STRIPLINES FOR CLIC PRE-DAMPING AND DAMPING RINGS*

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Abstract

The Compact Linear Collider (CLIC) study explores the scheme for an electron-positron collider with high luminosity and a nominal centre-of-mass energy of 3 TeV: CLIC will complement LHC physics in the multi-TeV range. The CLIC design relies on the presence of Pre-Damping Rings (PDR) and Damping Rings (DR) to achieve, through synchrotron radiation, the very low emittance needed to fulfill the luminosity requirements. The specifications for the kicker systems are very challenging and include very low beam coupling impedance and excellent field homogeneity: striplines have been chosen for the kicker elements. Analytical calculations have been carried out to determine the effect of tapering upon the high frequency beam coupling impedance. In addition detailed numerical modeling of the field homogeneity has been performed and the sensitivity of the homogeneity to various parameters, including stripline cross-section, have been studied. This paper presents the main conclusions of the beam impedance calculations and field homogeneity predictions.

INTRODUCTION

Kickers are required to inject beam into and extract beam from the PDR and DR. The demanding specifications for the CLIC PDR and DR are shown in Table 1 [1]. A stripline kicker consists of two, parallel, metallic electrodes connected, at each end, to the external circuit by coaxial feedthroughs. Each stripline is driven to equal but opposite potential. Each of the stripline plates with its adjacent ground planes (beam pipe walls) forms a transmission line for TEM waves [2].

The DR extraction kicker has the most demanding specifications for field homogeneity, therefore only the results for this kicker will be shown in the following.

Table 1: Specifications for the CLIC PDR and DR

Parameter	**PDR**	**DR**
Beam energy (GeV)	2.86	2.86
Deflection angle (mrad)	2	1.5
Aperture (mm)	40	20
Field rise and fall time (ns)	700	700
Pulse flat top duration (ns)	~ 160	~ 160
Flat top reproducibility	$\pm 1 \times 10^{-4}$	$\pm 1 \times 10^{-4}$
Injection stability	$\pm 2 \times 10^{-2}$	$\pm 2 \times 10^{-3}$
Extraction stability	$\pm 2 \times 10^{-3}$	$\pm 2 \times 10^{-4}$
Injection field uniformity(%)	$\pm 0.1_A$	$\pm 0.1_A$
Extraction field uniformity(%)	$\pm 0.1_A$	$\pm 0.01_B$
Repetition rate (Hz)	50	50
Available length (m)	~ 3.4	~ 1.7
Vacuum (mbar)	10^{-10}	10^{-10}

$_A$ over 3.5 mm radius
$_B$ over 1 mm radius

CHARACTERISTIC IMPEDANCE AND FIELD HOMOGENEITY OPTIMIZATION

The kicker cross section defines the characteristic impedance of the striplines and the homogeneity of the field inside the aperture. Therefore, the goal of these studies is to optimize the kicker cross section dimensions in order to achieve a 50 Ω characteristic impedance and the field homogeneity required.

Both characteristic impedance and field homogeneity have been calculated by using HFSS. The cross section optimization has been carried out by assuming an infinite kicker length, by modeling the cross section as a thin slice of the stripline kicker cross section, with adequate boundary conditions, in order to reduce the time of simulation. HFFS is a frequency domain code, therefore the simulation is run at the frequency of the fundamental mode of the pulse voltage applied to the kicker. It is possible to calculate the characteristic impedance using electrostatic simulations, because the characteristic impedance is a geometric property, which is independent of frequency.

By making use of symmetry in the structure, and applying appropriate boundary conditions, a half or a quarter of the structure can be simulated - substantially reducing the simulation time required. Both a half and quarter geometries have been modelled: the characteristic impedances calculated are $Z_0 = 49.494\ \Omega$ and $Z_0 = 99.037\ \Omega$, respectively. This result is according with the basic circuit theory, as two equal capacitors are in parallel.

The variables of the impedance and field homogeneity optimization process are the geometric dimensions of the cross section, which are presented in Fig. 1.

There is an analytical approximation for the impedance value in the case of a stripline with round chamber and plate type electrode, which is:

$$Z_0 \approx \frac{377}{\frac{\pi}{2} - \delta} ln \frac{a}{b}$$

where a is the inside radius of the vacuum chamber, b is the electrode height, and δ is the edge angle in rad. This approximation comes from the transmission line parameters of a coaxial line [3].

Two types of vacuum chamber have been studied, cylindrical and racetrack vacuum chambers, see Fig. 2. From

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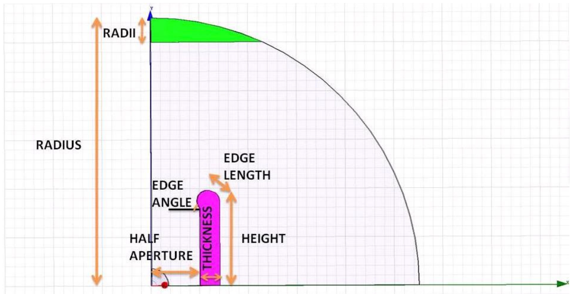

Figure 1: Geometric parameters for a cylindrical vacuum chamber and flat electrodes.

the beam impedance point of view, the racetrack vacuum chamber is the most suitable, because the change in the kicker geometry is not as abrupt as in the cylindrical case. However, the cylindrical vacuum chamber is the easiest chamber to manufacture. For that reason, the racetrack vacuum chamber is actually a cylindrical vacuum chamber with a plate in both the top and bottom (Fig. 2). These plates are connected to the vacuum chamber, so that they are at ground potential.

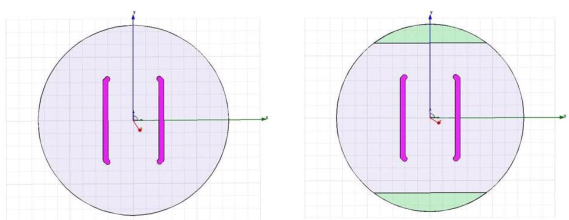

Figure 2: Flat electrodes in a cylindrical vacuum chamber (left) and in a racetrack type vacuum chamber (right).

The optimum values found for the geometric parameters of the DR kicker cross section are summarized in Table 2.

Table 2: Optimum Values for the Geometric Parameters of the DR Kickers

Vacuum chamber	Value	Electrodes	Value
Aperture	20 mm	Thickness	4 mm
Radius	55 mm	Height	38 mm
Radii	5 mm	Edge angle	70°
		Edge length	4 mm

For this geometry the maximum electric field has been calculated: this value should be below the Kilpatrick limit. The Kilpatrick limit gives the maximum electric field that can be achieved avoiding RF breakdown at the chamber walls, and can be calculated with the following relation:

$$f(MHz) = 1.64E^2 e^{-\frac{8.5}{E}}$$

where E is the Kilpatrick electric field in MV/m. The rise and fall times are 700 ns; which gives a Kilpatrick limit of 2.82 MV/m maximum for the electric field. In the simulations, the maximum electric field at the chamber walls is 1.11 kV/m for the cylindrical vacuum chamber, and 0.78 kV/m for the racetrack case. Therefore, there is no risk of RF breakdown, at the chamber walls, in the considered geometries.

Experience has shown that the maximum electrical field at the stripines plates should be less than 5 MV/m to avoid breakdown: the maximum predicted field is 1.33 MV/m. From the values for the cylindrical vacuum chamber, and by changing one by one the optimum parameters with a maximum variation of $\pm 25\%$, with $\pm 5\%$ steps, we have studied the sensitivity of the characteristic impedance and field homogeneity to all these parameters. The results are shown in Fig. 3 for the characteristic impedance and in Fig. 4 for the field homogeneity.

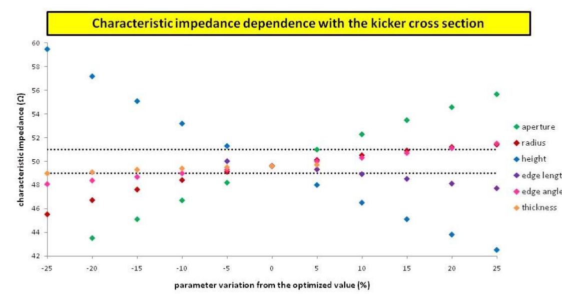

Figure 3: Characteristic impedance sensitivity to the cross section parameters variation.

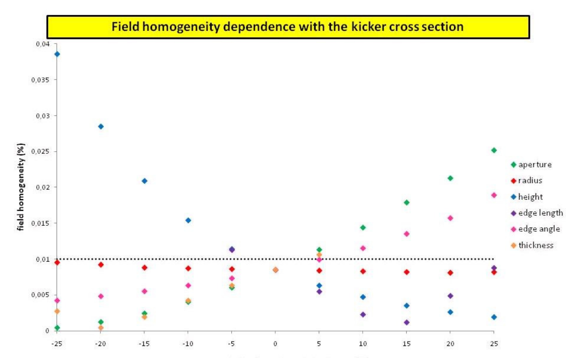

Figure 4: Field homogeneity sensitivity to the cross section parameters variation.

The characteristic impedance is sensitive to the vacuum chamber radius, the aperture and the electrode height. By increasing the vacuum chamber radius and the aperture, the characteristic impedance increases as well, while by increasing the electrode height, i.e. the electrode area, the characteristic impedance decreases. With the other electrode parameters the dependence is not important, due to the fact that there is little change in the electrode area.

In the case of the field homogeneity, there is an important dependence with the electrode height and the edge angle, i.e. the shape of the electrode, because it defines the shape of the electric field lines between both electrodes. Also the kicker aperture changes the field homogeneity; for a good homogeneity a small aperture is needed.

BEAM IMPEDANCE OPTIMIZATION: FIRST RESULTS

The beam impedance defines the interaction of the beam with the kicker, resulting in beam energy lost and a beam shape perturbation. Low beam impedance in the kicker represents a low risk of beam instabilities [2]. To reduce the beam impedance, an optimum tapering of the electrodes is needed. Tapering refers to a reduction in the distance between the electrodes and the beam pipe, in order to smooth the change of geometry seen by the beam when passing through the kicker aperture.

There is an analytical approximation for the longitudinal and transverse beam impedance in the case of both untapered and tapered stripline kicker. For the longitudinal beam impedance the analytical equations are [4, 5, 6]:

$$Z_{\parallel} \propto Z_c \left(\frac{\phi_0}{2\pi}\right)^2 \left[2\sin^2\left(\frac{\omega L}{c}\right) - i \sin\left(\frac{2\omega L}{c}\right)\right]$$

$$Z_{\parallel tapered} = Z_{\parallel}\left[\frac{\sin^2\left(\frac{\omega l}{c}\right)}{\left(\frac{\omega l}{c}\right)^2}\right]$$

where L is the kicker length, Z_c the common mode characteristic impedance of each stripline and ϕ_0 the fraction of image current intersected by each stripline, which corresponds to the coverage angle in the case of curved electrodes.

By using CST Particle Studio, the longitudinal beam impedance has been studied, and the initial results have been compared with the analytical equation (see Figs. 5 and 6).

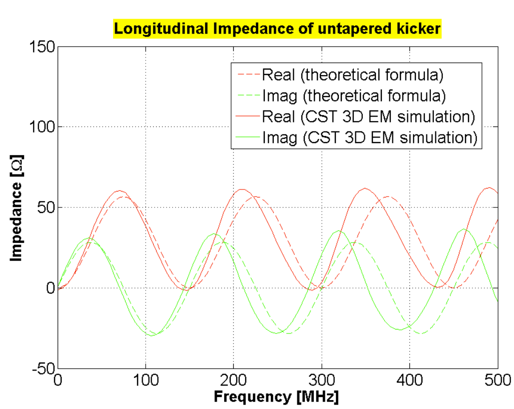

Figure 5: Longitudinal beam impedance: comparison of analytical equations for the untapered striplines with CST prediction.

In both cases, the comparison of the analytical equations with CST predictions is quite good. The main source of errors are presently thought to be due to the definition of the coverage angle used (effects magnitude) and effective length (effects frequency of maxima and minima). The transverse beam impedance case has yet to be studied.

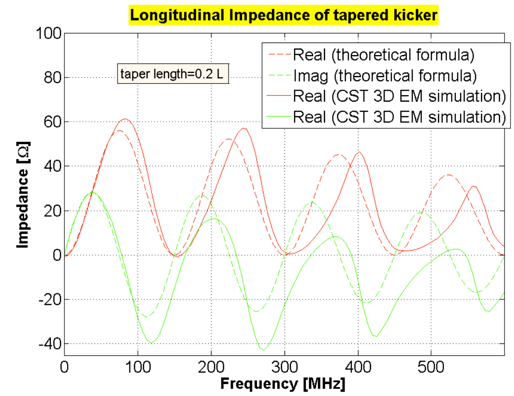

Figure 6: Longitudinal beam impedance: comparison of analytical equations for the tapered striplines with CST prediction.

CONCLUSIONS

The kicker design for the CLIC damping ring has been presented in this paper. By using HFSS simulations the stripline kicker cross section has been optimized in order to obtain the required characteristic impedance and field homogeneity.

3D models in CST Particle Studio have been used to study the longitudinal beam impedance. Initial predictions, for both untapered and tapered striplines, compare well with analytical equations.

Once the transverse beam impedance has been studied, the next step will be to optimize the tapering factor in order to decrease the beam impedance and calculate the wakefields, which will be useful for beam dynamics issues.

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