RF BARRIER CAVITY OPTION FOR THE SNS RING BEAM POWER UPGRADE

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Abstract

RF barrier cavities present an attractive option for facilitating the path to higher beam intensity in the SNS power upgrade. Barrier cavities lead to flat longitudinal current densities, thus minimizing bunch factor effects. In addition to allowing more beam to be injected in this fashion, flat current profiles may lead to increased e-p instability thresholds due to reduced multipacting during the trailing stage of the bunch. Finally, it is possible to inject self-consistent beam distributions into barrier buckets, thus providing the additional advantages of uniform transverse beam density (good for meeting target constraints) and little or no halo (good for low losses). Simulations addressing all these issues are presented and discussed.

INTRODUCTION

Studies to upgrade SNS from 1.44 MW to powers of 3 MW and beyond [1] are underway. The baseline SNS operating scenario involves delivering 60 pulses every second to the target. Each pulse will accumulate 1.5×10^{14} protons at 1.0 GeV in the accumulator ring over 1060 turns, resulting in a beam power of 1.44 MW. The strategy for the upgrade is to initially increase the beam power to 3 MW by maintaining the 60 Hz pulse rate while increasing the beam intensity to 2.5×10^{14} protons at 1.3 GeV accumulated over 1100 turns. There are also scenarios to push the power to an ultimate value of 5 MW. The design of the baseline SNS was carried out to accommodate the upgrade with relatively few modifications. At such high beam intensities it will be necessary to carry out exhaustive beam dynamics studies and to consider innovative ideas for the mitigation of possible instabilities.

A number of potential benefits are associated with the use of barrier cavities. Because barrier cavities concentrate their waveforms in a small longitudinal region, they tend to reflect beam particles impulsively and elastically. Thus, at any given time most of the beam may be regarded as drifting and, over time, the beam energy distribution is preserved by barrier cavities. This leads to flat longitudinal beam profiles and to large beam currents for given peak current density. These properties suggest the possibility of higher stability limits. For a given overall beam current, the peak space charge density is lower. With flat longitudinal current distributions, electron cloud buildup due to multipacting in bunch tails should reduced. Finally, because of the uniformity of the longitudinal distribution, it may be possible to paint self-consistent transverse beam distributions [2]. However, because barrier cavities tend to preserve the energy distribution of the injected beam, it may be necessary to paint this beam in energy to provide desirable stability properties. A pair of energy spreader and energy corrector cavities that could accomplish this was deleted from the baseline SNS design, but these cavities could be revived for the upgrade. In this paper, we study a number of these issues for the SNS Upgrade computationally using the ORBIT Code [3].

ASSUMPTIONS

ORBIT is a computer code developed at Oak Ridge National Laboratory for multiparticle beam dynamics. It has been used primarily to study proton rings and transport lines. ORBIT contains many relevant physics models: symplectic single particle transport, a variety of lattice elements, space charge, impedances, apertures and collimators, alignment and field errors, injection and painting, self-consistent electron cloud dynamics, and more. We use it here to study the SNS Upgrade injection scenario. Of the physics models mentioned above, we employ all but the error models in the course of this work. We inject 2.5×10^{14} protons at 1.3 GeV over 1100 turns into the 248 meter SNS ring. Our injection painting schemes are carried over from the baseline SNS and, in the case of self-consistent distributions, from previous studies. There has been no attempt at optimization of painting. When energy painting is carried out, we use the parameters for the energy spreader and corrector cavities that were deleted from the baseline SNS. Basically, these cavities add an energy spread of ±4 MeV to the injected beam. For evaluation of losses we include a complete set of apertures for the ring and also the stripper foil and adjustable beam scrapers. The foil and scrapers are modeled to include small angle multiple Coulomb scattering, Rutherford scattering, and elastic and inelastic nuclear scattering, while the other apertures are taken to be perfect absorbers.

The baseline ring RF system in SNS is a dual harmonic waveform obtained from four cavities, $V = V_1 \times \sin(\varphi) - V_2 \times \sin(2\varphi)$, with $V_1 = 40$ and $V_2 = 20$. For our barrier cavity model we assume a simple waveform obtained from four identical cavities, $V = -V_1 \times \sin((\varphi - n\pi) \times \pi / \Delta)$ with $V_1 = 40$ for $|(\varphi - n\pi) \times \pi / \Delta| < \pi$, and $V = 0$ otherwise. The dual harmonic waveform leads to peaked beam current profiles, while barrier cavities give flat beam current profiles. Therefore, for given total bunch current, barrier cavities provide smaller peak current. The RF waveforms and resulting current profiles at the end of injection are shown in Figure 1.

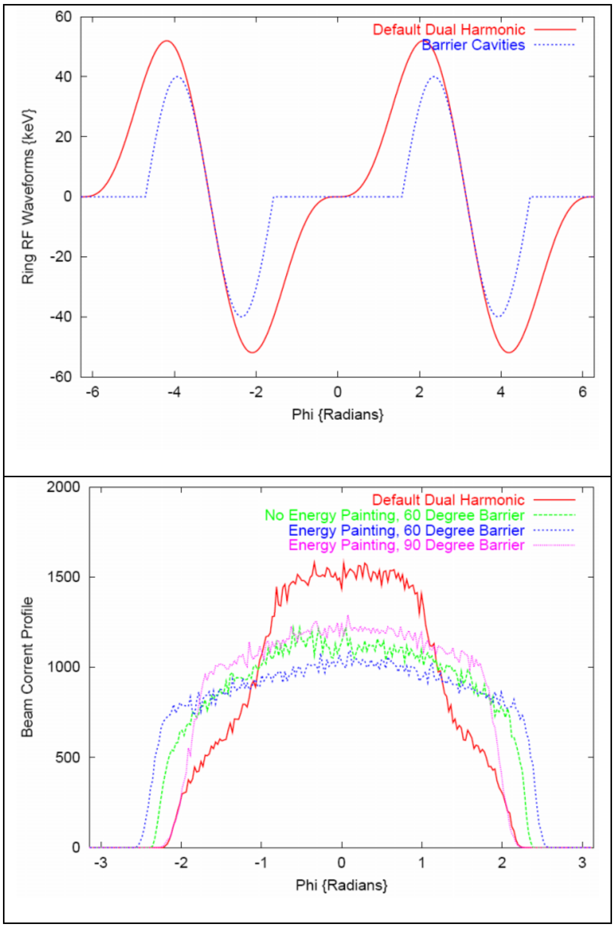

FIGURE 1. Top) Assumed dual harmonic and barrier cavity waveforms. Bottom) Beam current profiles for different RF waveforms.

Barrier cavities tend to preserve the energy distribution of the injected beam. Therefore, it may be necessary for reasons of beam stability to paint a broader energy distribution. This can be done with RF cavities upstream of the injection point. Figure 2 shows the energy distributions at the end of injection for the baseline dual harmonic RF cavities and for barrier cavities with and without injection painting. The amplitude and width parameters of the barrier waveform need to be adjusted to accommodate the energy distribution of the injected beam. In the case of no energy painting, we set $\Delta = 60°$, but with energy painting we had to increase to $\Delta = 90°$ to maintain the correct beam gap size.

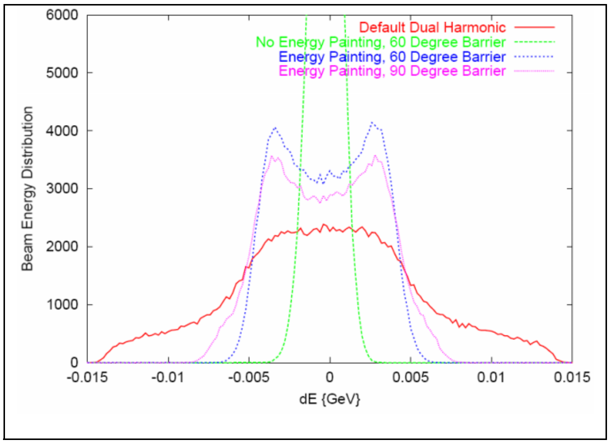

FIGURE 2. Energy distributions at the end of injection for different RF waveforms.

STABILITY CONSIDERATIONS

Because the peak charge density for a given beam current is lower with barrier cavities, space charge effects are less than with the dual harmonic RF waveform. This can be seen in Figure 3, which plots the tune footprints at the end of injection for three cases: 1) dual harmonic RF waveform and nominal transverse injection painting (red), 2) barrier cavity waveform with energy painting, $\Delta = 90°$, and nominal transverse injection painting (green), and 3) barrier cavity waveform with energy painting, $\Delta = 90°$, and transverse painting of a self-consistent distribution (blue). The bare tunes for these cases are $Qx = 6.23$, $Qy = 6.20$ for the nominal transverse painting and $Qx = 6.18$, $Qy = 6.18$ for the self-consistent distribution. The tune shifts are seen to be smaller for the barrier cavity cases than for the dual harmonic RF, with the smallest tune shifts being those for the self-consistent distribution. In all cases, the tune distributions stay well above the integer value at 6.0. Consequently, we observe no deleterious consequences due to space charge.

We studied the longitudinal stability for a number of cases. Using the dominant ring impedance of the extraction kickers, we found that if space charge is ignored and no energy painting done, there is a longitudinal instability. The threshold for this instability was observed at about 1.0×10^{14} protons. However, the inclusion of space charge in the calculation is observed to stabilize the beam, even at 2.5×10^{14} protons. Alternatively, the beam can be stabilized by energy painting, even when space charge is ignored. Figure 4 shows the longitudinal distribution at the end of injection for the unstable case ignoring space charge and its stabilization when space charge is considered.

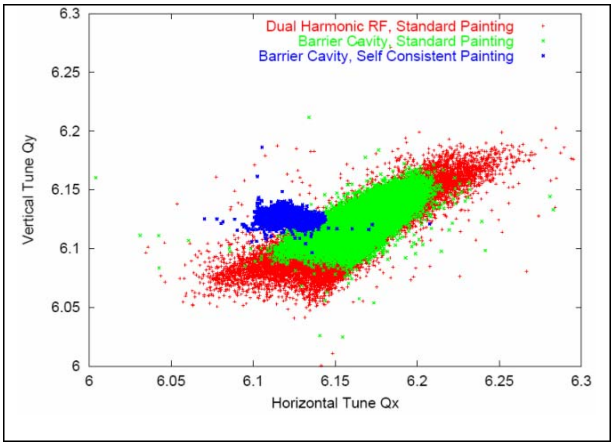

FIGURE 3. Tune footprints for three different RF and painting scenarios.

Again using the extraction kicker impedance, we find the threshold for transverse instability is about 4.0×10^{14} protons, assuming natural chromaticity, no painting of the energy distribution, and ignoring space charge. The neglect of space charge and lack of energy painting both tend to destabilize the beam so, except for the use of natural chromaticity which is stabilizing, these predictions err on the pessimistic side. To obtain the most pessimistic limits, we are now repeating the calculations with the lattice corrected to zero chromaticity. Figure 5 shows the mode amplitudes from this latter calculation for an unstable case at intensity 2.5×10^{14} protons, which is dominated by the modes n = 10-13. Based on results thus far, we estimate that the transverse instability threshold with zero chromaticity, neglecting space charge, and no painting in energy will be about 1.5×10^{14} protons. Although it appears that, when space charge effects are included, the actual beam at an intensity of 2.5×10^{14} protons will be stable, we believe that painting a broader energy distribution using an energy spreader cavity will provide an extra measure of safety. Although calculations of the threshold with chromaticity correction, energy painting, and space charge have not yet been carried out, we have run a 2.5×10^{14} proton simulation with all these effects included – and it is stable.

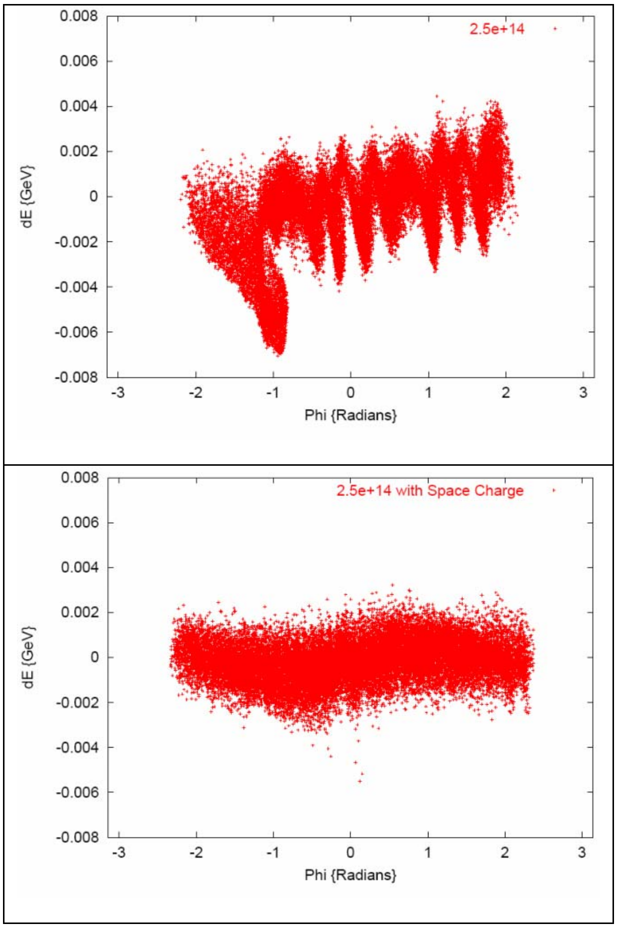

FIGURE 4. Longitudinal distribution following injection with no energy painting. Top) Ignore space charge. Bottom) Include space charge.

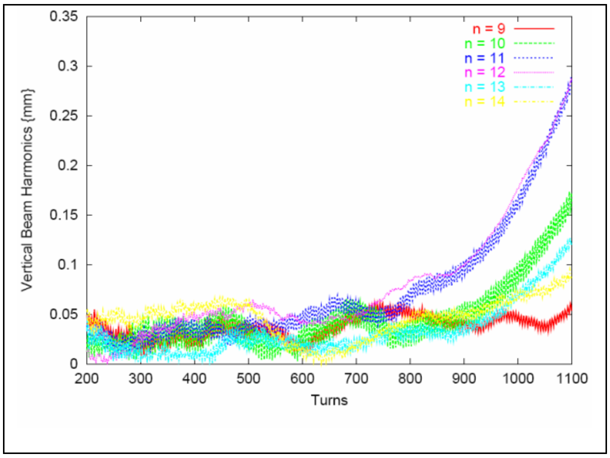

FIGURE 5. Mode amplitudes for vertical transverse impedance induced beam oscillations.

ELECTRON CLOUD FORMATION

In order to assess the effect barrier cavities may have on electron cloud formation, we applied

ORBIT's electron cloud model. Although this model is fully self-consistent, we ignored the electron forces on the protons here because we wanted to study the electron cloud development, and not the proton response, at this time. In this mode, the electron cloud model tracks the electrons in the presence of electron, proton, and external fields. The electron generation and wall interaction models were adapted from those of Furman and Pivi [4]. For the studies here, we assumed surface electron generation (no neutral gas) by the protons, a titanium-nitride coated stainless steel beam pipe for the electron surface interactions, and a circular beam pipe of 11 cm radius.

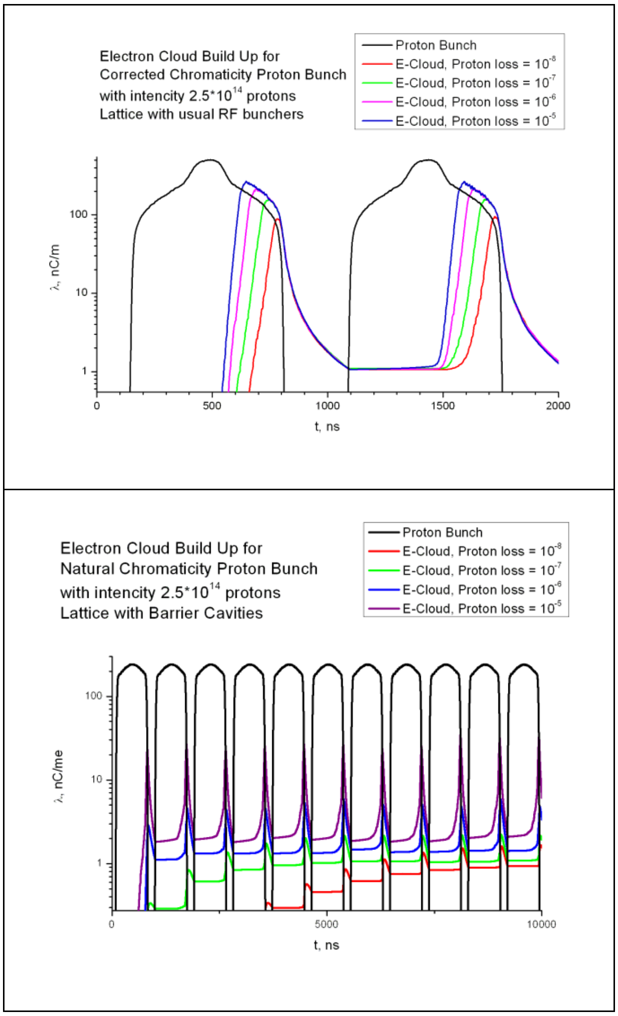

FIGURE 6. Proton bunch current and electron cloud density for Top) Dual harmonic RF Bottom) Barrier cavities.

For the peaked current profiles obtained using the dual harmonic RF, decreasing electrostatic potential and multipacting between electrons and the vacuum chamber can combine to give significant electron cloud buildup in the trailing portion of the bunch. As shown in Figure 6, this electron cloud buildup is an order of magnitude smaller using barrier cavities because the region where the potential falls off rapidly is narrow. Another important question is how many electrons survive the beam gap to serve as seeds for the next beam passage. This is answered in Figure 7, which shows that increasing the beam gap size leads both to smaller peak electron densities and to fewer electrons surviving the beam gap and seeding the next pass. For comparable beam gap widths, fewer electrons survive to the next passage with barrier cavities than for the dual harmonic RF.

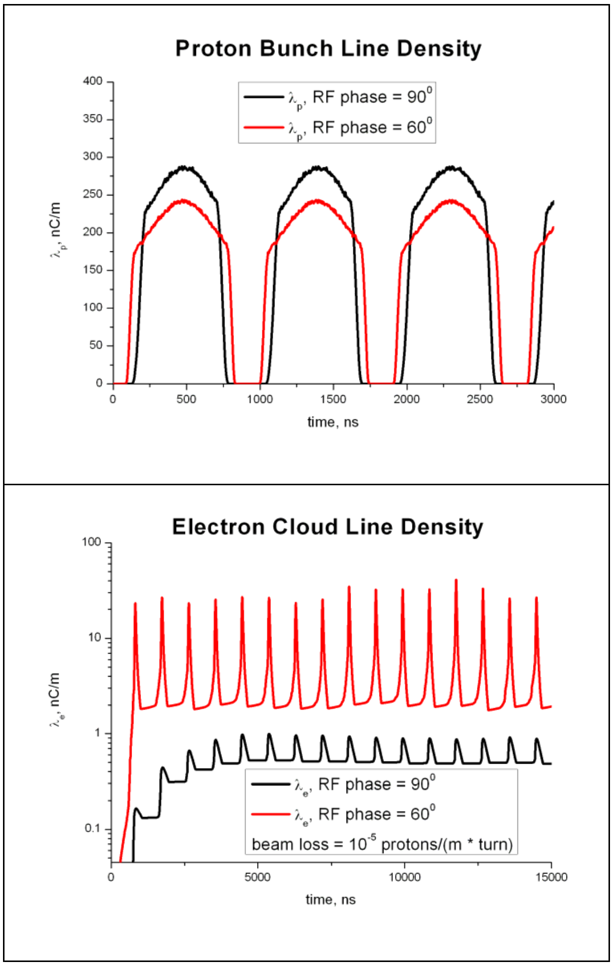

FIGURE 7. Top) Proton bunch currents and Bottom) electron cloud line densities for barrier cavities with two different beam gap widths.

SELF CONSISTENT BEAMS

Self-consistent beams are generalizations of the KV model. They have uniform charge density, elliptical shape, and hence linear space charge forces [2]. Furthermore, these properties are maintained by all linear transport. A variety of self-consistent beams has been found in one, two, and three dimensions. Because of their uniform charge density, self-consistent beams have small space charge tune shifts and, if matched to the lattice, they should produce very little halo.

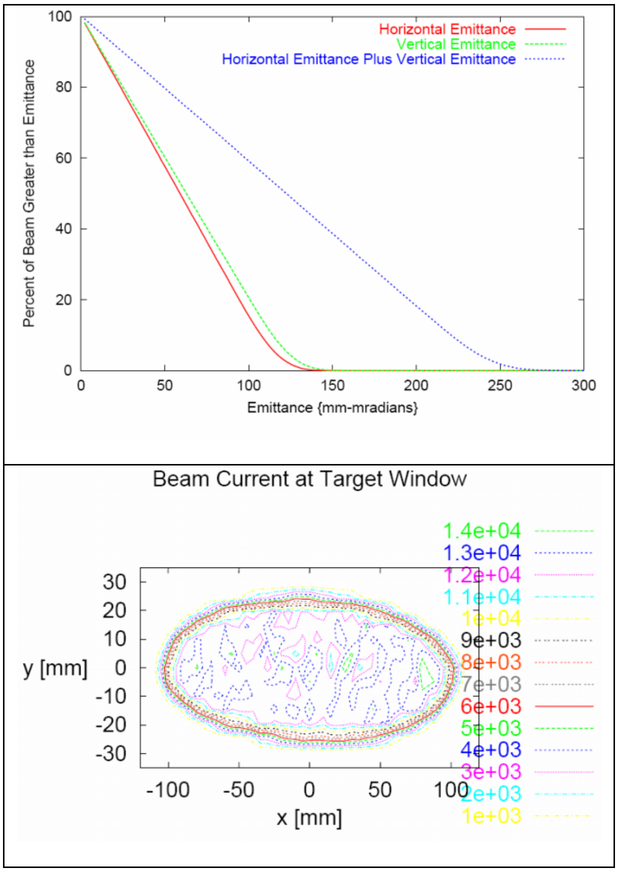

FIGURE 8. Top) Emittance distribution for barrier cavity self-consistent beam. Bottom) Current distribution of self-consistent beam at the target window.

Although three dimensional self-consistent distributions have been shown to transport well, it is not clear how to construct such beams through painting. On the other hand, it is possible to paint two dimensional transverse self-consistent distributions. These distributions are uniform in the longitudinal direction, which means that they can not be painted using usual RF cavities. Barrier cavities, however, do give uniform longitudinal distributions, so it is worth examining whether they can be used to paint 2D transverse self-consistent distributions. Figure 8 shows the result of our self-consistent beam painting using barrier cavities. The emittance distributions fall linearly, as they should for self-consistent beams, and the current distribution at the target window is elliptical and flat, as it should be. It is also worth noting that the peak current at the target window for the self-consistent distribution is only about 75% the value obtained using the baseline painting scheme.

FULL INJECTION SIMULATIONS AND CONCLUSIONS

Full injection simulations including space charge, extraction kicker impedance, and losses show very low beam losses, provided the adjustable beam scrapers are sufficiently retracted. With the scrapers set at the nominal values for the baseline SNS, total losses were unacceptable, ranging from 10^{-3} to 10^{-2} for several cases. However, when the scrapers were withdrawn, losses went to 1.8×10^{-4} for the dual harmonic RF and to 6.5×10^{-5} for barrier cavities. These losses were dominated by nuclear scattering due to foil hits, which was higher for the peaked bunches of dual harmonic RF.

These calculations suggest that RF Barrier cavities present an attractive option for the SNS Upgrade. Barrier cavities lead to flat current profiles. As a result, they give smaller space charge effects for given intensity; smaller electron cloud generation due to multipacting; and the possibility of painting self-consistent beams. Calculations indicate satisfactory stability with respect to the dominant extraction kicker impedance. However, it may be desirable to paint the injected energy distribution, since barrier cavities do not broaden that distribution significantly. Losses during injection can be made quite small, but to obtain these small losses we have extracted the adjustable scrapers.

ACKNOWLEDGMENT

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