TRANSVERSE PHASE SPACE PAINTING FOR THE CSNS INJECTION*

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Abstract

The CSNS accelerators consist of an 80 MeV proton Linac, and a 1.6 GeV rapid cycling synchrotron (RCS). The ring accumulates $1.88*10^{13}$ protons via H^- stripping injection in the phase CSNS-I. The injected beam is painted into the large transverse phase space to alleviate space-charge effects. The uniformity of beam emittance is important in reducing the tune shift/spread due to space charge effect. The paper introduces two parameters to evaluate the uniformity of a distribution. To satisfy the low-loss design criteria, extensive comparison of different painting scenarios has been carried out by using the simulation code ORBIT. This paper gives detailed studies on painting schemes and the dependence on the lattice tune, the injection peak current, and also chopping rate.

INTRODUCTION

The design goal of the CSNS is to obtain proton beam of 100/200 kW in two phases with a repetition rate of 25 Hz. After the H^- beam is converted to proton beam via stripping, the RCS accumulates and accelerates the proton beam to 1.6 GeV.[1-3].

The ring has a four-fold lattice with straight sections for the injection, extraction, RF and collimators. The Charge-exchange injection is preferred for BSNS because it allows a large number of turns to be injected without large beam loss. And transverse painting in phase space alleviates space charge effect by increasing the beam emittance and improving the uniformity of the beam distribution.

The zero-dispersion drift of 9 m in length houses the entire injection system, which contains a four-dipole chicane to form horizontal orbit bump of 50mm and dynamic symmetrically-placed bumps for the phase space painting in both horizontal and vertical phases. The injection system is designed to accommodate both *x-y* correlated and *x-y* anti-correlated painting schemes

SPACE CHARGE EFFECTS AND PHASE SPACE PAINTING

Space charge induced emittance growth and halo generation are potential sources of beam loss in high intensity rings such as BSNS/RCS. In such accelerators, uncontrolled beam losses, as small as 1 W/m could lead to important activation that makes hands-on maintenance difficult. For this reason it is important to study the effects of space charge on the beam dynamics especially the halo generation.

To reduce the tune shift/spread due to space charge effects, the key is to obtain a large beam emittance with good uniformity. However, currently there is no standard criterion to evaluate the uniformity of a beam distribution. This paper introduces two parameters to represent the uniformity. For the beam core, the ratio between the emittance with 90% particles included and the r.m.s emittance can be considered as one parameter (named as ξ_1). As beam halo is also very important, the ratio between the emittance with 99% particles included and the one with 90% is taken as the second parameter (named as ξ_2). Both parameters are normalized with the standard uniform distribution and can be expressed by the following formulae:

$$\xi_1 = \frac{\varepsilon_{90}}{3.24\varepsilon_{rms}},\ \xi_2 = \frac{\varepsilon_{99}}{1.21\varepsilon_{90}} \qquad (1)$$

Table 1 presents ξ_1 and ξ_2 values for some standard distributions. When both ξ_1 and ξ_2 are close to unit, the uniformity is good, larger ξ_1 means bad uniformity in the beam core and larger ξ_2 means a spare halo. Usually these two parameters describe quite well the uniformity of beam distribution on integral invariant. An angular parameter can be added to describe the angular distribution.

Table 1: ξ values for some standard distribution

	Uniform	Parabolic	Gaussian
ε_{rms}	1	1	1
ε_{90}	3.24	4.10	4.61
ε_{99}	3.92	5.40	9.21
ξ_1	1	1.27	1.42
ξ_2	1	1.09	1.65

PAINTING SCHEMES

The properties of circulating beam properties are critically dependent on the choice of painting schemes and the optimization of injection orbit bump. There are two basic painting schemes: correlated painting and anti-correlated painting.

With an *x-y* correlated bump setting, the phase spaces in both phases are painted from small to large emittance, which has the advantage that the beam halo is constantly painted over by freshly injected beam. However, the resulting beam profile is rectangular that is not preferred. In addition, the beam distribution has the singularity and is susceptible to the transverse coupling due to magnet misalignments and space charge force. On the other hand, anti-correlated painting scheme paints one plane from

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outer to inner and the other from outer to inner and results an elliptical profile. However, significant beam halo is produced in the plane from the outer to inner and extra aperture is needed for the magnet involved.

To achieve a uniform distribution in phase space with a constant density during the injection, theoretical bumps are the ones moving the closed orbit as a square-root function of time. Because the space charge effect alters the distribution, other kinds of bump functions including exponential and sinusoidal functions have been tried for optimization. According to simulation results, square-root functions are adopted for the correlated painting:

$$x = x_{max} - (x_{max} - x_{min})\sqrt{\frac{t}{t_{inj}}} \qquad (2)$$

$$y = y_{max} - (y_{max} - y_{min})\sqrt{\frac{t}{t_{inj}}} \quad (0 < t < t_{inj})$$

A combination of square root and exponential functions are used for the anti-correlated painting:

$$x = x_{max} - (x_{max} - x_{min})\sqrt{\frac{t}{t_{inj}}}$$

$$y = \begin{cases} \dfrac{y_{max} - (y_{max} - y_{min})(1.0 - e^{-1.7t/t_{inj}})}{(1.0 - e^{-1.7/t_{inj}})} (0 \le t \le 0.19 t_{inj}) \\ 0.9 * (y_{max} - y_{min})\sqrt{\dfrac{1.0 - t}{t_{inj}}} (0.19 t_{inj} \le t \le t_{inj}) \end{cases} \qquad (3)$$

Figures 1 and 2 show the simulated beam distributions in phase spaces at the injection end without chopping and RF voltage. The 3D ORBIT simulations [4] are performed by tracking $2*10^4$ macro-particles through the ring lattice with the space charge included and taking the designed specifications for the injection. Table 2 shows the injection conditions and some simulation results

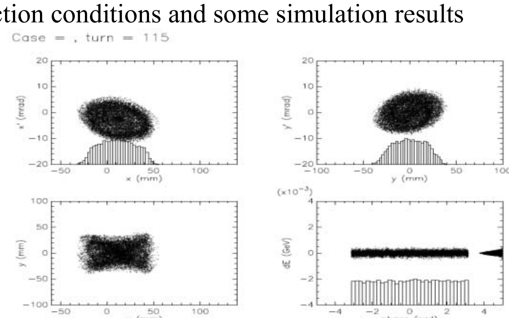

Figure1: Beam distribution in phase spaces at injection end by a *x-y* correlated phase space painting

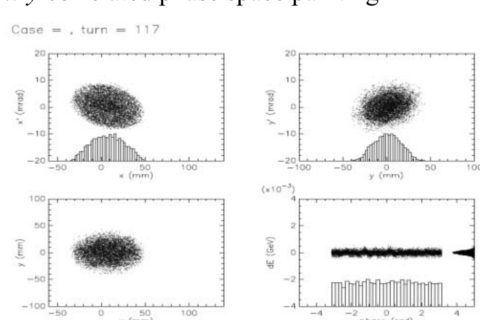

Figure 2: Beam distribution in phase spaces at injection end by a *x-y* anti-correlated phase space painting

Table 2: Injection conditions and simulation results

Circumference (m)	230.8	230.8
Tunes (Qx/Qy)	5.86/5.78	5.78/5.86
βx/βy at foil (m)	4.92/4.51	5.61/4.35
Injection energy (MeV)	80	80
Linac peak current (mA)	15	15
Injection emittance $\varepsilon_{x/y}$ (πmm.mrad, rms)	1.0	1.0
Accumulated particles	1.88×10^{13}	1.88×10^{13}
Painting scheme	Correlated	Anti-corr
Emittance at injection end (turn 117) $\varepsilon_x/\varepsilon_y$ (πmm.mrad)	329/308 (99%) 279/263 (95%) 246/235 (90%) 64/59 (rms)	306/308 (99%) 273/243 (95%) 249/220 (90%) 63/52 (rms)
ξ_1	1.18/1.22	1.21/1.30
ξ_2	1.10/1.08	1.01/1.15

OTHER FACTORS THAT INFLUENCE THE PAINTING RESULTS

Influence of working points

Space charge driven resonances lead to halo growth. In this section, the impact of varying the working point in the CSNS lattice with a correlated x-y painting scheme is presented. Figure 3 plots the growth of beam 99% beam emittance with different working points for a coasting beam. As seen in Figure 3, the emittance growth depends strongly on the working point. It grows fast in the case of un-split tunes. But with the split tune lattice, the vertical beam envelope variation (β_{max} /β_{min}) is reduced, the vertical emittance growth is also dramatically reduced It is apparent that the choice of working point is important.

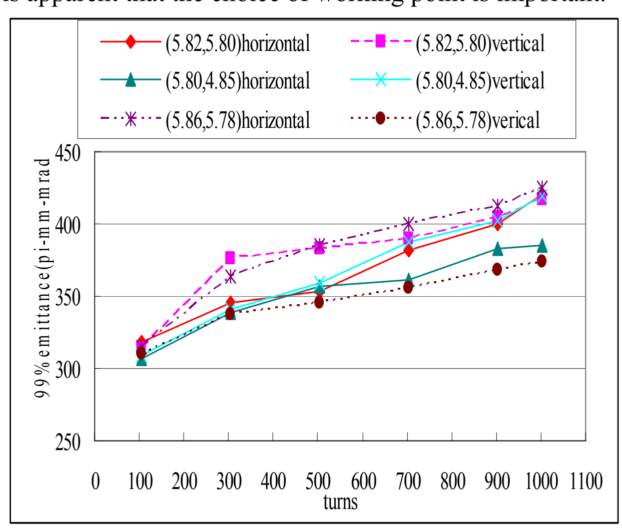

Figure 3 horizontal and vertical emittance growth for three of the working points

Injection with chopping injection

To reduce RF capture loss during the acceleration, the injection with chopping is probably necessary and under study. However, this kind of injection would increase the injection time and the proton traversal in the stripping foil. The impact of chopping injection on the transverse phase space painting has been studied. Figure 4 shows the emittance growth with time with a *x-y* anti-correlated painting scheme for the different chopping rate, 60%, 80% and non-chopping injection. It is evident that the space charge effect plays an important role in the case of chopping.

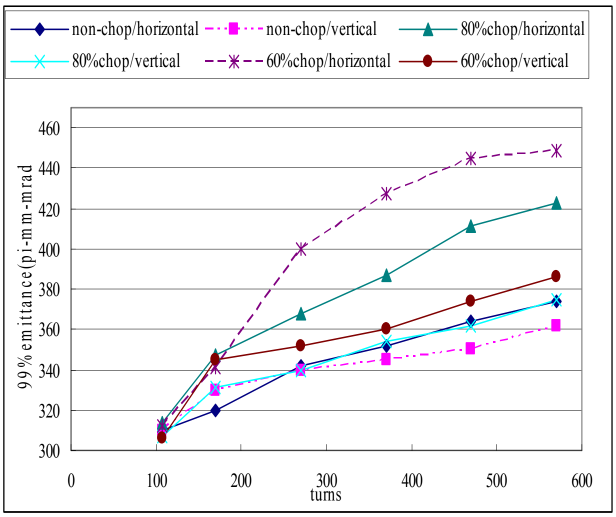

Figure 4 horizontal and vertical emittance growth

Injection peak current

The peak current of the linac beam has also impact to the painting process. On the one hand, it affects the injection time, on the other hand, it influences the phase space painting due to space charge effect, especially the halo production when the painting starts from outer in the case of anti-correlated painting. The peak current range of 5-35 mA is investigated for both correlated and anti-correlated painting schemes. The 99% emittances as the function of the peak current are shown in Figure 5. As a compromise, the peak current of 15mA is adopted for the CSNS-I.

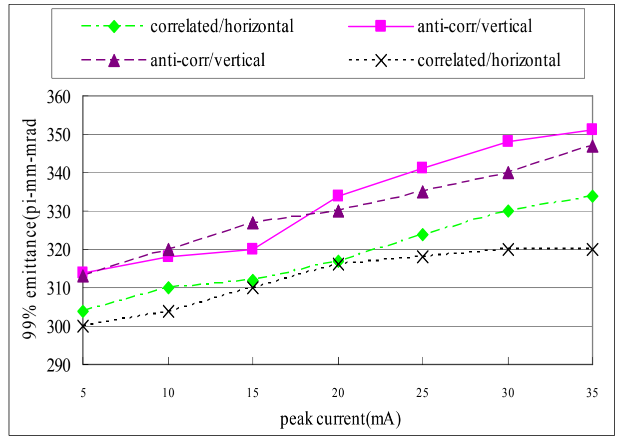

Figure 5 anti-correlated and correlated phase painting 99% emittance growth as a function of peak current

CONCLUSIONS

The whole injection system can be contained in a long drift of 9m in one of the dispersion-free long straights. Both correlated and anti-correlated painting schemes can be applied here. Two introduced parameters can be used to evaluate the uniformity of beam distribution. The ORBIT simulations show that emittance growth with anti-correlated painting is smaller than with correlated painting. The ring working point is found to have a strong impact on beam halo production. The injection with chopping and higher injection peak current also enhances the emittance growth.

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