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Physics Design and Study of the BSNS RCS Injection System*

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Abstract With the Beijing Spallation Neutron Source (BSNS) accelerator in design, intense H^- beams are first accelerated by the linac and then injected in the rapid cycling synchrotron (RCS) for accumulation and further acceleration. The injection system uses H^- stripping and phase space painting method to fill the large ring acceptance with the linac beam of small emittance. The method is crucial to maintain low beam loss rate during the accumulation and initial acceleration. Different from the injection design of similar high-intensity accelerators in the world, the BSNS ring injection is accomplished by magnetic elements that are completely contained in a 9 meter-long uninterrupted space of near-zero dispersion. With the accumulated 1.9×10^{13} particles, space charge effects play a very important role. The 3D simulations including space charge effects have been carried out to optimize the injection design. This paper presents the physics design, computer simulation results and design optimization of the injection system.

Key words rapid cycling synchrotron, H^- stripping injection, phase space painting, space charge effects, ORBIT code

1 Introduction

Since 1980's, spallation neutron sources based on high power proton accelerators and neutron scattering techniques have become a major tool in the studies of material structure. Stimulated from the great success of operating sources of from tens kW to hundreds kW, USA, Japan and EU are developing sources more powerful so that proton beam power will reach MW level. At the same time, hundreds of kW sources are also in great demand. China has proposed to construct the Beijing Spallation Neutron Source (BSNS, former named "Chinese Spallation Neutron Source [CSNS]") of several hundreds kW[1—3]. It will be constructed in two phases (BSNS-Ⅰ for 100kW, BSNS-Ⅱ for 200kW, see Table 1). The first phase of the project is expected to be completed around 2011. BSNS has two accelerators in cascade, with an 80/130MeV linac as the injector and a 1.6GeV rapid cycling synchrotron (RCS) as the main accelerator. The high power proton beam extracted from the RCS will be sent to a target station where spallation process in a heavy metallic target (Tungsten) converts the protons into neutrons. After being slowed down in moderators, the neutrons are transported to the spectrometers for user experiments.

Table 1. Main parameters of BSNS.

	BSNS-Ⅰ	BSNS-Ⅱ
beam power/kW	100	200
repetition rate/Hz	25	25
target number	1	1
average current/μA	62.5	125
proton energy/GeV	1.6	1.6
linac beam energy/MeV	80	130

For high intensity circular proton accelerators, injection via H^- stripping is actually the only practical

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method[4, 5]. The design of the RCS injection system is to inject the pre-accelerated H$^-$ beam into the RCS with high precision and high transport efficiency. At the same time, as strong space charge effects are the main causes for beam losses in such high intensity accelerator, it is needed to increase the beam emittance and beam uniformity in the RCS to control the influence of space charge effects. In order to do so, the phase space painting method of injecting the beam of small emittance from the linac into the large ring acceptance was developed and used in the BSNS as in other similar accelerators.

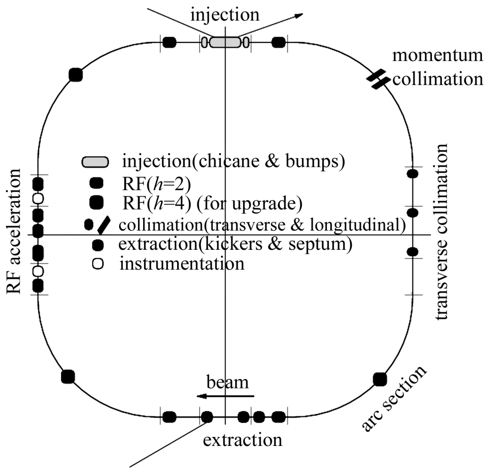

Fig. 1. RCS layout and functions.

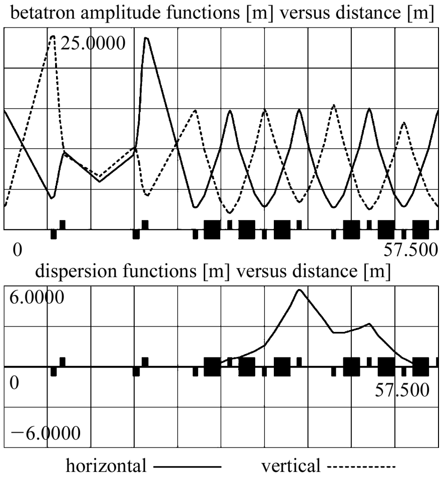

Fig. 2. The lattice functions for one RCS super-period.

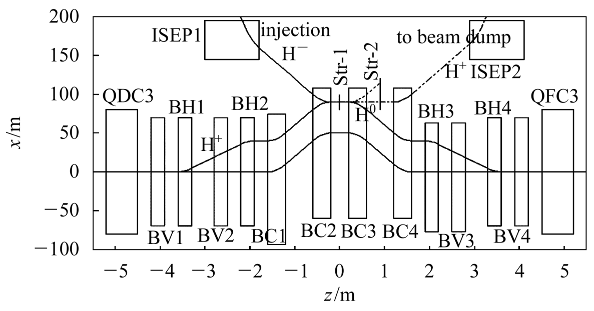

Fig. 3. Layout of RCS injection system. BC1—BC4: closed-orbit bump magnets; BH1—BH4: horizontal painting bump magnets; BV1—BV4: vertical painting bump magnets; QDC3 & QFC3: quadrupoles; ISEP1&2: injection and dump septum magnets.

2 Injection layout

Several injection schemes along with the RCS lattice schemes have been studied, and finally the design based on one long drift in a dispersion-free long straight section is favored. A dispersion-free long straight section other than a highly dispersive arc section is chosen for the design of the injection system due to the advantages: 1) the transverse phase space painting is not affected by the ramping bending magnets; 2) the ring properties are essentially not affected by the local orbit bumping and 3) the upgrading of the injection system in future is more feasible. At present, a four-fold anti-symmetric lattice has been chosen for the RCS, as shown in Fig. 1. Four dispersion-free long straight sections are for the RF cavities, the injection system, the extraction system and the collimation system. The lattice functions of the RCS ring are shown in Fig. 2.

The focusing structure of the RCS long straight sections uses DF doublets including one long drift of 9m in the center and two long drifts of 6m on the sides. The linac beam is injected into the RCS by using horizontal bending magnets; all the injection elements are accommodated within the long drift of 9m, see Fig. 3. In both the horizontal and vertical planes, phase space painting is performed by varying the position bump at the stripping foil. Two pairs of horizontal bump magnets (BH1—BH4) are for painting in x-x' plane, and two pairs of vertical bump magnets (BV1—BV4) are for painting in y-y' plane. Whereas two pairs of horizontal bump magnets (BC1—BC4) in the middle are for additional closed-orbit shift of 50mm, and this is important for the space clearance of the injection elements. The BC bump magnets will collapse after the beam injection to reduce the proton traversal in the stripping foil and to regain superperiodicity for the ring. All the bumpers are powered in series for the reason of eliminating tracking errors.

It is possible to use either position bump or angle sweeping or a mixture of them for phase space painting. The position bump method is carried out by moving the ring acceptance ellipse at stripping foil with the help of bump magnets within the ring; the angle sweeping method is carried out by sweeping the injection angle at the stripping foil with the help of bump magnets in the injection line. Two usual painting schemes are: to use position bump in both the horizontal and vertical planes and to use position bump in the horizontal plane but angle sweeping in the vertical plane. After the comparison, the first scheme is adopted for the BSNS.

The merits of the injection scheme are that the injection system is almost independent of the ring focusing structure, thus the operations such as the tune adjustment during the injection do not affect the painting process, and that everything in one long drift of 9m saves longitudinal space and avoids additional aperture requirement in the case of intercrossing with quadrupoles. The design is realizable for both BSNS-Ⅰ and BSNS-Ⅱ, considering the recent development in pulsed power supplies for fast bump magnets. The design of double waists at the injection point is very useful in decreasing the apertures for the bump magnets and minimizing the influence of the edge focusing of the bump magnets to the ring lattice.

3 Transverse phase space painting

3.1 Requirement of phase space painting

The beam emittance from the linac is small, about 1πmm·mrad in rms. If the H^- beam is injected directly into the ring through simple stripping, after tens or hundreds of turns, the space charge effects will blow-up the beam emittance. Although with a large ring acceptance, the nonlinear part of the space charge force will lead to non-uniformity of the beam distribution, thus large beam losses will probably happen. In order to reduce the beam losses that are critical in high power accelerators, painting into the large acceptance with good uniformity is usually required. One parameter indicating the influence of the space charge effects is the tune shift (Δv). According to the beam loss tolerance in different accelerators, the tune shift is controlled at about -0.3—-0.4 for hundreds kW accelerators and within -0.2 for MW accelerators. In the case of uniform distribution, the tune shift due to space charge effects can be expressed by:

$$\Delta v = -\frac{r_{\mathrm{p}} n}{2\pi\beta^2\gamma^3\varepsilon B_{\mathrm{f}}}\ , \tag{1}$$

where r_{p}=1.53×10^{-18}m for classical proton radius, n for accumulated particles, ε for un-normalized emittance, B_{f} for longitudinal bunching factor, β and γ for Lorentz factors. Table 2 shows the tune shifts due to space charge effects at BSNS-Ⅰ and BSNS-Ⅱ.

The accumulated particles in Table 2 correspond to beam powers of 120kW and 240kW at the extraction, respectively, relatively higher than the project goals. Beam losses of 2%—5% after the accumulation are also taken into account. After the accumulation, the beam bunching factor is about 1.0 in the case of non-chopping injection and depends on the chopping factor in the case of chopping injection. However, in all cases after initial acceleration (about 1ms), the bunching factor will reach to about 0.3 at BSNS-Ⅰ with only fundamental RF cavities and to about 0.4 at BSNS-Ⅱ with a dual harmonic RF system. At this critical moment, the tune shifts reach the maximum. For the ring acceptance of 540πmm·mrad and the collimated acceptance of 350πmm·mrad, the beam core emittance is chosen to be about 250πmm·mrad for this estimate.

Table 2. BSNS injection parameters and the tune shift due to space charge effects.

	BSNS-Ⅰ	BSNS-Ⅱ
E_{inj}/MeV	80	130
β	0.3885	0.4781
γ	1.0853	1.1386
n	1.9×10^{13}	3.8×10^{13}
B_{f}	0.3	0.4
ε/(πmm·mrad)	250	250
Δv	−0.33	−0.28

3.2 Painting scheme

As mentioned in Sections 2 and 3.1, the injection with phase space painting is mandatory to reduce the tune shift due to space charge effects. Even with the phase space painting, space charge effects still result in the emittance blow-up and thus a careful designed painting scheme is important to control the blow-up. Both the correlated painting and the anti-correlated painting schemes have been considered for the BSNS injection system. With the correlated painting scheme, the beam fills both the horizontal and vertical acceptance ellipses from inner to outer and the final distribution in the real space x-y will be almost rectangular. With the anti-correlated painting scheme, the beam fills the horizontal acceptance ellipse from inner to outer and the vertical acceptance ellipse from outer to inner and the final distribution in x-y will be elliptical. The latter is chosen as the nominal painting scheme for the BSNS, and Fig. 4 shows the positions of the RCS acceptance ellipse during the injection. At the same time, the correlated painting scheme is kept as an alternative, in which the injection point will be lifted by about 30mm in the vertical by using a pair of DC correctors in the injection line.

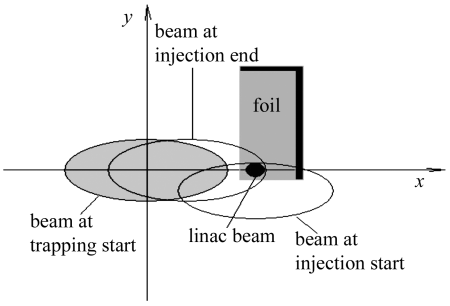

Fig. 4. Positions of the RCS acceptance ellipse during injection.

By using ORBIT code[6], one can simulate the injection process including space charge forces in 3-dimension. The painting curves (orbit bump varying with time) can be optimized by using the trial and error procedure. Fig. 5 shows the simulated beam distribution in phase spaces at the injection end with non-chopping, and Table 3 shows the statistical results.

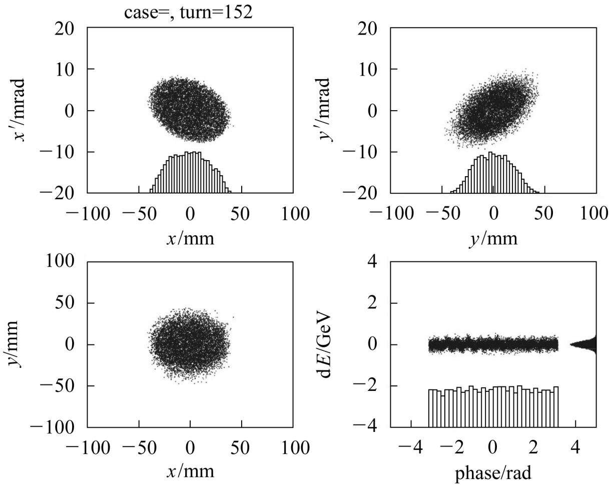

Fig. 5. Beam distribution in phase spaces at injection.

Other factors that influence the painting results, including the painted emittance, the injection peak current, the chopping injection, the ring working point, and the comparison between anti-correlated and correlated painting etc. are under study.

Table 3. Injection conditions and simulation results.

circumference/m	232
tunes(Q_x/Q_y)	5.78/5.86
β_x/β_y at injection point/m	5.17/5.99
injection energy/MeV	80
injection beam peak current/mA	15
injection emittance $\varepsilon_{x/y}$/(πmm·mrad, rms)	1.0
accumulated particles	1.9×10^{13}
painted emittance ($\varepsilon_{\rm px}/\varepsilon_{\rm py}$)/(πmm·mrad)	255/178
emittance at injection end (turn 152)	287/330(99%)
($\varepsilon_x/\varepsilon_y$)/(πmm·mrad)	255/252(95%)
	230/210(90%)
	114/89(50%)

4 Other considerations and discussions

4.1 Influence of the injection magnets to the RCS lattice

Because all injection elements are in a long drift of double waists and they are arranged almost symmetrically, the edge focusing effect of the bump magnets has negligible influence on the RCS focusing structure. The maximum change in β-function is about ±0.5m, and almost invisible at the injection point. The residual dispersion outside the section is also negligible. As all bump magnets will collapse after the injection, the super-periodicity of the ring will be recovered.

4.2 Partial stripping of H^- beam and stripped electrons

The H^- stripping injection requires that the acceleration and transport from the ion source to the injection point be with an H^- beam. Due to the Lorentz stripping of H^- beam in magnetic field, the magnetic field of the magnets in the high energy part of the linac, the injection beam line and the injection system is designed at a relatively low level. As the injection energy is 80/130MeV at the BSNS, even for possible upgrading to 230MeV, the maximum magnetic field of 0.7T is acceptable.

It is considered to use a carbon or an alumina foil of 50μg/cm^2 for BSNS-Ⅰ. ISIS uses the same thickness and obtains the stripping efficiency of about 98%[7]. BSNS-Ⅱ can use a thicker foil of 100μg/cm^2. Among those non- or partially stripped particles, the overwhelming majority is H^0 and very small part is still H^-. It is planned to strip the H^0 particles into protons with a thicker stripping foil and send them to the injection beam dump. The remained H^- beam can be stopped directly by an absorber. Some H^0 particles in excitation states are stripped by magnetic field when passing though BC3 magnet and become the ring beam halo. They will be removed by the ring transverse collimators.

Every H^- particle will produce two electrons when stripped into proton. If the electrons are left freely in the vacuum, they may enhance the possibility of e-p instability. On the other hand, the electrons are also harmful if bent back into the foil. Here the edge field of BC3 magnet is considered to bend the electrons to an electron catcher. The beam power of the electrons is below 20W even at BSNS-Ⅱ, so it is suitable for natural cooling.

4.3 Proton traversal in the stripping foil

Besides alleviating the space charge effects, the phase space painting can reduce the number of traversals of the circulating protons on the stripping foil, which might be a critical issue for the foil lifetime and beam losses. Even with the phase space painting, the circulating protons still have good probability to cross the stripping foil during the beam injection. Depending on the painting scheme, the proton traversal can be from about two to several tens. On the one hand, the proton trasversal increases the damage rate of the stripping foil or reduce its lifetime; on the other hand, the nuclear elastic scattering and the multi-scattering process by multiple crossing of protons through the foil will produce more beam halo and result in the increase of beam losses. Therefore, the phase space painting is designed not only to obtain a good beam distribution but also to reduce the proton traversal.

With the actual painting scheme, the proton traversal is about 3.4 and the maximum temperature of the foil is about 1193K.

5 Conclusions

BSNS/RCS employs H^- stripping injection method. The whole injection system is accommodated in a long drift of 9m in one of the dispersion-free long straights. Within the ring, it consists of four closed-orbit bump magnets, four horizontal painting bump magnets and four vertical painting bump magnets, all powered in series. The ORBIT simulations show that the anti-correlated painting scheme gives a good distribution in the transverse phase spaces. The injection system can satisfy the requirements for both BSNS-Ⅰ and BSNS-Ⅱ.

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北京散裂中子源RCS注入系统物理设计和研究*

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摘要　北京散裂中子源(BSNS)的主加速器——快循环同步加速器(RCS)采用H^-剥离注入方法, 将从直线加速器预加速的束流进行累积和进一步加速. 束流损失率的控制是该类高功率质子加速器所面临的关键问题之一, 而束流损失中很重要的部分是由空间电荷效应造成的. 为了减小该类束流损失, 注入系统设计中利用H^-剥离注入和相空间涂抹方法将直线加速器预加速的发射度较小的束流尽可能均匀地涂抹到较大的横向相空间中. 与其他的类似加速器相比, RCS注入系统将所有注入元件放在一个长为9m的无色散漂移节中以充分节省RCS环的纵向空间, 并使对注入系统的操作与对RCS主体的操作完全独立. 对于RCS累积的粒子数1.9×10^{13}, 空间电荷效应对粒子的运动有非常重要的作用, 本文介绍了采用ORBIT程序进行三维模拟计算并进行设计优化的结果. 还介绍了系统设计时需要考虑的其他重要因素, 如质子穿越、电子收集等.

关键词　快循环同步加速器(RCS)　H^-剥离注入　横向相空间涂抹　空间电荷效应　ORBIT程序

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