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PERFORMANCE AND UPGRADE CONSIDERATIONS FOR THE CSNS INJECTION*

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Abstract

For the proton synchrotron, the beam injection is one of the most important issues. In this paper, based on the China Spallation Neutron Source (CSNS), the injection methods have been comprehensively studied, including phase space painting and negative hydrogen stripping. By using the design scheme of the anti-correlated painting, the beam power has successfully reached 50 kW. However, some difficulties have been found in the higher power beam commissioning. In order to solve these key problems, flexibility in the CSNS design has been exploited to implement the correlated painting by using the rising current curve of the pulse power supply. The effectiveness of the new method has been verified in the simulation and beam commissioning. By using the new method, the beam power on the target has successfully risen to the design value. For the CSNS upgrade (CSNS-II), the injection energy is increased from 80 MeV to 300 MeV and the injection beam power is increased to about 19 times. Based on the CSNS experience and simulation results, it is hoped that the new painting injection scheme can not only greatly reduce the peak temperature of the stripping foil and the edge focusing effect of the chicane bump, but also need to be compatible with correlated and anti-correlated painting. After in-depth study, a new painting scheme has been proposed which not only achieves the design goals but also has many advantages.

INTRODUCTION

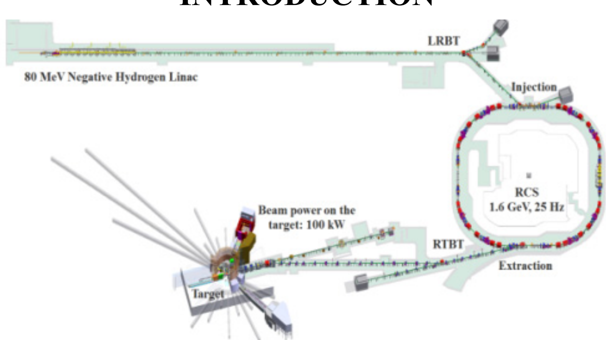

Figure 1: Layout of the CSNS.

The China Spallation Neutron Source (CSNS) accelerator [1, 2] consists of an 80 MeV negative hydrogen Linac and a 1.6 GeV rapid cycling synchrotron (RCS) with a repetition rate of 25 Hz. It accumulates an 80 MeV injection beam, accelerates the beam to the design energy of 1.6 GeV and extracts the high energy proton beam to the target [3]. Figure 1 shows the layout of the CSNS. The design goal of beam power on the target for the CSNS is 100 kW which has been achieved in Feb. 2020.

To increase the beam power on the target from 100 kW to 500 kW, the accelerator needs to be upgraded (CSNS-II), mainly including: Linac upgrade, injection system upgrade, and three dual harmonic cavities would be added to the RCS. Figure 2 shows the layout of the CSNS-II. It can be seen from the figure that the injection system upgrade is an important part of the CSNS-II. Table 1 shows the comparison of the injection beam parameters between the CSNS and CSNS-II.

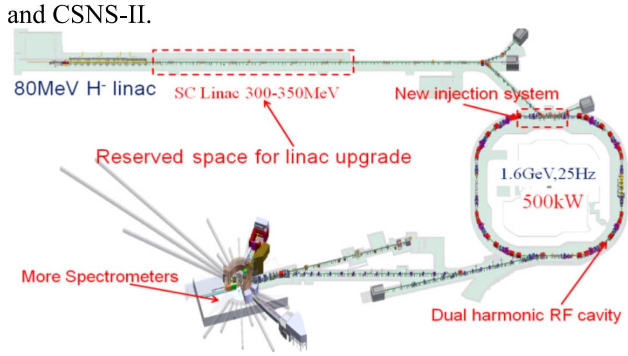

Figure 2: Layout of the CSNS-II.

Table 1: Comparison of the Injection Beam Parameters Between the CSNS and CSNS-II

Phase	CSNS	CSNS-II
Injection beam power (kW)	5	94
Linac energy (MeV)	80	300
Extraction beam energy (GeV)	1.6	1.6
Average beam current (μA)	62.5	312.5
Repetition frequency (Hz)	25	25
Proton number per pulse (10^{13})	1.56	7.8
Injection time (μs)	390	500
Injection beam size (mm/1σ)	1.0	1.5

The space charge effects are the core problem of the high intensity proton accelerator, and the main method to solve this problem is to use the phase space painting injection method. In addition, in order to break the restriction of Liouville's theorem, the negative hydrogen stripping method

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should be adopted in the injection process. That is, the linac accelerates the negative hydrogen beam, which is stripped into the proton beam before the injection, and then enters the ring through multi-turn injection. Since the injection process determines the initial state of the circulating beam and has an important influence on the beam accumulation, the injection beam loss is one of the decisive factors limiting the accelerator operation at high power. Therefore, the study, optimization and commissioning of the injection method play an important role in the high intensity proton synchrotron, which directly affects whether the accelerator can achieve the design goals and the safe and stable operation.

DESIGN SCHEME OF THE ANTI-CORRELATED PAINTING INJECTION

The injection system is the core component of the accelerator. For the CSNS accelerator, in order to reduce the beam loss, a combination of the negative hydrogen stripping and phase space painting is used to accumulate the high intensity beam in the RCS. Figure 3 shows the layout of the CSNS injection system. There are three kinds of orbit bumps: a horizontal bump which is generated by four dipole magnets (BH1-BH4) for the horizontal painting; a vertical bump which is generated by four dipole magnets (BV1-BV4) for the vertical painting; a fixed horizontal bump (BC1-BC4) in the middle for an additional closed-orbit shift of 60 mm. There are two carbon stripping foils: a main stripping foil and a secondary stripping foil. Their materials are both HBC. For the CSNS [4, 5], the anti-correlated painting method is adopted as the design scheme for the injection system.

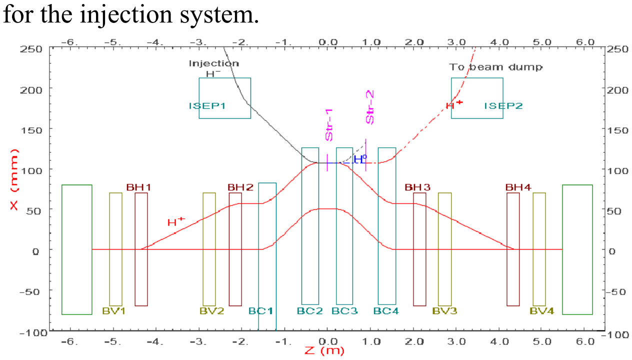

Figure 3: Layout of the CSNS injection system.

In the injection process of the anti-correlated painting, the circulating beam is painted from the center to the border in the horizontal plane and from the border to the center in the vertical plane. The injection point locates in the lower left corner of the main stripping foil to reduce the average number of times that each particle passes through the main stripping foil. Figure 4 shows the position variation of the circulating beam emittance ellipse in the anti-correlated painting process. Figure 5 shows BH and BV pulse current curves for the anti-correlated painting at the beginning of the beam commissioning.

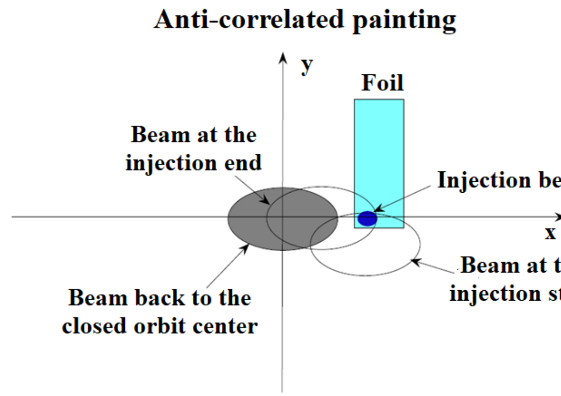

Figure 4: Schematic of the RCS acceptance ellipse and injection beam in the injection process of the anti-correlated painting.

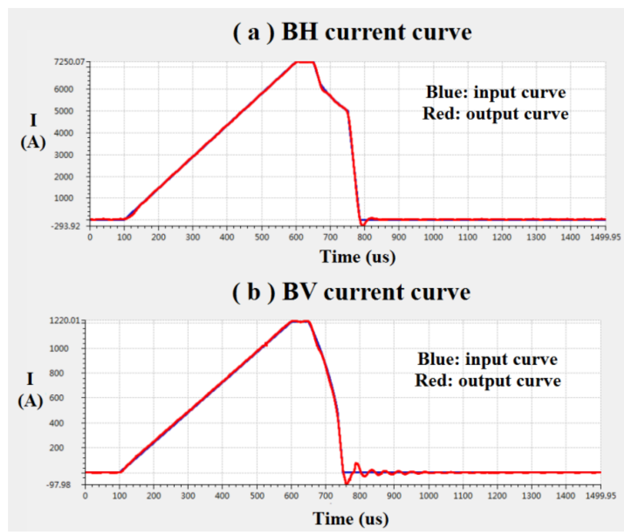

Figure 5: BH and BV pulse current curves for the anti-correlated painting at the beginning of the beam commissioning.

With the design scheme of the anti-correlated painting [6], after the injection beam parameters matching, stripping foil optimization, phase space painting optimization, and injection beam loss adjustment, the injection beam loss has been well controlled and the injection efficiency has been over 99%. Combined with other aspects of the beam commissioning, the beam power on the target has exceeded 50 % of the design value and the accelerator had achieved the stable operation.

ACHIEVE THE CORRELATED PAINTING BASED ON THE MECHANICAL STRUCTURE OF THE ANTI-CORRELATED PAINTING SCHEME

By using the anti-correlated painting, combined with other normal optimizations, the beam power of the CSNS accelerator has reached 50 kW in January 2019. However, in the higher power beam commissioning, a series of difficults has been encountered with the anti-correlated

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painting, for instance, too large beam size after painting, non-uniform beam distribution, large transverse coupling effect, and so on.

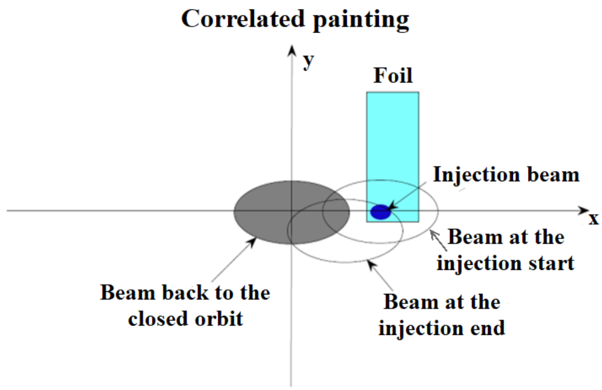

Figure 6: Schematic of the RCS acceptance ellipse and injection beam in the injection process of the correlated painting.

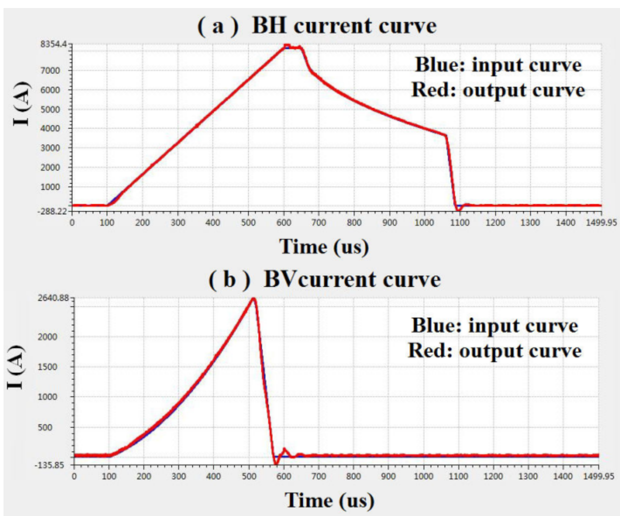

Figure 7: BH and BV pulse current curves for the correlated painting.

In order to solve these problems, a new method to perform the correlated painting based on the mechanical structure of the anti-correlated painting scheme has been proposed [7]. Specifically, flexibility in the CSNS design has been exploited to implement the correlated painting by using the rising current curve of the pulse power supply. Figure 6 shows the position variation of the circulating beam emittance ellipse in the correlated painting process. Figure 7 shows the BH and BV pulse current curves for the correlated painting.

The effectiveness of the new correlated painting method has been verified in the simulation and machine experiment. By using the new correlated painting method in the high power beam commissioning, the shackles that restrict the beam power increase have been unlocked and the beam power has been greatly increased to 80 kW in September 2019. Furthermore, with the new correlated painting method, combined with the optimizations of the tunes and chromaticity, the beam power on the target has successfully risen to the design value of 100 kW in February 2020.

NEW PAINTING INJECTION SCHEME FOR THE CSNS-II

Compared with CSNS, the injection energy of the CSNS-II is increased to about 4 times, the injection particle number is increased to 5 times, the injection beam power is increased to about 19 times, and the beam power on the target is increased to 5 times. Therefore, the injection system needs to be redesigned. Based on the experience of the CSNS and simulation results, if the traditional bump injection scheme similar to the CSNS is used directly, three main difficulties would be encountered. Firstly, the peak temperature of the main stripping foil is too high which is close to the melting point and it will affects the accelerator operation. Secondly, the beam dynamics is greatly affected by the edge focusing effect of the horizontal chicane bump. Thirdly, the single fixed painting mode may not be consistent with the real beam state of the future machine, which has great uncertainties. Figure 8 shows the temperature curve of the injection beam center at the main stripping foil for the CSNS-II while the traditional bump injection scheme similar to the CSNS is used. It can be seen that the peak temperature of the main stripping foil is very high.

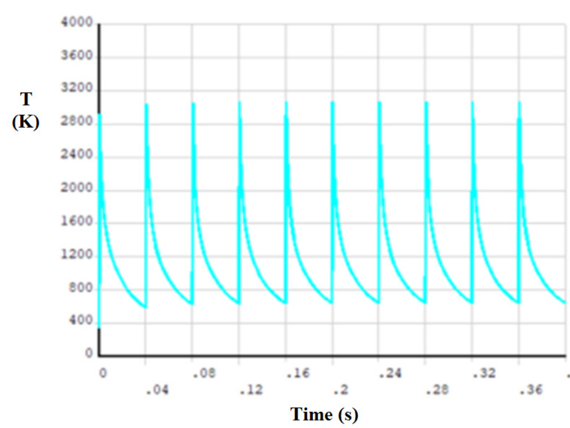

Figure 8: Temperature curve of the injection beam center at the main stripping foil for the CSNS-II while the traditional bump injection scheme similar to the CSNS is used.

In order to solve the three difficulties that mentioned in the above paragraph, it is necessary to search a new painting injection scheme for the CSNS-II. It is hoped that the new painting injection scheme can not only greatly reduce the peak temperature of the main stripping foil and the edge focusing effect of the chicane bump, but also need to be compatible with correlated and anti-correlated painting. With reference to the experience of the Spallation Neutron Source (SNS) [8, 9] and Japan Accelerator Research Complex (J-PARC) [10, 11, 12] on the physical design, beam commissioning and injection scheme selection, after in-depth analysis and simulation, a new painting injection scheme for the CSNS-II has been proposed.

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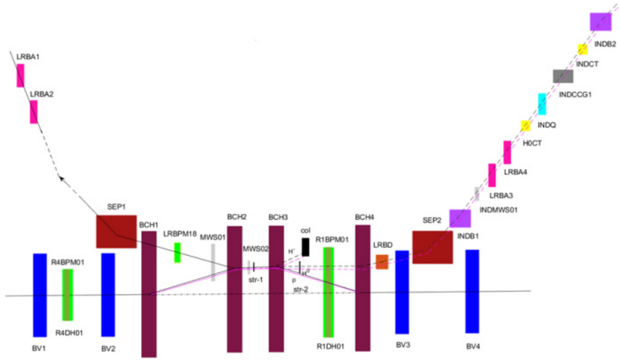

Figure 9: Layout of the new injection system for the CSNS-II.

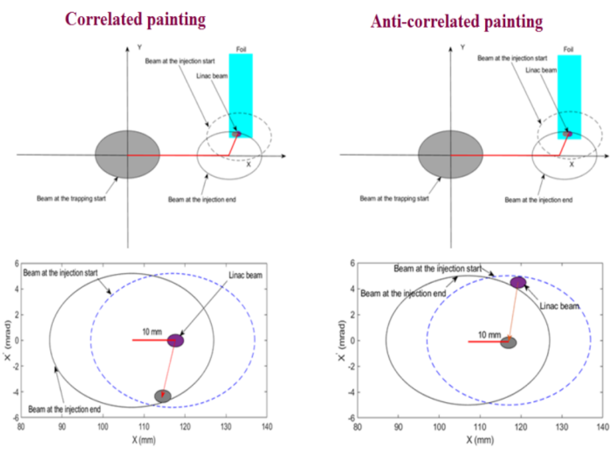

Figure 10: Schematic of the RCS acceptance ellipse and injection beam in the injection process of the new painting scheme.

For the new painting injection scheme, the chicane bump and horizontal painting bump are combined into one bump which makes the chicane bump "move", and the horizontal painting is performed by using the position and angular scanning at the same time. Figure 9 shows the layout of the new injection system for the CSNS-II. It can be found that there are many key magnets, including: 4 horizontal painting magnets (BCH1-4), 4 vertical painting magnets (BV1-4), 2 septum magnets (SEP1-2), 1 pulse septum magnet (LRBD) for angular scanning compensation, 2 DC dipole magnets (INDB1-2), 4 vertical DC bump magnets (LRBA1-4) for an additional vertical orbit shift of 30 mm, 1 DC quadrupole magnet (INDQ). Figure 10 shows the schematic of the RCS acceptance ellipse and injection beam in the injection process of the new painting scheme. It can be found from this figure that, for the injection beam, BCH can be used for horizontal angular scanning while the horizontal position is also scanned in a small range. For the circulating beam, the horizontal and vertical position scanning can be performed with the BCH and BV magnets. Residual H^0 beam at the waste beam outlet has an angular distribution with time and a small pulse magnet (LRBD) is installed for angular scanning compensation. BCH bump is irregularly shaped to allow the waste beam line to move a short distance along outside the RCS.

After a comprehensive simulation study of the painting process, the new painting scheme has been verified to be feasible and the design goals can be achieved. In addition, compared with the traditional bump painting scheme, the new painting scheme has many obvious advantages. Firstly, the advantages of position scanning and angular scanning have been combined. The peak temperature of the main stripping foil has been obviously reduced. Both correlated and anti-correlated painting can be performed. Secondly, since the BCHs are pulse magnets, their edge focusing effects are obviously reduced. Thirdly, since the bump magnet BCH2 which is used for angular scanning is very close to the injection point, the difficulty of large aperture of the injection port and transport line required by angular scanning is solved. In addition, compared with the traditional painting scheme, it saves four bump magnets. The space of the injection area is looser and it is easier to optimize the layout of the injection system. This is of great significance to the traditional injection area where space is tight. Finally, as a result of the angular scanning, the residual H^- beam hits an increased area on the vacuum chamber, and the radiation dose caused by it decreases obviously.

The new painting injection scheme is being applied for the CSNS-II accelerator. It can be also applied to other similar accelerators.

NEGATIVE HYDROGEN STRIPPING

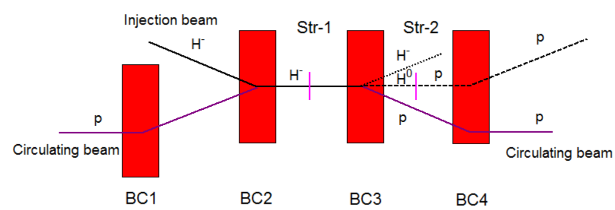

Figure 11: Schematic diagram of the negative hydrogen stripping injection.

Table 2: Main Parameters of the Stripping Foils for the CSNS and CSNS-II

Phase	**CSNS**		**CSNS-II**	
Foil	**Str-1**	**Str-2**	**Str-1**	**Str-2**
Material	HBC	HBC	HBC	HBC
Structure	Double-layer	Double-layer	Double-layer	Double-layer
Thickness (μg/cm^2)	100	200	260	450
Stripping efficiency	99.7%	100%	99.7%	100%

The CSNS accelerator adopts the foil stripping as the design scheme. Its stripping foil system consists of two stripping foils, including a main stripping foil and a secondary stripping foil. Figure 11 shows the schematic diagram of the negative hydrogen stripping injection for the CSNS. After the detail optimization of the stripping foil parameters [13], a double-layer HBC foil is instead of a single-layer DLC foil. The thickness of the main stripping foil is 100 μg/cm^2 and its stripping efficiency is 99.7%. For the secondary stripping foil, the thickness is 200 μg/cm^2 and its stripping efficiency is 100%. Table 2 shows the main parameters of the stripping foil for the CSNS and CSNS-II.

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For the CSNS-II, after in-depth analysis and simulation, the foil stripping is also selected as the design scheme. The stripping foil system also consists of two stripping foils. The main parameters of the stripping foils for the CSNS-II are given in Table 2.

CONCLUSION

In this paper, firstly, the design scheme of the anti-correlated painting for the CSNS has been introduced and the beam commissioning of the injection system has been studied in detail. In order to solve the difficulties when the beam power exceeds 50% of the design value, a new method has been proposed to perform the correlated painting based on the mechanical structure of the anti-correlated painting scheme. By using the new correlated painting, the beam power on the target has successfully risen from 50 kW to the design value of 100 kW. Secondly, a new painting injection scheme for the CSNS-II has been proposed. It not only realizes the compatibility of correlated and anti-correlated painting, but also greatly reduces the peak temperature of the main stripping foil and the edge focusing effect of the chicane bump. The new painting scheme has been verified to be feasible in the simulation and has obvious advantages compared with the traditional bump painting scheme.

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