ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-THBC4

OBSERVATION AND STUDY OF SPACE CHARGE EFFECT FREQUENCY SHIFTS IN HIGH-INTENSITY ACCELERATORS

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Abstract

The China Spallation Neutron Source Rapid Cycling Synchrotron(CSNS-RCS) is the first high-intensity pulsed proton accelerator in China and the fourth of its kind globally. One of the key challenges in enhancing its power is the space charge effect. Measuring the frequency shift induced by this effect is crucial for understanding and mitigating its impact. In our experiments, we varied the beam current by adjusting the injection pulse length and chopping rate. By employing a combination of narrow-band filtering and Fast Fourier Transform(FFT) techniques, we successfully observed a tune shift of approximately 0.02 induced by a beam power of 140 kW. These experimental results were then compared with simulation outcomes, showing good agreement.

INTRODUCTION

The China Spallation Neutron Source (CSNS) is the first high-intensity pulsed spallation neutron source in China and the fourth of its kind globally. It primarily consists of an 80 MeV (300 MeV in CSNS-II, and the upgrades schemes of CSNS is show in Table 1) negative hydrogen ion linear accelerator and a 1.6 kW rapid cycling synchrotron (RCS) [1]. The negative hydrogen ions are first accelerated through a 3 MeV Radio Frequency Quadrupole (RFQ) and an 80 MeV Drift Tube Linac (DTL). After acceleration, the ions are stripped of electrons by a carbon foil and injected into the RCS [2]. Following approximately 20,000 cycles, the beam is extracted by a kicker and transported through the Ring to Target Beam Transport line (RTBT) to the target, where pulsed neutrons are generated for spallation neutron research.

Table 1: Upgrades Schemes of the CSNS

Parameter	CSNS I	CSNS II
Beam power	100	500
Repetition Rate [Hz]	25	25
Inj. Energy [MeV]	80	300
Ext. Energy [GeV]	1.6	1.6
Beam Intensity [$\times 10^{13}$]	1.56	7.8
Harmonic number	2	4

The RCS is a crucial component of the accelerator, and the regulation of its beam dynamics is essential for the overall performance of the accelerator. The milestones in beam tuning are as follows:

- **2017**: Beam injection into the ring and stable acceleration were achieved.
- **March 2018**: Achieved 10 kW beam power, passing national acceptance.
- **End of 2018**: Supplied 50 kW beam power.
- **End of 2019**: Supplied 80 kW beam power.
- **2020**: Achieved 100 kW beam power, reaching the CSNS I design goal and stable operation.
- **2022**: Achieved 125 kW beam power.
- **2022**: Achieved 140 kW beam power.
- **2024**: Target to achieve 160 kW beam power.

Beam tuning tasks can be broadly divided into low-intensity tuning and high-intensity tuning. In low-intensity beam tuning, the primary focus is on verifying hardware parameters, such as the accuracy of power supply timing and the calibration of beam diagnostic equipment. This stage involves orbit correction and optics correction.In high-power commissioning, techniques such as transverse painting are employed to mitigate the growth of beam emittance due to space charge effects. Additionally, the introduction of sextupoles helps to correct chromaticity and instability issues. Figure 1 illustrates the power upgrade process of the spallation neutron source.

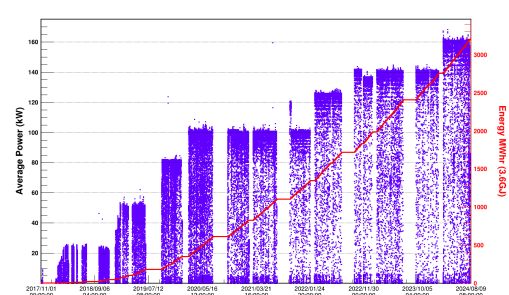

Figure 1: Power upgrade process of the spallation neutron source.

From the experience with spallation beam tuning, it is evident that low-intensity and high-intensity modes are not

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compatible. The lattice and orbit settings optimized for low-intensity beams require further adjustments and scans under high-intensity conditions to meet the machine's operational requirements. The primary objective of low-intensity tuning is to check the parameters of the accelerator's hardware systems, such as timing systems. In contrast, high-intensity tuning focuses on mitigating instabilities and addressing space charge effects. The following section of the article mainly includes an introduction to space charge theory, PyOrbit simulations, and experimental data analysis.

SIMULATION OF SPACE CHARGE EFFECT AND FREQUENCY SHIFT

Space charge effects are critical considerations in high-intensity beam physics [3], as they significantly influence the beam dynamics. These effects arise from the Coulomb repulsion between charged particles within the beam, leading to changes in the beam's transverse and longitudinal properties. Understanding these effects is essential for optimizing the performance of particle accelerators.

The incoherent tune shift refers to the change in the natural oscillation frequency of individual particles within the beam due to space charge forces. As the particle density increases, the Coulomb repulsion becomes more pronounced, leading to a reduction in the individual particle tune. This phenomenon is particularly important in high-intensity beams, where the space charge forces can cause substantial deviations in the particle trajectories, potentially leading to beam loss and reduced accelerator performance.

In contrast to the incoherent tune shift, the coherent tune shift pertains to the collective oscillation frequency of the entire beam as a single entity. When considering the beam as a whole, space charge forces result in a shift of the overall tune. This collective behavior is influenced by the spatial distribution and density of the particles, as well as the beam's transverse and longitudinal dimensions. The coherent tune shift is a critical parameter in beam stability studies, as it can lead to resonances and instabilities if not properly managed.

Both incoherent and coherent tune shifts are fundamental aspects of space charge effects that must be carefully analyzed and mitigated in the design and operation of particle accelerators. By understanding these shifts, researchers can develop strategies to control beam dynamics, enhance stability, and improve the efficiency of high-intensity accelerators.

Simulation with PyORBIT

PyOrbit [4] is a comprehensive simulation software designed to model the behavior of particle beams from injection to extraction. It is particularly effective in studying the impact of space charge effects on beam dynamics. This report details the simulation setup used to investigate the tune spread of a beam under the influence of space charge effects, using an initial distribution representative of a beam coming from a linear accelerator, followed by accumulation and acceleration processes. The simulation tracks the beam over 2000 turns, after which the tune spread information is dumped for analysis, as shown in Fig. 2.

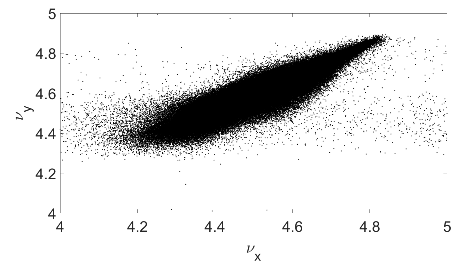

Figure 2: Tune Spread of the CSNS-RCS at 2000turn.

EXPERIMENTAL OBSERVATIONS

Experimental Setup

Figure 3 shows the layout of the CSNS-RCS(Due to abnormal data from R4BPM08 during the experiment, it is not shown in the figure). The CSNS-RCS consists of four superperiod units, each of which is mirror-symmetrical. The basic structure is a triplet. The CSNS-RCS has a total of 48 quadrupole magnets and 32 BPMs, meaning that each triplet structure, consisting of three magnets, contains two BPMs. Each BPM is named according to its proximity to the adjacent quadrupole magnet.

In our experiments, the beam current was varied by adjusting the injection pulse length and chopping rate. The experimental setup included narrow-band filtering and Fast Fourier Transform (FFT) techniques to analyze the beam's frequency components. The BPM data were collected turn-by-turn to observe the tune shifts.

Data Analysis

Two comparative experiments conducted by us on the evening of December 17, 2023, at 02:26 and 02:42. The chopper duty for the first experiment was 42, and for the second experiment, it was 87. Due to the different chopper duties, the number of particles injected per pulse and the length of the injected pulse beam were different, resulting in different numbers of particles for the two experiments.

Figure 4 corresponds to a particle number of 2.2e13, and Figure 5 corresponds to a particle number of 6.33e12. We performed Fast Fourier Transform (FFT) on the TBT data of the BPM and found that as the particle number decreased from 2.2e13 to 6.33e12, the horizontal working point increased from 0.7855 to 0.8105, an increase of 0.022.

Figures 4 and 5 show the overlay of the FFT data from 31 BPMs, with many spurious peaks. To determine the true working point, we used narrow-band filters and methods such as SOBI. Figure 6 shows the BPM FFT data after applying the narrow-band filter.The data was sampled at a rate of 1024 Hz, ensuring a high temporal resolution for capturing the relevant signal characteristics. To isolate the frequency components of interest, we applied a narrow-band filter with a passband ranging from 194 Hz to 236 Hz. This specific frequency range was chosen based on preliminary analyses that indicated the presence of significant signal features within this band. The application of this filter effectively attenuates frequencies outside the 194 Hz to 236 Hz range, thereby enhancing the clarity and accuracy of the subsequent analysis by reducing noise and other extraneous frequency components. This approach is particularly beneficial for identifying and studying the underlying dynamics of the system under investigation, as it allows for a more focused examination of the relevant spectral content. Before overlaying the FFT data, we removed interference signals from some BPMs using the SOBI method.

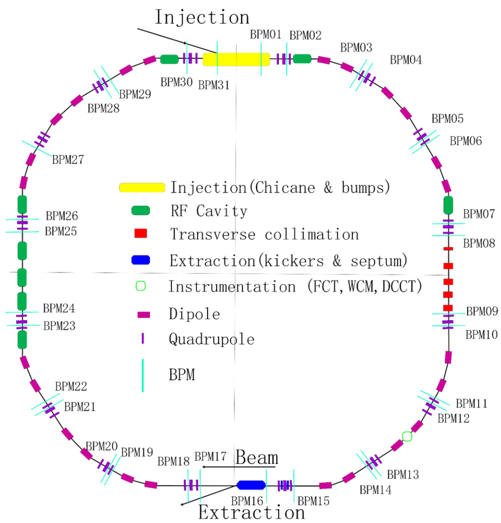

Figure 3: Layout of the CSNS-RCS.

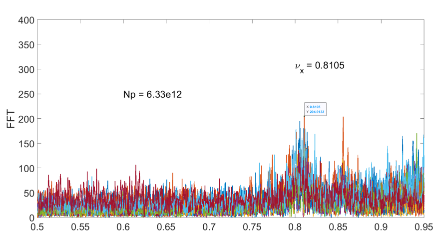

Figure 4: FFT spectrum of the BPM data showing the tune shift due to space charge effect at low intensity.

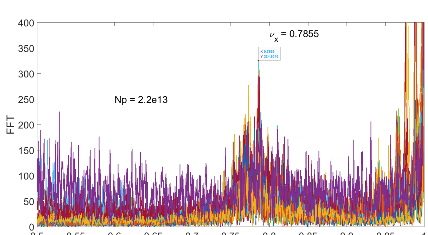

Figure 5: FFT spectrum of the BPM data showing the tune shift due to space charge effect at high intensity.

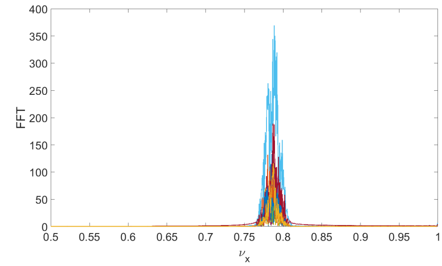

Figure 6: FFT of the BPMs using narrow-band filter.

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Results

Although we cannot yet definitively ascertain whether the frequency shift of the working point is due to space charge effects or transverse impedance, careful measurements have allowed us to observe the shift of the working point under high-intensity conditions. This finding is crucial for future measurements of the working point at different beam intensities and for the calibration of the optics.

CONCLUSION

The CSNS has made significant progress in understanding and mitigating the space charge effect on beam frequency. Our study, combining PyORBIT simulations, and experimental observations, provides a comprehensive understanding of the tune shifts induced by space charge. These findings are crucial for optimizing beam dynamics and achieving higher beam power in future operations.

ACKNOWLEDGEMENTS

The author would like to express gratitude for the insightful discussions with colleagues from the Physics Group. Special thanks are also extended to the Beam Diagnostics Group and the Operations Group for their invaluable assistance during the tune measurements.

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