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THE CORRECTION OF TIME-DEPENDENT TUNE SHIFT BY HARMONIC INJECTION

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Abstract

In the Rapid Cycling Synchrotron(RCS) of China Spallation Neutron Source(CSNS), transverse painting injection is employed to suppress the space-charge effects. The beta-beating caused by edge focusing of the injection bump magnets leads to tune shift. A new method based on the harmonic injection is firstly introduced to correct the time-dependent tune shift caused by the edge focusing effect of the chicane bump magnets in RCS. The simulation study was done on the application of the new method to the CSNS/RCS, and the results show the validity and effectiveness of the method.

INTRODUCTION

The China Spallation Neutron Source (CSNS) consists of an 80 MeV linac and a 1.6 GeV Rapid Cycling Synchrotron (RCS) with repetition rate of 25 Hz [1]. As shown in Fig. 1, an 80-MeV H^- beam is delivered from linac to the RCS injection point and stripped to proton by stripping foil. The RCS accelerates the protons up to the designed energy of 1.6 GeV and extracts the beam with the power of 100 kW to the neutron target [2].

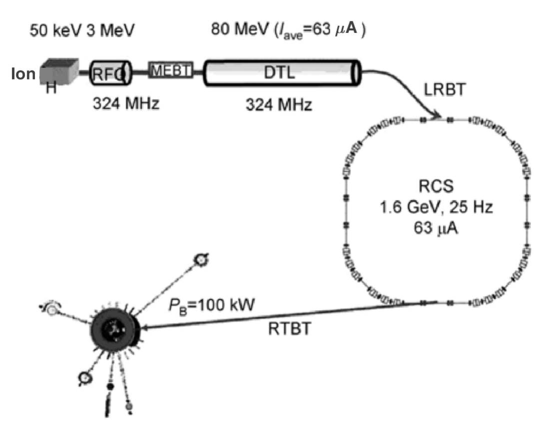

Figure 1: The schematic layout of CSNS.

The RCS employs painting injection in the transverse direction to achieve uniform beam distribution and suppress the space-charge effects [3]. Figure 2 shows the schematic view of the injection system. There are 12 bump magnets which are symmetrically distributed in one of the four straight sections in RCS. Eight bump magnets (BH1~4 and BV1~4) make a time dependent bump orbit during injection. The other four(BC1~4) bump magnets are used for generating horizontal chicane bump, which are excited by DC power supply, and the magnetic field is constant during the whole cycle. The edge focusing effects of the injection bump magnets cause beta-beating which will lead to time-dependent tune shift. Meanwhile the strongest space charge arise during the first few milliseconds, which coincide with the strongest edge focusing effect of BC. The deterioration of the betatron motion stability due to edge focusing may cause extra beam loss when increasing the beam intensity. To achieve high intensity beam with low beam loss, it is important to compensate the edge focusing effects. Due to painting bump magnets only operating in the first 0.4 ms, only the BC is considered in this paper.

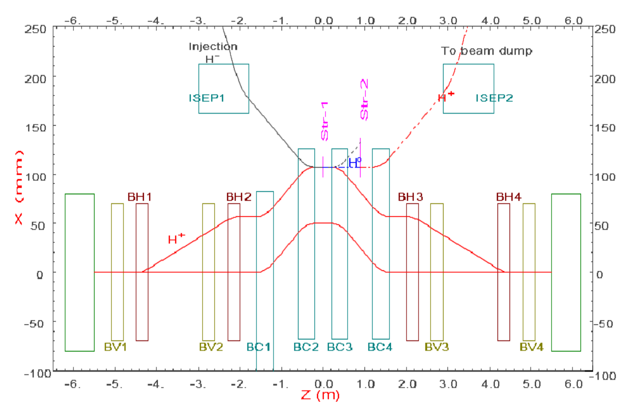

Figure 2: The schematic layout of injection system.

In RCS, the main quadrupoles are excited by White resonant power supplies [4], and the exciting current cannot be arbitrarily programed. Generally, this kind of perturbation could be corrected by trim-quadrupole, which is powered by programmable power supply [5]. However, there isn't trim-quadrupole available in CSNS/RCS. A new method based on harmonic injection was introduced to correct the edge focusing effects of BC in CSNS/RCS. In RCS, due to the eddy current effect and saturation of magnetic field, with the sinusoidal exciting current, the curve of magnetic field in a cycle is not sinusoidal. To compensate the magnetic field deviation, the harmonic injection was adopted, in which, the injected harmonic was obtained by a method based on the measured transfer function between exciting current and magnetic field [6]. By using this method, the curve of magnetic field in a cycle can be corrected very close to sinusoidal curve.

In this paper, the harmonic injection is adopted to correct the time-dependent tune shift through modifying the curve

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of magnetic field of the main quadrupoles to the objective curve. The simulation study shows that the method could effectively correct the time-dependent tune shift caused by the edge focusing effects of BC.

TIME-DEPENDENT TUNE SHIFT DUE TO THE EDGE FOCUSING EFFECT

Figure 3 shows a diagrammatic sketch of the edge focusing effect, the edge angles at the entrance (η_0) and the exit (η_e) of the bump magnet were assumed to same. The transfer matrices of the horizontal bump magnet in the horizontal and vertical direction were shown in Eqs. (1) and (2), respectively [7].

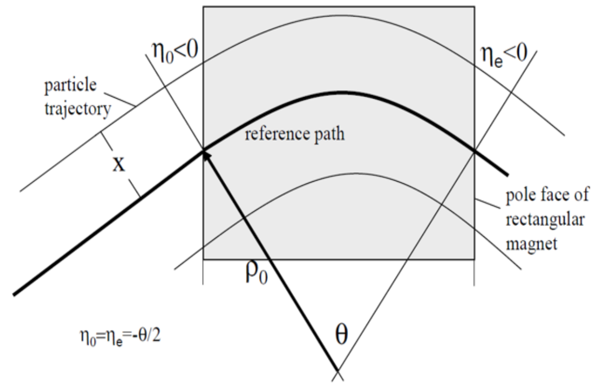

Figure 3: The diagrammatic sketch of the edge focusing.

$$M_x = \begin{pmatrix} 1 & 0 \\ \frac{tan\frac{\theta}{2}}{\rho_0} & 1 \end{pmatrix} \begin{pmatrix} cos\theta & \rho_0 sin\theta \\ -\frac{sin\theta}{\rho_0} & cos\theta \end{pmatrix} \begin{pmatrix} 1 & 0 \\ \frac{tan\frac{\theta}{2}}{\rho_0} & 1 \end{pmatrix} = \begin{pmatrix} 1 & \rho_0 sin\theta \\ 0 & 1 \end{pmatrix} \tag{1}$$

$$M_y = \begin{pmatrix} 1 & 0 \\ -\frac{tan\frac{\theta}{2}}{\rho_0} & 1 \end{pmatrix} \begin{pmatrix} 1 & \rho_0\theta \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -\frac{tan\frac{\theta}{2}}{\rho_0} & 1 \end{pmatrix} = \begin{pmatrix} 1-\theta tan\frac{\theta}{2} & \rho_0\theta \\ \frac{\theta tan^2\frac{\theta}{2}}{\rho_0} - \frac{2tan\frac{\theta}{2}}{\rho_0} & 1-\theta tan\frac{\theta}{2} \end{pmatrix}, \tag{2}$$

where θ is the bending angle of the bump magnet, ρ_0 is the bending radius, M_x and M_y are the transfer matrices of the horizontal bump magnet in horizontal and vertical direction respectively. And it is easily to prove that $\eta_0 + \eta_e = -\theta$.

The edge focusing forces act as a quadrupole magnet, but as shown in Eq. (1) the horizontal edge focusing effect is compensated by the intrinsic focusing property on the bending plane, while as shown in Eq. (2) the vertical edge focusing effect remains. This typical property of the edge focusing effect is different from a regular quadrupole. Thus, the beta-beating caused by the edge focusing of the horizontal injection bump magnets occurs only on the vertical plane.

MADX [8] was used to simulate the edge focusing effects. The simulation results were shown in Fig. 4, the maximum tune shift in the vertical plane is 0.02. The magnetic field of BC is constant but the beam energy is ramping up during the whole beam cycle, so the tune shift is time-dependent.

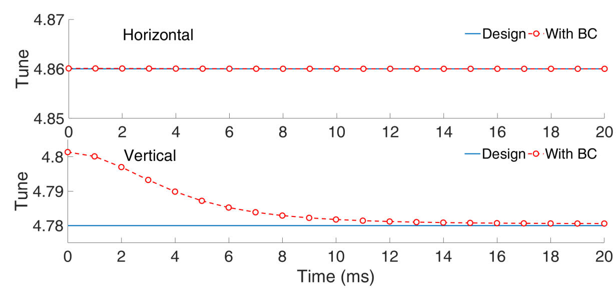

Figure 4: (Color)The tunes in one period with (red dash line with circles) and without (blue solid line) BC bump magnet.

CORRECTION SCHEME FOR THE EDGE FOCUSING EFFECT

According to the tune shift calculation in section 2, as shown in Fig. 4, the tune shift due to the edge focusing of BC is monotonically decreasing in the whole beam period of a RCS cycle, and the continuity of the tune shift makes it possible to be corrected by the harmonic injection. Different from the harmonic injection method used in the exciting curve correction for obtaining sinusoidal magnetic field in a cycle of RCS, the harmonic injection method used for correcting the time-dependent tune shift is to modify the curve of the magnetic field to an objective curve.

The detailed procedure, as shown in the Fig. 5, can be divided into following steps:

1. calculating the tune shift in a cycle of RCS. The calculation is performed every 1 ms, and a total of 21 points are chosen to perform the calculation in a cycle of 20 ms;
2. correcting the tune shift point by point in a cycle, and fitting the curve of magnetic field for different families of quadrupoles;
3. calculating the injecting harmonic to be injected into exciting current;
4. re-calculating tunes based on the curve of magnetic field excited by the corrected curve of exciting current.

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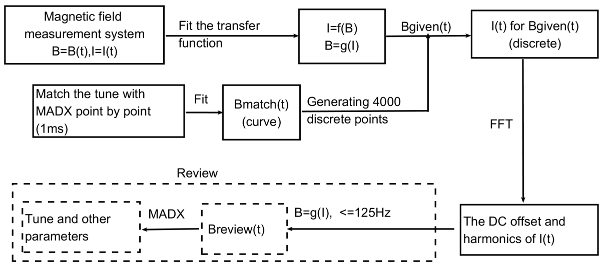

Figure 5: The flow process diagram of the correction of the edge focusing effect.

The key step is to obtain the injecting harmonics. The new method based on the transfer function could easily get the corresponding injecting harmonics from the objective curve of the magnetic field.

The transfer function is obtained through magnetic field measurement for AC mode. The magnetic field and exciting current at different time during the exciting current ramping are measured by using the harmonic coil measurement system [9], then the transfer function $I = f(B)$ and $B = g(I)$ are fitted based on the measured data, where I, B represent current and magnetic field respectively.

The objective curve of the magnetic field is obtained through matching the tune point by point and performing the fourier curve fitting on the matched results.

The MADX and MATLAB are used to perform the calculation and simulation. The matched results are a series of discrete points for each quadrupole family, and the objective curve of the magnetic field $B_{match}(t)$ are obtained by using fourier curve fitting.

In the simulation study, in order to verify the correction scheme, the curve of the exciting current which are generated from DC offset and time harmonics could be reconverted to magnetic field curve $B_{review}(t)$ through the transfer function $B = g(I)$. Then the tunes and other parameters could be obtained by applying $B_{review}(t)$ to the MADX model.

As shown in Fig. 6, the tunes in a cycle after correction are very close to the design value, in which the maximum deviation is decreased from 0.02 to 0.002.

CONCLUSION

The edge focusing effects of the bump magnets give rise to time-dependent tune shift in the whole beam period of a RCS cycle which may result in extra beam loss when increasing beam intensity. For the chicane bump magnet BC, a new correction method was introduced in this paper, which is based on the harmonic injection to the main quadrupoles. The simulation study show the validity and effectiveness of the new method. The tune in the whole RCS cycle could be adjusted very close to the designed value. The machine study will be done soon to apply this method in the RCS of CSNS.

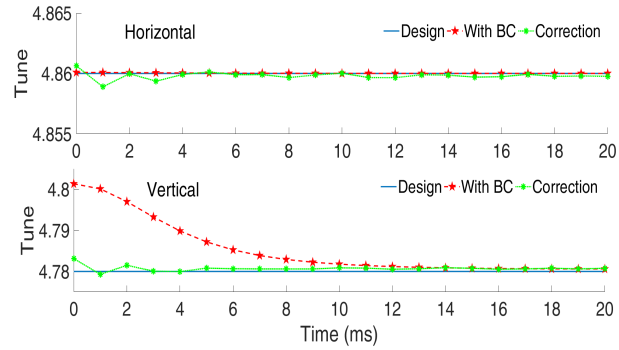

Figure 6: The tunes in one period with (red dash line with pentagram) and without (blue solid line) BC bump magnet compared with the tune after correction (green dot line with asterisk).

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