EXPLORING TRANSVERSE BEAM STABILITY IN THE SNS IN THE PRESENCE OF SPACE CHARGE*

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Abstract

The highest possible intensity in the machine is typically determined by the onset of coherent beam instabilities. Understanding the contribution of various effects to the damping and growth of such instabilities in the regime of strong space charge is thus of crucial importance. In this paper we explore transverse beam stability by numerical simulations using recently implemented models of transverse impedance and three-dimensional space charge. Results are discussed with application to the SNS accumulator ring.

1 INTRODUCTION

Recently, we explored the intensity limitation of the SNS governed by the space-charge effects and machine resonances [1]-[2]. The resulting space-charge limit studies and resonance driven loss model [3] showed that an intensity of $2 * 10^{14}$ protons is achievable with relatively low beam losses. However, those intensity-limitation studies did not include the effect of collective beam instabilities. Such instabilities may limit allowable operation to lower intensities.

This paper explores intensity limitation of the SNS associated with the transverse instability due to the impedance of the extraction kickers of the SNS, which is the largest contribution to the impedance budget of the SNS. Also, with these studies we begin systematic exploration of various effects on beam stability such as the effects of space-charge, chromaticity, external nonlinearities, etc.

2 NUMERICAL IMPLEMENTATION

In order to study collective beam dynamics, computational models for the impedance and 3D space charge have been developed and implemented [5] in the particle tracking computer code ORBIT [6]. Three-dimensional space charge calculation is required in this case because the transverse force due to the impedance depends on the product of beam current and the dipole moment of the beam. After these new algorithms were successfully benchmarked [5], they were implemented [7] in our SNS simulation package of the UAL [8]. In addition, one more method of transverse impedance calculation based on the wake-function approach [9]-[10] was also implemented and benchmarked [7]. These new models allow us comprehensive study of collective beam phenomena.

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3 IMPEDANCE MODEL

The transverse coupling impedance of the extraction kickers in the SNS provides the largest contribution to the impedance budget and may impact beam stability at high intensity [11]. Recent measurements of the transverse coupling impedance of one full-size model of the 14 extraction kickers [12] give a realistic estimate of this impedance contribution [13]. This impedance was significantly reduced with the 25 Ω external termination, and this configuration is now the baseline for the SNS. Based on the measured impedance, the fitting formula for the impedance of the full 14 kickers was constructed [13]. The resulting effective impedance is shown in Fig. 1. The kick is then modeled by a single impedance node with $Z_{effective}$ and an average β-function based on the β in all 14 kickers. Such an approach slightly overestimates the effect of the impedance compared to the distributed impedance scenario with the appropriate sizes of every kicker and corresponding β-function. The "average" approach can exceed the "distributed" approach by up to 20%, depending on kickers' location. As a result, our estimates of the thresholds presented here may be slightly conservative.

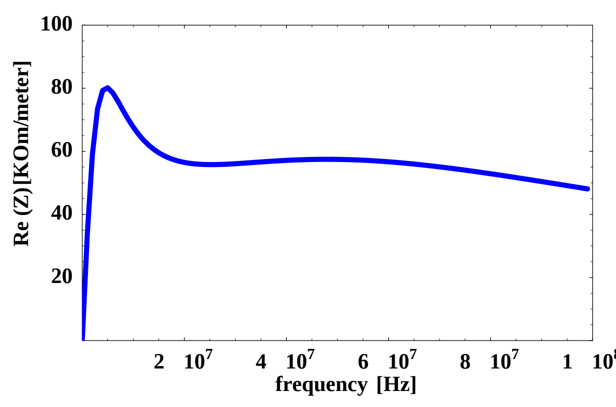

Figure 1: Real part of the transverse impedance for full 14 modules system of the SNS extraction kickers.

4 INSTABILITY THRESHOLDS AND INTENSITY LIMITATION

The studies of the instability threshold started with the linear space-charge model [4], and were later extended to the simulations with the non-linear space charge [4]-[5]. Preliminary studies with full-intensity beams indicated that

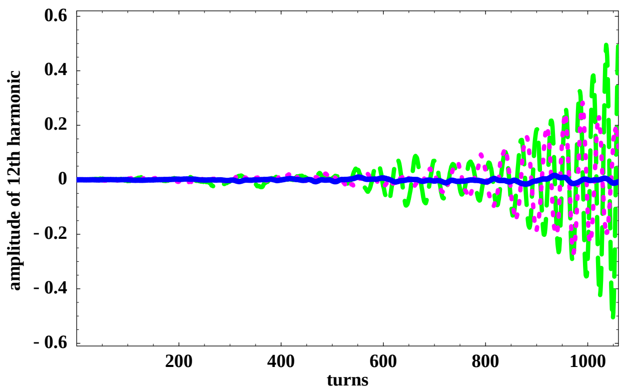

Figure 2: Time evolution of unstable harmonics.

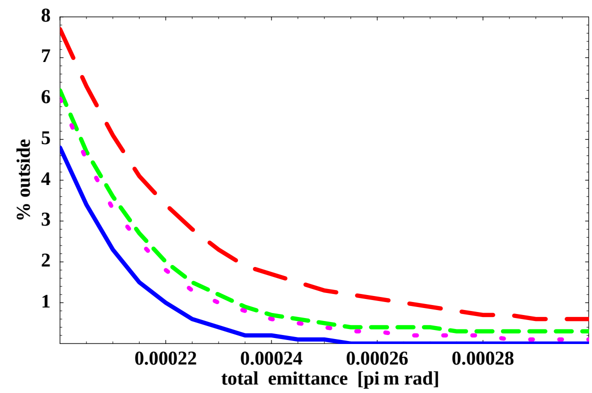

Figure 3: Beam halo for $N = 2 \cdot 10^{14}$ protons.

a 2MW SNS beam is near the instability threshold. We then proceeded with a realistic multi-turn injection scenario. In order to avoid numerical diffusion with the 3D space-charge model, we first obtained saturation of numerical parameters. This required the implementation of the code on the BNL/ITD parallel cluster which allowed us these time consuming calculations [14]. The simulations presented here are done with half a million particles using 20 dual CPU nodes.

An important feature of instability thresholds with realistic 1060-turn accumulation is the fact that final intensity is reached only at the end of accumulation right before the extraction. As a result, the beam may be stable during accumulation with not enough time for the instability to develop or lead to a significant halo growth.

4.1 $N = 2 \cdot 10^{14}$ *protons*

1. With natural chromaticity $\xi = -7$, harmonics above 6MHz have significant growth rates by the end of accumulation, which results in the onset of the instability and associated halo growth. Note that a similar case without including the space-charge forces moves the instability threshold to higher intensity, which demonstrates destabilizing effect of the space charge. Time evolution of unstable harmonics during 1060-turn accumulation (with the impedance shown in Fig. 1) is shown in Fig.2, where different cases correspond to 1) blue (solid line) - $\xi = -7$, no space charge 2) pink (dotted line) - $\xi = -7$, 3) green (short-dash) - $\xi = 0$. All simulations presented are done with the 3D space charge and $b = 11$ cm unless indicated otherwise. Here b is average chamber radius and a is the radius of the beam which reaches 4 cm by the end of accumulation.

2. Setting $\xi = 0$, decreased the instability threshold and resulted in larger beam halo. This is shown in Figs. 2- 3, for the harmonics and beam halo, respectively. In Fig. 3, in addition to unstable cases described in Fig. 2, the red (long-dash) line is a case with larger b/a ratio (impedance, $\xi = 0$, $b = 20$ cm), and blue (solid) line is the reference space-charge halo without impedance. It was found that for $\xi = 0$, the beam is more unstable without the space charge (not shown in Figures) due to the lack of the stabilization mechanism at low frequency (below 2MHz). Here, space charge might play a stabilizing role due to the frequency spread associated with the beam pipe image effects.

3. Nonlinear spread due to octupoles can help but most likely will be unsufficient for operation at these intensities.

4.2 $N = 1.5 \cdot 10^{14}$ *protons*

1. Natural chromaticity of $\xi = -7$ is enough to stabilize the beam at these intensities. The associated tune spread is tolerable with respect to resonance losses, due to effective space-charge tune depression.

2. With $\xi = 0$, the beam becomes unstable. Growth of the unstable beam modes starts right before extraction, resulting in some halo growth. This is shown in Figs. 4-5, where 1) pink color (solid line) corresponds to $\xi = -7$ case, and 2) green color (dash) corresponds to $\xi = 0$. For this intensity, it thus seems possible to avoid instability by working with the natural chromaticity. Also, additional Landau damping can be provided by octupoles. A feedback system for this intensity may not be required but it is recommended.

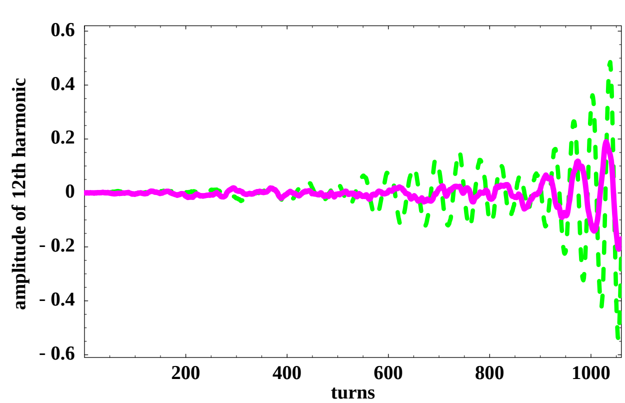

Figure 4: Time evolution of unstable harmonics.

For $N = 1.0 \cdot 10^{14}$ protons, the beam is expected to be stable with $\xi = -7$. Even with $\xi = 0$, no significant halo is observed by the end of accumulation.

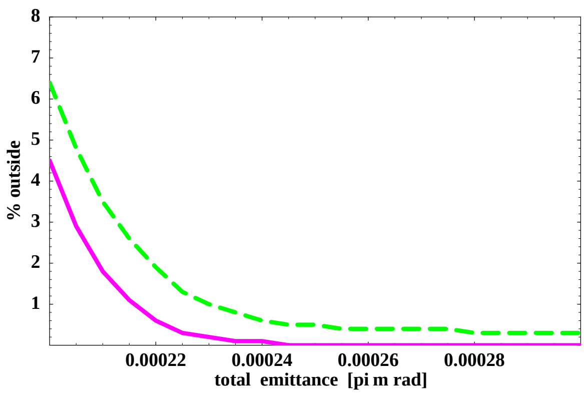

Figure 5: Beam halo for $N = 1.5 \cdot 10^{14}$ protons.

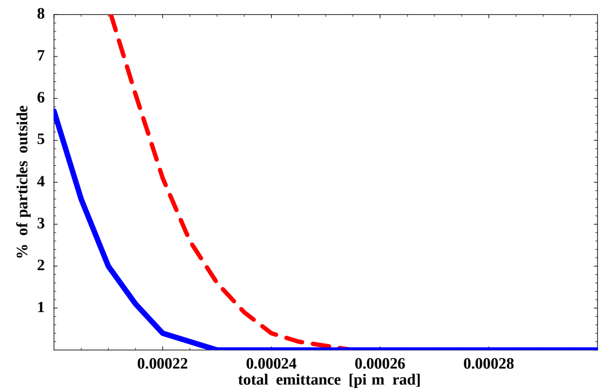

Figure 6: Beam halo at the end of 1060-turn injection ($N = 2.0 \cdot 10^{14}$) due to the impedance offset 1) solid line - no impedance, 2) dash line - impedance with offset.

5 VARIOUS DAMPING MECHANISMS AND BEAM STABILITY

The extraction kicker impedance with the 25Ω termination is rather large for very low frequencies, where Landau damping is not yet effective. For a special case without space charge and zero chromaticity, the low frequency component of the unstable mode is larger than when space charge is included, which results in an increase of the net growth rate. This is in agreement with simple analytic estimates, which indicate that such a beam is approximately a factor of two above the threshold for $N = 2 \cdot 10^{14}$ intensity. The natural chromaticity effectively damps low-frequency harmonics. As a result, the net effect of the space charge (in the presence of chromaticity) was found to be destabilizing with decreasing instability threshold from $2 \cdot 10^{14}$ to around $1.5 \cdot 10^{14}$.

Among possible stabilization mechanisms observed are the b/a dependence and stabilization with the octupoles of an appropriate sign. Increasing the b/a ratio decreases the instability threshold, since image-induced tune spread along the bunch, associated with the longitudinal current density, becomes less effective. Figure 3 shows this effect with more pronounced beam halo for larger b/a ratio. Comprehensive exploration of these effects will be presented in the future in a more detailed report.

6 EFFECT OF IMPEDANCE OFFSET

The extraction kickers of the SNS are not centered with respect to the zero closed orbit. They are offset from the center in order to save on mechanical dimensions when the full-size accumulated beam is extracted [12]. As a result, the longitudinal beam centroid will experience a kick different from the head and tail of the beam, due to the longitudinal current distribution along the bunch. This results in a ”banana-shape” distortion along the beam or oscillation of beam centroid. This effect does not lead to an instability but contributes to overall emittance growth [3]. Figure 6 shows this effect for the stable case without space charge and $\xi = -7$. Painting to a smaller emittance can help to minimize losses at the scraper acceptance but it is limited due to $1/2$ resonance response [1].

7 SUMMARY

In this paper we apply recently developed models of the 3D space charge and transverse impedance to explore the intensity limitation in the SNS due to the collective instability governed by the transverse impedance.

8 ACKNOWLEDGMENT

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