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Study of Painting Injection Method for High-Intensity Proton Synchrotrons

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Date: 2023-12-14T00:00:00+00:00

Abstract

Space charge effect constitutes one of the fundamental challenges in high-intensity proton accelerators, exerting its most pronounced influence during the injection and initial acceleration phases. The adoption of phase space painting methodologies, coupled with optimization of the painting process, can effectively alleviate the impact of space charge effects on beam injection efficiency, acceleration efficiency, and emittance growth. Transverse phase space painting techniques can be classified into correlated painting and anti-correlated painting. In this paper, we first present a comprehensive investigation of transverse phase space painting methods for high-intensity proton synchrotrons, encompassing various painting approaches and their implementation schemes. Subsequently, based on the China Spallation Neutron Source (CSNS) injection system, we conduct a detailed analysis of the beam injection process and anti-correlated painting design configuration, thoroughly examining the underlying causes for the reduction of the actual vertical painting range and the influence of bump magnet edge focusing effects on painting efficacy and beam dynamics. Additionally, we briefly delineate the methodology for implementing correlated painting utilizing the anti-correlated painting mechanical structure and its pivotal contribution to achieving the CSNS design parameters. Finally, in response to the future accelerator requirement for online switching between different painting injection techniques, we propose a novel injection scheme capable of simultaneously realizing both correlated and anti-correlated painting, accompanied by detailed validation, simulation, and optimization.

Full Text

Preamble

Study on the Painting Injection Methods for High-Intensity Proton Synchrotrons

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Abstract

Space charge effects represent one of the core challenges in high-intensity proton accelerators, exerting their greatest influence during injection and initial acceleration stages. Employing phase-space painting methods with optimized painting processes can effectively mitigate the impact of space charge effects on beam injection efficiency, acceleration efficiency, and emittance growth. Transverse phase-space painting methods can be categorized into correlated painting and anti-correlated painting. This paper presents a comprehensive investigation of transverse phase-space painting techniques for high-intensity proton synchrotrons, encompassing various painting methods and implementation approaches. Based on the injection system of the China Spallation Neutron Source (CSNS), we conduct a detailed study of the beam injection process and the anti-correlated painting design scheme, with in-depth exploration of the mechanisms behind the observed reduction in actual vertical painting range and the influence of edge focusing effects from bump magnets on painting performance and beam dynamics. Additionally, we briefly describe the method for implementing correlated painting using the existing mechanical structure designed for anti-correlated painting and its critical role in achieving the CSNS design goals. Finally, addressing the future requirement for online switching between different painting injection methods in advanced accelerators, we propose a novel injection scheme capable of simultaneously realizing both correlated and anti-correlated painting, which has been thoroughly demonstrated, simulated, and optimized.

Keywords: proton synchrotron; injection; painting; space charge effect
Classification: O572.21+1
Document code: A
doi:

1 Introduction

Spallation neutron sources are large-scale scientific facilities that utilize medium-to-high energy proton beams extracted from high-intensity proton accelerators to bombard heavy metal targets, generating copious neutrons through spallation reactions [1]. Currently operational pulsed spallation neutron sources worldwide include the Spallation Neutron Source (SNS) in the United States [2-3], the

Japan Proton Accelerator Research Complex (J-PARC) [4-5], the ISIS Neutron and Muon Source in the United Kingdom [6-7], and the China Spallation Neutron Source (CSNS) [8-10]. Spallation neutron source accelerators belong to the category of high-intensity proton accelerators, characterized by two prominent features: significant space charge effects and pronounced beam collective instabilities. The adoption of painting injection methods combined with process optimization can effectively alleviate the influence of space charge effects on beam injection efficiency, acceleration efficiency, and emittance growth. Beam collective instabilities can be suppressed through optimized tuning of working points and chromaticity.

The CSNS accelerator complex comprises a linear accelerator, a Rapid Cycling Synchrotron (RCS), and two beam transport lines [11]. The RCS accumulates low-emittance injection beam through multi-turn injection into a high-emittance circulating beam, accelerates the beam energy from 80 MeV to 1.6 GeV, and then extracts the beam to bombard a tungsten target. The extracted beam power is 100 kW with a repetition rate of 25 Hz. The CSNS Phase-II (CSNS-II) accelerator upgrade [12] primarily includes increasing the linear accelerator energy (to 300 MeV), comprehensive upgrade and renovation of the injection system, and addition of magnetic alloy second-harmonic cavities to the RCS. The main objective of CSNS-II is to increase the target beam power by a factor of five, reaching 500 kW. [Figure 1: see original paper] illustrates the layout diagrams of CSNS and CSNS-II.

2 Injection Methods and Injection System

Space charge effects [13-14] constitute one of the fundamental challenges in high-intensity proton accelerators, with maximum impact during injection and initial acceleration phases. Phase-space painting injection methods [15-16], through optimized painting schemes, can effectively mitigate space charge effects on beam injection efficiency, acceleration efficiency, and emittance growth. To circumvent Liouville's theorem limitations, the H^- stripping injection method [17-18] is employed during injection: the linear accelerator accelerates H^- beams, which are stripped into proton beams before injection into the ring accelerator, then accumulated through multi-turn injection. Since the injection process determines the initial state of the circulating beam and significantly influences the beam accumulation process, injection beam loss [19] represents a critical factor limiting high-power accelerator operation. Consequently, research, optimization, and tuning of injection methods are essential for proton synchrotrons, directly impacting whether the accelerator can achieve design specifications and operate safely and stably.

For high-intensity proton synchrotrons, phase-space painting offers numerous advantages: substantially reducing space charge effects, increasing accumulated beam intensity, minimizing beam loss, and significantly decreasing the average number of times the beam traverses the stripping foil, thereby reducing foil temperature rise and scattering effects. Phase-space painting methods can be classified into two categories: correlated painting and anti-correlated painting. Correlated painting involves painting the phase-space ellipse from center to edge or edge to center simultaneously in both horizontal and vertical directions, whereas anti-correlated painting employs opposite painting directions in the horizontal and vertical planes. Regarding the implementation of painting injection beams into the ring accelerator's acceptance phase space, two approaches exist: bump and angle sweep. The bump method utilizes four dipole magnets to form a closed orbit bump, displacing the closed orbit at the injection point. The angle sweep method scans the injection beam's incident angle at the injection point. The selection of painting methods and implementation approaches is crucial for high-intensity proton synchrotrons, directly affecting the injection system's physical design and accelerator performance.

3 CSNS Painting Injection Method

During the CSNS physical design phase, comparative simulation studies of correlated and anti-correlated painting during injection and acceleration processes demonstrated that, at the nominal working point (4.86, 4.78), anti-correlated painting exhibited smaller injection beam loss and weaker transverse coupling effects compared to correlated painting. Therefore, CSNS adopted anti-correlated painting as the design scheme [20-22]: horizontal position painting from inside to outside, vertical position painting from outside to inside, with both horizontal and vertical directions utilizing the falling edge of pulsed power supply current curves. [Figure 2: see original paper] illustrates the position evolution of the RCS acceptance ellipse during anti-correlated painting. The figure shows that during injection, the circulating beam moves from positive maximum toward the center in the horizontal direction and from negative maximum toward the center in the vertical direction, with the injection point located at the lower left corner of the main stripping foil.

The CSNS injection system primarily consists of: a horizontal painting bump comprising four horizontal pulsed dipole magnets, a vertical painting bump comprising four vertical pulsed dipole magnets (BV), a horizontal fixed bump (BC) comprising four horizontal DC dipole magnets (BH) providing a 60 mm position offset, two DC septum magnets (ISEP), a main stripping foil system (Str1), a secondary stripping foil system (Str2), and a beam dump. [Figure 3: see original paper] presents the layout diagram of the CSNS injection system.

3.1 Beam Injection

During beam injection, precise injection timing calibration and injection parameter matching are essential to ensure accurate injection of linear accelerator beam into the ring accelerator and achieve high-efficiency beam accumulation.

Injection pulsed power supply timing must be synchronized with injection beam and circulating beam. During beam commissioning, we developed a precise injection timing calibration method comprising the following steps: (1) Acquire the standard injection timing signal (T0), RCS RF signal, and circulating beam signal from a designated beam position monitor (BPM) using an oscilloscope to determine the temporal relationship between the circulating beam signal and the standard injection timing signal; (2) Measure turn-by-turn (TBT) position data of the circulating beam using the designated BPM to obtain the temporal relationship between the pulsed power supply and the standard injection timing signal (T0); (3) By comparing these two temporal relationships, determine the timing relationship between the circulating beam signal and the pulsed power supply. This method enables precise adjustment and calibration of injection timing, as shown in [Figure 4: see original paper]. In the figure, the designated BPM (R1BPM01) is located within the horizontal and vertical bumps, with TBT data from the first approximately 30 turns representing interference signals. Based on machine studies, [FIGURE:4(a)] reveals that the circulating beam signal lags the standard injection timing signal by approximately 3 s. [FIGURE:4(b)] shows the injection completion time point measured from the horizontal pulsed power supply current curve (2 s per revolution), from which, after subtracting the injection process duration, the horizontal pulsed power supply timing is determined to lag the standard timing by 4 s. Consequently, the circulating beam signal leads the horizontal pulsed power supply timing by 1 s, requiring the horizontal pulsed power supply timing to be advanced by 1 s. [FIGURE:4(c)] shows the injection completion time point for the vertical pulsed power supply current curve, revealing that the vertical pulsed power supply timing leads the standard timing by 2 s. Thus, the circulating beam signal lags the vertical pulsed power supply timing by 5 s, requiring the vertical pulsed power supply timing to be delayed by 5 s. Beam commissioning results confirm the feasibility of this precise injection timing adjustment method.

[Figure 5: see original paper] illustrates the relationship between injection beam, circulating beam, and dumped beam during injection. When injection beam and circulating beam parameters are mismatched, substantial beam loss and uncontrollable emittance growth occur, necessitating precise injection parameter matching. Injection parameter matching encompasses three aspects: Twiss parameters, dispersion function, and phase-space coordinates. In the physical design, the injection region is located in a dispersion-free straight section, with magnetic focusing structure designed to make the α-function near zero at the injection point, facilitating straightforward Twiss parameter and dispersion function matching, which has been confirmed during beam commissioning [23]. For phase-space coordinate matching, we developed a precise injection phase-space coordinate matching method based on multi-turn injection and Fourier analysis [24], with beam experiments demonstrating effective suppression of injection phase-space coordinate mismatch.

3.2 Anti-Correlated Painting Injection

For the CSNS RCS, the injection system employs anti-correlated painting as the design scheme. During beam commissioning, implementation of anti-correlated painting with detailed optimization of injection beam parameters, painting range, painting curve, and transverse coupling effects achieved excellent control of injection beam loss, with injection efficiency exceeding 99%. Combined with other beam tuning and optimization efforts, the target beam power surpassed 150% of the design value, enabling stable accelerator operation [23].

During painting range optimization, we observed that the actual optimal horizontal painting range aligned well with the design value, whereas the actual optimal vertical painting range was significantly smaller than designed. Through in-depth analysis, two primary causes were identified: (1) The actual aperture of the BH3 ceramic vacuum chamber (150 mm) is substantially smaller than the design value (163 mm), reducing the actual vertical painting area to only 70% of the theoretical design; (2) At the actual working point (4.81, 4.87), edge focusing effects from the horizontal fixed bump magnets increase the effective vertical painting range experienced by the beam by 25% compared to the set value, as shown in [Figure 6: see original paper]. Restoring the BH3 ceramic vacuum chamber aperture to the design value and accounting for edge focusing effects would yield an actual painting range of approximately 24 mm, perfectly matching the theoretical vertical painting range.

During painting injection commissioning, we discovered that edge focusing effects from injection bump magnets significantly impact painting performance and beam dynamics. For the CSNS RCS, due to the short duration and small angle of painting bumps BH and BV, their edge focusing effects are much smaller than those of the horizontal fixed bump BC. Therefore, this study focuses on the influence of BC magnet edge focusing effects on painting performance and beam dynamics. First, because the fixed bump magnet distribution lacks fourfold symmetry, its edge focusing effects disrupt the fourfold symmetry of the RCS magnetic focusing structure, leading to substantial emittance growth. [Figure 7: see original paper] illustrates the impact of fixed bump BC magnet edge focusing on beam emittance (99.9%), showing significant horizontal and vertical emittance growth due to broken RCS fourfold symmetry. Second, fixed bump magnet edge focusing affects bump height and consequently painting range, with the variation coefficient of bump height differing substantially across different working point modes. [Figure 8: see original paper] shows the effect of fixed bump BC magnet edge focusing on vertical painting bump BV height, demonstrating substantial deviation of actual vertical painting bump BV height from the theoretical set value. Finally, fixed bump magnet edge focusing causes bump leakage, affecting the global closed orbit. [Figure 9: see original paper] presents the impact of fixed bump BC magnet edge focusing on the global closed orbit, revealing that BC magnet edge focusing induces BV bump leakage, resulting in a large global closed orbit distortion reaching up to several tens of millimeters.

Multiple mitigation strategies can address the impact of fixed bump magnet edge focusing on painting performance and beam dynamics. First, to alleviate emittance growth caused by disruption of RCS fourfold symmetry, AC correction quadrupoles (16 or 24 pieces) can be added to the RCS to correct the symmetry breaking and reduce emittance growth. Additionally, converting fixed bump magnets from DC to AC type reduces continuous edge field duration, thereby decreasing emittance growth. Second, for the discrepancy between actual vertical painting bump BV height and theoretical set value caused by edge focusing, the set value can be corrected by multiplying it by the fixed variation coefficient for a given working point. Finally, for bump leakage caused by fixed bump magnet edge focusing that significantly affects the global closed orbit, the original single-power-supply scheme for vertical painting bump magnets BV can be modified to a dual-power-supply scheme (BV2 and BV3 sharing one supply, BV1 and BV4 sharing another) to ensure local bump closure.

3.3 Method for Implementing Correlated Painting Using Anti-Correlated Painting Mechanical Structure

Employing anti-correlated painting, CSNS achieved a beam power of 50 kW in January 2019. However, subsequent intensive commissioning campaigns failed to further increase beam power due to severe challenges including excessively large post-painting bunch size, non-uniform beam distribution, and strong transverse coupling effects, resulting in excessive beam loss that prevented stable operation at higher power. To address these issues, we proposed and developed a method to implement correlated painting using the existing mechanical structure designed for anti-correlated painting after thorough analysis, simulation, and testing; detailed results are available in reference [25]. This method was successfully applied to CSNS RCS beam commissioning, resolving numerous difficulties encountered during high-power beam tuning [25]. Combined with other optimizations, the target beam power ultimately reached the design specification of 100 kW with stable accelerator operation.

4 New Injection Scheme for Simultaneous Correlated and Anti-Correlated Painting

Based on CSNS accelerator commissioning experience, since correlated and anti-correlated painting each possess distinct characteristics, selecting a single fixed painting method during the initial design phase may not accommodate the actual beam conditions of the completed machine, potentially compromising accelerator performance or even preventing achievement of acceptance specifications. Therefore, we sought a new injection scheme capable of simultaneously implementing both correlated and anti-correlated painting, enabling post-construction switching between painting methods according to actual beam conditions and avoiding failures caused by inappropriate initial design choices, thereby achieving accelerator design specifications most efficiently.

[Figure 10: see original paper] illustrates the relationship between the RCS acceptance ellipse and injection beam. The proposed new injection scheme, drawing inspiration from the painting scheme currently employed at the Spallation Neutron Source (correlated painting) [2] and the method described above for implementing correlated painting using anti-correlated painting mechanical structure [25], is designed based on correlated painting principles while accommodating anti-correlated painting. For correlated painting, both horizontal and vertical directions employ pulsed current falling curves for painting. For anti-correlated painting, the horizontal direction uses pulsed current falling curves while the vertical direction uses pulsed current rising curves. [Figure 10: see original paper] shows that for correlated painting, at injection start the RCS circulating beam orbit coincides with the injection point in both horizontal and vertical directions, deviating maximally from the normal closed orbit center and painting the central region of phase-space acceptance; near injection completion, the orbit moves away from the injection point in both planes, painting the peripheral region of phase-space acceptance. For anti-correlated painting, at injection start the circulating beam orbit approximately coincides with the injection point in the horizontal direction (deviating maximally from the normal closed orbit center) while being far from the injection point vertically, painting the central region horizontally and peripheral region vertically; near injection completion, the orbit moves away from the injection point horizontally while coinciding vertically, painting the peripheral region horizontally and central region vertically. Thus, correlated painting proceeds from center to edge in both planes, whereas anti-correlated painting proceeds from center to edge horizontally and edge to center vertically.

For correlated painting, the horizontal and vertical offsets of the painted beam center relative to the circulating beam closed orbit can be expressed as:

$$x = x_{\text{max}} - \frac{x_{\text{max}} - x_{\text{min}}}{T_{\text{inj}}} \times t, \quad x' = 0,$$

$$y = y_{\text{max}} \times \left(1 - \frac{t}{T_{\text{inj}}}\right), \quad y' = 0,$$

where $x_{\text{max}} - x_{\text{min}}$ is the horizontal painting range, y_{max} is the vertical painting range, and T_{inj} is the injection time.

For anti-correlated painting, the horizontal and vertical offsets of the painted beam center relative to the circulating beam closed orbit can be expressed as:

$$x = x_{\text{max}} - \frac{x_{\text{max}} - x_{\text{min}}}{T_{\text{inj}}} \times t, \quad x' = 0,$$

$$y = y_{\text{max}} \times \left[1 - \left(1 - \frac{t}{T_{\text{inj}}}\right)\right], \quad y' = 0.$$

For both painting methods, the linear accelerator beam injection point is set at $(x_{\text{max}}, y_{\text{max}})$ and remains fixed during injection.

CSNS-II Accelerator Injection Beam Parameters | Injection Beam Parameter | Value | |——————|——-| | Injection energy (GeV) | 0.3 | | Average beam current (A) | MATH_0 | | Particles per pulse | 7.8$×10^{13}$ | | Repetition frequency (Hz) | 25 | | Injection beam power (kW) | 117 | | Injection beam pulse width (s) | MATH_1 |

Py-ORBIT is an internationally recognized multi-particle simulation tracking code for high-intensity proton synchrotrons, with simulation results validated by multiple laboratories [26-27]. Based on CSNS-II accelerator injection beam parameters (Table 1), detailed simulations of both correlated and anti-correlated painting processes using Py-ORBIT demonstrate that beam loss, emittance, and beam distribution satisfy stable accelerator operation requirements for both methods. [Figure 11: see original paper] and [Figure 12: see original paper] show beam distribution maps after completion of correlated and anti-correlated painting injection, respectively. The new injection scheme thus successfully enables simultaneous implementation of both correlated and anti-correlated painting injection.

5 Summary and Outlook

This paper presents an in-depth study and discussion of transverse phase-space painting methods and implementation approaches for high-intensity proton synchrotrons. Based on the CSNS injection system, we investigated the beam injection process, developing a precise injection timing calibration method and a precise injection phase-space coordinate matching method. We conducted detailed studies of the anti-correlated painting design scheme, identified the causes of reduced actual vertical painting range, and thoroughly investigated through simulation and beam experiments the impact of fixed bump magnet edge focusing effects on beam emittance, vertical bump height, and global closed orbit. Additionally, we briefly introduced the method for implementing correlated painting using the anti-correlated painting mechanical structure and its crucial role in achieving CSNS design specifications.

Since correlated and anti-correlated painting each have distinct characteristics, selecting a single fixed painting method during initial design may not accommodate the actual beam conditions of the completed machine, potentially compromising accelerator performance or preventing achievement of acceptance specifications. Therefore, this paper proposes a novel injection scheme capable of simultaneously implementing both correlated and anti-correlated painting, with detailed demonstration, simulation, and optimization. This new painting injection scheme enables accelerators to switch painting methods according to actual post-construction beam conditions, avoiding failures caused by inappropriate initial design choices and achieving design specifications most efficiently. The new painting injection scheme is also applicable to other similar accelerators internationally, enabling switching between correlated and anti-correlated painting within a given injection design framework.

Acknowledgments

We thank LIU Huachang, ZHANG Yuliang, QI Xin, LI Xiao, ZHANG Wenqing, DENG Changdong, LU Xiaohan, LI Yong, LI Zhiping, ZHU Peng, XU Zhihong from the Dongguan Research Division of the Institute of High Energy Physics, Chinese Academy of Sciences, and other CSNS colleagues for valuable discussions and assistance during this research.

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