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# PARAMETERS MEASUREMENTS OF PROTON BEAM EXTRACTED FROM CSNS/RCS

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*Abstract*

In order to study the emittance evolution of the circulating beam in the fast-cycling synchrotron (RCS) of the Chinese Spallation Neutron Source (CSNS), parameter measurements of the beam extracted at different times were carried out. The measurements were mainly based on wire-scanners mounted in RCS to target transport line (RTBT) for beam profile measurement, and different methods were applied in the solution processes. The emittance and C.S parameters of the extracted beam at different times were obtained and studied, which provided an important reference basis for the beam commissioning of RCS. The beam envelope along the RTBT has been matched and re-measured, which was in good agreement with the design optics.

## INTRODUCTION

China Spallation Neutron Source (CSNS) [1] is a high intensity accelerator based scientific research facility. The accelerator complex is mainly composed of an 81 MeV H- linac as the injector and a 1.6 GeV rapid cycling proton synchrotron (RCS). The high-energy proton beam extracted from the accelerator bombards on the target to generate neutrons through spallation reaction. Tungsten is used as the target material with heavy water as the cooling media. The high-energy neutrons are then cooled down by moderator to become thermal or cold neutrons, which meet for the neutron scattering experiments. CSNS first target station accommodates at least 18 neutron scattering instruments and 4 are available by 2019. Figure 1 shows the schematic diagram of CSNS facility.

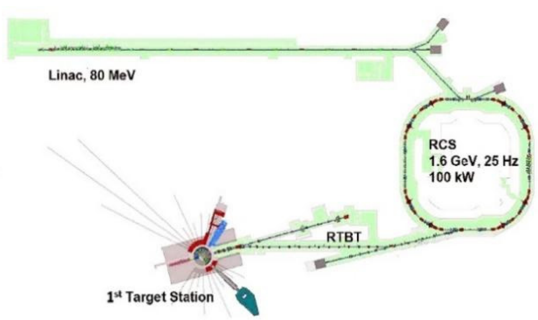


Figure 1: Schematic diagram of CSNS.

The beam commissioning of CSNS started in the summer of 2015 and the first proton beam was bombarded onto the target in July 2017 to produce neutrons. After two and a half years of beam commissioning, the beam power was gradually upgraded to the design value of 100 kW.

In the process of RCS beam commissioning and beam power increase, reducing the beam loss in RCS at high current intensity was always a major task. Among the many sources of beam loss, space charge effect was the dominant one. Space charge force can cause frequency shift, drive resonance, and produce beam halo, which will lead to emittance growth and beam loss. In order to study the evolution and growth of beam emittance in the whole cycling period of 20 ms in RCS, and to understand the influence of various physic parameters on beam emittance, different tools were used as probes to get the beam parameters at specific cycling turns [2]. By manipulating the timing of the 8 extraction kickers in RCS, circulating beam can be extracted and measured the at specified times.

## PARAMETERS MEASUREMENTS OF EXTRACTED BEAM FROM RCS

The RTBT transports the high-power proton beam from RCS to the target station, and meets the requirements of the target station for the transverse density distribution of proton beam. Another auxiliary branch RDBT (Ring to the Dump Beam Transport line) of 41 m long attaches to the trunk line after RTB01, is used for beam commissioning. 8 vertical kickers and 1 horizontal lambertson magnet are used for the proton beam extraction from the RCS ring [3], see Fig. 2.

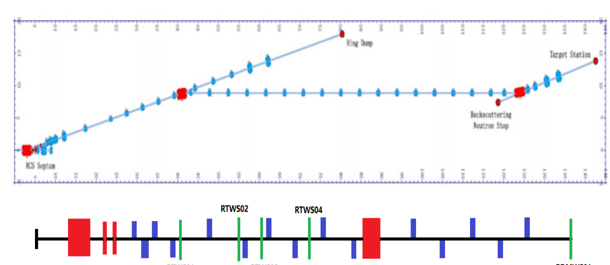


Figure 2: Layout of RTBT and RDBT beam transport line.

We used four wire scanners mounted in the RTBT extraction-matching section and one multi-wire scanner in the RDBT to measure the emittance and C.S parameters of the RCS extracted beam. This section contains a total of 15 quadrupole magnets (RTQ01 ~ RTQ10, RDQ01 ~ RDQ05) and each magnet is powered separately. The beam window and dump is at the end of the RDBT and the multi-wire scanner is installed in front of the beam window.

The signal data measured by the wire scanners is output in a fixed data format after electronic conversion, as shown in Fig. 3. The three curves of black, blue and red represent the beam distribution in three directions: horizontal, vertical and oblique 45°. Multi-wire scanner has no scanning function, it uses horizontal and vertical mesh structure to wire. The beam distribution can be given in real time, but the accuracy is slightly worse.

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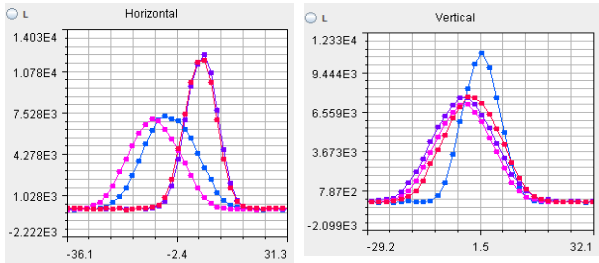

Figure 3: Measured results by wire scanners in RTBT. Left: horizontal profiles, Right: vertical profiles.

The extracted beam distribution and injection painting setting are closely related. It can be seen that the beam measured profiles are very close to the Gaussian distribution, which is easy to analyse to obtain the RMS size. The measurement results of the three wire scanners at the appropriate positions can uniquely determine the three degrees of freedom of the transverse phase ellipse, the emittance ε, and the C.S parameters α, β. The analysis of a larger number of wire scanners results can effectively reduce the impact of measurement errors.

## BEAM PARAMETERS ANALYSIS

After obtaining the beam RMS sizes at 5 different positions, we use two methods to obtain the beam emittance and C.S parameters at the extraction point upstream of the wire scanners. At the same time, we also use different RTBT lattices to ensure that the beam parameter measurement results obtained under different RTBT lattices are consistent.

### *XAL Solver*

The first tool used to analyse the measurement results of wire scanner is wire analysis code in XAL [4]. There are four algorithms in XAL: Directed Step, Random Search, Random Shrink Search and Simplex Search. Another algorithm is the initial algorithm to guarantee the initial point will be considered as a possible solution.

In the analysis process, the first step is to set the initial parameters of a point upstream of the RTBT wire target (such as the RCS extraction point), including the beam emittance ε, C.S parameter α, β and search range. In the second step, different methods are used to calculate the beam size at the location of wire scanners. For RTBT, the space charge effect can be ignored, and only the linear beam optics is considered. Then, the error is obtained by comparing the calculated with the measured sizes. If the error is large, the new initial parameters are replaced, and the above process is repeated until the set error standard is reached.

The advantage of this method is that it can call external programs (such as PARMILA, etc.) to calculate the beam transmission, which can meet more complex calculation requirements, such as the transmission of low-energy beam parameters [5]. However, the calculation time is closely related to the setting of initial parameters, which may take a long time. Therefore, we also tried other methods to overcome the shortcomings of XAL tools.

### *SVD Method*

The second method is to directly solve the parameters of the beam through matrix. The method has enough precision in calculating the transition of beam without considering the effect of space charge, which can meet the requirements of our experiment.

According to the beam transfer theory, the C.S parameters from one point to another meet the following relationship:

$$\begin{bmatrix}\beta\\\alpha\\\gamma\end{bmatrix}_2=\begin{bmatrix}M_{11}^2 & -2M_{11}M_{12} & M_{12}^2\\ -M_{11}M_{21} & M_{11}M_{22}+M_{12}M_{21} & -M_{12}M_{22}\\ M_{21}^2 & -2M_{21}M_{22} & M_{22}^2\end{bmatrix}\begin{bmatrix}\beta\\\alpha\\\gamma\end{bmatrix}_1 \quad (1)$$

Because the beam size is equal to emittance times beta function, then Eq. (1) can be converted into Eq. (2):

$$\begin{bmatrix}M_{11}^2 & -2M_{11}M_{12} & M_{12}^2\\ -M_{11}M_{21} & M_{11}M_{22}+M_{12}M_{21} & -M_{12}M_{22}\\ M_{21}^2 & -2M_{21}M_{22} & M_{22}^2\end{bmatrix}\begin{bmatrix}\varepsilon\beta\\\varepsilon\alpha\\\varepsilon\gamma\end{bmatrix}_1=\begin{bmatrix}a_1^2\\a_2^2\\a_3^2\end{bmatrix}_2 \quad (2)$$

Where a1, a2 and a3 represent the beam size downstream. We have completed the programming of this method in XAL, which can solve Eq. (2) and get the C.S parameters and emittance at the extraction point. Compared with the previous one, the SVD method can find the solution faster.

According to the real RTBT lattice and using the above two methods, we can get the parameters of the beam at different times. In order to study the evolution and growth of beam emittance in the whole cycling period of 20ms in RCS, circulating beam needs be extracted and measured the at specified times.

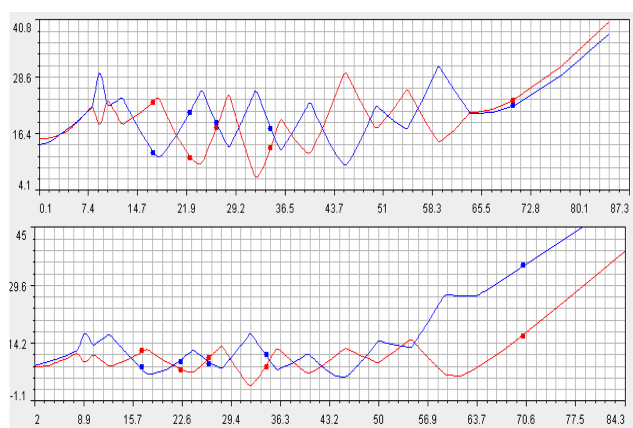

Figure 4: Beam envelope fitting when beam extracted at different time: upper: 5 ms, lower: 20 ms Solid dots: measurement result (red: horizontal, blue: vertical). Solid line: beam envelope fitted.

By adjusting the timing of the 8 extraction kickers, circulating beam were extracted and measured the at the 3rd, 5th, 20th ms with different current intensities. Figure 4 shows the fitting results of 2 sets of measured beam size (dot) and beam envelope (solid line). It can be seen from the figures that the error of fitting the measurement results of five wire scanners with the beam envelope curve is very

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small. We can conclude that the errors of measurement and analysis are both small, and the beam parameters obtained from this method have high accuracy.

Table 1 shows the analysis results of beam parameters at 5th ms and 20th ms in RCS of (4.80/4.86 ~ 4.77/4.77) mode, including C.S parameters and non-normalized emittance in horizontal and vertical directions. The beam transverse emittance at 3rd and 5th ms provide an important reference for RCS optimization. Meanwhile, by comparing the measurement results with the simulation results, we could verify the accuracy of the simulation results of the beam dynamics with space charge effect under high current conditions.

Table 1: Measured Parameters Results of Extracted Beam

| Parameter | 5 ms | 20 ms |
|---|---|---|
| Energy (MeV) | 222 | 1600 |
| Emit-x (π.um) | 35.318 | 10.144 |
| α_x | 0.116 | 0.205 |
| β_x | 6.729 | 6.409 |
| Emit-y (π.um) | 35.823 | 11.03 |
| α_y | -0.014 | 0.053 |
| β_y | 5.807 | 5.731 |

## BEAM OPTICS OF RTBT

According to the measured beam parameters and the different requirements of the target for the beam distribution, we re-matched the optics of RTBT and all the 9 wire scanners along RTBT performed the measurement. Together with the fitted beam envelope, the results are all shown in Fig. 5. The deviation between the beam size measured by 9 wire scanners and the fitted beam envelope is still very small which indicated real lattice optics of RTBT is rather close to the design one.

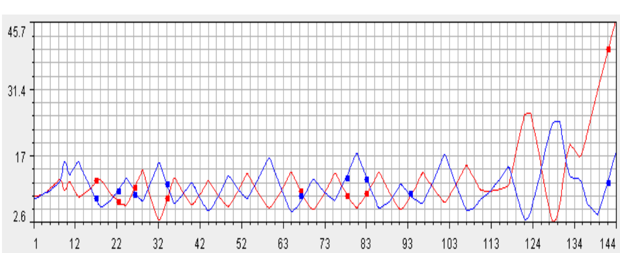


Figure 5: Beam envelope in RTBT. Solid dots measurement result (red: horizontal, blue: vertical). Solid line: beam envelope fitted.

Based on the measurement of the beam parameters, we can accurately control the beam optics in the 144 m long beam line from the RCS to the target. The beam parameters in the last 24 section of RTBT will directly affect the beam distribution at target, so our measurement work provided the conditions for the beam homogenization at the target. The subsequent beam commissioning results showed that the homogenization operation of beam distribution at target reduced the peak power density and the beam loss outside the target effectively.

## CONCLUSION

In this paper, we report the measurement result of parameters of beam extracted form RCS. By manipulating the timing of the 8 extraction kickers, circulating beam can be extracted and measured the at specified turns. The measurements were carried out by wire scanners mounted in the RTBT transport line during beam commissioning of CSNS/RCS. Different methods were applied in the results analysis. From the results, we got to know the evolution of beam emittance in the whole cycling period of 20 ms. Based on the measurement of the beam parameters, we accurately controlled the beam distribution along the RTBT beam line and the surface of the spallation target.

## ACKNOWLEDGEMENT

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