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# PROGRESS TOWARD A SELF-CONSISTENT BEAM AT THE SPALLATION NEUTRON SOURCE*

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*Abstract*

We have proposed to inject a self-consistent "rotating" beam into the Spallation Neutron Source Accumulator Ring (SNS). Self-consistent beam distributions are defined to be ellipsoidal, or elliptical in 2D, distributions that have uniform density and that retain these properties under all linear transformations. We have made much progress since the original proposal. We have demonstrated computationally the feasibility of injecting a rotating beam under realistic physics assumptions. We have optimized the injection scheme with respect to beam loss and to minimum necessary hardware changes. We have also determined how existing SNS beam diagnostic equipment can be used to verify the self-consistency of the injected beam. This paper will report the details of this work as well as the status of plans to carry out the self-consistency experiments.

## INTRODUCTION

Last year we presented a paper at this conference describing a proposal to inject a self-consistent "rotating" beam into the Spallation Neutron Source (SNS) accumulator ring [1]. Since then, we have completed detailed studies to determine the optimal injection scenario that can be carried out using the present configuration with minimal changes to machine hardware. This paper describes these studies and presents the optimal case that we intend to inject.

When we say that a beam is self-consistent, we mean that it has an ellipsoidal, or elliptical in 2D, distribution of uniform density and that it retains these properties under all linear transformations. As such, self-consistent beams have some desirable properties including uniform density, small tune shift and tune spread, and potentially small halo generation. Such distributions are solutions of the time-dependent Vlasov equation, and their mathematical properties are described in detail in Ref. [2]. Because self-consistent distributions are singular, they are hard to realize in practice. However, one particular self-consistent beam, the "rotating" distribution is a good candidate for painting into the SNS ring. Over time, we have carried out numerous simulations using the ORBIT Code [3] to ascertain the feasibility of painting a rotating distribution into SNS. These previous studies are described in detail in Refs. [1, 2, 4] and references therein. We will now discuss the finalization of these efforts and present the optimal case for injection.

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## FINDING THE OPTIMUM

In Ref. [1], we presented simulations showing that a self-consistent beam could be injected into the SNS ring provided that the ring was modified to add two solenoids of strength 1.4 T and length 0.5 m symmetrically at positions of equal horizontal and vertical beta functions in one of the straight sections, which we chose to be the RF buncher straight section. In these simulations it was necessary to shift the injection point by more than a centimeter in both the horizontal and vertical directions to mitigate the effects of fringe fields arising from a pair of quadrupole doublets in the injection straight section that were traversed off-axis by the circulating beam during painting. Shifting the injection point by this amount is a major concern in SNS because the trajectories of unstripped beam to the injection dump are very sensitive to changes in injection parameters. Consequently, we focused on our models of quadrupole fringe fields, and we found a bug in a complex multiplication operator used in the quadrupole fringe field routine. Repairing this bug allowed the painting of a self-consistent beam without shifting the injection spot. However, because the beam does traverse the quadrupole doublets in the injection straight section off-axis, we developed an extended fringe field model that is more accurate than our usual hard-edge model and used it for those magnets.

With the fringe field issue resolved, we moved on to consider painting and beam losses. A consequence of the off-axis beam transport is that beam loss can increase because of scraping. To address this issue, the simulations incorporated a detailed description of the machine geometry, including element offsets and apertures. Injection of a rotating beam requires painting to an Eigen function such that x-y' and y-x' are linearly dependent. In such a scheme there are an infinite number of possibilities that take advantage of the freedom of choice of the phase of the rotating beam at the injection point. For example, we could paint with a linear relationship between x-y' while holding y-x' constant, or vice versa. We experimented with a number of these possibilities and found that losses could vary from nearly 100% when painting purely in y-x' to almost zero when painting purely in x-y'. With the exception of the painting waveforms, the lattice settings were the same in all these cases, which led to comparable beam sizes. The variation in beam losses results from steering the beam either closer to or further from the beam pipe, and not from any variation in the beam size. The losses in all these painting schemes occur at the focusing quadrupole in either the upstream or downstream doublet, where the horizontal beam offset is large. This situation is exacerbated when x' is varied in the painting scheme. For this

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reason, the x-y' painting scheme is best with respect to losses. Another advantage of the x-y' painting scheme is that a reasonable beam size can be obtained without any injection kicker power supplies changing sign. Adopting the x-y' painting scheme and painting to the maximum beam size attainable with no kicker power supply sign changes, only 0.03% of the beam is lost. This is quite acceptable for our purposes.

Another question related to the painting scheme is whether the kickers are capable of providing the necessary kicks. We found that they are not unless further adjustments are made. The constraint on the beam size arises from the second vertical kicker, which must kick the beam vertically by a substantial amount to provide the necessary y' at the stripper foil. Two steps were taken to mitigate this circumstance: 1) The beam energy was reduced to 0.6 GeV, the minimum at which the ring has been operated, in order to obtain a larger kick with a given magnetic field; and 2) Four orbit corrector magnets in the injection straight section were used to create a closed orbit bump that could be combined with the injection kickers to provide greater y' at the stripper foil for a given kicker setting. With the use of both these steps, we were able to produce a simulation of an injected self-consistent beam in the SNS ring.

## SENSITIVITY OF SOLUTION

Having demonstrated that it is possible to paint a self-consistent distribution into the SNS ring, it was necessary to determine the sensitivity of self-consistency with respect to a number of parameters. Some of these involve the strength and placement of the solenoid magnets. Earlier studies called for two solenoids of length 0.5 m and strength 1.4 T to be placed symmetrically at locations of equal vertical and horizontal beta functions in the RF straight section of the ring. In order to assess the possibility of reducing the magnetic field in the solenoids, we carried out a series of identical calculations, varying only the solenoid field strength. The results demonstrated that self-consistency remains quite strong down to field strengths of about 0.6 T. We have chosen a somewhat more conservative value of 0.85 T for the solenoid magnets to be fabricated for this experiment.

We also considered the sensitivity to the placement of the solenoid magnets. To test this, we carried out four calculations, identical except for solenoid placement. We moved the magnets approximately one meter upstream or downstream in combinations. The results in all cases were virtually identical, showing that self-consistency is not sensitive to the exact placement of the solenoids.

Another issue of concern is the sensitivity of self-consistency to the x-y tune separation. One requirement for painting a rotating self-consistent beam is equality of the horizontal and vertical tunes. In order to determine how precisely this condition must be satisfied by the bare tunes, we carried out a series of injection calculations with horizontal tune $Q_x = 6.18$, identical except for the vertical tune setting. In this study, the vertical tune ranged from $6.13 \leq Q_y \leq 6.23$. Self-consistency was checked in these cases by comparing the average horizontal and vertical incoherent tunes, correlation coefficients between x-y' and between y-x', and the horizontal and vertical beam profiles throughout the simulations. The results showed very strong self-consistency for vertical bare tunes at and above 6.18, which decreases at lower tunes. In the range of tunes where self-consistency was found, the beam emittances adjusted in just such a way that the average incoherent tunes were nearly equal allowing the beam to rotate. At lower bare tunes $Q_y$, the beam encounters the half integer resonance at $Q_y = 6$, which effects the ability of the beam to be self-consistent. In any case, the $Q_y$ scan demonstrates that there is a comfortable range of tunes about $Q_x = Q_y$ in which self-consistent beams can be painted. In summary, the ability to achieve a self-consistent beam does not appear to be overly sensitive to the lattice settings.

## OBSERVATION AND CONFIRMATION

The above discussion indicates that it should be possible to paint a self-consistent rotating distribution into the SNS accumulator ring. However, there is little point in doing so unless the self-consistency can be confirmed. The diagnostics in SNS that can be used to observe injected beams include five wire scanners and a harp in the Ring to Target Beam Transport Line (RTBT), which carries the extracted beam from the ring to the target, and an electron scanner in the ring, which can be used to make non-destructive profile measurements during accumulation. Although the details of the correlations that are associated with self-consistency change as the beam is transported through channels where the vertical and horizontal phase advances differ, the beam will remain self-consistent in the limit of all linear transport. This implies that the beam should remain elliptical with constant density. Also, because the correlations are transported with the beam, it should be possible to observe strong correlations in various transverse quantities, with the details depending on location.

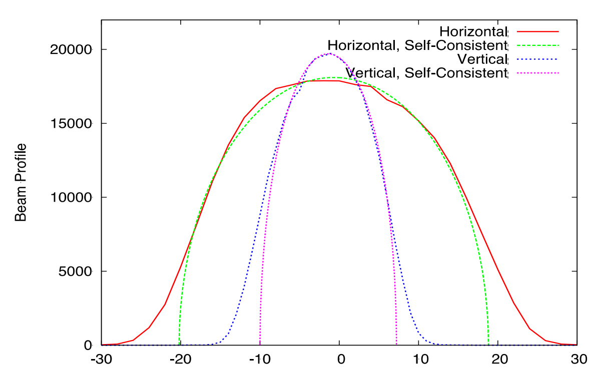


Figure 1: Horizontal and vertical profiles of the accumulated beam, with superimposed self-consistent profiles, taken at the wire scanner WS20 in the RTBT after accumulation at 300 turns.

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Figure 1 shows horizontal and vertical profiles of the accumulated beam transported after 300 turns to the location of the wire scanner WS20 in the RTBT. Comparison of the simulated results with superimposed self-consistent profiles shows good agreement throughout the beam core. The wings at the edges in the simulation are due to nonlinear and collective effects and to finite injected beam size. It is a straightforward task to measure these profiles experimentally.

The point raised above regarding correlations is illustrated in Table 1. The table shows the normalized correlation coefficients for x-y, x-y′, y-x′, and x′-y′ at the locations of the foil (ring), the electron scanner (ES, ring), the wire scanners WS02, WS20, WS21, WS23, WS24, and the Harp (all in the RTBT). The coefficients $c_{xx'}$ and $c_{yy'}$ are not shown because these are simply related to the Courant-Snyder α parameters and are, therefore, not very useful. Table 1 shows that these quantities vary from strongly to weakly correlated depending on the relationship of the horizontal and vertical phases at the location where they are observed. The measurement of these correlations in addition to the beam profiles will provide strong evidence that the beam is self-consistent.

With horizontal, vertical, and diagonal wire scanners, such as those available in the RTBT, several quadrupole scans can be used to reconstruct the full 4D sigma matrix even in the absence of coupling elements. From the sigma matrix one can extract the correlation coefficients to compare with those shown in Table 1. We are currently investigating the RTBT optics that will be used for this measurement.

Table 1. Correlation Coefficients at Diagnostics

| Location | $c_{xy}$ | $c_{xy'}$ | $c_{yx'}$ | $c_{y'x'}$ |
|---|---|---|---|---|
| Foil | -0.15 | 0.71 | -0.57 | 0.02 |
| ES | 0.38 | 0.72 | -0.58 | -0.71 |
| WS02 | 0.37 | 0.66 | -0.56 | -0.67 |
| WS20 | 0.69 | 0.32 | -0.69 | -0.19 |
| WS21 | 0.52 | -0.26 | 0.15 | 0.39 |
| WS23 | 0.64 | -0.11 | 0.54 | 0.05 |
| WS24 | 0.72 | 0.67 | -0.66 | -0.47 |
| Harp | -0.44 | 0.60 | -0.50 | 0.60 |

## CONCLUSIONS

This paper has summarized the results of extensive computational studies performed to support our proposal to paint a rotating self-consistent distribution into the SNS accumulator ring. The calculations were performed using realistic physics models and a detailed representation of the ring configuration. In particular, we employed symplectic transport with fringe fields, space charge, transverse and longitudinal impedances, injection and foil scattering, RF focusing, and beam loss due to a complete set of apertures and collimators. We developed an extended fringe field tracking model that was used for the quadrupole doublets in the injection straight section. We examined a variety of possible painting scenarios to determine whether they could be applied without necessitating a change in the injection kicker polarities and whether they resulted in acceptable losses. This led to the adoption of an x-y′ painting scheme. We studied the ability of the injection kickers to support the self-consistent painting. It was found that the achievable strength of the second vertical kicker is a limiting factor. However, by lowering the beam energy and utilizing orbit corrector dipoles in the injection straight section, we found that it is possible to paint a self-consistent rotating distribution into the SNS ring. Finally, to determine the robustness of the self-consistent painting, we studied sensitivity to solenoid field strength and placement and to the tune separation. Results of these calculations show that there is not a great sensitivity to any of these factors and that it should be possible to paint a rotating beam for a range of settings.

We also discussed what measurements can be made to validate the self-consistency of the painted beam. The existing diagnostic hardware, consisting of wire scanners and harp in the RTBT transport line and an Electron Scanner located in the ring, can be used to provide profile measurements and correlation functions between transverse variables that will strongly support the demonstration of self-consistency.

The only hardware change that we envision is the installation of two solenoid magnets of length about 0.5 m and strength of 0.85 T symmetrically in the RF straight section of the ring. As a result, we conclude that it is feasible to paint a rotating self-consistent distribution into the SNS ring. Finally, the computational results yield beams of more uniform and lower transverse density than are found for the present correlated SNS painting scheme. Such beams are very desirable for high intensity, fixed target accelerators such as SNS.

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