

Pulsed octupole magnet for beam instability mitigation in Rapid Cycling Synchrotron

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Abstract

The Rapid Cycling Synchrotron (RCS) in the China Spallation Neutron Source (CSNS) operates as a high-intensity proton accelerator. The coupled bunch instability was observed during the RCS beam commissioning, which highly limits the beam power. To investigate the dynamics of instability under increased beam power, a pulsed octupole magnet with a gradient of 900T/m³ is developed. The magnet system integrates an octupole magnet with a pulsed power supply. The field is carefully measured to examine the performance before installation into the tunnel. After the installation of the magnets, beam measurements are performed to confirm the effectiveness of the instability mitigation on an actual proton beam. The measurement results show that the instability can be suppressed by using the pulsed octupole magnet, particularly at the high energy stage in an acceleration cycle, meeting the requirements for stable operation of the accelerator. Additionally, when the instability is completely suppressed through chromaticity optimization, octupole magnets can significantly enhance the RCS transmission efficiency, which is crucial for controlling beam loss. The pulsed octupole magnet offers significant progress of beam stability in the RCS, providing valuable experience for further beam power enhancement.

Full Text

Preamble

Pulsed Octupole Magnet for Beam Instability Mitigation in Rapid Cycling Synchrotron

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The Rapid Cycling Synchrotron (RCS) in the China Spallation Neutron Source (CSNS) operates as a high-intensity proton accelerator. During RCS beam commissioning, coupled bunch instability was observed, which severely limits the achievable beam power. To investigate instability dynamics under increased beam power, a pulsed octupole magnet with a gradient of 900 T/m^3 has been developed. The magnet system integrates an octupole magnet with a pulsed power supply. The magnetic field was carefully measured to verify performance prior to installation in the tunnel. Following magnet installation, beam measurements were performed to confirm the effectiveness of instability mitigation on an actual proton beam. The results demonstrate that the instability can be suppressed using the pulsed octupole magnet, particularly during the high-energy stage of an acceleration cycle, meeting the requirements for stable accelerator operation. Additionally, when instability is completely suppressed through chromaticity optimization, octupole magnets can significantly enhance RCS transmission efficiency, which is crucial for controlling beam loss. The pulsed octupole magnet represents significant progress in beam stability for the RCS, providing valuable experience for further beam power enhancement.

Keywords: China Spallation Neutron Source, rapid cycling synchrotron, coupled bunch instability, octupole magnet

Introduction

Octupole magnets have been extensively employed in ring accelerators to cure transverse instabilities, as evidenced by their application in various facilities including the Photon Factory electron storage ring at KEK [1], the Main Ring at J-PARC [2] in Japan, the LHC [3] at CERN in Switzerland, the SIS100 synchrotron [4] in Germany, and BEPC [5] in China. The tune spread increases with octupole field strength, thereby enhancing Landau damping. However, due to the nonlinear nature of the field, octupole magnets reduce the dynamic aperture [6], which restricts their operational strength. Consequently, while instabilities have been successfully controlled in many cases [1, 2, 5], some accelerators—notably the J-PARC Main Ring [2]—have experienced beam loss resulting from reduced dynamic aperture after instability suppression. Furthermore, the nonlinear dynamics of octupole magnets become increasingly complex under space charge effects, which may reduce the efficacy of Landau damping.

Therefore, a comprehensive understanding of octupole magnet applications for mitigating instabilities is crucial for the proton Rapid Cycling Synchrotron (RCS), where the magnetic field changes rapidly and the beam size is relatively large [2, 7, 8].

The China Spallation Neutron Source (CSNS) [9, 10] is a high-intensity proton accelerator facility. The accelerator complex comprises two main components:

a Negative Hydrogen (H^-) Linac [11-13] and an RCS [7, 14]. The RCS features a four-fold lattice structure with a circumference of 227.92 meters, including 24 dipole magnets and 48 quadrupole magnets. Each super-period of the RCS consists of a straight section and an arc section. The RCS accelerates the proton beam from 80 MeV to 1.6 GeV at a repetition rate of 25 Hz. The designed beam power of CSNS is 100 kW, corresponding to $N_p = 1.56 \times 10^{13}$ particles per pulse. Beam commissioning of the RCS began in 2017. An unforeseen instability in the horizontal plane was first observed [15, 16], emerging as a critical challenge during beam commissioning. A series of measurements provided valuable insights and practical guidance for instability mitigation. After two years of beam commissioning and gradual power ramp-up, the RCS achieved the target beam power of 100 kW in February 2020. Currently, with the aid of AC sextupole magnets [17], trim quadrupole magnets [18], and 2nd harmonic cavities [19, 20], the beam power in the RCS has been increased to 170 kW, corresponding to $N_p = 2.65 \times 10^{13}$ particles per pulse.

In Phase II of CSNS (CSNS-II) [21], the beam power on the target will be upgraded to 500 kW, while the energy on the target will remain unchanged (the RCS injection energy will be increased to 300 MeV to mitigate space charge effects). This implies a substantial increase in beam intensity (equivalent to $N_p = 7.8 \times 10^{13}$ particles per pulse). As RCS beam intensity increases, high-intensity effects become more severe. Notably, the instability observed during CSNS beam commissioning presents a significant challenge for complete suppression at CSNS-II.

We investigated the potential of employing an octupole magnet to address instability in the RCS, and consequently, a pulsed octupole magnet was proposed and developed in 2022. Following careful field measurements, the magnet system was seamlessly integrated into the accelerator in the summer of 2023. In subsequent machine studies, extensive beam experiments were conducted, including magnetic field calibrations and validation of instability suppression. These experiments yielded several positive results for suppressing instability, demonstrating the feasibility of using octupole magnets to mitigate instabilities in the CSNS RCS.

This paper begins with a summary of RCS instabilities in Sec. II, highlighting the requirement for octupole magnets in suppressing the instability, as discussed in Sec. III. Sec. IV introduces the design of the magnet and its power supply, while Sec. V describes the magnetic field measurements. Sec. VI presents beam measurements for instability mitigation. Detailed discussions on the application of octupole magnets in the RCS are provided in Sec. VII, followed by a summary in the concluding section.

II. Beam Instability in the RCS

An unexpected instability was observed during the beam power increase from 20 kW to 50 kW in 2019, worsening with further power increases. A series

of comprehensive measurements [22] were undertaken to characterize the instability during a typical acceleration cycle, revealing that the issue is a coupled bunch instability. When the instability occurs, beam position oscillations are observed in the transverse plane. The instability exhibits sensitivity to the tune, as illustrated in Fig. 3 [Figure 3: see original paper] of Ref. [23]. Variations in the tune lead to corresponding shifts in the timing of instability occurrences.

Taking the case of $\nu_x = 4.80$ as an example, as shown in Fig. 1 [Figure 1: see original paper], the turn-by-turn (TbT) beam position in the horizontal plane and transmission efficiency in the RCS are presented as functions of beam population. Starting from the lowest bunch intensity, the horizontal beam position begins to oscillate after injection. The oscillation amplitude becomes larger as beam intensity increases. The centroid's positive envelope on a logarithmic scale is linearly fitted, and the growth time is extracted. For a beam intensity of $N_p = 1.56 \times 10^{13}$ per pulse, equivalent to a beam power of 100 kW, the growth time is less than 1 ms. In the experiment, only the coupled mode of one is determined for the normal bunch mode (two bunches). The instability is first observed in the horizontal plane and subsequently may appear in the vertical plane as beam power increases at $\nu_y > 4.86$. The coupled mode of the vertical instability is the same as that in the horizontal plane. Impedance studies confirm that the instability is induced by resonant impedance from the RF shield on the ceramic chamber [23, 24].

Comprehensive measurements provide valuable insights and practical guidance for mitigating the instability, such as tune and chromaticity optimization. By applying optimized tune and chromaticity, the instability has been successfully suppressed at a beam power of 100 kW [15]. Following beam commissioning, the designed DC sextupole field was upgraded to an AC sextupole field [17]. This upgrade allows for dynamic control of chromaticity over the entire acceleration cycle, thereby enhancing beam transmission efficiency and suppressing instability simultaneously. Consequently, the RCS transmission efficiency was significantly improved, and instabilities were fully mitigated at a beam power of 170 kW.

Fig. 1. (Color online) TbT beam position in the horizontal plane (left) and RCS beam transmission efficiency (right) vary with beam intensity under a tune of (4.80, 4.86) with natural chromaticity. Red, green, and blue dots correspond to beam populations of 1.56×10^{13} , 1.25×10^{13} , and 0.62×10^{13} per pulse, respectively.

III. Requirement of Octupole Field for Instability Mitigation

Based on the classical calculation of tune shift [25], the magnetic field of an octupole magnet in accelerators can be formulated as $B_y + iB_x = K_3(x + iy)^3$, where B_x and B_y represent the horizontal and vertical magnetic fields, respectively. For a particle rigidity $B\rho$ with magnet length l , the octupole

integrated strength is given by $K_3 = \frac{1}{B\rho} \int k_3 dl$, where k_3 is the field gradient.

The horizontal and vertical magnetic fields are written as:

$$B_x = K_3(3x^2y - y^3), \quad B_y = K_3(x^3 - 3xy^2)$$

Octupole magnets are utilized to control the tune shift in the transverse plane. Under reasonable simplifications [1, 26], the horizontal and vertical amplitude-dependent tune shifts are described as:

$$\begin{aligned} \Delta Q_x &= \sum J_{x,i} K_{3,i} - \sum \beta_{x,i} \beta_{y,i} K_{3,i} \\ \Delta Q_y &= \sum J_{y,i} K_{3,i} - \sum \beta_{x,i} \beta_{y,i} K_{3,i} \end{aligned}$$

where the summation represents the sum across all magnets indexed by i . β_x and β_y are the horizontal and vertical betatron functions, respectively. J_x and J_y denote actions in the transverse plane, with their average value related to the beam emittance ϵ by $2\langle J \rangle = \epsilon$. As indicated by the equations, the amplitude-dependent tune shifts are linear functions of the octupole field strength. For an example estimation in the CSNS RCS, assuming four octupole magnets of identical strength K_3 , with $\beta_x = \beta_y = 8$ m at magnet locations and $J_x \approx J_y = 30\pi \cdot \text{mm} \cdot \text{mrad}$, the tune shift is $\Delta Q_x = \Delta Q_y = -7 \times 10^{-4} \cdot K_3$.

The required root mean square (RMS) frequency spread $\Delta\omega$ to suppress this instability can be expressed as [27]:

$$\Delta\omega \geq (\Delta\omega)_{\text{dyn}} \sqrt{\pi/2}$$

with the dynamic part of the wake-induced betatron frequency shift $(\Delta\omega)_{\text{dyn}}$, which relates to the growth time τ [28] as $(\Delta\omega)_{\text{dyn}} = 1/\tau$. Assuming a growth time of 0.5 ms, the required frequency spread for suppressing instability is $\Delta\omega \geq 2.5 \times 10^3$ Hz. This implies the tune shift must be greater than 0.005, requiring an integrated octupole field strength of $K_3 \approx 7$ T/m² to effectively mitigate the instability.

To further investigate the efficacy of the octupole field in mitigating instability, we conducted 6D macroparticle tracking simulations using existing code [29], which includes a representation of a single octupole magnet. A resonant wake from ceramic chambers, as detailed in TABLE 1, is employed. The simplified physical model for the interaction between the beam and the wake field accumulates the wake force into a kick momentum. Macroparticles experience wake field effects at interaction points in each revolution. To track particle dynamics with energy ramping, the transfer matrix of synchrotron motion is included in the simulation. The tune shift caused by the octupole field is related to the transverse amplitude. The painting process in the RCS has been included in the simulation, making the beam distribution closer to realistic conditions. The TbT beam position oscillation with varying octupole strengths is displayed in Fig. 2 [Figure 2: see original paper], clearly showing a reduction in oscillation

amplitude as octupole strength increases. Two tunes displaying observed instability over the acceleration cycle are simulated at a beam power of 100 kW. The results clearly demonstrate the mitigating effect of the octupole field. Additionally, the simulation indicates additional beam loss in the presence of the octupole field after mitigating instability during the acceleration cycle. Therefore, the octupole magnetic field should be rapidly reduced to minimize beam loss.

TABLE 1 . Main parameters used in simulation.

Parameter [unit]	Value
Bunch number	2
Beam power [kW]	100
Beam energy [GeV]	1.6
Res. impedance R_s [$M\Omega/m$]	1
Res. frequency f_r [MHz]	37.5
Quality factor Q	10
Wake decay time [turns]	104
Number of macroparticles	1×10^4

Fig. 2. (Color online) Simulated TbT beam position with the resonant wake in TABLE 1 in terms of octupole field strength, where the beam power is 100 kW at tunes of $\nu_x = 4.80$ (left) and $\nu_x = 4.90$ (right), respectively.

IV. Design of Pulsed Octupole Magnet

To dynamically control the tune spread over an acceleration cycle and minimize beam loss in the RCS, a pulsed octupole magnet is proposed. The required field gradient of the pulsed octupole magnet is related to the betatron function at the octupole magnet location. To mitigate eddy current and ohmic losses [30], ceramic chambers must be utilized. These chambers are already employed in dipoles, quadrupoles, and injection painting magnets in the RCS with limited free space available.

The lattice in the RCS employs a triplet structure with four-fold symmetry [7]. This design effectively mitigates the effects of low-order structural resonances. In addition, existing magnets—including sextupole magnets [17], trim quadrupole magnets [18], and correctors [31]—have successfully maintained this symmetry. Consequently, four octupole magnets are proposed. The location near quadrupoles QF06 in every super-period, as shown in Fig. 3 [Figure 3: see original paper], is chosen to accommodate the octupole magnets. This choice preserves lattice symmetry while effectively utilizing the available ceramic chambers. At the octupole magnet locations, the horizontal and vertical betatron functions are 8.3 m and 8.0 m, respectively.

According to calculations from Fig. 2, K_3 is determined to be 20 T/m^2 at the low-energy stage. Considering a beam power of 500 kW at CSNS-II, the target K_3 value should be close to 100 T/m^2 . As energy increases, the required octupole magnetic field strength for instability suppression decreases. At the high-energy stage, a field gradient of $K_3 \approx 20 \text{ T/m}^2$ is necessary to completely mitigate instability. We set the target K_3 value to 45 T/m^2 at injection energy of 300 MeV (equivalent to 15 T/m^2 at extraction energy of 1.6 GeV) to reduce manufacturing complexity. The octupole strength in this design is insufficient to completely suppress RCS instability on its own. Nevertheless, it is adequate when utilized alongside existing mitigation strategies. This integral magnetic field translates to a field gradient of $k_3 = 900 \text{ T/m}^3$. TABLE 2 provides the main parameters of the octupole magnets and power supply in the RCS. The octupole field switching is designed to be completed within 3 ms , with a field change rate of less than $210 \text{ T/m}^3/\text{ms}$.

TABLE 2. Main parameters of octupole magnets and power supply in the RCS.

Parameter [unit]	Value
Magnet number	4
Effective length [mm]	207
Maximum field gradient k_3 [T/m^3]	900
Changing rate of field gradient [$\text{T/m}^3/\text{ms}$]	< 210
Aperture [mm]	160
Good field radius [mm]	70
High-order field error [%]	< 0.5
Self-inductance [mH]	1.2
Number of power supplies	4
Maximum peak current [A]	620
Maximum peak voltage [V]	740
Changing rate of current [A/ms]	133
Current tracking error [%]	< 3

Fig. 3. (Color online) Magnet layout in the RCS, including four pulsed octupole magnets (dark red). Deep yellow, pink, cyan, and blue denote dipole, sextupole, focusing, and defocusing quadrupole magnets, respectively.

A. Octupole Magnet

The magnet, characterized by a core length of 0.2 m and a diameter of 256 mm , is designed to match the physical aperture in the RCS. Fig. 4 [Figure 4: see original paper] displays a full 3D diagram of the octupole magnets and the 2D model with magnetic flux line distribution. The successful implementation of AC sextupole magnets [32] has provided valuable insights for the design and fabrication of pulsed octupole magnets. To enhance mechanical rigidity and facilitate installation of the ceramic vacuum chamber, the pulsed magnet adopts

an upper and lower half-in-one structure. The iron core is composed of 0.5 mm thick silicon steel insulated laminations coated with B-stage epoxy resin. The end plate is constructed from stainless steel. The magnetic field is estimated after pole chamfering, and the total high-order field error is less than 0.5%. Excitation curve calculations reveal that the nonlinearity of the integral magnetic field is less than 3%. Each magnet is powered individually. To mitigate induced voltage caused by dynamic current, a 16-turn coil is selected, ensuring that the corresponding induced voltage of the power supply remains within an acceptable level.

Fig. 4. (Color online) 3D diagram of octupole magnets (left) and 2D model with distribution of magnetic flux lines (right).

The primary objective of dynamic magnetic field simulation is to compute the eddy current distribution and temperature rise within the iron core of the magnets. To enhance computational efficiency, a 1/8 core segment is utilized for analysis with the ELEKTRA/TR module in OPERA software [33]. This approach enables extraction of the magnetic field and other parameters at different excitation currents. A dedicated post-processing program is developed to process calculation results. The average heat source density data obtained from eddy current analysis is then imported into the TEMPO/ST module to calculate the temperature field, thereby determining the final temperature rise at various locations within the magnet core.

Following the setting of material constants and parameters, the dynamic magnetic field is simulated. Fig. 5 [Figure 5: see original paper] presents the reference curve of magnetic field versus excitation current in the simulation. Over a 40 ms period, 200 output points are obtained, with a convergence accuracy of 1×10^{-3} using a reasonable mesh grid. Eddy current effects in the iron core cause the magnetic field to change more slowly than the current, with a maximum time delay of approximately 0.2 ms. The peak eddy current reaches 12 A, corresponding to the maximum rate of change in excitation current. After slotting the end plate, the maximum temperature rise recorded is around 50°C.

B. Power Supply

The octupole is powered individually by a programmable power supply, which is an essential component in precision applications requiring high current and precise control. The maximum change rate is limited to 133 A/ms, corresponding to an excitation voltage of approximately 740 V considering the magnet inductance. The maximum current is 620 A to allow for a safety margin. The power supply system utilizes a standardized modular switch-mode design, achieving a total output of $\pm 740V/\pm 620A$ through series connection of standardized power modules. It comprises a front stage, an isolation transformation circuit, and a back stage. The front stage employs a soft-switching parallel resonant circuit to minimize switching interference and noise. The isolation transformation circuit enhances power supply stability. The back stage features an H-bridge

chopper and output filter, enabling bidirectional current and voltage output. With an equivalent switching frequency of approximately 60 kHz, the system meets demands for rapid magnetic field shutdown. The power supply achieves a target stability of 0.2% and current tracking accuracy of less than 3%. This level of stability ensures the power supply can deliver steady current over prolonged periods. The power supply is synchronized with the CSNS 25 Hz timing, ensuring alignment with dipole and octupole magnetic fields in the RCS. Additionally, the system includes comprehensive fault protection functions to ensure operational safety.

V. Field Measurement

Before magnet installation into the RCS tunnel, field measurements were conducted to evaluate magnet performance. These measurements ensure the magnetic field conforms to design specifications, thereby preventing potential alignment and operational issues.

A. Static Field Measurement

Static field measurements are performed to validate the physical design and manufacturing precision of the magnet. A Hall sensor [34] and a radial rotating coil [35] are employed in these measurements, utilizing a DC power supply. The repeatability of the Hall sensor is approximately 1×10^{-4} , while that of the radial rotating coil is better than 2×10^{-4} . The static magnetic field is measured up to 600 A in increments of 10 A. Fig. 6 [Figure 6: see original paper] displays the measured excitation curve of the center field gradient. At an excitation current of 514 A, the measured field is 900 T/m^3 . The maximum measured center field is 1021 T/m^3 at 600 A. The measured results are in good agreement with calculated values. The effect of core saturation is negligible, and the field gradient is directly proportional to the excitation current I with $k_3 = 1.751 \times I$. The effective length, derived from the measured center field gradient and integrated field gradient, is 0.207 m. Furthermore, the dispersion of the integral magnetic field among magnets is measured, showing that the dispersion is less than 1.5%.

Fig. 6. (Color online) Excitation curve of the center octupole field gradient. The red diamond denotes the measured result at $r = 70 \text{ mm}$, and the green line presents that at $r = 118 \text{ mm}$.

B. Dynamic Field Measurement

The purpose of AC measurement of the magnets is to determine the dynamic response relationship between current and magnetic field, as well as the time delay induced by excitation current waveforms. A stationary coil is utilized in the measurement. A timing clock synchronizes acquisition of the current signal and the induced voltage signal of the magnetic field. The coil coefficient is calibrated using Hall measurement results to enhance measurement accuracy and

obtain the absolute value of the integral magnetic field. During measurement, the magnet is first powered by a sinusoidal current to heat and reach a thermally stable state in about 2 hours. Fig. 7 [Figure 7: see original paper] displays the excitation current and integral magnetic field curves corresponding to the reference waveform in Fig. 5, where only the beam acceleration period is presented. The magnetic field changes almost synchronously with the current curve, with a time delay of approximately 0.2 ms during the acceleration cycle. Additionally, different excitation current waveforms are employed, including triangular, trapezoidal, and sine waves. The maximum time delay recorded is around 0.3 ms. The repeatability for a given waveform is 0.1%.

Through these rigorous measurements, the octupole magnet and its corresponding power supply have demonstrated remarkable precision and stability. Consequently, we conclude that the magnet system complies with design specifications, providing essential data support for subsequent applications in the RCS.

Fig. 7. (Color online) The response of the integrated magnetic field gradient to the excitation current over 30 trials. The red lines represent the excitation currents, and the green lines represent the integrated magnetic field gradients.

VI. Beam Measurement of the Instability

Following magnet installation, a beam test with the octupole field was promptly conducted. Initially, critical magnetic field measurements with the beam were executed, including magnetic field alignment and synchronized measurements with the RCS timing. Subsequently, extensive measurements for instability mitigation were performed.

The tunes play a significant role in impacting the instability. The TbT bunch position is analyzed for observed instability covering the entire ramping process. The total number of particles is $N_p = 2.2 \times 10^{13}$ per pulse, corresponding to a beam power of 140 kW. Fig. 8 [Figure 8: see original paper] shows measured beam positions and beam populations with and without the optimized octupole field curve, including horizontal tunes of 4.80, 4.86, and 4.90, respectively. The oscillation amplitudes at the three distinct horizontal tunes display considerable variation as shown in Figs. 8(b), (c), and (d). When the octupole magnet is off, instabilities are observed for all tunes. With the optimized octupole field curve for different tunes shown in Fig. 8(a), the instability can be entirely suppressed, and the transmission efficiency is also enhanced during the acceleration cycle. These results confirm that the octupole magnet is effective in suppressing RCS instability, as predicted.

In the operational tune with $\nu_x = 4.80$, the instability is successfully suppressed through chromaticity optimization [17]. Following this, we increased the octupole magnet strength to examine its impact on the beam. As illustrated in Fig. 9 [Figure 9: see original paper], with an optimized curve shown on the left, the octupole magnets further improved RCS transmission efficiency on the right, which was not anticipated in the initial design. The octupole magnet strength

applied is very weak, with $k_3 \approx 1 \text{ T/m}^3$, as depicted in the left panel. We propose that this enhancement is due to compensatory effects of the octupole magnets on nonlinearities in the RCS. As a result, octupole magnets have been employed in subsequent operations to boost transmission efficiency.

Fig. 8 [Figure 8: see original paper]. (Color online) Experimental results of octupole magnet mitigation of instabilities at different timings. (a) shows the applied k_3 curves for different tunes. The TbT bunch positions and beam populations with and without the field curve are depicted for horizontal tunes of 4.80 (b), 4.86 (c), and 4.90 (d), respectively.

Fig. 9. (Color online) The RCS transmission efficiency (right) with and without the octupole field curve (left) in operation. The instability is fully suppressed through chromaticity optimization in this case.

In the RCS, space charge effects are predominant during the low-energy phase, especially before 5 ms. As beam energy increases, space charge effects diminish. According to existing literature [36], the strength of octupole magnets required to suppress instabilities increases significantly under strong space charge effects. For a bunched beam, the dynamics influenced by nonlinearities due to octupoles are complex, and thus Landau damping cannot be adequately described by simplified dispersion relations [37]. This complexity is addressed in our study through detailed measurements.

As shown in Fig. 8, instability is observed at different times depending on the tune. At $\nu_x = 4.80$, instability occurs at the low-energy stage where space charge effects are strong. Conversely, at $\nu_x = 4.90$, instability is observed at the high-energy stage with weak space charge effects. This scenario allows for experimental comparison of space charge effects on the coupled bunch instability. By setting the tunes to $\nu_x = 4.80$ and $\nu_x = 4.90$ at a beam power of 140 kW, and adjusting beam parameters to induce strong horizontal oscillations, the octupole magnet strength is then incrementally increased to mitigate the instability until it is fully suppressed. The growth times of instabilities and the corresponding octupole strengths are summarized in TABLE 3. Proportional calculation indicates that $k_3 = 8.4 \text{ T/m}^3$ is required to suppress the instability with a growth time of 3.2 ms at $\nu_x = 4.80$. Compared to instability occurring under weak space charge effects, the required octupole field strength significantly increases for RCS instability mitigation under strong space charge effects, as shown in TABLE 3.

TABLE 3 . Growth time and required octupole strength to mitigate the RCS instability at different tunes.

Parameter [unit]	Value $\nu_x = 4.80$	Value $\nu_x = 4.90$
Instability observed time [ms]	3.2	12.5
Space charge tune shift	0.3	0.1
Growth time [ms]	3.2	2.1

Parameter [unit]	Value $\nu_x = 4.80$	Value $\nu_x = 4.90$
Required k_3 [T/m ³]	8.4	2.1

VII. Discussion

In the CSNS/RCS, octupole magnets have shown excellent performance in suppressing instability at the high-energy stage (approximately after 10 ms). They achieve complete suppression of the instability and maintain 100% transmission efficiency, thus meeting requirements for long-term stable accelerator operation. Despite the effectiveness of octupole magnets in suppressing instabilities and improving transmission efficiency at the low-energy stage, the RCS transmission efficiency remains inadequate for operational demands (about 10% loss in Fig. 8). This is evident for tunes of 4.80 and 4.86 in Fig. 9. At present, chromaticity optimization is primarily used to suppress instability and achieve high RCS transmission efficiency during operation. Based on this, we performed tests to assess the impact of octupole magnets on transmission efficiency. The results showed that as octupole magnet strength increased, transmission efficiency progressively decreased.

An energy deviation for the RCS beam at injection is introduced to mitigate space charge effects [38]. The maximum momentum shift $\Delta p/p$ is close to 1%. To address the transmission efficiency issue, we performed a detailed analysis, including second-order chromaticity effects and dynamic aperture. The octupole magnet is placed in the arc with dispersion function $D_x \approx 4.0$ meters, and the tune shift due to second-order chromaticity [39] is expressed as $k_3\beta D_x(\Delta p/p)^2$, where β is the beta function.

The second-order chromaticity in the vertical plane is measured using the pulsed octupole magnet. The vertical tune is determined by acquiring the TbT bunch position. An extraction kicker [40] is implemented to induce visible oscillation in the vertical plane, providing better accuracy compared to the designed tune excitation [41]. Typically, tune measurements are conducted over 1024 turns at 11 ms, and the timing of the vertical kicker can be adjusted to the moment of interest. The second-order chromaticity is determined by fitting tunes versus momentum shift, which is controlled by modulating the RF frequency. The measurement is carried out at a low beam power of 20 kW. Fig. 10 [Figure 10: see original paper] presents measured tunes with and without the octupole field at different momentum shifts. For each momentum shift, measurements are taken five times. A box plot visualizes the raw data, and the median difference for the two cases is fitted to determine the second-order chromaticity. With momentum deviation $\Delta p/p$, the tune shift is inferred as $\Delta\nu_y \approx 10 \cdot (\Delta p/p)^2$.

Notably, only the designed white noise excitation is used to measure the tune in the RCS. The second-order chromaticity in the horizontal plane is not measured due to poor measurement accuracy with this white noise. Given similar horizontal and vertical beta functions at the octupole magnet, the second-order

chromaticity in the horizontal plane is approximately assumed to be equal to that in the vertical plane. Based on this calculation, the maximum tune shift due to second-order chromaticity in the RCS is approximately 0.001, which is significantly smaller than the space charge tune shift of 0.3 [42]. Consequently, beam loss due to second-order chromaticity can be ignored.

Utilizing a simplified lattice at a constant energy of 80 MeV, we perform a comprehensive calculation of the dynamic aperture at various energy deviations, as depicted in Fig. 11 [Figure 11: see original paper]. Chromaticity correction is implemented using the sextupole magnet. Cases with only chromaticity correction (a) and with only an octupole field (c) are also presented for comparison. In the horizontal plane, the dynamic aperture is larger than the physical aperture of 60 mm for the case of only chromaticity correction (a), achieving a beam transmission efficiency of approximately 100% in actual operation. However, the dynamic aperture significantly diminishes with octupole fields. The dynamic aperture notably decreases for the case of only an octupole field (c), particularly for the case of additional chromaticity correction (b). At the low-energy stage, both beam size and momentum spread are relatively large. Under these conditions, even a weak octupole field may induce beam loss. As beam energy increases, beam size and momentum spread decrease. At the high-energy stage, the beam can maintain stability even with a stronger octupole field. Consequently, it is essential to increase the dynamic aperture to improve RCS transmission efficiency at the low-energy stage. A viable approach to restoring RCS transmission efficiency is to relocate the octupole magnets, which is the subject of ongoing research.

Fig. 10. (Color online) Measured tune in terms of momentum shift with and without octupole magnet, where the red solid line represents the median when the magnet is OFF, while the green dashed line indicates that when the magnet is ON.

Fig. 11. (Color online) The dynamic aperture in terms of $\Delta p/p$ (dp), where the tune is (4.80, 4.86) at constant energy of 80 MeV. (a) is optimized chromaticity and octupole off, (b) is optimized chromaticity of (-9, -9) and $k_3 = 5 \text{ T/m}^3$, and (c) is natural chromaticity and $k_3 = 5 \text{ T/m}^3$.

VIII. Conclusion

Coupled bunch instability has been observed in the CSNS RCS. As power levels increase in CSNS-II, more methods for suppressing this instability are being explored. One such method involves using octupole magnets to provide Landau damping. The pulsed octupole magnet system has been developed in the RCS. One octupole magnet is accommodated in every super-period to preserve lattice symmetry and efficiently use existing ceramic chambers. Field measurements confirm that the magnet satisfies design values. After magnet installation, preliminary measurements of the instability were performed.

The instability is successfully suppressed by implementing the designed pulsed

octupole magnets. At the high-energy stage, the instability can be fully suppressed using the pulsed octupole magnet without any additional beam loss, thereby meeting requirements for long-term stable CSNS operation. However, at the low-energy stage, although the octupole magnet effectively suppresses the instability, RCS transmission efficiency still falls short of operational conditions. This may be attributed to reduction in dynamic aperture, necessitating further optimization to improve transmission efficiency, including relocation of octupole magnets. Moreover, when instability is completely suppressed through chromaticity optimization, octupole magnets can significantly enhance RCS transmission efficiency, which is crucial for controlling beam loss during current CSNS operations. More detailed measurements on instability mitigation should be carried out in future machine studies. Nevertheless, significant advancement in beam stability has been achieved in these preliminary measurements, providing valuable experience for further beam power enhancement.

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