SPACE CHARGE AND MAGNET ERROR SIMULATIONS FOR THE SNS ACCUMULATOR RING[*]

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Abstract

The effects of space charge forces and magnet errors in the beam of the Spallation Neutron Source (SNS) accumulator ring are investigated. In this paper, the focus is on the emittance growth and halo/tail formation in the beam due to space charge with and without magnet errors. The beam properties of different particle distributions resulting from various injection painting schemes are investigated. Different working points in the design of SNS accumulator ring lattice are compared. The simulations in close-to-resonance condition in the presence of space charge and magnet errors are presented.

1 INTRODUCTION

One of the major performance requirements for the SNS accumulator ring [1] is keeping an average uncontrolled beam loss under 10^{-4}. Space charge forces and magnet error/misalignment are two of the major sources of emittance growth, halo/tail formation and beam loss. This paper reports the studies on these effects in the transverse direction only. The study related to longitudinal beam manipulation is reported separately [2].

2 COMPUTER SIMULATIONS AND CODE BENCHMARKING

Two major particle-tracking codes, SIMPSONS [3] and ORBIT [4], have been used and benchmarked in BNL. Fig. 1 shows an example of a good agreement reached by the two codes. Good agreements have also been found with KV- and Waterbag-distributions.

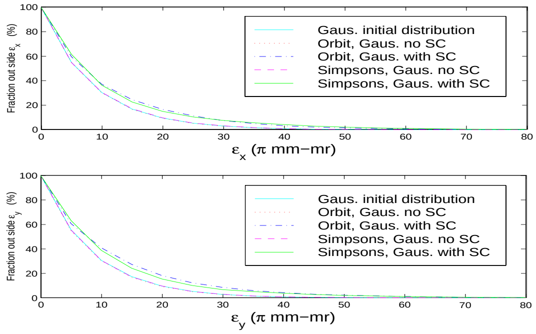

Fig. 1 Comparison of particle emittance distributions in a full-intensity beam with a Gaussian distribution simulated with computer codes SIMPSONS and ORBIT.

This study is carried out with SIMPSONS, which allows inclusion of space charge. The magnet error and misalignment are included through TEAPOT [5] outputs. All the physical quantities used in the simulations [6] are chosen according to the specifications in the design [1].

3 EFFECTS OF SPACE CHARGE

The transverse emittance growth and halo/tail formation in the circulating beam are critically dependent on the choice of painting schemes and the optimization of injection orbit bumps [6]. There are two basic painting schemes — correlated and anti-correlated painting — incorporated in the SNS accumulator ring design.

For correlated painting, both the emittance ε_x and ε_y of circulating beam are painted from small to large during the injection. The resulting beam distribution may satisfy the target requirements. However, the beam profile is susceptible to transverse coupling due to space charge forces and magnet error/misalignment, which in turn makes it difficult to preserve the beam shape. The simulation result including space charge (red dots/lines) is compared to that without space charge (blue dots/lines) in Fig. 2 with identical physical and numerical parameters. All the particle distributions and emittance distributions presented in Figs. 1, 2 and 3 are simulated at one integer split-tune working point (ν_x=5.82, ν_y=4.80). The upper left and right graphs show the distributions in (x, x') and (y, y') phase space respectively. The lower graphs show the distribution in (x, y) space and the distribution of 4-D phase space areas occupied by single particles.

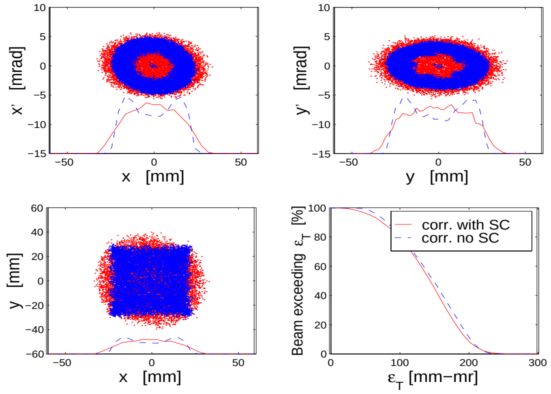

Fig. 2 Particle distribution and emittance distribution resulting from an example of correlated painting.

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The resulting oval beam profile from anti-correlated painting is immune to the transverse coupling. However, unlike correlated painting, it does not have the capability of painting over the halo/tail. There is an excessive halo/tail produced at the early stage of painting and growing larger during the entire injection (see Fig. 3).

In order to take the advantages of both correlated and anti-correlated painting, an oscillating painting scheme was proposed at BNL [7]. During injection, the closed orbit moves back and forth between anti-correlated and reverse anti-correlated painting with slowly increasing amplitude. Fig. 4 shows simulation result from an oscillating painting, in which all the physical and numerical parameters are kept the same as in the anti-correlated painting presented in Fig. 3. At the end of injection, we obtain a beam distribution with less tail/halo than the ones from anti-correlated or reverse anti-correlated painting alone. However, it requires aperture of 150% full beam emittance in both *x*- and *y*-directions, and is technically challenging for the programmable power supplies. The capability to accommodate oscillating painting for SNS injection with a high–Q resonant power supply is currently under investigation.

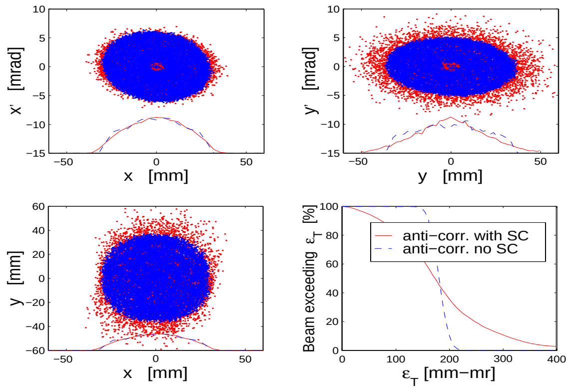

Fig. 3 Particle distribution and emittance distribution resulting from an example of anti-correlated painting.

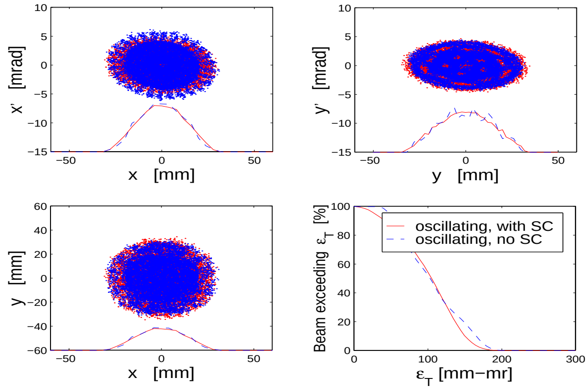

Fig. 4 Particle distribution and emittance distribution resulting from an example of oscillating painting.

Space charge forces can drive particles into the resonance. For example, one of designed SNS working points (ν_x=5.82, ν_y=5.80) is very close to space charge induced coupling resonance ($2\nu_x$-$2\nu_y$=0). It has been reported in the previous studies [8, 9, 10] that emittance growth is larger at this working point than at split-tune working point. In Fig. 5 we compare halo/tail growth due to space charge forces between unsplit-tune and split-tune working points for correlated painting.

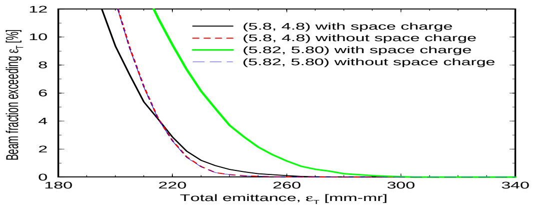

Fig. 5 Comparison of halo/tail growth due to space charge forces between unsplit-tune and split-tune working points.

4 EFFECTS OF MAGNET ERRORS

The beam emittance growth and halo/tail formation can be significantly enhanced when it is driven by both space charge forces and magnet error/misalignment. In Fig. 6 we illustrate these effects at working point (5.82, 5.80) with computer simulations including magnet field errors and misalignments listed in Tables 1-3. Table 1 and 2 list the expected integral magnetic errors of the ring dipoles and quadrupoles, respectively. The multipoles for the dipole magnets are extracted from the calculation of the design geometry. The multipoles for the quadrupole magnets are extracted and scaled from the measurement data of the AGS Booster magnets. Table 3 shows the expected misalignment based on the survey data of AGS Booster and the AGS-to-RHIC transfer line.

The investigations of effects due to the systematic alignment errors are carried out by including systematic skew quadruple component. The full (99.9%) emittance growth is plotted in Fig. 7 with one quadrupole per lattice super-period rolled by the same angle. Clearly, global coupling induced by systematic skew quadruple component can be reduced by tune splitting.

Table 1 Expected and simulated magnetic errors of ring dipoles. The multipole strengths are normalized to 10^{-4} of the main field at the reference radius R_{ref}=13cm.

Order	Normal		Skew	
	$\langle b_n \rangle$	$\sigma(b_n)$	$\langle a_n \rangle$	$\sigma(a_n)$
Body	[unit]			
2	-0.2	0.0	0.0	0.0
4	0.8	0.0	0.0	0.0
6	-0.8	0.0	0.0	0.0
8	-3.0	0.0	0.0	0.0

Table 2 Expected and simulated magnetic errors of ring quadrupoles. The multipole strengths are normalized to 10^{-4} of the main field at the reference radius R_{ref}. (For regular ring quadrupoles, R_{ref}=10cm; large ring arc quads, R_{ref}=13cm; and ring straight quads, R_{ref}=13cm).

Order	Normal		Skew	
	$<b_n>$	$\sigma(b_n)$	$<a_n>$	$\sigma(a_n)$
Body	[unit]			
2	0.0	-2.46	0.0	-2.5
3	0.0	-0.76	0.0	-2.0
4	0.0	-0.63	0.0	1.29
5	0.20	0.0	0.0	1.45
6	0.0	0.02	0.0	0.25
7	0.0	-0.63	0.0	0.31
8	0.0	0.17	0.0	-0.11
9	0.70	0.0	0.0	1.04

Table 3 Expected and simulated alignment errors of ring magnets based on the survey measurement of the AGS Booster and the AGS-to-RHIC transfer line magnets.

Item	Expected Error	Simulated Error
Integral field, magnet-to-magnet variation (rms)	10^{-4}	-
Integral field, transverse variation within R_{ref} (rms)	10^{-4}	-
Ring dipole sagitta deviation	3 cm	-
Magnet center position (rms)	0.1-0.5 mm	0.1 mm
Magnet longit. position (rms)	0.5	-
Mean field roll angle (rms)	0.2 - 1.0 mr	0.1 mr

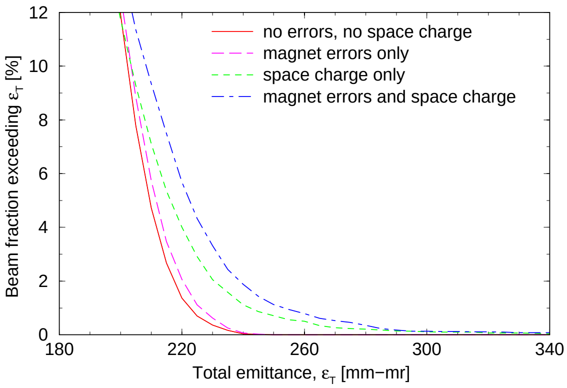

Fig. 6 The effects of beam halo/tail driven by space charge and magnet errors.

5 CONCLUSION AND DISCUSSION

Space charge forces, magnet error and misalignment, each play very important role in beam emittance growth, halo/tail formation and beam loss. When all these sources are present, the effect can be largely enhanced depending on the choice of working points. A horizontal-vertical tune split can significantly suppress emittance growth, halo/tail formation and beam loss caused by coupling through space charge and magnet error/misalignment.

The study with both space charge forces and magnet error/misalignment in the SNS accumulator ring is preliminary. Efforts will be continuously made to further understand these effects. To investigate beam loss under 10^{-4}, simulations including more effects with larger number of macro-particles are needed. Currently, at BNL, work is in progress on UAL [11] development, code benchmarking and parallel processing.

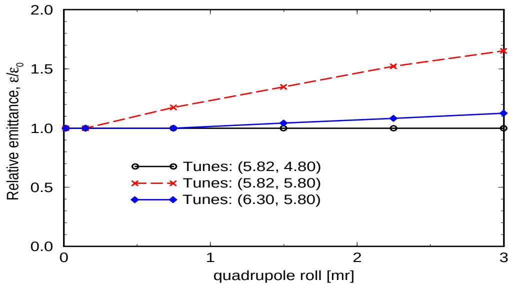

Fig. 7 Full (99.9%) emittance growth as a function of systematic quadrupole roll for unsplit tune, half-integer split tune, and integer split-tune working point. Space charge and other form of magnet errors are not included.

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