Studies of Transverse Phase Space Painting for the CSNS RCS Injection*

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Abstract The China Spallation Neutron Source (CSNS) accelerators consist of an 80MeV proton linac, and a 1.6GeV rapid cycling synchrotron. The ring accumulates 1.88×10^{13} protons via H^- stripping injection in the phase CSNS-Ⅰ. The injected beam is painted into a large transverse phase space to alleviate space-charge effects. The uniformity of the beam emittance after the injection is important in reducing the tune shift/spread due to the space-charge effects. The paper introduces three parameters to evaluate the uniformity of a beam distribution. To control emittance growth and reduce halo generation, different painting schemes have been compared by using the 3D simulation code ORBIT. The detailed studies on painting schemes and the dependence on the lattice tune, the injection peak current, and chopping rate are also presented.

Key words H^- stripping injection, phase space painting, space-charge effects, uniformity evaluation parameters

1 Introduction

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

The ring has a four-fold lattice with straight sections for the injection, extraction, RF and collimators[2]. The charge-exchange injection is required at the CSNS because it allows a large number of turns to be injected without large beam loss. In addition, transverse painting in phase space alleviates the space-charge effects by increasing the beam emittance and improving the uniformity of the beam distribution.

A zero-dispersion drift of 9m in length is used to accommodate the entire injection system, which contains a four-dipole chicane to form the horizontal orbit bump of 50mm and the symmetrically-placed dynamic bumps for the phase space painting in both horizontal and vertical phases[3]. The injection system is designed to accommodate both the correlated and the anti-correlated painting schemes.

2 Space-charge effects and phase space painting

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

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on the beam dynamics especially the halo generation.

To reduce the tune shift/spread due to the space-charge effects, the key is to obtain a large beam emittance with a good uniformity together with a large acceptance design for the RCS. The beam emittance from the linac injector is very small compared with the RCS acceptance. However, currently there is no standard criterion to evaluate the uniformity of a beam distribution. Here three parameters are introduced to evaluate the uniformity. Two parameters represent the action property in phase space and the third represents the angular property. For the beam core, the ratio between the emittance with 90% particles included (ε_{90}) and the r.m.s emittance ($\varepsilon_{\rm rms}$) can be considered as one parameter (named as ξ_1). As the beam halo is also very important, the ratio between the emittance with 99% particles included (ε_{99}) 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:

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

The angular parameter η is defined by:

$$\eta=\sqrt{\frac{1}{n-1}\sum_{i}^{n}(N_i-\bar{N})^2}\Big/\bar{N}\ , \tag{2}$$

where N_i and $\bar{N}$ are the number of particles at the ith discrete angle position and the average number.

Table 1. ξ values for some standard distribution.

	uniform	parabolic	Gaussian
$\varepsilon_{\rm rms}$	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

Note: Emittance is in arbitrary unit, as only relative values are important.

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 a beam distribution on integral invariant. Ideally, the parameter η is close to zero, and a larger value means non-uniform angular distribution.

3 Phase space painting schemes

There are several methods that are usually used for the phase space painting. At the RCS and in both transverse planes, the painting is achieved by moving the closed orbit at the stripping foil as a function of time (called painting curve) with pairs of injection bump magnets while keeping the injected beam stationary.

The properties of the circulating beam are critically dependent on the choice of painting schemes and the optimization of the painting curves. Both the correlated painting and the anti-correlated painting schemes are incorporated in the RCS.

With a correlated bump setting, the phase spaces in both planes are painted from small to large emittance, which has the advantage that the beam halo is constantly painted over by the freshly injected beam. However, the resulting beam profile is rectangular that is not desired. In addition, the beam distribution has the singularity and is susceptible to the transverse coupling due to the magnetic field imperfection and the space-charge force. On the other hand, with an anti-correlated bump setting, the phase spaces are painted from outer to inner in one plane and from inner to outer in the other. Ideally, this painting scheme produces a distribution with an elliptical transverse profile that is immune to the transverse coupling, and a uniform density distribution. However, significant beam halo is produced in the plane from outer to inner due to the space-charge force and extra aperture is also needed for the magnets involved.

To achieve a uniform distribution in the phase space with a constant linac current during the injection, theoretically perfect bumps are the ones moving the closed orbit as a square-root function of time. Because the space-charge effect alters the distribution, this theoretical painting curve should be modified by the trial and error method. Other kinds of painting curves including exponential and sinusoidal functions have also been tried for the optimization. According to the simulation results, square-root functions are adopted for the correlated painting scheme:

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

$$y=y_{\max}-(y_{\max}-y_{\min})\sqrt{\frac{t}{t_{\rm inj}}}\quad (0<t<t_{\rm inj})\ ,\qquad (3)$$

where $x_{\min}$, $x_{\max}$, $y_{\min}$, $y_{\max}$ are for the bump ranges in mm, $t_{\rm inj}$ is for the injection time in ms.

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

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

$$y=\begin{cases} y_{\max}-(y_{\max}-y_{\min})\dfrac{1-{\rm e}^{-1.7t/t_{\rm inj}}}{1-{\rm e}^{-1.7/t_{\rm inj}}} \\ (0\leqslant t\leqslant 0.19t_{\rm inj}) \\ 0.9(y_{\max}-y_{\min})\sqrt{1-\dfrac{t}{t_{\rm inj}}} \\ (0.19t_{\rm inj}<t\leqslant t_{\rm inj}) \end{cases}\ ,\qquad (4)$$

Figures 1 and 2 show the simulated beam distributions in the phase space at the injection end without chopping and with RF on. 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.

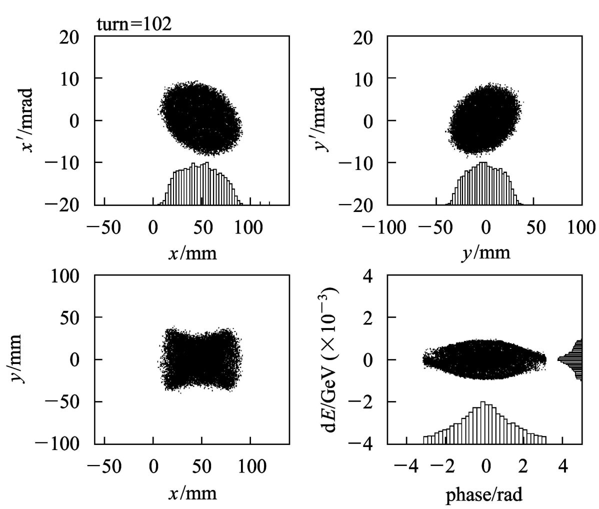

Fig. 1. Beam distribution in phase spaces at the end injection by correlated phase space painting.

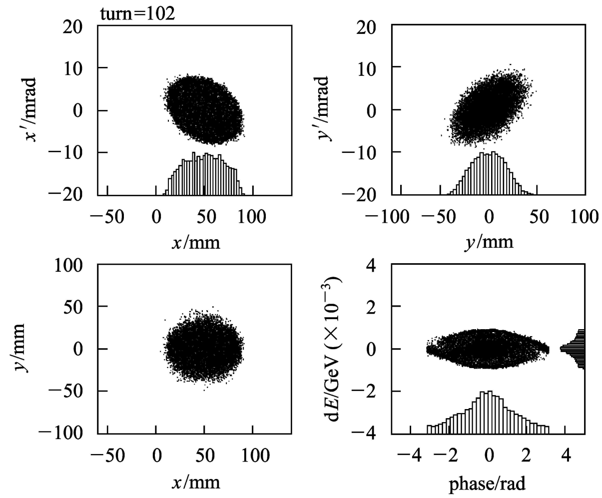

Fig. 2. Beam distribution in phase spaces at the end injection by anti-correlated phase space painting.

Table 2. Injection conditions and simulation results.

circumference/m	230.8	230.8
tunes(Q_x/Q_y)	5.86/5.78	5.78/5.86
β_x/β_y 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
	329/308 (99%)	306/308 (99%)
emittance at injection end (turn 117)	279/263 (95%)	273/243 (95%)
$\varepsilon_x/\varepsilon_y$/(πmm·mrad)	246/235 (90%)	249/220 (90%)
	64/59 (rms)	63/52 (rms)
$\xi_1(x/y)$	1.18/1.22	1.21/1.30
$\xi_2(x/y)$	1.10/1.08	1.01/1.15
η	0.09	0.05

Note: Statistical error is about 0.01 for the parameter η.

4 Other factors influencing the painting results

4.1 The influence of working point

Space-charge effects usually set a limitation on the accumulated particles for medium-energy high-intensity proton synchrotrons. The transverse tune shifts due to space-charge are orders of magnitude larger than the longitudinal ones due to the long bunch, thus the longitudinal and transverse space-charge effects usually can be treated separately. To prevent the significant emittance growth, it is necessary to maintain the incoherent tunes of the beam away from low-order resonances, especially those structure resonances. The choice of the working point is based on both the space-charge driven resonances and higher order resonances excited by the lattice nonlinearity in the presence of the space-charge induced tune shift.

A survey of the bare tune has been carried out for both the anti-correlated and the correlated painting schemes. The simulation results at working points (5.86, 5.78) and (5.78, 5.86) with the anti-correlated painting scheme are shown in Figs. 3 and 4, respectively, where the tune footprints correspond to the tune spread due to the space-charge alone. The tune spread with (5.86, 5.78) is larger than one with (5.78, 5.86) in the case of anti-correlated painting, and this can be explained by the reasons that the former meets the stronger fourth order resonance in the vertical plane during the painting process and a worse beam distribution is obtained. Thus the working point

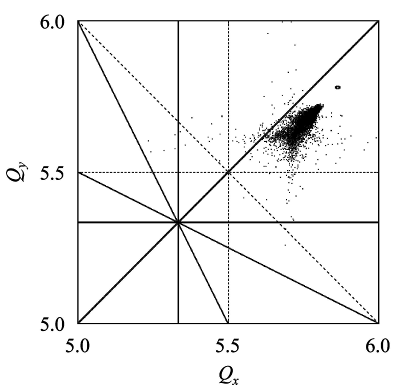

Fig. 3. Tune spread due to the space-charge with anti-correlated painting (Bare tune Q_x/Q_y=5.86/5.78; Solid lines for structure resonances).

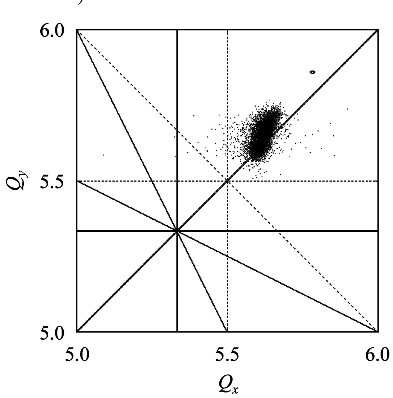

Fig. 4. Tune spread of due to the space-charge with anti-correlated painting (Bare tune Q_x/Q_y=5.78/5.86; Solid lines for structure resonances).

(5.78, 5.86) instead of the nominal one (5.82, 5.80) is adopted for the anti-correlated painting scheme during the injection phase, but will be moved below the coupling resonance line after the injection. This adjustment can be carried out by using the programmed trim quadrupoles.

4.2 Injection with chopping

To reduce the RF capture loss during acceleration, the injection with chopping is usually helpful. However, this kind of injection will increase the injection time that increases the proton traversal in the stripping foil, and shorten the bunching length that may result in a large tune shift/spread. The impact of chopping rate on the transverse phase space painting has been studied by using ORBIT. Fig. 5 shows the emittance growth with time with an anti-correlated painting scheme for the different chopping rate: 60%, 80% and non-chopping. In each of these cases the painting curve was optimized individually to minimize the emittance growth. It is evident that the space-charge effects play an even more important role in the case of chopping. With the lower chopping rate, the beam rms emittance and halo grow faster. Thus no chopping or high chopping rate will be used for CSNS-Ⅰ.

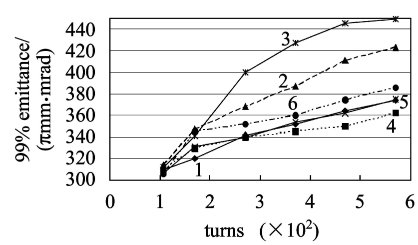

Fig. 5. Emittance growth with different chopping rates.
1. non-chop/horizontal; 2. 80% chop/horizontal; 3. 60% chop/horizontal; 4. non-chop/vertical; 5. 80% chop/vertical; 6. 60% chop/vertical.

4.3 The peak current of linac beam

The peak current of the linac beam has also impact on 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 paint-

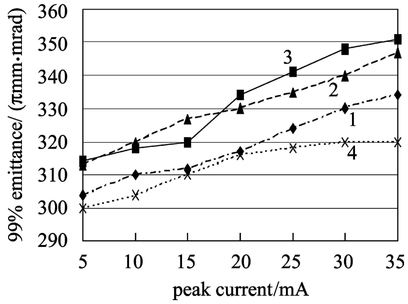

Fig. 6. Emittance growth as a function of peak current.
1. correlated/horizontal; 2. anti-corr/vertical;
3. anti-corr/vertical; 4. correlated/horizontal.

ing starts from outer in the case of anti-correlated painting. The peak current range of 5—35mA has been investigated for both the correlated and anti-correlated painting schemes. In each of these cases the painting curve was optimized to minimize the emittance growth. The 99% emittance contours as a function of the peak current are shown in Fig. 6. As a compromise between the emittance growth and the injection time, the peak current of 15mA is adopted for the CSNS-Ⅰ.

5 Conclusions

The whole injection system can be contained in a long drift of 9m in one of the dispersion-free long straights. Both the correlated and the anti-correlated painting schemes can be applied here but the latter is taken as the nominal one. Two introduced parameters can be used to evaluate the uniformity of beam distribution that is useful in the optimization of the painting process. The ORBIT simulations show that the emittance growth with the anti-correlated painting is smaller than that 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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CSNS RCS注入横向相空间涂抹的研究*

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摘要 中国散裂中子源(CSNS)加速器系统由80MeV的直线加速器和1.6GeV的快循环同步加速器(RCS)构成. CSNS第一阶段采用H^-剥离注入方法, 将粒子数累积至1.88×10^{13}. 注入束流被涂抹在较大的横向相空间内, 以减小空间电荷效应. 粒子注入后, 为了降低由空间电荷效果引起的工作点漂移和工作点弥散, 束流分布的均匀性很重要. 引入了评估束流分布均匀性的三个参数. 为了抑制注入过程中束流发射度和束晕的增长, 通过采用三维的模拟程序ORBIT, 对不同的横向相空间涂抹方案进行了比较. 同时还介绍了工作点、注入峰值流强和斩波调制比等因素对注入过程的影响.

关键词 H^-剥离注入 横向相空间涂抹 空间电荷效应 分布的均匀性评估参数

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