HALO AND SPACE-CHARGE ISSUES IN THE SNS RING *

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Abstract

The latest designs for high-intensity proton rings require minimizing beam-induced radioactivation of the vacuum chamber. Although the tune depression in the ring is much smaller than in high-intensity linacs, space-charge contributions to halo formation and, hence, beam loss may be significant. This paper reviews our current understanding of halo formation issues for the Spallation Neutron Source (SNS) accumulator ring.

1 INTRODUCTION

Space-charge (SC) is a fundamental limitation in high-intensity circular accelerators. In the SNS, which pushes beyond existing intensity levels, SC effects will be especially important. The importance of SC and halo formation in high-intensity linacs has been widely recognized (see extensive literature in [1]; also some new developments were recently reported [2]). In rings, however, an understanding of these issues appears to be even more important: for economic reasons, in a linac one can attempt to accept the halo, while in a ring one must try to avoid halo formation because of a relatively small beam pipe acceptance / beam size ratio. A discussion of halo formation issues in circular accelerators was recently presented [3]. Also, the definition of "halo" was specifically discussed [4] with the conclusion that what really matters is the source of halo. In general a halo can develop by any number of mechanisms; the "parametric halo" in linacs is just a special case of a halo caused by the parametric resonance. In this paper we discuss various mechanisms of halo formation in circular accelerators and their application to the SNS.

2 DEVELOPMENT OF PARAMETRIC HALO

The parametric resonance mechanism, which is believed to be the main cause of SC induced halo in linacs, is not necessarily the main source of halo in rings. This resonance between the motion of individual ions and collective beam oscillations is governed by the rms beam mismatch. It can be shown that the main 1:2 parametric resonance is possible for any non-zero SC. The halo extent associated with this resonance is large not only for very strong tune depressions of the order of $\eta \sim 0.5$ (typical in linacs) but also for tune depressions of only a few percent $\eta \sim 0.98$ (typical in high-intensity rings). The separatrix width of this 1:2 resonance is governed mainly by the beam mismatch, although some dependence on tune depression does exist. In the limit of zero SC, the motion near the core is very regular, and the rate at which particles are driven to the 1:2 resonance becomes very small; in addition, the unstable fixed points of the 1:2 resonance move further from the origin. Therefore, for the SC typical in high-intensity rings ($\eta \sim 0.98$), it will take much more time for particles to be trapped in the 1:2 resonance than for typical linac tune depressions. The rate of halo development thus becomes the most important question when one tries to estimate the effect of the parametric resonance on halo formation in rings. Computer simulations with a full-intensity KV beam confirm both the existence of parametric halo at $\eta \sim 0.98$ and a very slow growth rate [5]. However, in the SNS the use of multi-turn injection makes the situation quite different from the simplified assumption of a full-intensity beam. First, the final intensity is reached only at the end of injection, just before extraction; this leaves no time for a parametric halo to develop. Second, the mismatched modes of the beam may be damped by the phase mixing associated with multi-turn injection. To summarize, mechanisms other than parametric resonance may be more important for halo development in high-intensity rings. Thorough studies of various mechanisms that can lead to beam tail growth are required because of the low tolerance for uncontrolled beam loss.

3 EFFECT OF RESONANCES

3.1 *Effective SC tune shift*

Machine resonances play a major role in halo formation. The leading part of the SC force can be described in terms of the incoherent tune shift. One typically assumes that if this incoherent tune shift is large enough, it can place individual particles on low-order betatron resonances. For a uniform-density beam the maximum incoherent tune shift is given by

$$\Delta\nu_{max} = \frac{N r_p}{8\pi\beta^2\gamma^3 B_f \tilde{\epsilon}}, \qquad (1)$$

where N is the number of protons in the bunch, r_p is classical proton radius, B_f is the bunching factor, and $\tilde{\epsilon}$ is the unnormalized rms beam emittance. For typical SNS parameters this formula gives $\Delta\nu_{max} \approx 0.15$.

The above procedure for predicting SC limits is based on the assumption of constant beam size. However, the

* Work supported by the US Department of Energy

beam envelope modulation produces an electric field that exactly cancels the gradient perturbation for this intensity. This effect has long been recognized [6]; the general theory was developed by F. Sacherer [7]. The resonance condition should be modified to include the effect of envelope oscillations. The standard resonance condition is

$$\frac{n}{m} = \nu_0 - \Delta\nu, \qquad (2)$$

where n is the excited harmonic in the magnet, and m corresponds to the order of the resonance. The more accurate resonance condition can be written as [8]

$$\frac{n}{m} = \nu_0 - C_m \Delta\nu, \qquad (3)$$

where coefficient C_m represents the effect of the coherent oscillations. To avoid confusion with the coherent tune shift associated with the image forces, we will refer to the above modified tune shift as "effective" rather than "coherent". With $C = 1$, the resonance occurs at the incoherent tune. In fact, $C_m \to 1$ for large values of m. The largest difference of this coefficient from unity occurs for the half-integer resonance, $m = 2$. (C_m coefficients can easily be obtained from [9, 10] and are summarized, for example, in [3, 8, 11].) Consider, for example, a round beam, and neglect all high-order resonances. In the case of close tunes in x and y planes, one obtains $n/2 = \nu_0 - \Delta\nu/2$ for the symmetric mode of collective beam oscillations, and $n/2 = \nu_0 - 3\Delta\nu/4$ for the antisymmetric mode. In the case of a working point with a large tune split ($|\nu_{0x} - \nu_{0y}| > \Delta\nu/4$) the envelope oscillations in x and y are essentially decoupled, and the resonance condition becomes $n/2 = \nu_0 - 5\Delta\nu/8$. For the SNS example, with $(\nu_x, \nu_y) = (6.3, 5.8)$ and $\Delta\nu_{max} \approx 0.15$, the effective tune shift is then $\Delta\nu_{effective} = 5\Delta\nu/8 = 0.09$, and the SC limit becomes less restrictive.

3.2 *Choice of working point and SC resonances*

SC forces and magnet field errors can drive particles into resonances, resulting in increased emittance and particle loss. Using the concept of "effective" tune shift helps one find the most suitable working points. However, besides machine resonances there are also SC-induced resonances. Their importance was first shown for the dominant coupling resonance [12], and then for some non-coupling resonances [13, 14]. Therefore, the choice of working point should also take into account SC-induced resonances. For the SNS the dominant coupling resonance, $2\nu_x - 2\nu_y = 0$, was observed in numerical simulations with full-intensity beams [15, 5, 16] and multi-turn injection [16]; this prompted our decision to move away from the $(5.82, 5.8)$ working point [17]. Multi-stage halo formation caused by the mismatch initially produced by the 1:4 SC resonance has also been observed [15, 5]. In addition to the dominant coupling resonance which is present even in the absence of errors, there exist other SC coupling resonances which become excited in the presence of magnet errors. Analytical and numerical work on this subject is currently in progress.

4 OTHER MECHANISMS

The development of a beam halo also depends strongly on the choice of painting scheme and beam profile.

4.1 *Painting schemes*

Anti-correlated painting is designed to produce an elliptical transverse beam profile of uniform density, but, in the presence of the SC, it generates an excessive halo [17, 18]. Thus, special schemes are required to minimize halo production [18]. Correlated painting has the advantage of constantly painting over the beam halo, but even in this case careful bump optimization is needed to achieve low beam loss. Shown in Fig. 1 are beam tail distributions of three different bumps for correlated painting, where we plot the percentage of particles outside a given emittance (in π mm mrad). The bump which collapses as a square-root function (red color) performs better than the other two bumps, which decay exponentially with different time constants τ ($\tau = 0.6$: pink color, $\tau = 0.3$: blue color). Simulations were done with ORBIT [19], where SC was the only source of non-linearity.

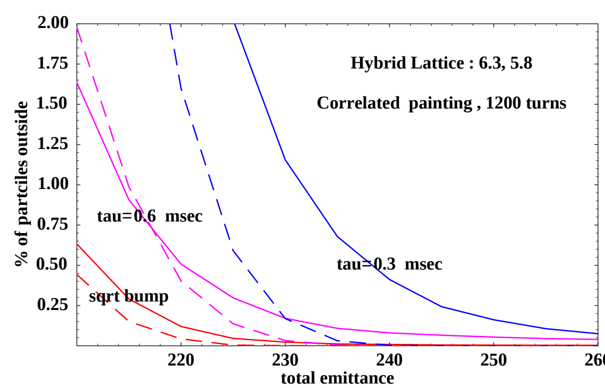

Figure 1: Beam halo distribution for correlated painting with three different bump functions. Solid and dashed lines correspond to simulations with and without SC, respectively.

4.2 *Beam profile*

In the case of correlated painting, the beam is painted to a square shape; this results in a "singular" distribution along the diagonals. In Figs. 2 and 3 we present 2-D density plots (X-Y) for the square-root bump function without SC and with SC, respectively. Simulations were done with ORBIT [19] without magnet errors. The inclusion of SC leads to rapid azimuthal diffusion and some spreading in the radial direction. For this case the 2-D beam densities, based on simulations, agree well with analytic predictions.

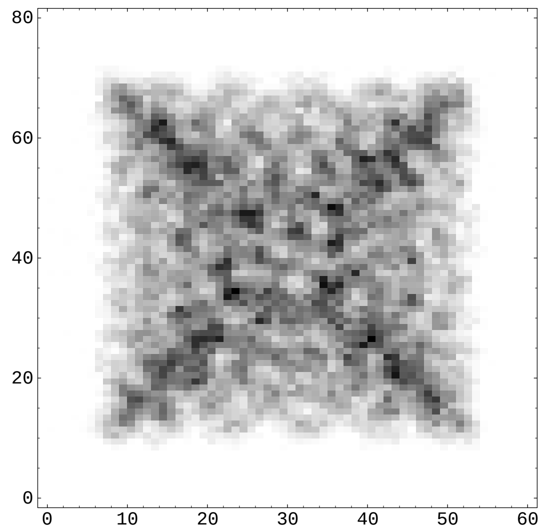

Figure 2: 2-D density plot (X-Y) for correlated painting with square-root bump (without SC)

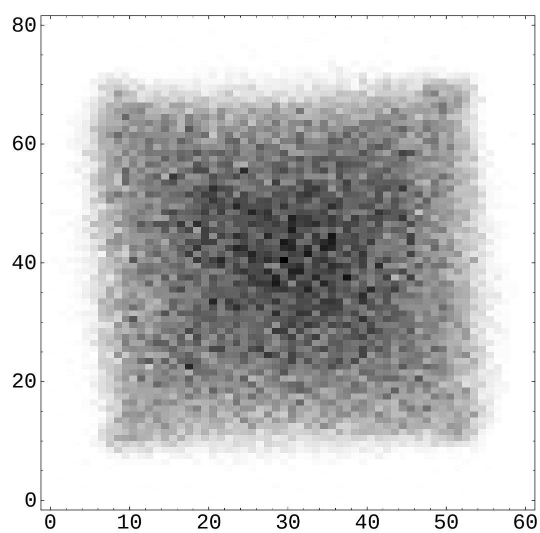

Figure 3: 2-D density plot (X-Y) for correlated painting with square-root bump (with SC)

5 SIMULATIONS

Because of the complexity of SC behavior in Rings, analytic estimates of halo formation are very limited. Hence realistic computer simulations are required. Most of our previous SC simulations were done with ORBIT and SIMPSONS [20]. Various painting schemes were analyzed to obtain desired target requirements and minimize halo development [18]. Recently, a new SNS package was developed using the Unified Accelerator Library (UAL). Its nonlinear single-particle dynamics was successfully benchmarked [21] against MARYLIE [22] and FTPOT [23], and its SC dynamics against ORBIT. This new package allows us to study complex beam dynamics (for example, with SC and magnet errors both present). A detailed report on the development of this package and SC simulation studies with magnet errors will be presented elsewhere [24].

ACKNOWLEDGMENT

We thank M. Blaskiewicz, A. Luccio, J. Holmes and J. Galambos for helpful conversations. We also thank the Spallation Neutron Source team for dicussions and support.

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