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APPLICATION OF PROGRAMMABLE TRIM QUADRUPOLES IN BEAM COMMISSIONING OF CSNS/RCS

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Abstract

The China Spallation Neutron Source (CSNS) achieved its design beam power of 100 kW in 2020 and is currently stably operating at 140 kW with a tolerable beam loss level after a series of suppression methods. In the process of increasing beam power, 16 programmable trim quadrupoles were installed in the Rapid Cycling Synchrotron (RCS) of CSNS to enable rapid variation of tunes, effective adjustment of twiss parameters, and restoration of lattice superperiodicity through the machine cycle. This paper will provide a detailed introduction to the design of the trim quadrupoles and various applications in beam commissioning. The beam experiments show that the trim quadrupoles play a crucial role in increasing beam power after exceeding 100 kW.

INTRODUCTION

CSNS is a high-power pulsed spallation neutron source, which consists of an accelerator, a target station and several spectrometers [1]. The accelerator chain includes a negative hydrogen (H^-) linac and a rapid cycling synchrotron (RCS). The H^- beams at 80 MeV are injected from the linac into the RCS via a multi-turn charge-exchange process, accelerated to 1.6 GeV within 20000 turns in the RCS, and extracted to shoot the tungsten target with a repetition frequency of 25 Hz to produce neutrons. The design output beam power is 100 kW in CSNS-I and 500 kW in CSNS-II. The beam commissioning of CSNS/RCS started in May 2017 and the first neutron beam was successfully obtained on August, 2017. In February 2018, the output beam power reached 10 kW. Since then, a step-by-step beam commissioning process has been performed to further increase the beam current and beam power. In February 2020, the design goal of 100 kW beam power has been successfully achieved with a tolerable beam loss level [2]. In September 2022, the beam power has been raised to 140 kW and further enhanced to more than 150 kW in this year.

It was found that the lattice of CSNS/RCS requires more precise tuning as the beam power increases. To address issues such as rapid adjustment of the tunes and twiss parameter correction through the machine cycle, similar high-intensity synchrotron like ISIS and J-PARC have installed pulsed trim quadrupoles (QTs) [3, 4]. During the summer maintenance period in 2021, 16 programmable QTs are installed in the CSNS/RCS for beam parameters correction. The subsequent beam experiments have demonstrated that the QTs played a significant role with enhanced beam power. The article is organized as follows: the first part introduces the design scheme of the QTs. The second part focuses on three different applications of the QTs during beam commissioning in CSNS/RCS. Finally, there is a summary and discussion.

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DESIGN OF TRIM QUADRUPOLES

The CSNS/RCS is a four-fold symmetric structure and adopts a triplet cell as the fundamental unit of the lattice model. The layout of the magnets in one super-period is shown in Fig. 1. The 48 main quadrupole magnets in the whole ring are powered by 5 sets of power supplies. By comparing the correction effects of the β-beat and tunes with different numbers and positions of QTs, it was finally determined to install 4 QTs in one super-period, as shown in green in the Fig. 1. The QTs are placed at one end of the main quadrupole magnet QDs, as shown in Fig. 2. Each QT has a 136 mm bore radius and shares a ceramic vacuum tube with the neighboring main quadrupole. The core length of each QT is set to as short as 150 mm due to the limited installation space. Unlike the main quadrupole magnets, all QTs are designed to be independently powered, allowing a fine tuning of the β-functions and bare tunes at 21 time points in one 20 ms ramping time. The maximum current change rate of the QTs is 300 A/ms, ensuring fast operating the tunes even in the high-energy region.

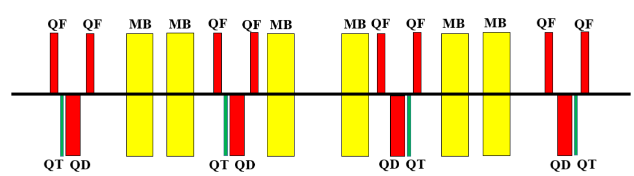

Figure 1: Layout of QTs in one super-period.

APPLICATIONS

Tunes Optimization

The harmonic injection method for the main quadrupole power supplies was used in CSNS/RCS, causing a relatively smooth variation of the tunes throughout the entire cycle and limited tuning capability with main quads in short time, especially for rapidly variation. However, the installation of QTs enables fast variation of tunes for a specific energy range or tuning in the entire cycle. Here are two examples.

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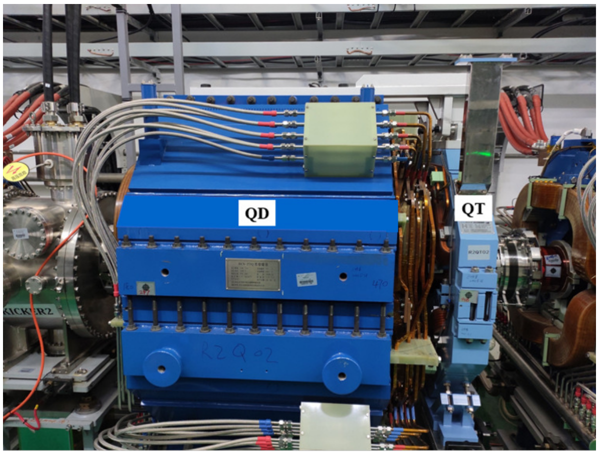

Figure 2: The main quad (QD) with a QT in the tunnel.

Due to the dynamic edge fields of the main quads through machine cycle on the CSNS/RCS ring [5], the tunes of the entire ramping time deviates from the design value (4.86, 4.80). By using QTs, the tunes can be compensated to the design value through the 20-ms ramping time. The correction effect is shown in Fig. 3.

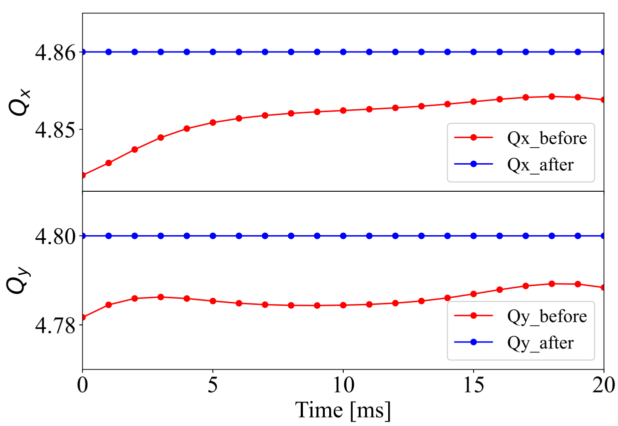

Figure 3: Tunes before and after correction in one cycle.

During beam commissioning, it was found a very strong horizontal betatron oscillations occurs at certain tunes and beam powers [6]. For example, at the design tunes (4.86, 4.80), when the output beam power exceeds 40 kW, strong coherent oscillation occurs at around 2000 turns measured by turn-by-turn BPMs. The preliminary studies have shown that this coherent oscillation are caused by the resistive wall head-tail instability, which is highly correlated with the beam power and tunes.

It was found that using sextupole magnets can significantly reduce the betatron oscillation amplitude, but it is still hard to completely suppress it for high-intensity beams, causing difficulties in routine operation. It was also found that the betatron oscillation amplitude can be further reduced by fine tuning the QTs. In the beam commissioning in October 2022, the horizontal tune was operated from 4.804 to 4.793 and the vertical operating point from 4.802 to 4.816 at 3 ms to 4 ms with QTs. After the tuning, the beam became stable and met the requirements for routine operation. Figure 4 are the magnetic field gradient curves before and after tuning QTs.

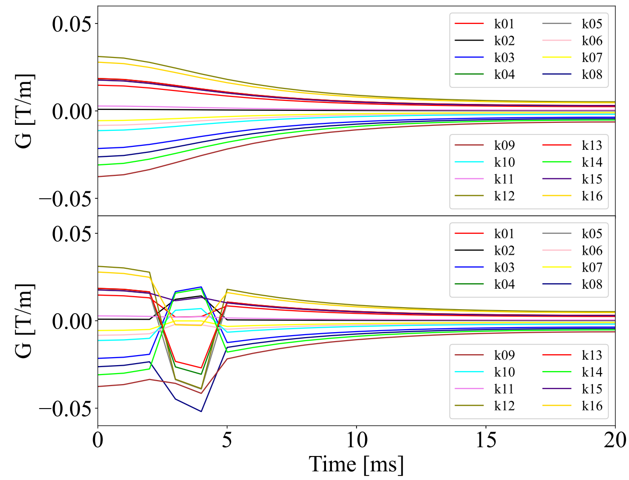

Figure 4: Magnetic field gradient curves of QTs before and after optimization.

Periodic Recovery

The CSNS injection system consists of 12 rectangular magnets. Eight of them are pulsed-type bump magnets, which are used to generate dynamic orbit bumps in the horizontal and vertical plane during the injection process. The other four horizontal dipole magnets, provide additional fixed horizontal orbit bumps to accommodate the injected beams from the linac.

According to the edge focusing effect of a dipole magnet, the injection horizontal bump magnet can cause focusing effects in the vertical plane but has no effect on the horizontal plane (the vertical bump magnet is just the opposite). Through calculations by MAD-X, it is found that the edge focusing of fixed horizontal bump magnet causes the distortion of the β-function, with a vertical β-beat of about 13% in design tune (4.86, 4.80). Additionally, it also causes the distortion of vertical tune, with a tune shit of about 0.02 at the injection time. Most importantly, the numerical simulations via PyORBIT revealed that the edge focusing effect leads to a rapid emittance growth and significant beam loss. To mitigate the emittance growth, the QTs were used to restore the symmetry of the lattice. The beam experiments showed significant improvements in emittance growth and beam loss with QTs. The following are some experimental results.

The β-function is a direct physical parameter that reflects the effectiveness of QT correction. There are various methods to measure the β-function, the orbit response matrix method was used here. To minimize beam loss during the measurement, the beam power was controlled below 10 kW. Figure 5 shows the β-functions for two super-periods when the beam is accelerated for 1 ms. The blue and red curves are theoretical computations with and without QTs respec-

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tively, and the blue and red solid dots are the corresponding measurement results. As shown in the plots, the measured β-function is in good agreement with the theoretical β-function. Furthermore, the maximum β_y-function is significantly reduced and most of the β-beat was effectively corrected by QTs to less than 5%, which proves that QTs have a significant correction effect on β-beat.

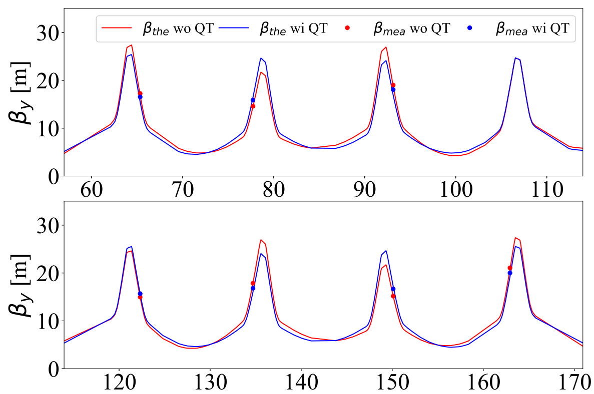

Figure 5: Measurement results of β_y-functions without (red dots) and with (blue dots) QTs in the CSNS/RCS.

Figure 6 shows the comparison of beam survival rates in the CSNS/RCS with and without QTs within 45 min at 125 kW. From the figure, it can be seen that after using QTs, the beam survival rate in the RCS increased from 96.4% to 98.1%. This means the beam loss in the ring was reduced by about 2%. Based on the results, we predict that QTs will play an important role in reducing beam loss as the beam power increases.

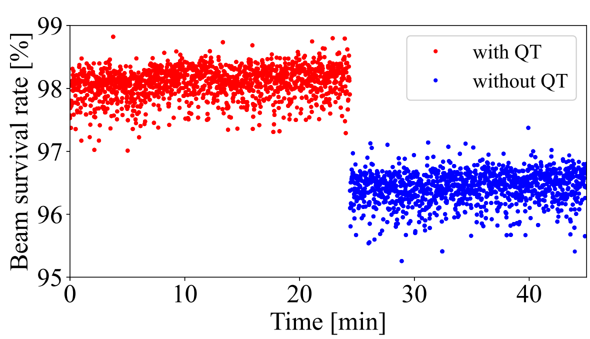

Figure 6: Beam survival rates with and without QTs.

BBA Measurement

The offset of the beam position monitor (BPM) with respect to the magnetic center of the quadrupole can be determined by the method of the beam-based alignment (BBA), which was successfully applied in many accelerators. However, it is not applicable in the ring like CSNS/RCS with main quads sharing several power supplies. Even in reported studies, the measurement errors of BPM offsets are large due to imprecise calculation models. For high-intensity beams, it is crucial to control the closed orbit within a small range, so it is urgent to know the true closed orbit in the CSNS/RCS ring.

Accurate measurement of BPM offset was carried out smoothly after installing 16 programmable QTs in the CSNS/RCS ring. Figure 7 shows the interface of BBA measurement application. The horizontal axis represents the BPM measurement value, and the vertical axis represents the rms value of the disturbance to the closed orbit caused by the change in the QT strength. A quadratic curve is applied to fit the data, and the minimum value of the curve indicates that when the beam is at this position, the change in the QT strength causes the least disturbance to the closed orbit. At this point, it is assumed that the beam passes through the center of this QT, and the corresponding value of the horizontal coordinate represents the offset of the measured BPM. Through measurements, it was found that some BPM offsets are relatively large, reaching around 4 mm.

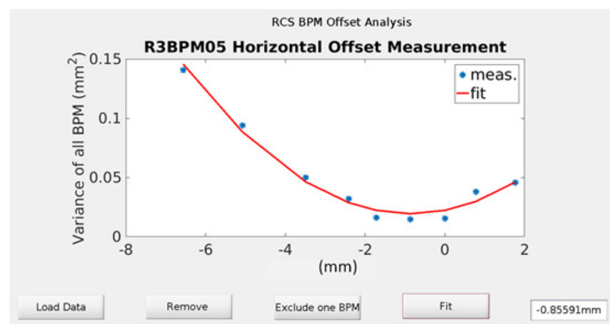

Figure 7: Interface for BBA measurement application.

Other Applications

The beta function can also be measured with QTs based on the tune shift caused by the variation of QT strength. Additionally, the relationship between the tunes and the beam loss was automated recorded through changing QT strength with a small step, which can be utilized to study various resonances and nonlinear behaviours.

SUMMARY AND CONCLUSION

To address issues such as rapid adjustment of the working point, correction of twiss parameters, and periodic restoration of the lattice in the CSNS/RCS acceleration process, 16 programmable trim quads were installed. The beam tests have demonstrated that the trim quads play a crucial role in improving beam power.

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