INJECTION OF A SELF-CONSISTENT BEAM AT THE SPALLATION NEUTRON SOURCE*

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Abstract

We propose to demonstrate the injection of a self-consistent beam into the Spallation Neutron Source (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. Self-consistent distributions exhibit linear space charge forces and, because of their linear transport properties, may undergo very little halo formation if realized in practice. Some self-consistent distributions may also be manipulated to generate flat beams. Self-consistent distributions involve very special relationships between the phase space coordinates, making them singular in some respects and difficult to realize experimentally. The most famous self-consistent distribution is the K-V distribution, but now many other self-consistent distributions have been discovered. One such distribution, the 2D rotating distribution, can be painted as a coasting beam into the SNS accumulator ring, with slight modification of the lattice. Because the bunch length in the SNS ring is very long, it is expected that the coasting beam assumption will be a good approximation during accumulation. However, it is unknown how robust self-consistent distributions will be under real world transport in the presence of nonlinearities and other collective effects. This paper studies these issues and the mitigation of unwanted effects by applying realistic detailed computational models to the simulation of the injection of rotating beams into SNS. The result is a feasible prescription for the injection of a rotating self-consistent distribution into the SNS.

BACKGROUND

During the years 2003-2006, a few of us at SNS worked on one of the many interesting topics suggested by Slava Danilov: self-consistent beams. The idea was to find solutions to the Vlasov equation that are characterized by elliptical distributions of uniform density in real n-dimensional space and the retention of these properties, shape and density, under all linear transport, even in the presence of space charge. We refer to beams having these properties as self-consistent distributions.

Aside from mathematical interest, there are potential practical advantages of such distributions. They would exhibit no losses, at least under linear transport. They would embody smaller maximum space charge tune shifts than peaked density distributions. They could provide uniform density footprints for high intensity fixed target applications. Finally, they can be manipulated to give flat beams, at least when space charge effects are weak.

Prior to our work, the only known self-consistent distribution was the famous K-V distribution. However, injecting a K-V distribution into a real accelerator is not feasible. Our hope was to find self-consistent distributions that could be practically injected and that would be robust under real transport including (in addition to space charge) nonlinearities, impedances, and other loss mechanisms.

The tangible results of this early work were published in a journal article and in several conference proceedings [1-5]. After this, emphasis shifted to SNS operations and physics. But now interest has revived, and we have begun an effort to inject a self-consistent beam into the SNS ring.

SUMMARY OF PREVIOUS WORK

The initial 2003 journal article [1] was mainly a mathematical exercise. It demonstrated the existence, techniques for constructing, and classification of numerous self-consistent distributions in n dimensions. It described the mathematical form of the distributions, which could be written as functions of constants of the motion times products of delta functions involving linear relationships between the generalized coordinates. It proved the preservation of self-consistency in all linear transformations, and it constructed envelope equations for self-consistent distributions in 2D and 3D. Finally, it presented a simulation, using the ORBIT Code [6], of injection of a 2D self-consistent distribution including space charge into a linearized SNS lattice as a coasting beam (no gap, no ring RF).

This distribution was classified, in the nomenclature of the paper, as a {2,2} distribution, meaning a 2D distribution with 2 delta functions, one relating x to y’ and the other relating y to x’. The notation {n,m} means n dimensions and m delta functions. We commonly call the {2,2} distribution a rotating distribution because the beam rotates in the transverse plane. Three conditions had to be met to inject the rotating distribution. The painted horizontal and vertical emittances had to increase linearly in time to yield constant charge density. The painted horizontal and vertical phases had to differ by 90° to obtain an elliptical distribution in transverse space. Finally, the vertical and horizontal tunes had to be equal to maintain a constant relationship between the horizontal and vertical particle phases. Including space charge, this means that horizontal and vertical emittances must be equal.

Subsequent work was mostly computational, with the emphasis on systematically introducing increasingly real-

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istic effects: chromaticity and nonlinearities, fringe fields, foil scattering and collimation, impedances, bunched beams, and real injection (as opposed to artificial bumps). These steps were carried out independently and sometimes in parallel. Chromaticity, nonlinearities, and fringe fields were introduced and found to destroy self-consistency due to the coupling of two degenerate eigen-solutions. The introduction of a pair of solenoids into the RF straight section broke the degeneracy, making self-consistent painting possible. By manipulating self-consistent beams using skew quadrupoles, but ignoring space charge, it was shown that flat beams, of interest in colliders, could be produced. The required injection kicker waveforms necessary to paint rotating self-consistent beams in SNS were worked out and shown to be possible. At the time, this was not tested in ORBIT simulations, where only artificial bumps were employed. The final approach toward reality in the early work was to replace the coasting beam assumption by that of a chopped bunched beam. Since the length of the beam in the SNS ring is about 200 meters, this should be possible so long as the longitudinal density is kept uniform. During this early work prior to SNS operation, the design ring dual harmonic RF focusing called for 40 kV in the first harmonic and 20 kV in the second harmonic. These large voltages distorted the current profile significantly away from uniformity and destroyed self-consistency. As a computational experiment, we replaced the dual harmonic RF cavities by barrier cavities, which maintained a constant density longitudinal profile. Simulations with the barrier cavities showed that it was possible to inject a chopped rotating self-consistent beam into the SNS ring. After this, we ceased work on self-consistent beams, partly because we could not paint a self-consistent beam with the dual harmonic RF system at its design values but mostly because SNS commissioning and operation was getting underway.

RECENT PROGRESS

A decade has passed since the above-described work was completed and SNS is now operating in production mode. One of the things that we learned as SNS evolved is that the ring RF can maintain the beam gap with much smaller voltages, well under 10 kV in both the first and second harmonics. Such low voltages should lead to much less distortion of the longitudinal current profile than occurs for the design values. With this, we now propose to complete our computational studies of self-consistent rotating beam injection into SNS and, if the results are positive, proceed to demonstrate this experimentally.

Beginning where we had left off, we had simulated the injection of a rotating self-consistent distribution into SNS. The simulation employed equal tunes of 6.18, full nonlinear transport including fringe fields, solenoids in the lattice, production beam intensity, foil scattering, apertures and losses, 2.5D (sliced) space charge, and transverse and longitudinal impedances. There were two unrealistic limitations, namely, barrier cavities and artificial bumps for painting. Thus, the first tasks were to repeat the calculations using the present, much lower, dual harmonic RF settings and including the real bumps in the injection painting scenario.

Our first test was to replace the barrier cavities by the SNS dual harmonic RF. Rather than using the design cavity voltages of 40 kV first harmonic and 20 kV second harmonic we employed voltages of 4 kV in both the first and second harmonics. These values are in the range of current production voltages and are sufficient to maintain the beam gap. The resulting longitudinal beam profile was somewhat more peaked than that obtained with barrier cavities, but still quite broad and uniform. In the transverse plain, the injected distribution retained its self-consistency. This left only the injection painting to demonstrate.

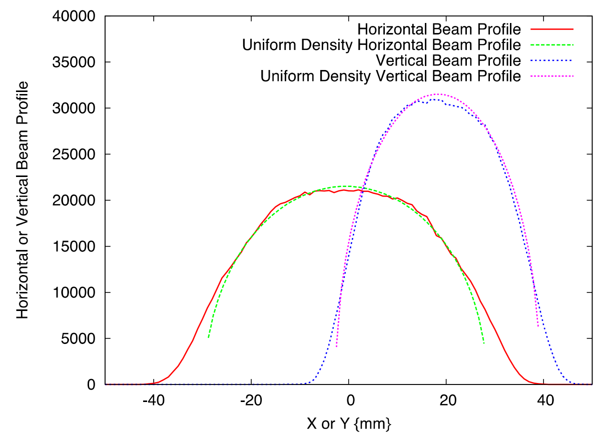

Figure 1: Comparison of horizontal and vertical accumulated beam profiles from simulation with those for an exactly self-consistent beam. Agreement is excellent except at the edges, where the effect of the finite size of linac beam at the foil causes some spreading.

In the artificial bump method, the injection kickers are treated as drifts and the closed orbit passes through the centers of all lattice elements. Injected beam is added at the location of the stripper foil with the correct coordinates relative to the closed orbit. With full injection painting, the closed orbit is kicked with the appropriate time dependence and injected beam is added at the actual foil location. The main difference between these two schemes is that the closed orbit passes through the element centers in the former but it encounters the elements off center in the latter. Although this doesn't sound especially threatening, there are two quadrupole doublets in the injection chicane, and the beam encounters those magnets well off center. When quadrupole fringe fields are included in the calculations, their effects become significant because the strength of their contribution increases off axis. In our initial calculations using the real injection painting, this proved sufficient to destroy the self-consistency of the beam. Subsequent studies concentrated on the mitigation the fringe field effects by moving the kicked closed orbit closer to the axes of the quadrupole doublets. As a result, the following measures were adopted: We moved the foil and injection spot closer to the closed orbit by 1.6 cm in x

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and in y to allow a smaller injection painting bump. This allows the beam to pass closer to the axis of the doublet magnets. We also increased the fields in the injection chicane dipole magnets by 20% to provide more of the injection bump inside the doublets, hence reducing the painting bump further. These changes should be experimentally feasible. In addition, we chose to paint a smaller beam (60% size) in the transverse dimensions to reduce the painting swings of the kickers further. A simulation adopting these measures resulted in the successful painting of a self-consistent rotating beam.

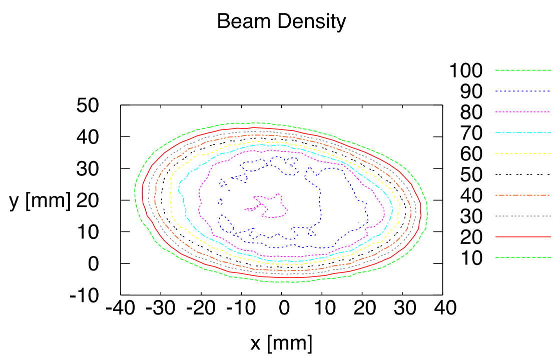

Figure 2: Footprint of simulated self-consistent beam at target. The density is very uniform, as it should be for a self-consistent beam.

Figures 1 and 2 show results are for this final best case. In Figure 1, the horizontal and vertical profiles are compared with the exact profiles for a self-consistent beam. The agreement is excellent except at the edges, where effect of finite size of linac beam at foil causes some spreading. Figure 2 shows the footprint of the simulated self-consistent beam at the target. The density is very uniform, as it should be for a self-consistent beam.

HARDWARE MODIFICATIONS

Some hardware modifications will be required to realize the present simulation experimentally. We must add two solenoid magnets to the RF straight section at locations where the horizontal and vertical betatron functions are approximately equal. Calculations show that these magnets need to be 0.5 m in length and capable of 1.5 Tesla field strength. There is sufficient space at the desired locations to accommodate this change. Also, because of the injection scheme for self-consistent painting, it will be necessary to modify three injection kickers (two horizontal and one vertical, but we may be able to optimize this) to be bipolar. The required injection waveforms will then be easily achievable. Before undertaking the design and implementation of these changes, there are a few more considerations to assure, and possibly improve, the feasibility of the present solution.

NEXT STEPS AND CONCLUSIONS

Our next steps will be to further check the feasibility of the above changes with respect to some additional issues. Mitigation of fringe field effects proved to be the most difficult aspect of achieving a realistic self-consistent injection simulation. The fringe field model used in the simulations is a hard-edge model. Because of the critical dependence of the simulation results on the fringe fields, we are implementing an extended fringe field model in the code to improve the accuracy of the model. Also, because the injection scheme is significantly different from that used in production, it will be necessary to study its impact on the unstripped waste beams.

In summary, computational studies indicate that a self-consistent beam can be created in SNS if the stripper foil and injection spot can be moved 1.6 cm toward the closed orbit in each transverse direction, three injection kicker power supplies are reconfigured to allow sign changes in the waveforms, the injection chicane dipole magnet currents are increased by 20%, and a pair of solenoids is added to one of the straight sections.

If we can show that self-consistent beam distributions can be practically realized, and if they perform as expected, it should be possible to lower the beam loss in high intensity rings, to improve beam distributions on targets, and possibly to improve collision rates in colliders and heavy ion fusion machines.

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