for addressing ring physics and operation issues in SNS.

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