DESIGN AND SIMULATION OF THE STRIPLINE TRANSVERSE QUADRUPOLE KICKER FOR HLS II*

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Abstract

In order to investigate the possibility of exciting a transverse quadrupole mode oscillation of the electron bunch in the HLS II storage ring, we design a stripline transverse quadrupole kicker. The characteristic impedance of some modes (dipole modes, sum mode, quadrupole mode) of the optimized stripline kicker must match 50Ω characteristic impedance of the external transmission lines so as to reduce the reflected power. We use nonlinear least square method to optimize the kicker and compare characteristic impedances of calculation using 2D Possion code and fitted function of several variables, and then we get optimized size with integrated use of Possion code and fitted function of several variables. Using the 2D Possion code, we simulate the electric field distribution of dipole modes when the horizontal or the vertical electrodes are at opposite unit potentials, and the electric field distribution of quadrupole mode using quadrupole kicker. We verified that the designed stripline kicker can excite a transverse quadrupole mode oscillation of the electron bunch.

INTRODUCTION

In the upgrade project of the Hefei Light Source (HLSII), to investigate some properties of the transverse quadrupole oscillation, we design a transverse quadrupole kicker. This paper mainly introduces the design and simulation of the transverse quadrupole kicker.

The HLSII transverse quadrupole kicker model is shown in Fig. 1. The left and right electrodes are horizontal electrodes,the top and bottom electrodes are vertical electrodes. To match with the shape of the HLSII storage ring,the shape of horizontal electrodes is curved, just like C-shape, and the shape of vertical electrodes is flat, referring to the design of BESSY II stripline kicker [1]. The stripline length is 183.8 mm and the overall length of the kicker is 300 mm.

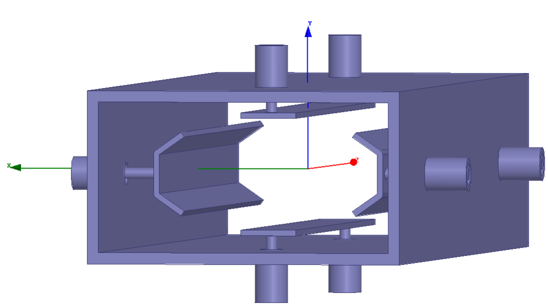

Figure 1: The transverse quadrupole kicker model in the HFSS.

IMPEDANCE MATCHING

Each of the stripline electrodes with its adjacent vacuum pipe forms a transmission line of characteristic impedance Z. Each stripline should be matched to the external transmission lines to reduce the reflected power at the coaxial feedthroughs, characteristic impedance of the external transmission lines is 50Ω, this requires Z=50Ω. The formula to calculate the characteristic impedance is as follows [2]:

$$Z = \frac{(V_1 - V_2)^2}{2Ec} \quad (1)$$

Where c is the speed of light, $V_1$and V_2 are the respective electric potential of the stripline electrode and the vacuum pipe. When V_1=±1V and V_2=0V, the simplified formula is Z=1/ (2cE).

The characteristic impedance of some modes are shown in Table 1. Given different electrodes with corresponding magnitude and sign of the voltage, characteristic impedance of different modes are generated. For an optimized transverse quadrupole kicker, the characteristic impedance of these modes should satisfy the following equation:

$$Z_0^2 = Z_{dipole1}Z_{dipole2} = Z_{dipole3}Z_{dipole4} = Z_{sum}Z_{quad} \quad (2)$$

Where Z_0 is characteristic impedance of the external transmission lines, its value is 50Ω.

Table 1: Characteristic Impedance of Some Modes

	top electrode	bottom electrode	left electrode	right electrode
$Z_{dipole1}$			+1 V	-1 V
$Z_{dipole2}$	+1 V	-1 V		
$Z_{dipole3}$	+1 V	-1 V	+1 V	-1 V
$Z_{dipole4}$	-1 V	+1 V	-1 V	+1 V
Z_{sum}	+1 V	+1 V	+1 V	+1 V
Z_{quad}	+1 V	+1 V	-1 V	-1 V

OPTIMIZATION METHOD AND STEP

For a set of data, we assume that W is the dependent variable and x, y, z etc. are the independent variables, and we select a set of known functions f_j (j=1,2,3,…,m) and establish regression equation as follows:

* Supported by the National Science Foundation of China (10875117, 11005105, 11175173)
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$$\hat{W}_i = \sum_{j=1}^{m} k_j f_j(x_i, y_i, z_i, \ldots) \quad (3)$$

We find a set of regression coefficients k_j (j=1,2,3,…,m), which makes residual sum of squares of regression value of each group of data and experiment value minimal. Residual sum of squares is

$$S(k_1, k_2, \ldots, k_m) = \sum_{i=1}^{n} (\hat{W}_i - W_i)^2 \quad (4)$$

According to the necessary condition that function of several variables takes extremum, when residual sum of squares is minimal, we can get

$$\frac{\partial S}{\partial k_j} = 0\left(j = 1, 2, \ldots, m\right) \quad (5)$$

Using equations (4) and (5) we can get a group of equations about k_1, k_2,…, k_m, as follows:

$$\left\{\begin{array}{l} \sum_{i=1}^{n} f_1(x_i, y_i, z_i, \ldots)[\sum_{j=1}^{m} k_j f_j(x_i, y_i, z_i, \ldots) - W_i] = 0 \\ \ldots \\ \ldots \\ \sum_{i=1}^{n} f_m(x_i, y_i, z_i, \ldots)[\sum_{j=1}^{m} k_j f_j(x_i, y_i, z_i, \ldots) - W_i] = 0 \end{array}\right\} \quad (6)$$

We make matrix **R** as follows:

$$\mathbf{R} = \begin{bmatrix} f_1(x_1,y_1,z_1,\ldots) & f_2(x_1,y_1,z_1,\ldots) & \ldots & f_m(x_1,y_1,z_1,\ldots) \\ f_1(x_2,y_2,z_2,\ldots) & f_2(x_2,y_2,z_2,\ldots) & \ldots & f_m(x_2,y_2,z_2,\ldots) \\ \ldots & \ldots & \ldots & \ldots \\ f_1(x_n,y_n,z_n,\ldots) & f_2(x_n,y_n,z_n,\ldots) & \ldots & f_m(x_n,y_n,z_n,\ldots) \end{bmatrix}$$

$$\mathbf{K} = (k_1, k_2, \ldots, k_m)^T, \quad \mathbf{W} = (w_1, w_2, \ldots, w_n)^T$$

Then equations (6) can be transformed into a matrix form:

$$\mathbf{R}^T\mathbf{R}\mathbf{K} = \mathbf{R}^T\mathbf{W} \quad (7)$$

When f_1(x, y, z,), f_2(x, y, z,), f_m(x, y, z,) are linearly independent, R^TR is invertible, and equations (6) have the only solution as follows:

$$\mathbf{K} = (\mathbf{R}^T\mathbf{R})^{-1}\mathbf{R}^T\mathbf{W} \quad (8)$$

We use equation (8) to obtain matrix **K**, then get regression equation.

The cross-section of HLS transverse quadrupole kicker is shown in Fig. 2. There are four variables, they are h_x,h_y,W_x,W_y,the length of these variables is variable, but they have a range, the range of each variable is : $h_x \in [5,15]$, $h_y \in [3,10]$, $W_x \in [10,25]$, $W_y \in [15,40]$.

We set the function of characteristic impedance of the HLS II transverse quadrupole kicker as follows:

$$\begin{aligned} Z = {} & k_0 + k_1 h_x + k_2 h_y + k_3 W_x + k_4 W_y + k_5 h_x^2 \\ & + k_6 h_y^2 + k_7 W_x^2 + k_8 W_y^2 + k_9 h_x h_y + k_{10} h_x W_x \\ & + k_{11} h_x W_y + k_{12} h_y W_x + k_{13} h_y W_y + k_{14} W_x W_y \end{aligned} \quad (9)$$

We use 39 groups of different values of *hx, hy, Wx, Wy* and calculated corresponding characteristic impedances using Possion code and equation (8) to obtain matrix **K**,

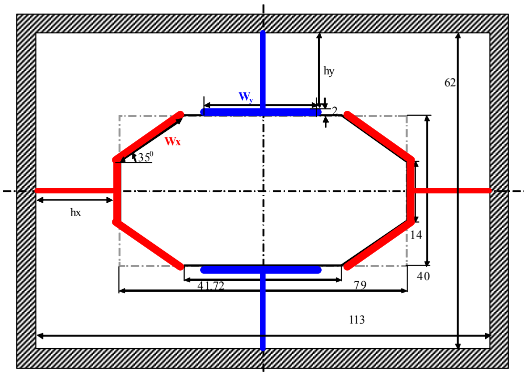


Figure 2: The cross-section of HLS transverse quadrupole kicker.

then get regression equations as follows:

$$\begin{aligned} Z_{\rm quad} = {} & 39.3137 + 2.2287 h_x + 5.5120 h_y - 0.3750 W_x \\ & - 0.8959 W_y - 0.0324 h_x^2 - 0.2291 h_y^2 - 0.0021 W_x^2 \\ & + 0.0170 W_y^2 + 0.0446 h_x h_y - 0.0401 h_x W_x - 0.0238 h_x W_y \\ & + 0.0146 h_y W_x - 0.0452 h_y W_y - 0.0172 W_x W_y \end{aligned} \quad (10)$$

The corresponding fitted functions of several variables for $Z_{\rm dipole1}$, $Z_{\rm dipole2}$, $Z_{\rm dipole3}$, $Z_{\rm dipole4}$, $Z_{\rm sum}$ are similar to $Z_{\rm quad}$. The fitting rms of $Z_{\rm dipole1}$, $Z_{\rm dipole2}$, $Z_{\rm dipole3}$, $Z_{\rm dipole4}$, $Z_{\rm sum}$ and $Z_{\rm quad}$ are 0.0597Ω, 0.2770Ω, 0.1027Ω, 0.1027Ω, 0.1090Ω, and 0.1277Ω.

The Figure. 3 shows that characteristic impedances of calculation of $Z_{\rm quad}$ using these two methods are very close, this indicates that using fitted function of several variables to calculate characteristic impedances of transverse quadrupole kicker is very effective.

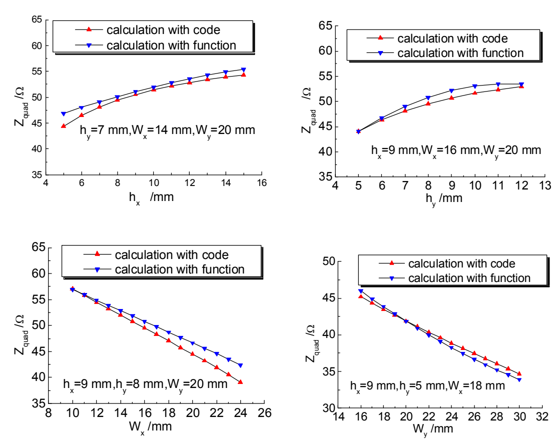
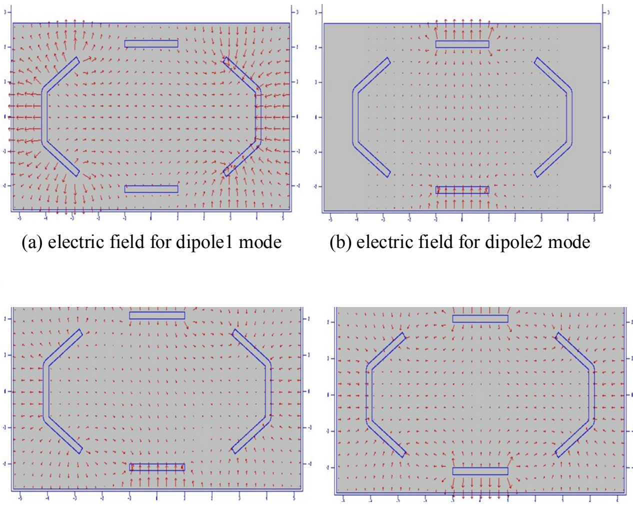


Figure 3: Value of characteristic impedances using code and fitted function.

ELECTRIC FIELD SIMULATION

Using the 2D Possion code, we simulate the electric field distribution for dipole modes and quadrupole mode using quadrupole kicker. Fig. 4 shows the electric field distributions of these modes.

ISBN 978-3-95450-115-1



(a) electric field for dipole1 mode (b) electric field for dipole2 mode

(c)electric field for dipole3 mode (d) electric field for quadrupole mode

Figure 4: electric field line distributions in the kicker.

RESULT AND ANALYSIS

We can get the best optimization size of the transverse quadrupole kicker with integrated use of Possion code and fitted function given above, the best optimization size is h_x=11 mm, h_y=5 mm, W_x=15 mm, W_y=20 mm, the corresponding characteristic impedances are: $Z_{dipole1}$ = 50.0649Ω, $Z_{dipole2}$= 50.2024Ω, $Z_{dipole3}$=$Z_{dipole4}$=49.9775Ω, Z_{sum}=60.9312Ω and Z_{quad}= 46.4217Ω.

Using the 2D Possion code, when we set the electric potential of four transverse quadrupole kicker stripline electrodes as 20 V, around the center beam line, the electric field along the X and Y is shown in Figure. 5.

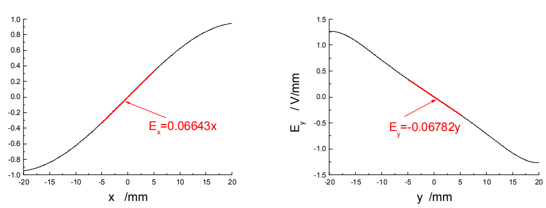


Figure 5: E-field along the x and y axis when quadrupole excitation is generated.

As is shown in Figure. 5, we can get

$$\left|\frac{\partial E_x}{\partial x}\right|_{(0,0)}\Big| \approx 0.06643\left(V/mm^2\right)$$

$$\left|\frac{\partial E_y}{\partial y}\right|_{(0,0)}\Big| \approx 0.06782\left(V/mm^2\right)$$

Then, the quadrupole-strength of K is [3 4 5]:

$$K_x = \frac{e}{E_0}\left|\frac{\partial E_x}{\partial x}\right|_{(0,0)}\Big| \approx 8.30\times10^{-11}\left(1/mm^2\right)$$

$$K_y = \frac{e}{E_0}\left|\frac{\partial E_y}{\partial y}\right|_{(0,0)}\Big| \approx 8.48\times10^{-11}\left(1/mm^2\right)$$

Where E_0=800 MeV, it is the energy of the electron beam stored in the HLS II storage ring.

The amplitude of the tune modulation is

$$\delta\nu_x = \frac{K_x l}{4\pi}\beta_x \approx 8.50\times10^{-6}$$

$$\delta\nu_y = \frac{K_y l}{4\pi}\beta_y \approx 3.72\times10^{-6}$$

Where the transverse quadrupole kicker length of l is 183.8 mm, β_x and β_y are the horizontal and vertical betatron function at the location of the transverse quadrupole kicker, the values of β_x and β_y are 7 m and 3m.

Due to a parametric resonance effect, the amplitude of the betatron motion grows at a growth rate given by

$$\alpha_{g,x} = \pi f_0 \delta\nu_x \approx 121.05 \quad \left(s^{-1}\right)$$

$$\alpha_{g,y} = \pi f_0 \delta\nu_y \approx 52.98 \quad \left(s^{-1}\right)$$

Where f_0 is revolution frequency, its value is 4.533 MHz.

When the radiation damping and the other damping effects are taken into account, the betatron oscillation grows if the above growth rate exceeds the transverse damping rate. In the upgrade project of the HLS II, the transverse radiation-damping rate is 47~50 s^{-1}, $\alpha_{g,x}, \alpha_{g,y}$ >47 s^{-1}, so this transverse quadrupole kicker can excite transverse quadrupole oscillation.

CONCLUSION

We have established an optimization method for the HLS II transverse quadrupole kicker and verified this kicker can excite transverse quadrupole oscillation, the manufacture and test of the kicker should be our next work in near future.

REFERENCES

[1] S. Khan, T. Knuth et al., “Longitudinal and Transverse Feedback Kickers for the BESSY II Storage Ring”, Proceedings of PAC1999, New York, 1999, p. 1147.

[2] W.B. Li, B.G. Sun, Z.R. Zhou et al., “Design and Simulation of the Transverse Feedback Kicker for HLS II”, Proceedings of IPAC2011, San Sebastian, 2011, p. 496.

[3] Y. Cao, B.G. Sun, P. Lu et al., “Measurement and Analysis of Betatron Function in the HLS”, High Power Laser & Particle Beams 17(5), (2005) 775.

[4] S. Sakanaka, Y. Kobayashi, T. Mitsuhashi et al., “Excitation and Detection of a Transverse Quadrupole-Mode Bunch Oscillation in the KEK Photon Factory Storage Ring”, Jpn. J. Appl. Phys. 42 (2003) 1757.

[5] S. Sakanaka, Y. Kobayashi, T. Mitsuhashi et al., “Excitation of a Transverse Quadrupole-mode Oscillation of the Electron Bunch Using a High-Frequency Quadrupole Magnet”, Proceedings of PAC01, Chicago, 2001, p. 393.