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STUDY ON THE INJECTION BEAM COMMISSIONING AND PAINTING METHOD FOR CSNS/RCS*

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Abstract

In this paper, firstly, the beam commissioning of the injection system for CSNS/RCS will be studied, including: timing adjustment of the injection pulse powers, injection beam parameter matching, calibration of the injection painting bumps, measurement of the painting distribution, injection method adjustment, application of the main stripping foil, optimization of the injection beam loss and radiation dose, etc. Secondly, the painting methods for the CSNS/RCS will be studied, including: the fixed-point injection method, anti-correlated painting method and correlated painting method. The results of the beam commissioning will be compared with the simulation results. Combining with other precise optimizations, the beam power on the target has successfully reached the design value of 100kW and the stable operation of the accelerator has been achieved.

INTRODUCTION

The China Spallation Neutron Source (CSNS) is a high power proton accelerator-based facility [1, 2]. It consists of an 80 MeV H$^-$ Linac, a 1.6 GeV rapid cycling synchrotron (RCS), two beam transport lines, a target station, and several instruments. The RCS accumulates the injection beam, accelerates the beam to the design energy of 1.6 GeV and extracts the high energy beam to the target. Its repetition rate is 25 Hz. The design goal of the beam power on the target is 100 kW [3] which had been achieved in Feb. 2020. Figure 1 shows the layout of the CSNS.

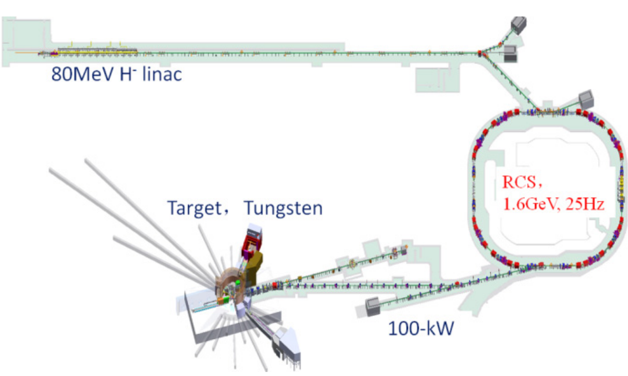

Figure 1: Layout of the CSNS.

Since 2016, the CSNS had begun the accelerator beam commissioning. Figure 2 shows the historical curve of the beam power on the target. It can be seen that: in Nov. 2017, the first 10 kW beam power on the target had been operated for a short while; in Mar. 2018, the beam power over 20 kW had been achieved in the test operation; in Jan. 2019, the beam power was gradually increased to over 50 kW with well controlled beam loss; in Sep. 2019, the beam power in user operation was increased to 80 kW step by step; in Feb. 2020, the beam power was increased to 100 kW to achieve the design goal; in Oct. 2021, the beam power had exceeded 120 kW.

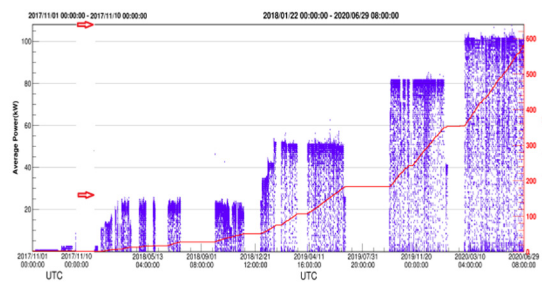

Figure 2: Historical curve of the CSNS beam power.

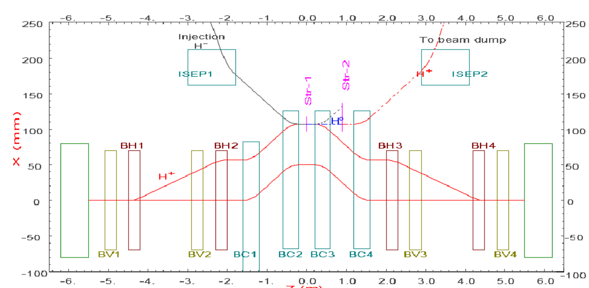

Figure 3: Layout of the CSNS injection system.

The injection system is the core component of the accelerator and the injection beam loss is one of the decisive factors that limit whether the RCS can operate at the high beam power [4]. In order to reduce the beam loss, a combination of the H$^-$ stripping and phase space painting method is used to accumulate a high intensity beam in the RCS [5]. Figure 3 shows the layout of the CSNS injection system. There are three kinds of orbit bumps: a horizontal bump generated by four dipole magnets (BH1-BH4) for painting in the horizontal plane; a vertical bump (BV1-BV4) for painting in the vertical plane; 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.

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For the CSNS [6], the anti-correlated painting method is adopted as the design scheme for the injection system.

In this paper, the beam commissioning of the injection system and painting methods for the CSNS/RCS will be studied in detail. The results of the beam commissioning will be compared with the simulation results. Combining with other precise optimizations, the beam power on the target has successfully reached the design value of 100 kW and the stable operation of the accelerator has been achieved.

BEAM COMMISSIONING OF THE INJECTION SYSTEM

In this section, the results and problems of the beam commissioning for the CSNS injection system will be studied, including: timing adjustment of the injection pulse powers, injection beam parameter matching, calibration of the injection painting bumps, measurement of the painting distribution, injection method adjustment, application of the main stripping foil, optimization of the injection beam loss and radiation dose, etc. After the above optimizations, the injection beam loss has been well controlled and the injection efficiency has been over 99%.

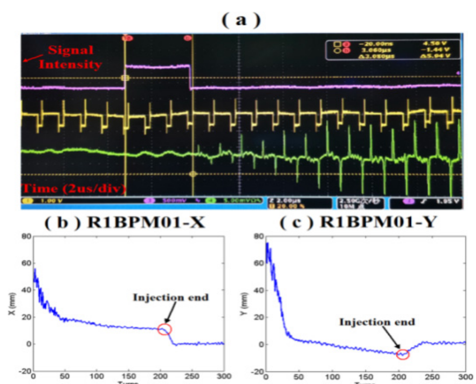

Figure 4: The timing adjustment of the injection pulse powers.

Timing Adjustment of the Injection Pulse Powers

The timing adjustment of the pulse power supply (injection timing adjustment) is very important for the injection beam commissioning. For the CSNS, a new method for precisely adjusting the injection timing have been proposed. Firstly, the standard injection timing signal (T0), the RCS frequency timing signal, and the circulating beam signal can be obtained from a special beam position monitor (R1BPM01) by using the oscilloscope. Then, the timing relationship between the circulating beam and standard injection timing can be given. By using the R1BPM01, the turn-by-turn (TBT) position data of the circulating beam can be measured, and the timing relationship between the pulse power supply and the injection standard timing can be given. By comparing these two timing relationships, the timing relationship between the circulating beam and the pulse power supply can be obtained. As a result, the injection timing can be accurately adjusted. Figure 4 shows the timing adjustment of the injection pulse powers.

Injection Beam Parameters Matching

A mismatch between the injection beam and circulating beam can result in large beam loss and an undesirable transverse emittance growth. There are three aspects which should be considered in the injection beam parameters matching: twiss parameters, beam orbit, and dispersion function.

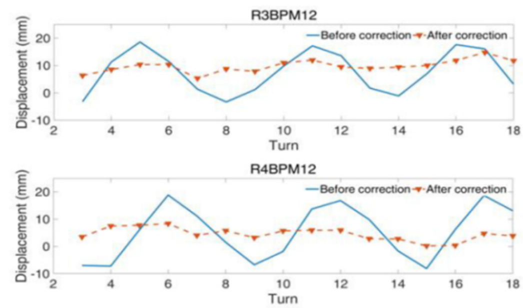

Figure 5: The detected betatron oscillation at two different BPMs before and after the correction for the injection beam.

For the CSNS/RCS, during the beam commissioning, the requirement of the injection twiss parameters matching and dispersion function matching were easy to satisfy. Therefore, we focused on the methods of the orbit matching between the injection beam and circulating beam. After the machine study, a new method based on multi-turn injection and Fourier fitting was developed to match the injection beam orbit [7]. Figure 5 shows the detected betatron oscillation at two different BPMs before and after the correction for the injection beam. The machine study results show that the mismatch of injection parameters can be well depressed by using this new method.

Calibration of the Injection Painting Bumps

In order to control and optimize the phase space painting results, the positions and ranges of the horizontal and vertical painting need to be adjusted accurately. Therefore, in the early stage of the beam commissioning, the calibration of the injection painting bump sizes were very important and need to be done as soon as possible.

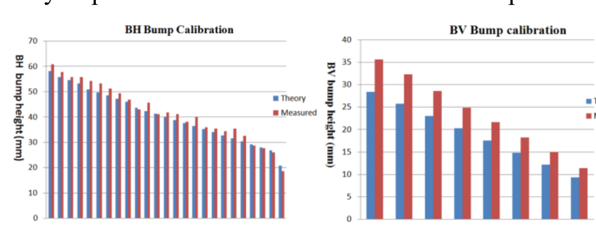

Figure 6: Comparison of the measured and theoretical values of the BH and BV bump sizes.

After the calibration of the injection painting bumps, Fig. 6 shows the comparison of the measured and theoretical values of the BH and BV bump sizes. It can be found that: for the horizontal bump, the calibration error is smaller than 4 mm which is caused by the system errors

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and measurement errors of the two BPMs; for the vertical bump, the difference between the theoretical and measured values is large which is mainly caused by the BC edge focusing effect.

The BC edge focusing effect mainly affects the four-fold symmetry of the RCS, the BV bump height, and causes the disclose of the BV bump. From the simulation results by using the code Py-ORBIT [8], in the current working point mode, the BC edge focusing effect causes about 30% variation of the BV bump, as shown in Fig. 7.

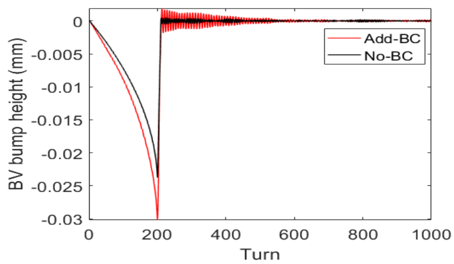

Figure 7: BV bump height with and without the BC edge focusing effect.

Measurement of the Painting Distribution

In order to better adjust and optimize the painting method, the painting distribution needs to be measured. With the fast extraction scheme, after the injection painting completed, the circulating beam can be extracted quickly and the transverse beam distribution can be measured by a multi-wire scanner (MWS) on the beam transport line from the RCS to the target (RTBT). Therefore, the transverse beam sizes and beam distribution after the injection painting completed can be obtained. Figure 8 shows the RCS direct-current current transformer (DCCT) display for the fast extraction scheme and the transverse beam distribution measured by a multi-wire scanner on the RTBT.

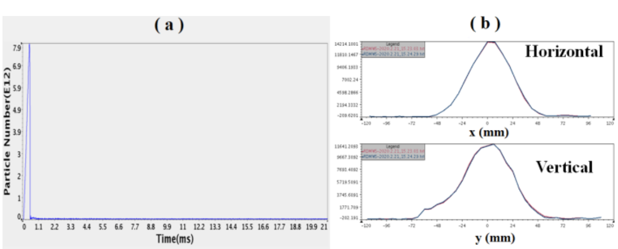

Figure 8: (a) RCS DCCT display for the fast extraction scheme; (b) the transverse beam distribution measured by a multi-wire scanner on the RTBT.

Injection Method Adjustment

In the early stage of beam commissioning, since the precise position of the injection point was unknown and the injection beam power was relatively small, in order to inject the Linac beam into the RCS as soon as possible, the fixed-point injection method was selected. Latter, in order to increase the beam power and reduce the beam loss, the phase space painting in the horizontal plane was used. Finally, the phase space painting in both horizontal and vertical planes was used, and the painting ranges and painting curves were studied and optimized.

When the beam power on the target was less than 80 kW, after the detailed optimization, the anti-correlated painting method can meet the requirements for the stable operation of the accelerator. However, when the beam power on the target exceeded 80 kW, the beam loss was very large. A new method was proposed to perform the correlated painting method. By using this new correlated painting method, the beam loss and the beam distribution were much better. Then, the beam power on the target has reached the design value of 100 kW.

Application of the Main Stripping Foil

During the beam commissioning of the injection system, the main stripping foil was optimized: the material of HBC and the thickness of 0.44 μ m were used for the main stripping foil; the double-layer foil was instead of the single-layer foil to reduce the injection beam loss; after detailed measurement, at the design beam power of 100 kW, the service life of the main stripping foil was only 1.5 months; if overused, the stripping foil would be severely deformed.

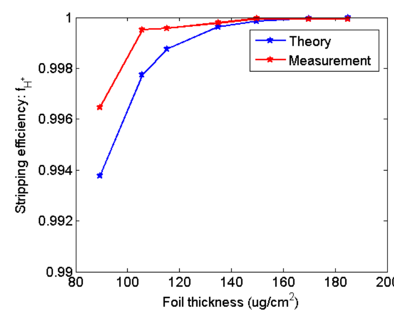

Figure 9: Measured and theoretical stripping efficiencies.

In order to control the injection beam loss, the measurement of the stripping efficiency is very important [9, 10]. During the beam commissioning, a method to measure the stripping efficiency [4] was proposed and applied. By using this method, the stripping efficiencies for different foil thicknesses were measured. Figure 9 shows the comparison of the measured and theoretical stripping efficiencies. It can be found that there is a little difference between the theoretical and actual measured results. This difference is mainly caused by the measurement errors of the stripping foil thickness and INDCT. For the CSNS, the stripping efficiency of the main stripping foil is greater than 99.7% at present.

Injection Beam Loss and Radiation Dose

The injection beam loss is the main source of the RCS beam loss which is one of the decisive factors that limit whether the RCS can operate at the high beam power. There are several main sources of the injection beam loss, including: injection parameter mismatch; low stripping efficiency; stripping foil scattering; unstripped H^- beam loss; stripped electrons. After in-depth machine study, three solutions to reduce the injection beam loss have been found. Firstly, the injection beam parameters

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matching should be more accurately. Secondly, the painting ranges and painting curves should be optimized more accurately. Thirdly, the thickness, structure and material of the main stripping foil should be optimized.

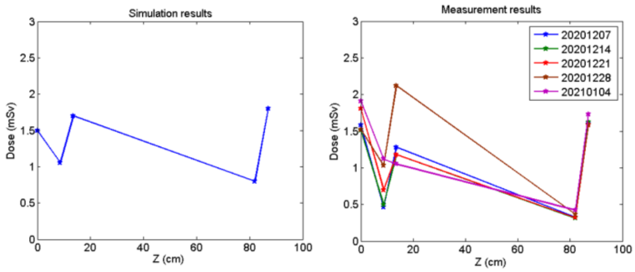

Figure 10: Simulation and measurement results of the residual doses in the injection region.

By using the codes FLUKA [11] and ORBIT [12], the beam transport and particle scattering of the main stripping foil can be simulated. After week by week measurement, the residual doses in the injection region can be obtained. Figure 10 shows the simulation and measurement results of the residual doses in the injection region. It can be seen that, from the simulation results, the maximum residual dose caused by the foil scattering is less than 2 mSv. By comparing the simulation results and measurement results, it can be confirmed that the particle scattering of the main stripping foil is the most important source of the residual doses in the injection region.

STUDY ON THE PAINTING METHOD

During the beam commissioning, different injection methods were used in different periods. In the early stage, since the precise position of the injection point was unknown and the beam power was relatively small, the fixed-point injection was selected. When the beam power on the target was less than 80 kW, the anti-correlated painting method of the design scheme can meet the requirements for the stable operation of the accelerator. When the beam power on the target exceeded 80 kW, the beam loss was very large. A new method was proposed to perform the correlated painting method. By using this new method, the beam power on the target has reached the design value of 100 kW.

Fixed-point Injection

The fixed-point injection method means the Linac beam injected into the ring at a fixed point. Figure 11 shows the schematic of the RCS acceptance ellipse and injection beam in the fixed-pointing injection process. It can be seen that the relative position of the injection beam and circular beam is unchanged during the injection process. In the early stage of beam commissioning, since the precise relative position of the injection beam and circular beam was unknown and the injection beam power was very small, in order to inject the beam into RCS as soon as possible, the fixed-point injection method was selected.

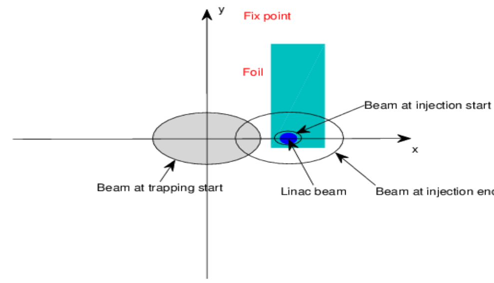

Figure 11: Schematic of the RCS acceptance ellipse and injection beam in the fixed-point injection process.

While the fixed-point injection method was used, there was a sudden beam loss which cannot be removed during the injection process. Figure 12 shows the RCS DCCT display while the fixed-point injection was used. It can be found that there was sudden beam loss during the injection process no matter the matching of the injection beam and circulating beam. The machine study shows that the sudden beam loss increases with the off-center position between the circulating beam and injection beam.

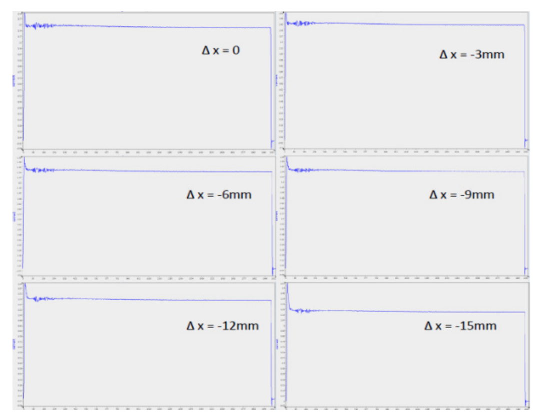

Figure 12: RCS DCCT displays while the fixed-point injection was used. △x is the off-center position between the circular beam and injection beam.

Anti-correlated Painting Method

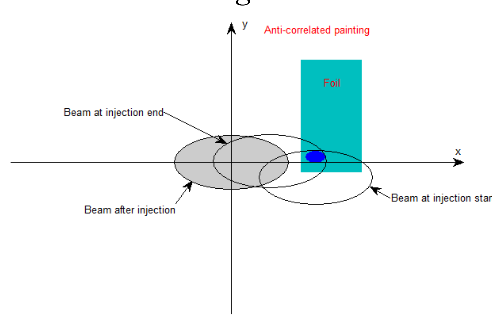

Figure 13: Schematic of the RCS acceptance ellipse and injection beam in the injection process for the anti-correlated painting method.

The anti-correlated painting method is adopted as the design scheme for the CSNS injection system. In the injection process, 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

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point locates in the lower left corner of the main stripping foil to reduce the traversal times. Figure 13 shows the schematic of the RCS acceptance ellipse and injection beam in the injection process.

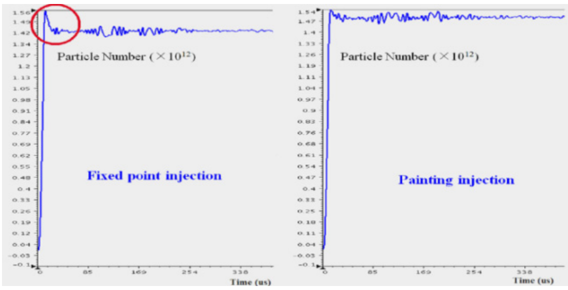

Figure 14: RCS DCCT displays when the fixed-point injection and painting injection were used.

In the above section, it can be found that when the fixed-point injection method was used, there was a sudden beam loss in the injection process. By using the transverse phase space painting instead of the fixed-point injection, the sudden beam loss in the injection process was gone. Figure 14 shows the RCS DCCT display when the fixed-point injection and painting injection were used. It can be found that, with the transverse phase space painting, the sudden beam loss was gone and the injection efficiency was improved.

With the anti-correlated painting method of the design scheme, 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 kW and achieved the stable operation.

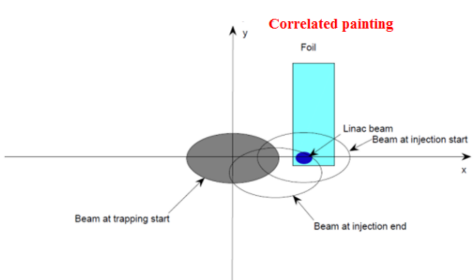

Figure 15: Schematic of the RCS acceptance ellipse and injection beam in the injection process for the correlated painting method.

Correlated Painting Method

When the beam power on the target exceeded 80 kW, the beam loss was very large. In order to reduce the beam loss and increase the beam power on the target, after in-depth machine study, a new method was proposed to perform the correlated painting method [13]. By using the rising edge of the vertical pulse current curve instead of the falling edge for painting in the vertical plane, the correlated painting scheme can be carried out. Figure 15 shows the schematic of the RCS acceptance ellipse and injection beam in the injection process. Figure 16 shows the BH and BV pulse current curves for the anti-correlated painting scheme and correlated painting scheme.

By using the correlated painting method, the beam loss of the RCS was greatly reduced, the painting distribution was much better, and the beam intensity in vertical phase space was effectively mitigated. Then, the beam power on the target has reached the design value of 100 kW.

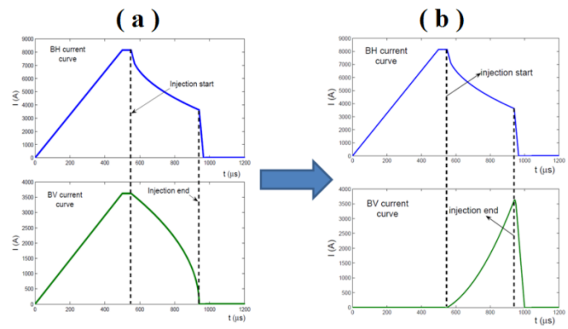

Figure 16: BH and BV pulse current curves for the anti-correlated painting scheme (a) and correlated painting scheme (b).

CONCLUSIONS

Firstly, the beam commissioning of the injection system for the CSNS/RCS was studied and discussed, including: timing adjustment of the injection pulse powers, injection beam parameter matching, calibration of the injection painting bumps, measurement of the painting distribution, injection method adjustment, application of the main stripping foil, optimization of the injection beam loss and radiation dose, etc. Secondly, the injection painting methods were studied, including: the fixed-point injection method, anti-correlated painting method and correlated painting method.

Compared to the simulation results of the design scheme, the transverse beam distribution, transverse coupling effect and beam loss of the actual anti-correlated painting were somewhat different. In order to reduce the beam loss and increase the beam power on the target, a new method was proposed to perform the correlated painting method for CSNS/RCS. By using the correlated painting method, the beam loss and the beam distribution were much better. Then, the beam power on the target has reached the design value of 100 kW.

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