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THE DESIGN IMPROVEMENT OF TRANSVERSE STRIPLINE KICKERS IN TPS STORAGE RING

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Abstract

An improved design of horizontal stripline kicker for transverse feedback system has been replaced in January 2017. A rapid surge of vacuum pressure near the old horizontal kicker was observed when we tested the high current operation in TPS storage ring in April 2016. A burned vacuum feedthrough of the horizontal kicker was discovered during a maintenance shutdown. The improved design has reduced the reflection of the driving power from horizontal feedback system and the beam induced RF heating. Based on the experience learned from this improved design of horizontal stripline kicker, we also work out the improved design for the vertical kickers as well. The major modifications of the improved designs for both the horizontal and the vertical stripline kickers are described. The results of RF simulation performed with the electromagnetic code GdfidL are also reported.

INTRODUCTION

The designs of both the horizontal and the vertical stripline kickers for bunched beam feedback in Taiwan Photon Source (TPS) were adapted from the SLS/ALBA design [1, 2]. The type-N vacuum feedthroughs of horizontal kicker were found damaged due to over heating during high current operation in 2016. The original horizontal kicker was replaced by an improved design in January 2017. Details of the design improvement of horizontal stripline kicker have been reported [3]. Since the same type of vacuum feedthroughs are used in the vertical kickers, there is a concern whether we will encounter similar problems as the original horizontal kicker did or not. To ensure a reliable operation at the designed beam current 500 mA in the future, we embark on the design improvement for the vertical stripline kicker.

From the beam experiments conducted with the improved horizontal kicker, we discover that the beam induced signal is the dominant source which could damage the drive amplifier connected at the downstream ports. The priority is given to the matching of even mode impedance when we improve the design of vertical kicker. The same design concept that is effective in greatly reducing the loss factor of horizontal kicker [3] is also applied to the vertical kicker. A 3-D electromagnetic code GdfidL [4] is used for the simulation studies of this improved vertical kicker.

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DESIGN IMPROVEMENT

Since there is limited space available for the installation of transverse kickers in TPS storage ring, there is no taper section in the design of stripline kickers. The transverse profile of kicker electrodes should be flushed to the inner surface of racetrack beam pipe in order to reduce the broadband impedance. A section view of the existing vertical stripline kicker is shown in Fig. 1. The width of electrodes is 42.7 mm, the length is 280 mm and the cross section of racetrack beam pipe is 68 mm x 20 mm.

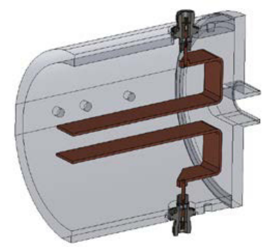

Figure 1: The section view of the existing vertical stripline kickers in TPS storage ring. The longitudinal gap between the electrodes and the end plate is 10 mm.

Impedance Matching

To prevent the beam induced signal propagating towards the downstream ports, the even mode impedance Z_{even} should be matched to the terminating line impedance (typically 50Ω). For maximum transmission of signal coming from the drive amplifier at the downstream ports, the necessary condition given by the theory of coupled transmission lines should be satisfied [5, 6]:

$$Z_{even} Z_{odd} = Z_0^2 \tag{1}$$

where Z_0 is the terminating line impedance.

For beam pipes of small cross section, it is difficult to satisfy both conditions for a good impedance matching of stripline electrodes. We choose to match the even mode impedance in order to minimize the beam induced signal at the downstream ports where the drive amplifier of feedback system is connected to.

The geometry of proposed improvement of vertical stripline kicker is shown in Fig. 2. The stripline electrodes are flushed to the inner surface of racetrack beam pipe for the reduction of broadband impedance. The summary of mode impedance for the existing vertical stripline kicker and the proposed improvement is listed in Table 1. The distribution of electrical fields of the odd mode of the improved design is shown in Fig. 3. The comparison of simulated results of the time domain reflectometry (TDR) for the existing and the improved vertical kicker is shown in Fig. 4.

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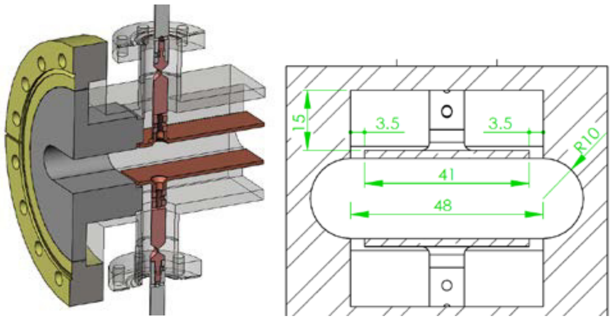

Figure 2: A 3-D section view (left) and 2-D cross section drawing of the improved vertical stripline kicker (right). The dimensions are in units of [mm].

Table 1: The Summary of Mode Impedance for the Existing Vertical Kicker and the Proposed Improvement

	Existing kicker	Improved design
Z_{even} [Ω]	150.55	50.08
Z_{odd} [Ω]	49.92	34.27
Z_{even}* Z_{odd}	7515	1716

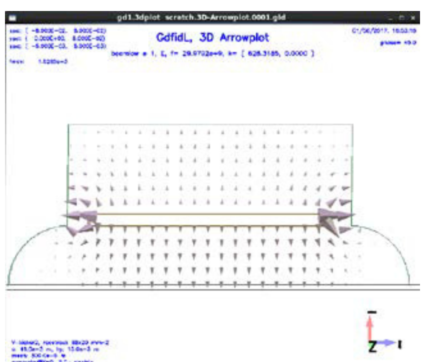

Figure 3: The simulated pattern of electrical fields of the odd mode in the improved design. Only half the structure is depicted.

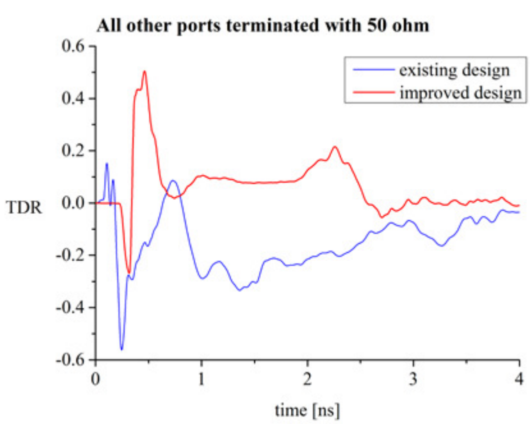

Figure 4: The simulated results of TDR for the existing (blue) and the improved vertical kicker (red). All other three ports are terminated with 50 Ω in the simulations.

The simulated spectra of S_{11} parameter for the existing vertical kicker and the improved design are shown in Fig. 5. As shown in Fig. 4 and Fig. 5, the reflection of driving signal from the power amplifier at the downstream port is much reduced in the improved design. The improved design of vertical kicker has a better impedance matching than the existing one in present user operation.

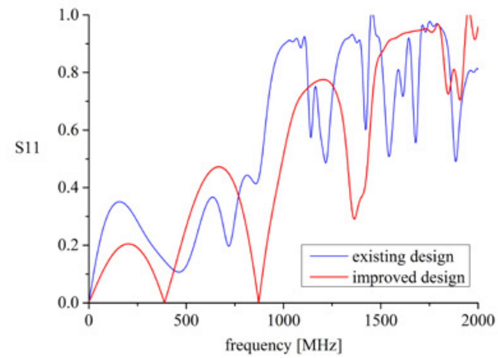

Figure 5: The simulated spectra of S_{11} parameter for the existing vertical kicker (blue) and the improved design (red).

Reduction of Loss Factor of the Kicker Module

One of the design objectives is to achieve a significant reduction of loss factor of the entire kicker module. A rectangular indentation of depth 4 mm is machined on the end plate to shield the edge of stripline electrode as depicted in Fig. 6. The length of stripline electrode is 276 mm. The 7/8 EIA vacuum feedthroughs made by Kyocera are adopted for this improved design.

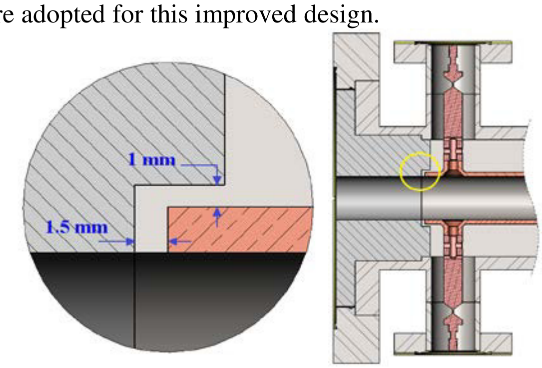

Figure 6: The design of end plate used to reduce the loss factor of kicker module (right). The edge of stripline electrode is shielded by a rectangular indentation of depth 4 mm on the end plate (left).

The calculated loss factors for the existing design and the improved design are listed in Table 2. There are 864 RF buckets in TPS storage ring. In routine operation the storage ring is typically filled with 600 bunches. The average power dissipated by particle beams at 500 mA total current is estimated approximately by the following expression:

$$\langle P \rangle \approx \frac{\Delta E}{T_b} \tag{2}$$

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where ΔE is the parasitic energy loss per bunch, and T_b is the RF period. The loss factor of the improved design is a factor of 4.5 smaller than the existing vertical kicker.

Table 2: The Calculated Loss Factor and Average Power Dissipated by Particle Beams at 500 mA Total Current (rms bunch length= 4.5 mm)

	Loss factor [V/pC]	**Dissipated Power [W]**
Old design	1.070	1108.6
Improved design	0.238	246.6

The trapped longitudinal higher-order-mode (HOM) is analyzed by GdfidL using both the time-domain solver and the eigenmode solver with absorbing boundary conditions. The longitudinal impedance of the entire kicker module of the improved design is shown in Fig. 7. The RF parameters of dominant resonant modes calculated by GdfidL are list in Table 3. The longitudinal coupled bunch instabilities driven by these resonant modes are considered for total beam current 500 mA. The calculated growth time using formulas of the theory of bunched beam instabilities [7] for total beam current 500 mA is listed in Table 3. The longitudinal radiation damping time of TPS storage ring is 6.08 ms. The improved design of vertical kicker will not cause longitudinal coupled bunch instabilities at 500 mA.

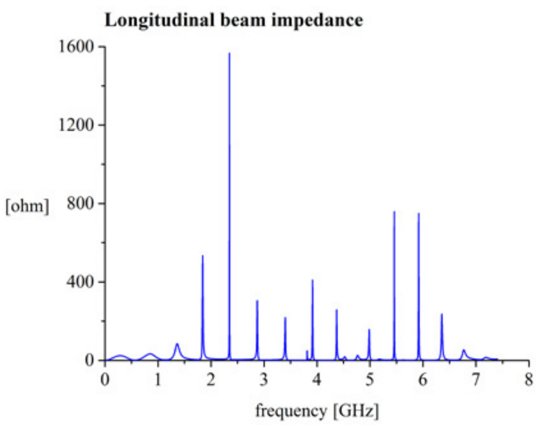

Figure 7: The longitudinal impedance simulated by GdfidL for the entire kicker module of improved design. The spectral resolution is 0.4 MHz.

Table 3: RF Parameters of Dominant Resonant Modes Calculated by GdfidL and the Estimated Instability Growth Time

f **[GHz]**	**R/Q [Ω]**	**Q_{total}**	**Growth time [ms] at 500 mA total current**
2.348	1.879	834	78.1
5.918	0.507	1480	83.7

Calculation of Transverse Shunt Impedance

We use the results of analytical theory [8] and simulations of GdfidL to estimate the transverse shunt impedance of vertical kicker. The relation between the longitudinal beam impedance $Z_{\parallel}$ and the longitudinal shunt impedance $R_{\parallel}$ of a rectangular stripline kicker with a matched load is [8]

$$Z_{\parallel} = \frac{R_{\parallel}}{4} \tag{3}$$

For devices like a cylindrical resistive wall pick/kicker, the following relations hold [8]

$$R_{\perp} = R_{\parallel}(1/kb)^2 \tag{4}$$

$$Z_{\perp} = \frac{Z_{\parallel}}{kb^2} \tag{5}$$

where k is the wave number, $R_{\perp}$ the transverse shunt impedance, $Z_{\perp}$ the transverse beam impedance, and b is the radius of beam pipe. If we approximate the vertical gap of a racetrack beam pipe as the diameter of a cylindrical pipe, we can get an approximate relation between the transverse shunt impedace and the transverse beam impedance as [9]

$$R_{\perp} = \frac{4\,\mathrm{Re}(Z_{\perp})}{k} \tag{6}$$

One can simulate the transverse beam impedance of the entire kicker module with GdfidL and deduce the transverse shunt impedance by using Eq. (6). This is the method-1 we used to calculate the transverse shunt impedance.

Another approach to obtain the transverse shunt impedance is to calculate the transverse beam voltage $V_{\perp}$ or kick voltage exerted on the particle beam by the feedback system for a given input power P_{in}. Then, the shunt impedance is given by the definition $R_{\perp} = V_{\perp}^2 / 2P_{in}$. The transverse beam voltage is defined as [8]

$$V_{\perp} = \frac{\beta c \Delta p_{\perp}}{e} \tag{7}$$

For an ultra-relativistic particle beam interacting with the electromagnetic fields, the transverse beam voltage becomes

$$V_{\perp} = \int \{\vec{E}_{\perp}(\vec{r},t) + [\vec{c} \times \vec{B}(\vec{r},t)]_{\perp}\} ds \tag{8}$$

In the simulation code GdfidL, the transverse wakepotential is calculated from the simulated longitudinal wakepotential by using the Panofsky-Wenzel theorem [4],

$$W_{\perp}(x,y,z) = \int_{-\infty}^{z} \nabla_{\perp} W_{\parallel}(x,y,\tau)\, d\tau \tag{9}$$

The transverse wakepotential defined in GdfidL has the units of [V]. For ultra-relativistic particle beam interacting with the electromagnetic fields, the expression of transverse wakepotential as defined in GdfidL becomes the one given by Eq. (8). One can excite the downstream ports of stripline kicker and calculate the transverse wakepotential with a very small drive charge in GdfidL

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simulations. As long as the drive charge used in GdfidL simulations is small enough, the calculated transverse wakepotential is only contributed by the electromagnetic fields excited by the input power in downstream ports. This is the method-2 we used to calculate the transverse shunt impedance. We excite each downstream port of vertical kicker by 0.5 W (total input power of 1 W) and calculate the transverse wakepotential with a small drive charge 10^{-22} C. The amplitude of transverse wakepotential is the amplitude of transverse beam voltage. The transverse shunt impedance is calculated from the expression $V_{\perp}^2/2$ [4]. A comparison of transverse shunt impedances calculated by the analytical theory, method-1, and method-2 for the improved design is shown in Fig. 8.

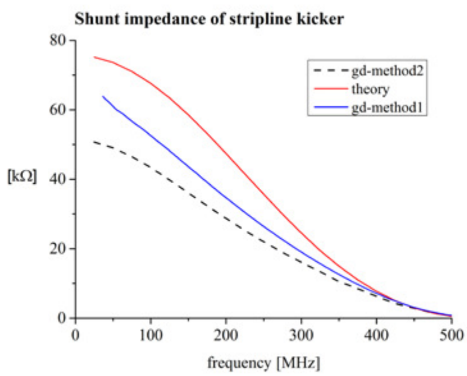

Figure 8: The transverse shunt impedance of the improved design calculated by the analytical theory and GdfidL simulations.

The effects of electromagnetic fields excited in a transverse kicker is to cause an angular kick to the beam trajectory,

$$\Delta y' = \int F_{\perp} ds \Big/ (e\upsilon B_0\rho) = V_{\perp} \Big/ (cB_0\rho) \qquad (10)$$

where $B_0\rho$ is the magnetic rigidity of particle beam. Using the definition of transverse shunt impedance, the kick strength per turn of the feedback system is rewritten as

$$\Delta y' = \frac{\sqrt{2P_{in}R_{\perp}}}{cB_0\rho} \qquad (11)$$

When the damping limit of the transverse feedback is reached, the beam induced voltage/turn equals to the maximum transverse beam voltage (kick voltage)/turn [10]. The maximum input power required for a transverse kicker at its damping limit is given by [10]

$$P_{\max} = |V_b|^2 \big/ 2R_{\perp} \qquad (12)$$

where $V_b = I_0 \Delta y Z_{y,eff}$.

The following parameters are used: chromaticity= 2, I_0= 500 mA, Δy= 3 mm, fractional vertical tune q_y= 0.24, and all phase-I insertion devices (IDs) in TPS storage ring. The effective vertical impedance due to resistive wall at the strongest unstable mode (1-q_y) is $Z_{y,eff}$ = 3.95 MΩ/m. If we drive the improved vertical kicker with a maximum input power 500 W, the kick voltage/turn, the kick strength/turn, and the maximum input power required at the damping limit of kicker are listed in Table 4.

Table 4: The Calculated Vertical Kick Voltage/Turn and the Kick Strength/Turn for an Input Power of 500 W

	Theory	Method-1	Method-2
$R_{\perp}$ [kΩ]	75	65	51
$P_{\max}$ [W]	234	270	344
$V_{\perp}$ [V]/turn	8660	8062	7141
$\Delta y'$ [μrad]/turn	2.88	2.68	2.37

SUMMARY

We have improved the design of horizontal and vertical stripline kickers. The loss factor is reduced by a factor of 3.37 for the horizontal kicker and 4.50 for the vertical one. The simulation reveals that trapped longitudinal resonant modes in both the horizontal and vertical stripline kickers will not cause the longitudinal coupled bunch instabilities at the designed beam current 500 mA. The emphasis of impedance matching for the improved vertical kicker is placed on the matching of even mode impedance to the impedance of terminating lines (50 Ω). The transverse shunt impedance is calculated from GdfidL simulations using two different methods. The estimated kick strength per turn of the improved vertical kicker indicates the kick strength is sufficient to damp the resistive wall instabilities with all phase-I IDs at 500 mA.

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