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REDUCTION OF BEAM INDUCED RF-HEATING IN THE HORIZONTAL STRIPLINE KICKER AT THE TPS

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Abstract

In preparation for 500 mA operation at the Taiwan Photon Source (TPS), we redesigned the horizontal stripline kicker for the beam feedback system to gain a smaller loss factor with higher shunt impedance. We introduced ground fenders (see Fig. 1) to this new design which resulted in the reduction of the loss factor and substantial increase of the kicker shunt impedance. The transverse profile of the kicker electrodes was matched to the racetrack beam pipe in the straight sections to minimize broadband impedance. The ground fenders can reduce the leakage of image currents through the gaps between the two strip line electrodes and also help to achieve a better impedance matching for the TEM modes in the transmission lines formed by the stripline electrodes and beam pipe in the kicker. The RF design and analysis of trapped resonant modes in the kicker were simulated by the 3-D electromagnetic code GdfidL [1]. Results of the RF design and analysis of trapped resonant modes will be discussed together with analytical estimates of coupled bunch instabilities at a beam current of 500 mA.

INTRODUCTION

The Atomic Energy Council of Taiwan approved in March 2019 the license to operate the TPS at a beam current of 500 mA. In preparation for this high beam current, we redesigned the horizontal stripline kicker to reduce beam induced RF-heating and increase the kicker shunt impedance. The horizontal stripline kicker presently in use was installed in January 2017 [2]. In the proposed redesign, we matched the transverse stripline electrode profile to the racetrack beam pipe in the straight sections to minimize broadband impedance. To improve the impedance matching of stripline kicker TEM modes, we introduced ground fenders [3] to reduce the difference between the characteristic impedances of even and odd modes. The ground fenders also help to reduce the leakage of image currents through gaps between the two electrodes. As a result, the loss factor is reduced by 20.6 % and the kicker shunt impedance is increased by a factor of 2.38 compared to the kicker presently in use. The trapped resonant modes in the kicker module were simulated with the 3-D electromagnetic code GdfidL [1] while the growth time of coupled bunch instabilities driven by these modes was estimated analytically for both the longitudinal and transverse directions and a maximum beam current of 500 mA. The analysis shows that we can avoid coupled bunch instabilities if we operate the storage ring with vertical chromaticities larger than two.

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RF DESIGN OF STRIPLINE KICKERS

The mechanical design of the proposed horizontal stripline kicker is shown in Fig. 1. The vertical electrode gaps are reduced from 30 mm to 20 mm and ground fenders are attached to the circular housing duct of the kicker module. Vacuum feedthroughs of type 7/8 EIA and manufactured by Kyocera 7/8 EIA vacuum feedthroughs made by Kyocera are used. The same design concept for the end plates in the kicker presently installed is applied to minimize the loss factor. The detailed design of end plates projected to the x-z plane is shown in Fig. 2.

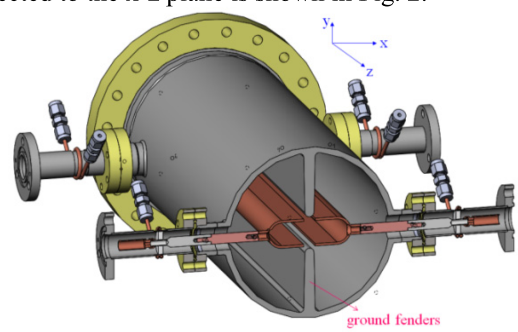

Figure 1: The mechanical design of the proposed horizontal kicker. Ground fenders are introduced to improve the impedance matching of TEM modes and reduce the loss factor as well.

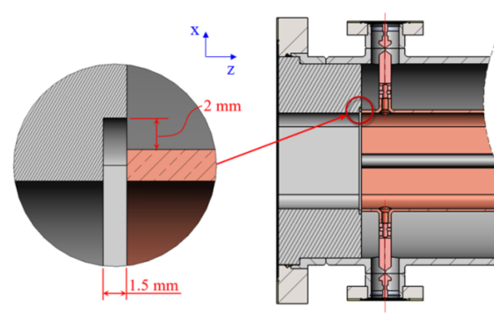

Figure 2: The detailed design of end plates projected to the x-z plane.

Impedance Matching

When a transverse beam feedback system is in operation, there are two TEM modes present in the kicker module. One is the odd mode excited by the driving voltages of feedback system at two downstream ports. Another is the even mode excited by the particle beams. For maximum transmission efficiency of the driving voltage, we need to match the input impedance as seen at each driving port, to the terminating line impedance Z_0 (typically 50 Ω). To minimize damage to the RF amplifiers

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connecting to the downstream ports, we need to match the impedance of the even mode to the terminating line impedance Z_0 such that the beam induced voltage propagating toward the downstream ports is minimized. The optimum matching for the mode impedances is given by [4]

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

When the kicker is excited by the feedback system in the odd mode, the central plane, at x= 0, is a neutral plane between the electrodes [5]. The ground fenders reduce the capacitive coupling between both electrodes which helps the optimum matching of mode impedances. The comparison of mode impedances between the presently installed and proposed kicker is listed in Table. 1 and the simulated electric field pattern of the odd mode in the central region of the proposed design is shown in Fig. 3. Simulated reflection spectra for S_{11} are shown in Fig. 4 and the simulated results in the time domain reflectometry (TDR) are shown in Fig. 5.

Table 1: Impedance of TEM Modes in the Proposed and Installed Horizontal Kickers

	Proposed	Installed
Z_{even} [Ω]	49.680	66.585
Z_{odd} [Ω]	39.269	34.702

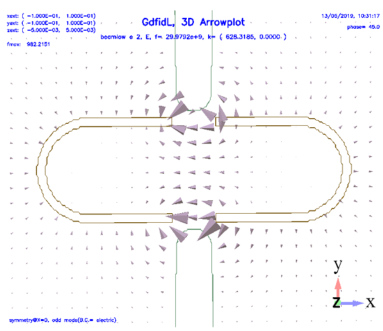

Figure 3: Simulated electric field patterns for the odd mode in the central region of the proposed kicker design.

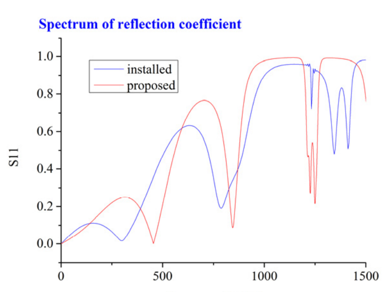

Figure 4: Simulated S_{11} reflection spectra for the installed and proposed kicker designs.

Since beam pipe apertures in modern light sources are small, it is difficult to match the characteristic impedance of both, the odd and even modes, to 50 Ω. For the protection of RF amplifiers in the feedback system, we chose to place more weight on the matching of the even mode and compromise the transmission efficiency of the driving voltages at the downstream ports to an acceptable level.

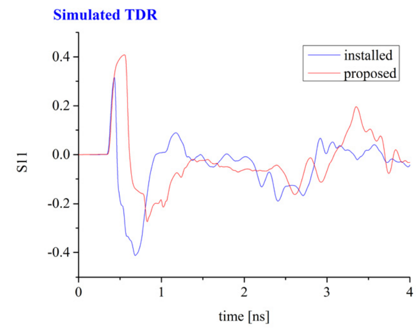

Figure 5: Simulated results of the TDR for the installed and proposed kicker designs. The time delay is manually adjusted for ease of comparison.

Transverse Shunt Impedance

The transverse shunt impedance of a stripline kicker is estimated by calculating the transverse beam voltage $V_\perp$ [6] exerted on the particle beam by the feedback system for a given input power P_{in} and is given by $R_\perp = V_\perp^2 / 2P_{in}$. For ultra-relativistic particle beams interacting with electromagnetic fields, the expression of transverse wake potentials, as defined in GdfidL [1], becomes the transverse beam voltage. We excite each downstream port of the stripline kicker with a power of 0.5 W and calculate the transverse wake potential with a very small test charge of 10^{-22} C in GdfidL simulations. With the amplitude of the transverse wake potential, we can calculate the transverse shunt impedance from the expression $V_\perp^2 / 2$ [7]. The transverse shunt impedances for the installed and proposed kicker designs are shown in Fig. 6.

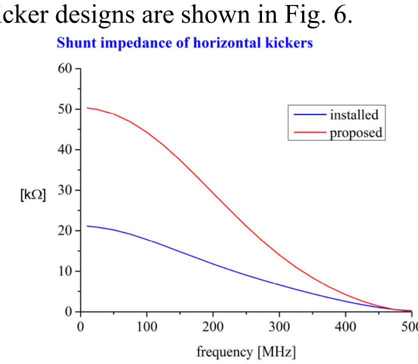

Figure 6: The transverse shunt impedances of the installed and proposed kicker designs. The shunt impedance of the proposed design is higher by a factor of 2.38.

BEAM INDUCED RF-HEATING AND COUPLED BUNCH INSTABILITIES

Trapped resonant modes and loss factors were calculated for the proposed design in time domain GdfidL simulations. The harmonic number of the TPS storage ring is 864, but in routine operation, the storage ring is filled with only about 600 bunches. The average power of beam induced RF-heating can be expressed by

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

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where ΔE is the parasitic energy loss per bunch, and T_b is the RF period. The calculated loss factors and average power dissipated by particle beams at a total beam current of 500 mA for the installed and proposed kicker designs are listed in Table 2.

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

	Loss factor [V/pC]	**Dissipated Power [W]**
Installed kicker	0.310	250.1
Proposed design	0.246	198.4

The simulated beam impedance spectrum for the longitudinal and vertical plane is shown in Fig. 7 and Fig. 8, respectively. The horizontal beam impedance is too small to be of any concern.

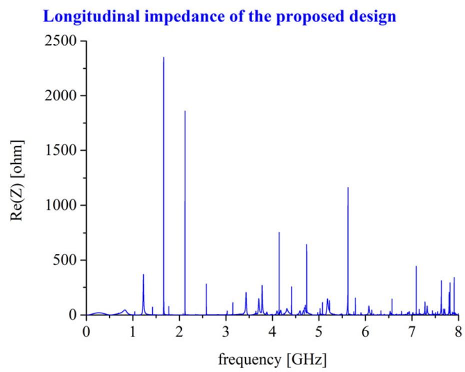

Figure 7: Simulated longitudinal beam impedance spectrum with a resolution of 0.2 MHz for the proposed kicker design.

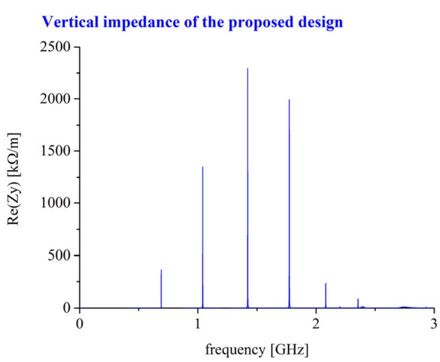

Figure 8: Simulated vertical beam impedance spectrum with a resolution of 0.2 MHz for the proposed kicker design.

The growth time of coupled bunch instabilities due to trapped resonant modes was calculated using theoretical formulas for bunched beam instabilities [8] and total beam current of 500 mA. Dominant resonant modes and analytical instability growth times in the longitudinal and vertical directions are listed in Table 3 and Table 4, respectively. The radiation damping time of the TPS storage ring is 6.08 ms for longitudinal and 12.17 ms for vertical oscillations. From analytical estimates, we find no longitudinal coupled bunch instabilities driven by resonant modes in the proposed kicker design. However, there will be vertical coupled bunch instabilities, driven by resonant modes in the proposed design if the storage ring is operated with vertical chromaticities equal to unity. Based on analytical formulas of bunched beam instabilities, the vertical chromaticities must be larger than two in order for radiation damping to suppress the vertical coupled bunch instabilities driven by resonant modes.

Table 3: RF Parameters of Dominant Longitudinal Resonant Modes Calculated with GdfidL and Estimated Instability Growth Times

***f* [GHz]**	**R/Q [Ω]**	**Q_{total}**	**Growth time [ms] at 500 mA total current**
1.644	2.434	965	81.78
2.121	1.039	1791	87.95
5.624	0.484	2404	60.64

Table 4: RF Parameters of Dominant Vertical Resonant Modes Calculated with GdfidL and Estimated Instability Growth Times if the Vertical Chromaticity is equal to Unity

***f* [GHz]**	**$R_\perp/Q$ [Ω/m]**	**Q_{total}**	**Growth time [ms] at 500 mA total current**
1.041	1050.2	1285	10.09
1.422	1699.4	1349	9.10
1.774	1264.9	1575	17.02

CONCLUSION

The proposed kicker design with ground fenders has been thoroughly analysed with GdfidL simulations and analytical formulas for bunched beam instabilities at a total beam current of 500 mA. The average power of beam induced RF-heating is reduced by 20.6 % compared to the presently installed kicker. The characteristic impedance of the even mode in the proposed design is well matched to 50 Ω and a reasonably good impedance match for the odd mode has been achieved. The shunt impedance of the proposed design is larger by a factor of 2.38 than for the installed kicker. The trapped resonant modes will not cause beam instabilities in the longitudinal and horizontal directions. There are two prominent resonant modes in the vertical plane, but as long as the TPS storage ring is operated with vertical chromaticities larger than two, the radiation damping can effectively suppress these vertical coupled bunch instabilities.

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