Proc. 13th International Beam Instrumentation Conference,Beijing JACoW Publishing
ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-TUP12

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OPTIMIZATION OF THE KICKER/BPM DESIGN WITH TAPERED STRIPLINES *

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Abstract

The injection kicker design exploiting striplines and linear taper connections of the striplines to the feedthroughs was proposed and has been successfully used in the DAΦNE electron-positron collider. Such a design has helped to reduce the device beam coupling impedance, to improve the uniformity of the deflecting electromagnetic fields and to provide better matching with the feedthroughs. In this paper we propose using nonlinear taper connections in order to decrease further the beam coupling impedance. We have performed numerical simulations and analytical studies of several nonlinear tapers demonstrating that the coupling impedance can be substantially reduced while keeping or even improving the transfer (signal) impedance of the stripline kickers (or BPM). The effect of the nonlinear tapering is particularly important for short stripline devices when the taper length is limited due to lack of available space and/or when the striplines are moved closer to the beam in order to increase the device shunt (signal) impedance.

INTRODUCTION

Stripline kickers are commonly used for injection in the storage rings and in the transverse feedback systems. The beam coupling impedances of the kickers, normally due to non smooth transitions from feedthroughs to striplines, show large contributions to the total impedance budget. In the high energy, low emittance light sources, the necessity of the short pulse bottom width and strong deflection field requires the kicker to have a short length and a small gap between the electrodes, respectively.

Besides, in the future machines a drastic reduction of the stored beam perturbation during the injection is mandatory to improve their performance. This is particularly important for the top-up operation in the modern synchrotron light sources. So the use of several advanced injection schemes has been proposed and elaborated in order to solve these problems and to overcome the limitations, one can see for example the review papers [1, 2]. These are swap-out injection, injection with a nonlinear magnet kicker, longitudinal on-axis injection, and a shared oscillation scheme using a fast kicker etc. For most of such schemes, kickers with short pulses with a pulse length comparable to the bunch spacing are required. Stripline kickers are a natural choice to satisfy this requirement. The beam coupling impedance of the striplines depends on the characteristic impedance of a transmission line formed by the strips and the vacuum chamber pipe Z_c, the strip length l and its radius r as well as on the strip coverage factor g, [3]

$$Z_{\parallel}(\omega) = Z_c \left(\frac{g}{2\pi}\right)^2 \left(\sin^2\frac{\omega l}{c} + j\sin\frac{\omega l}{c}\cos\frac{\omega l}{c}\right) \quad (1)$$

$$Z_{\perp}(\omega) = \frac{c}{r^2}\left(\frac{4}{g}\right)^2\left(\sin^2\frac{g}{2}\right)\left[\frac{Z_{\parallel}}{\omega}\right]. \quad (2)$$

However, these formulas are obtained in the approximation that all RF power induced by the impedance is dissipated in the external loadings. One has to take into account the other very important impedance contribution arising due to the beam-excited electromagnetic fields which do not couple to the loadings. For example, the parasitic HOMs can be trapped in the kicker structure. In addition, the abrupt transitions between the striplines and feedthroughs can be yet another large impedance source. As a possible solution for impedance reduction, the tapered stripline kickers, designed and successfully used for beam injection in DAΦNE [4], can be considered. The same design with the linear tapers has been proposed also for use in the ILC damping rings [5] and is considered for application in DIAMOND-II [6] and APS-U [7].

In this paper we investigate if an application of nonlinear tapers connecting the striplines to the feedthroughs can help decreasing further the beam coupling impedance. Indeed, in the past it was demonstrated that a considerable impedance reduction can be achieved by using the nonlinear tapering for azimuthally symmetric structures [8–10]. Similarly we study if the nonlinear tapers can be useful also for the striplines. However, differently from the azimuthally symmetric case, the striplines have a finite width that has to vary along the tapers in such a way to keep the stripline characteristic impedance constant. This is necessary in order to avoid multiple reflections and to match the striplines and the external feedthroughs.

Here we considered several typical nonlinear functions for the tapered part of the strips Figs.1 and 2.

$$h(z) = h_{min}(1 + (h_{max}/h_{min} - 1)z/L) \quad (3)$$

$$h(z) = h_{min}(h_{max}/h_{min})^{z/L} \quad (4)$$

$$h(z) = \frac{h_{min}}{(1 + ((h_{min}/h_{max})^{1/2} - 1)z/L)^2} \quad (5)$$

$$h(z) = \frac{h_{min}}{1 + ((h_{min}/h_{max}) - 1)z/L}, \quad (6)$$

with h(z) being the distance between strips and a beam along the beam path z.

* This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement [871072].
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ISBN: 978-3-95450-249-3 ISSN: 2673-5350 doi: 10.18429/JACoW-IBIC2024-TUP12

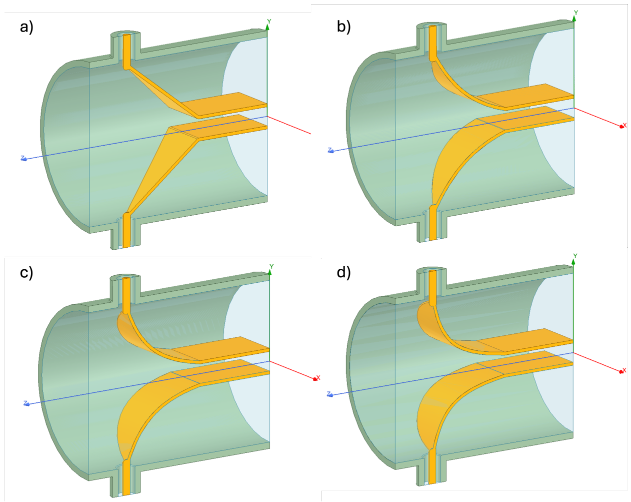

Figure 1: Simulated stripline structures a) linear taper, b) exponential taper, c) inverse square taper, d) hyperbolic taper.

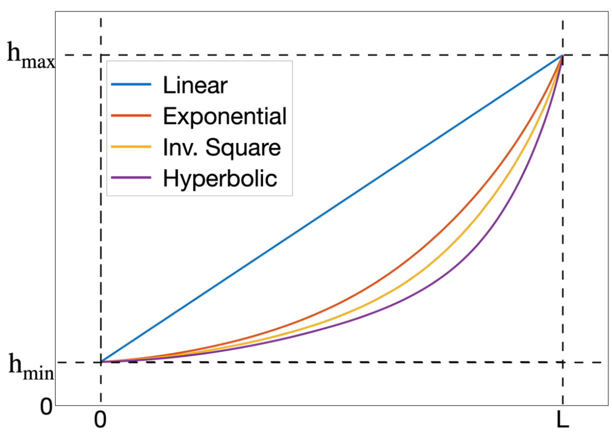

Figure 2: The functions used for tapered parts of the stripline: linear Eq. (3), exponential Eq. (4), inverse square Eq. (5), hyperbolic Eq. (6).

SIMULATIONS AND MODELLING

In order to evaluate the beam coupling impedance of discussed tapered stripline kicker designs, we utilized the numerical simulation tools. The simulations considered four different tapering functions: linear Eq. (3), exponential Eq. (4), inverse square Eq. (5), and hyperbolic Eq. (6). The taper length, gap between the strips, strip length and width were kept constant across all configurations. The vacuum chamber and striplines were modeled with realistic material properties and boundary conditions. Matching each stripline to the 50 Ω external transmission lines was crucial for optimal power transfer. This was achieved by choosing the stripline width and its distance from the vacuum chamber walls. Additionally, the positioning of the transitions from the stripline to the coaxial input/output lines were optimized to minimize reflection to the amplifier. In particular, the stripline dimensions along the tapered part have been chosen to keep the same characteristic impedance along beam path z.

The main parameters used in the simulations are summarized in Table 1.

Table 1: Simulation Parameters

Parameter	Value
Strip length (l)	200 mm
Taper length (L)	50 mm
Gap between strips (b)	12 mm
Characteristic impedance (Z_c)	50 Ω

The kicker's efficiency is characterized by the transverse shunt impedance parameter R_S', defined as the ratio of the square of the "transverse voltage" $V_\perp$ to twice the forward power P_{fw} at the kicker inputs [11–13]:

$$R_S' = \frac{V_\perp^2}{2P_{fw}}, \tag{7}$$

where $V_\perp$ is the integral of the transverse component of the Lorentz force per unit charge along the beam axis:

$$V_\perp = \int_0^l (\vec{E} + \vec{v} \times \vec{B}) \mathrm{d}z. \tag{8}$$

For a differential mode driven stripline transverse kicker, R_S' is calculated as:

$$R_S' = 2Z_c \left(\frac{g_{trans}}{kh}\right)^2 \sin^2(kl). \tag{9}$$

Here, $Z_c \approx 50$ is the transmission line's characteristic impedance, $g_{trans} \approx 1$ is the coverage factor, $k = \omega/c$, h is the stay clear radius (12 mm), and l the electrode length (≈200 mm).

Comparisons between discussed stripline designs transverse shunt impedance across wide frequency band are illustrated in Fig. 3, taking into account the electric ($E_y(z)$) and magnetic ($B_x(z)$) field components [14, 15].

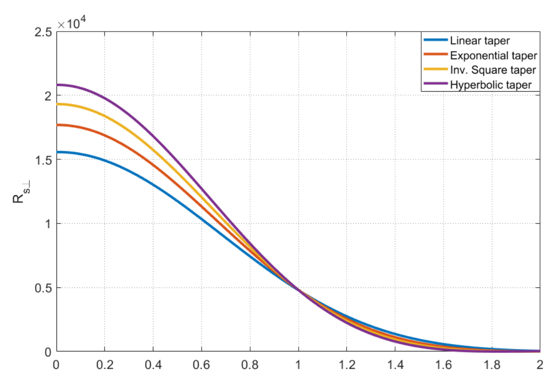

Figure 3: Transverse shunt impedance versus frequency.

RESULTS

The time-domain electromagnetic codes calculate the wake potentials due to a Gaussian bunch of given length. By

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the choice of appropriate boundary conditions at the symmetry planes of the structure, one can separately calculate monopole and dipolar wake potentials. Figure 4 presents the wake potentials resulting from a bunch with rms length of 5 mm.

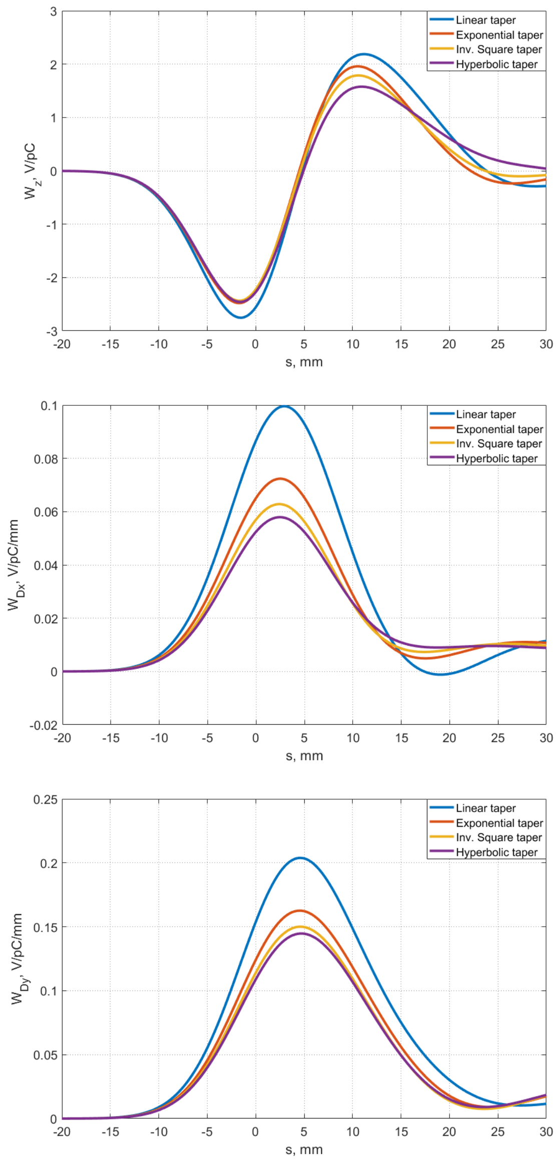

Figure 4: Longitudinal, dipole horizontal and vertical wake potentials respectively for different tapering functions.

Furthermore, the kick factor, a key quantity characterizing the transverse single bunch dynamics, was evaluated. For small aspect ratios, the dominant scaling with the bunch length is $\kappa_{\text{Dy}} \approx 1/\sigma_z$, expected in the inductive regime. However, depending on the aspect ratio of the gap between the strips and vacuum chamber radius, forming somewhat an ellipsoid shape, the kick factor may deviate from this behavior for shorter bunch lengths, indicative of an intermediate regime [9]. The resulting loss and kick factors for different taper functions are presented in Tables 2 and 3.

Table 2: Loss Factors

	Wake-Loss-Factor	Unit
Linear:	1.380018e+00	V/pC
Exponential:	1.196212e+00	V/pC
Inverse Square:	1.203277e+00	V/pC
Hyperbolic:	1.209588e+00	V/pC

Table 3: Kick Factors

	Kick-Factor x	**Kick-Factor y**	Unit
Linear:	-6.840428e-02	-1.327580e-01	V/pC/mm
Exponential:	-5.037268e-02	-1.068364e-01	V/pC/mm
Inverse Square:	-4.401820e-02	-9.837109e-02	V/pC/mm
Hyperbolic:	-4.080152e-02	-9.439061e-02	V/pC/mm

These results highlight the importance of the geometric design of stripline kickers in minimizing beam coupling impedance and optimizing kicker efficiency. The choice of tapering function and the aspect ratio of the structure significantly influence the impedance characteristics and the resulting kick factors.

CONCLUSION

Previous studies have employed linear or exponential taperings for striplines to improve functionality and directivity [16–18]. In this paper, these studies were extended by presenting a comprehensive analysis of beam induced wake fileds.

The results demonstrate that for the stripline devices (kickers, BPMs) with the same total strip length and gap between the strips and having the same characteristic impedance, the nonlinear tapering can add several beneficial features. In particular, it can enhance the stripline functionality, by increasing the transverse shunt impedance and providing better characteristic impedance matching along the strips. In addition, the nonlinear tapering results in a significant reduction of the beam coupling impedance and respective loss and kick factors.

Overall, the choice of tapering function and structure aspect ratio significantly impacts impedance characteristics and kicker efficiency. Nonlinear tapers are especially beneficial for compact stripline devices with space constraints, offering a promising solution for advanced accelerator facilities requiring minimized beam perturbation during injection.

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