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Design of a stripline kicker for tune measurement in CSNS RCS

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Abstract: For CSNS RCS tune measurement, tune value is measured by exciting the bunch with a strip-line kicker fed with white noise and using a FFT algorithm. This article simulates the strip-line kicker in RCS and the efficiency of the kicker is discussed in a Matlab environment. The parameters of the kicker with an arc electrode structure such as a VSWR, wake impedance, and thermal state are analyzed based on the advantages of this design.

Key words: strip-line kicker, Accelerator Toolbox for Matlab, VSWR, wake impedance, thermal analysis

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1 Introduction

CSNS RCS is designed to accelerate a proton beam to 1.6 GeV at a 25 Hz repetition rate; during this process, the cyclotron frequency of the beam is changed from 0.51 MHz to 1.21 MHz. The design tune of RCS Q_x/Q_y is 4.86/4.78, and the harmonic number h is 2 [1]. The bunch is planed to be excited by the kicker fed with white noise and a turn-by-turn position in the BPM will be used to get the tune value. For RCS, it is enough to choose a frequency range of white noise from 0 to 5 MHz.

Three possible designs have been considered for the design of the kicker, such as an arc electrode, a planar electrode without a border and a planar electrode with a border. Every design has its own merits and disadvantages. In general, parameters such as the wake impedance, uniformity of electric field, VSWR, shunt impedance, loss factor and thermal property should be calculated and analyzed. In principle, not every parameter can be optimized, but we try and balance the parameters to make the overall performance better.

From the viewpoint of restraining the collective instability, wake impedance is important, so wake impedance of these designs is discussed first to find a primary design.

2 Calculation of wake impedance of the kicker

Three types of structure are compared, and the characteristic impedance of each design is matched with the 50 Ohm load. Wake impedance of the kickers is calculated using CST Particle Studio [2]. For accurate calculations, as short a driving bunch as possible should be used. We choose 20 mm as the sigma value for the Gaussian shaped bunch, and the bunch has a horizontal offset of 20 mm to the structural center of the kicker. The material of kicker is stainless steel. The mesh number used for calculations is more than 4 M. The amplitude of wake impedance in the z direction of each kicker together is shown in Fig. 1.

Figure 1 shows that below a frequency of 2 GHz, an arc electrode kicker has a lower wake impedance value, which means that the bunch will lose less power in this structure than the other two designs, and it is helpful to restrain the collective instability of the bunch during running. The peak value is about 240 Ohm. Additionally, the arc electrode kick has a smaller structure than the other two when the characteristic impedance is matched to 50 Ohm, so the arc electrode kicker is chosen as our first design.

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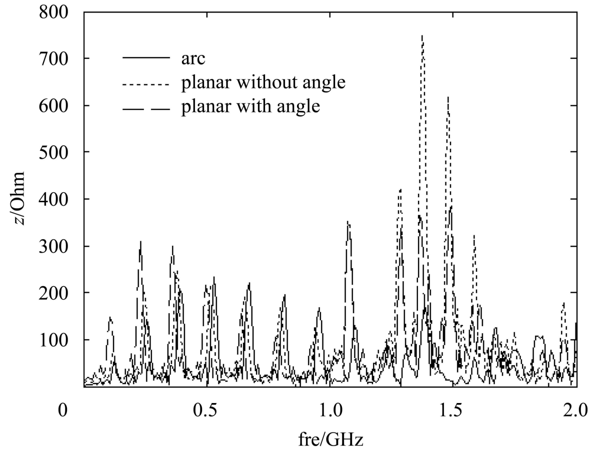

Fig. 1. Amplitude of wake impedance in the z direction of three kickers.

3 The response of a single particle

During tune measurement, the bunch is considered to be a single particle. The bunch is excited and its turn-by-turn position at one BPM is measured. The exciting angle at the nth turn in the simulation is obtained from the following formulas [3]

$$\Delta x'_n = \theta_{\rm rms}\sqrt{\frac{2}{N}}\sum_{j=0}^{N-1}\cos\left[2\pi\frac{\Omega_j}{\omega_0}n+\phi_j\right], \qquad (1)$$

$$\theta_{\rm rms} \approx \frac{eL}{pc}\left(1+\frac{1}{\beta}\right)\frac{\sqrt{ZP}}{d}, \qquad (2)$$

$$\Omega_j = \Omega_0+j\frac{\Delta\Omega}{N-1}, \qquad (3)$$

where L is the length of the electrode (980 mm), p is the momentum of the beam, here 1 GeV is considered, β is the relativistic velocity, P is the power for feeding each electrode, d is the radius of the electrode (85 mm), ω_0 is the cyclotron angular frequency, Ω_0 is the lower limit of the frequency of white noise, $\Delta\Omega$ is the bandwidth of white noise, and ϕ_j is the phase at jth exciting, ϕ distributes randomly in the range of 2π.

The response of single particle is simulated using the Matlab [4] Accelerator Toolbox [5]. The bunch is tracked for 1500 turns, during this process the bunch is excited turn-by-turn using the angle calculated from the formula (1) when the bunch travels along the kicker. The amplitude of the transverse position sometimes may not be excited because of the random phase of white noise. As ϕ distributes randomly in the range of 2π, it means that white noise may play a part in excitation at this time but may play a part in suppression next time, so the exciting effect depends on the state of the random phase during the exciting process. A 1024 turn-by-turn beam position is recorded after the last exciting, and the position data is analyzed with a FFT algorithm to find the tune in the frequency domain.

The amount of power feeding the electrode is also considered. The bunch could not be excited effectively if we chose a lower power source and there is a high cost if we chose a high power source. Three different power values are compared. Because the position resolution of the BPM in RCS is 0.1 mm, the bunch is planed to be excited to 1 mm in order to get a good SNR for tune measurement. The efficiency of the kicker with different power feeds is shown in Fig. 2. The average value of the position at the 1500 th turn for different power values is calculated, and an offset of 0.336 mm for 500 W, 0.689 mm for 1000 W and 0.973 mm for 1500 W is obtained. For RCS, 1000 W is chosen as our power level for feeding the strip-line kicker.

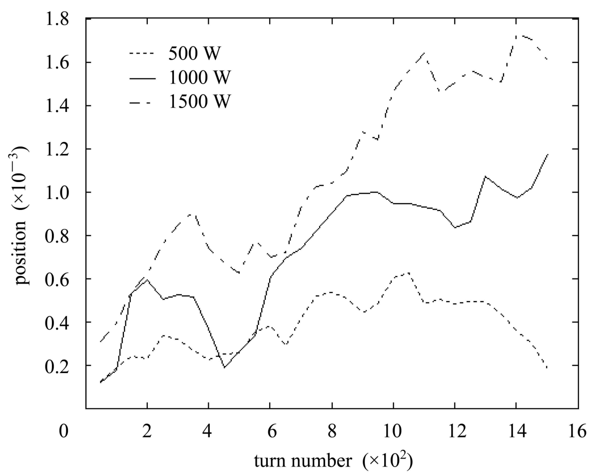

Fig. 2. Efficiency of the kicker with different power feeds.

4 The optimization of uniformity of electric field of the kicker

Bunches should feel a uniform electric field when they travel along the kicker. The coverage angle of the electrode has an effect on the uniformity of the electric field. For small values of coverage angle, the field generated by the strip is similar to that of a simple wire, while, for large values there is a shielding effect of the deflecting field given by the strip itself [6]. One quarter of the structure with coverage angle indication is shown in Fig. 3. Several results are compared based on different coverage angles, and the optimum angle is 98°. In this case, two directions have a better uniformity of electric field. The electric field at 5.25 cm on the x axis and 5.86 cm on the y

axis corresponds to the uniformity 90%. The uniformity of the electric field in x direction normalization and y direction normalization is shown in Fig. 4.

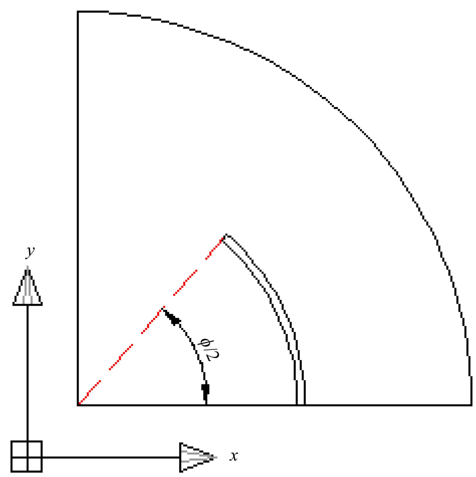

Fig. 3. One quarter of the structure with indication of the coverage angle.

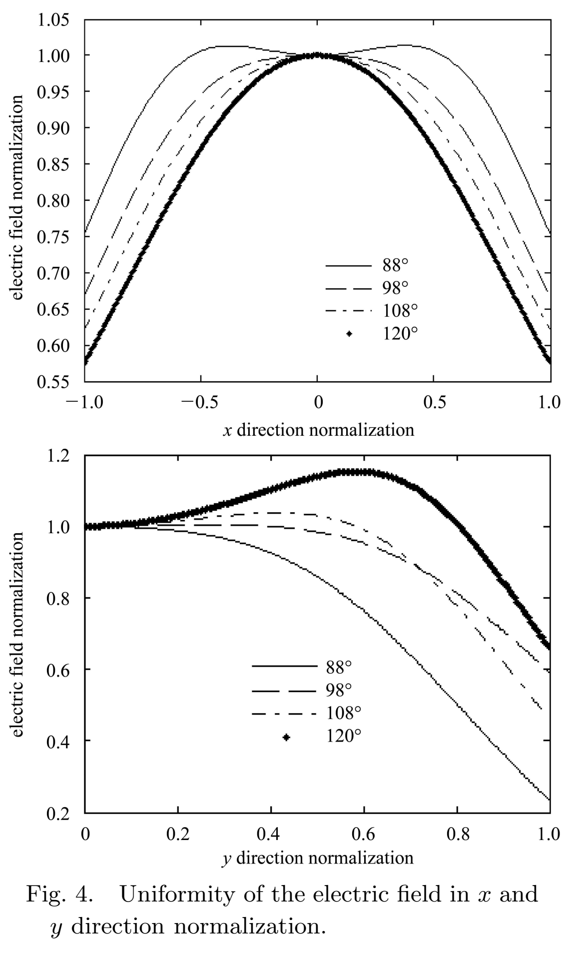

Fig. 4. Uniformity of the electric field in x and y direction normalization.

5 The choice of length of the electrode and the taper of the kicker

The length of electrode has impact on the exciting angle, and the longer the electrode is, the greater the impact is. The total length of the kicker is not more than 1 m, limited by the element arrangement of RCS. The length of the taper is fixed, and by increasing the length of the electrode, we find that the values of VSWR become larger monotonously. Similarly, when the length of the electrode is fixed, we find that the longer the length of taper is, the larger VSWR is. There is a difference in impact between the length of the electrode and the taper. By increasing the length of the arc electrode from 680 mm to 980 mm, the length of the taper shortens from 155 mm to 5 mm in each side. When the length of the electrode is increased to 980 mm, and the length of taper shortens to 5 mm, VSWR is obviously improved, and it is helpful to improve the efficiency of the power feed, so a value of 980 mm is chosen as the length of the electrode. The VSWR result corresponding to different lengths of the electrode and the taper at 5 MHz is shown in Fig. 5.

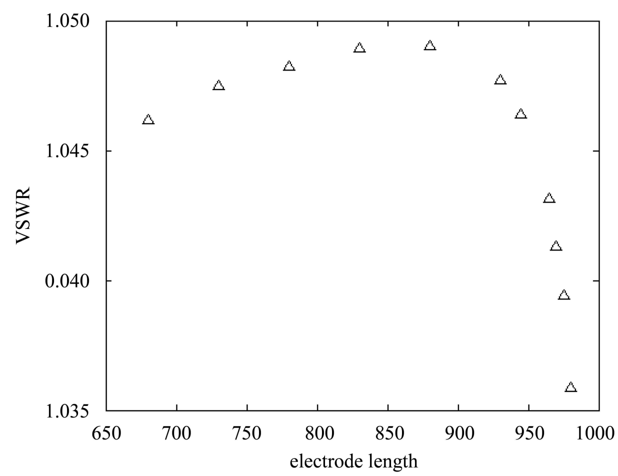

Fig. 5. VSWR results corresponding to different lengths of the electrode and the taper at 5 MHz.

6 Calculation of the shunt impedance of the kicker

The kicker efficiency is described by the shunt impedance parameter R_S, defined as the ratio between the square of the nominal voltage $V_\perp$ and twice the forward power P_{fw} at the kicker inputs [7].

$$R_S = V_\perp^2/2P_{fw},$$

where the voltage $V_\perp$ is defined as the integral of the component of the Lorenz force per unit charge along the beam axis:

$$V_\perp = \int_0^l (\bar{E} + \bar{v} \times \bar{B})_\perp dz.$$

For a strip-line transverse kicker driven in the differential mode, the shunt impedance can be calculated according to the formula [6]

$$R_{\rm S}=2Z_{\rm c}\left(\frac{g_{\rm trans}}{kh}\right)^2\sin^2(kl),$$

where $Z_{\rm c}(\approx 50\ \Omega)$ is the characteristic impedance of the transmission line considering the electrode and the vacuum chamber as inner and outer conductors, $g_{\rm trans}$ is the coverage factor

$$g_{\rm trans}=\tanh\left(\frac{\pi w}{4r_{\rm p}}\right),$$

where w is the arc length of the electrode, and $r_{\rm p}$ is the radius of the electrode, for our kicker, coverage factor is about 0.87, $k=\omega/c$, h is the stay radius (85 mm) and l is the length of the electrode (980 mm). The shunt impedance of our design is no less than 10000 Ohm within 5 MHz. The shunt values of designs with a different coverage angle have been compared, and the result is shown in Fig. 6. The result shows that the larger the coverage angle of the kicker, the larger the value of shunt impedance of the design. Considering the difference between 98° and 108° at 5 MHz is only 6%, and from the calculating result we know the 98° has a better uniformity of electric field, so the angle 98° is chosen as our design parameter.

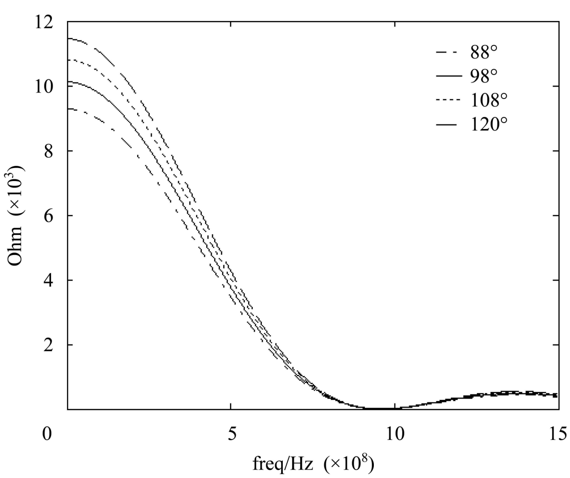

Fig. 6. Shunt values of designs with different coverage angles.

7 Calculation of loss factor and thermal state of the kicker

The kicker is made of a lossy material stainless steel, so there will be a higher or lower deposit of power in the electrode, though most of the power is absorbed by the terminal matching load. The power loss due to long bunch is considered. Here we choose 10m as the sigma value for the standard deviation of the Gaussian shaped bunch, and the wake loss factor we obtain is 9.72e-8 V/pC. There are two bunches in RCS and each bunch contains 1.56e13 particles. The average current, 3 A is considered, and the power loss is calculated from the following formula is 1.75 W.

$$P=\frac{k\times I_{\rm b}^2\times n_{\rm b}}{f},$$

where k is loss factor, $I_{\rm b}$ is the average current, $n_{\rm b}$ is the harmonic number, and f is the frequency, here 1 MHz. For the calculation of the transient thermal state, the initial temperature is 20 ℃. The deposit 1 W is assigned to the electrode uniformly, and the outside surface of the kicker meets the conditions of natural convection. The results show that the temperature of the electrode hardly changes for a transient process of 300 s. When the process reaches a steady thermal state, the maximum temperature of the electrode is no more than 30 ℃. By calculating the deformation based on the steady thermal result, the maximum deformation calculated is 0.07 mm, and there is little effect on the mechanical performance and uniformity of the electric field of the kicker.

8 Conclusions

The technical design and parameter analysis of the strip-line kicker in CSNS RCS is presented. Three designs are compared and an arc electrode kicker is chosen as our first design for its compact structure. Some details and technical issues will be discussed later, and we will adopt a more appropriate solution according to requirements in practice.

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