REVIEW ON THE EFFECTS OF CHARACTERISTIC IMPEDANCE MISMATCHING IN A STRIPLINE KICKER

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Abstract

A stripline kicker operates as two coupled transmission lines, with two TEM operating modes, known as odd and even modes. The characteristic impedance of these two modes is generally different, both only tend to the same value either when the electrodes are widely separated or when the electrodes are very close to the beam pipe wall. In all other cases, the even mode characteristic impedance is always higher than the odd mode characteristic impedance. The specifications required for a kicker operating in a low emittance ring are usually very challenging. In this situation it is desirable to match the even mode characteristic impedance of the striplines to the resistance of their termination. However a mismatched odd mode impedance can significantly influence the striplines performance. This paper presents predictions for the influence of the odd mode characteristic impedance upon the contribution of each field component, electric and magnetic, to the deflection angle. In addition, the variation of the characteristic impedance and field homogeneity with frequency are presented.

INTRODUCTION

Two main sources of characteristic impedance mismatch must be considered in the striplines for beam extraction from the CLIC Damping Rings (DRs): (1) the variation of the characteristic impedance with frequency, and (2) the odd mode characteristic impedance mismatch between the striplines and the termination impedance. The influence of these upon the deflection angle, as well as the effect of frequency upon the field homogeneity, will be explained in the following.

HIGH AND LOW FREQUENCY EFFECTS

The characteristic impedance mismatch due to frequency effects has been studied by calculating both the odd and even mode characteristic impedances for frequencies up to 100 MHz. The impedance is calculated from the predicted inductance and capacitance per unit length of the striplines, for each operating mode, using Opera2D [1]. For the electrostatic studies, a voltage of ±12.5 kV is assigned to the electrodes, whereas for the AC studies an average current density for the electrodes, with a value of 3.6 A/mm^2, has been defined. This current density has been calculated considering that the striplines are terminated in 50 Ω [2]: hence the pulse current is 250 A. In addition, the electrodes have a simulated conductivity of 3.03×10^7 S/m, to represent the Al6063 aluminium alloy used in the manufacturing of the electrodes. Predictions are shown in Fig. 1.

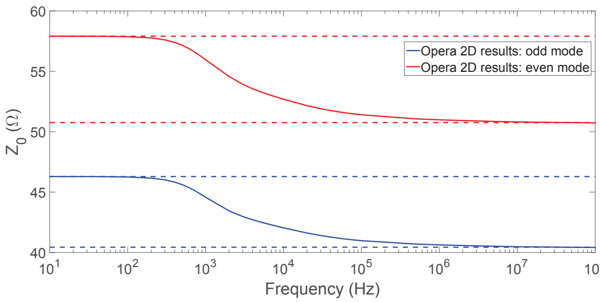

Figure 1: Odd (blue) and even (red) mode characteristic impedances versus frequency. The dashed lines show the upper and lower values.

At low frequencies, and up to approximately 100 Hz, the characteristic impedance is almost constant at its highest value. A general equation for calculating characteristic impedance is $Z_0 = \sqrt{L/C}$, where L is the total inductance per unit length and C is the capacitance per unit length, calculated from the predicted energy stored with the AC magnetic and electrostatic solvers of Opera2D, respectively. At higher frequencies, from approximately 3 MHz, the characteristic impedance reaches its minimum value. This value can be also analytically calculated by $Z_0 = 1/cC$, where c is the speed of light. This equation was previously used to study the characteristic impedance of the stripline kicker for beam extraction from the CLIC DRs [2]. The increase of the characteristic impedance at low frequencies, by 14.5 % in both cases, is due to the effect of the internal inductance of the electrodes, which increases the total inductance.

At high frequencies, the distribution of current is caused by both skin effect and proximity effect and hence, in the stripline kicker, the current is only distributed on the surface of the electrodes, as shown in Fig. 2, bottom. A frequency of 500 kHz is chosen as it approximately corresponds to the fundamental frequency of a pulse flat-top of 1 μs, which is the required duration for the 1 GHz specification for the extraction kicker from the CLIC DRs [2]. At DC and low frequencies, the current density is uniform and independent of the material properties (Fig. 2, top): in this case, the internal inductance of the conductors influences the characteristic impedance.

Deflection Angle

For the CLIC DR striplines, the deflection angles have been studied as a function of frequency. The equations used for calculating the deflection angle due to the electric and magnetic fields are $\alpha_E = E(0,0)L/E_b$ and $\alpha_B = cB(0,0)L/E_b$, respectively, where $E(0,0)$ and $B(0,0)$ are the electric and magnetic fields calculated, at the centre of the aperture, using Opera2D, $L = 1.7$ m is the striplines

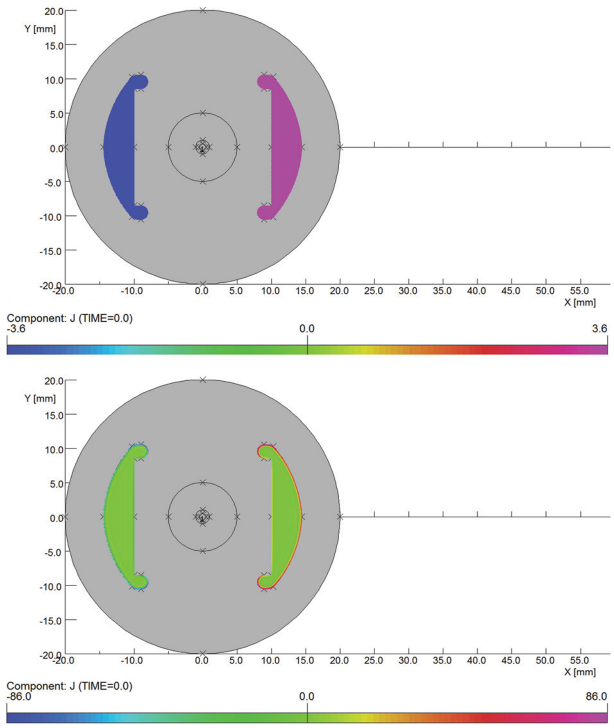

Figure 2: Current density distribution (in A/mm^2) for the optimum stripline geometry at two different frequencies: 50 Hz (top) and 500 kHz (bottom).

length, and E_b = 2.86 GeV is the beam energy for the CLIC DRs. The results are shown in Fig. 3.

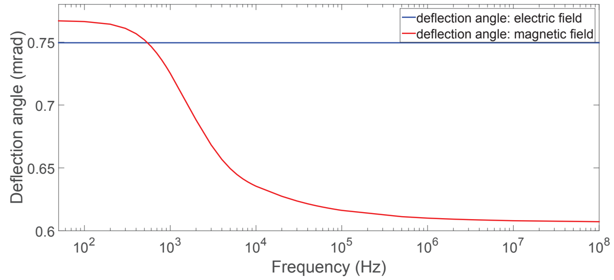

Figure 3: Deflection angle resulting from the predicted electric and magnetic fields versus frequency, for the optimum geometry of the striplines (±12.5 kV, ±250 A).

The electric field contribution to the deflection angle is constant at 0.75 mrad (taken from an electrostatic simulation), whereas the magnetic field contribution decreases from a value slightly larger than 0.76 mrad at 50 Hz, to a value of approximately 0.6 mrad, at higher frequencies: the shape of the magnetic deflection curve, versus frequency, is similar to the shape of the curves shown in Fig. 1.

Field Homogeneity

The uniformity of the electromagnetic field was originally studied considering an electrostatic problem and assuming that the uniformity of the electric and the magnetic field would be the same [2]. However, the magnitude of the magnetic field has now been shown to change with frequency (Fig. 3), hence it is necessary to also study the magnetic field homogeneity as a function of frequency.

The maximum field inhomogeneity allowed is ± 0.01%, over 1 mm radius, although a radius of 0.5 mm could also be accepted from beam optics considerations [3]. The magnetic field uniformity at different frequencies, for the optimized stripline geometry [2], has been studied with Opera2D, throughout two circle areas of 1 mm and 0.5 mm radius, and the results are shown in Fig. 4.

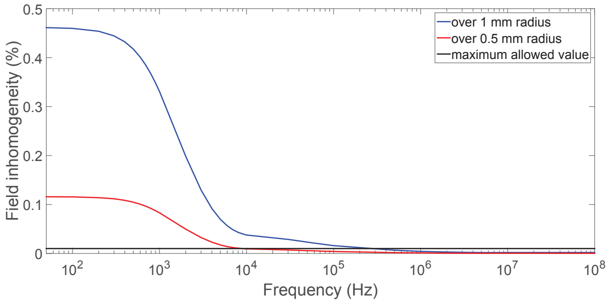

Figure 4: Magnetic field inhomogeneity versus frequency, over 1 mm radius (blue) and 0.5 mm radius (red). The maximum allowed inhomogeneity, ±0.01%, is shown in black.

When considering 1 mm radius, the field uniformity requirement is achieved for frequencies above approximately 500 kHz. If the good field region is reduced to 0.5 mm radius, the field uniformity requirement is achieved above 10 kHz.

The horizontal electric and vertical magnetic fields at different radii between 1 mm and 0.2 mm, in the centre of the striplines aperture, have been summed in order to calculate the inhomogeneity of the total field. Results are shown in Fig. 5, for a frequency of 500 kHz, for an arc angle from 0° (horizontal line) to 360°.

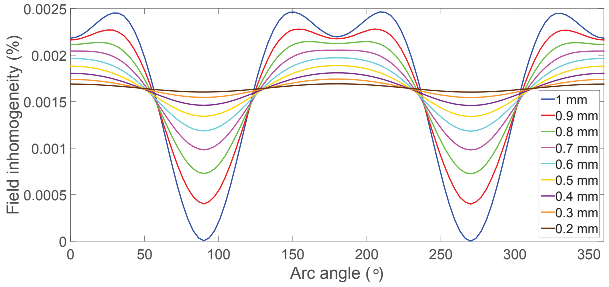

Figure 5: Total electromagnetic field inhomogeneity as a function of the arc angle, for a frequency of 500 kHz.

For an AC frequency of 500 kHz, the field inhomogeneity is larger at bigger radii: however the field inhomogeneity around the arc is always below the maximum allowed value, ±0.01%. In addition, a relatively small reduction in the radius considered results in a significant decrease in the field inhomogeneity.

ODD MODE IMPEDANCE MISMATCHING EFFECTS

The characteristic impedance of the CLIC DR striplines, at a frequency of 500 kHz, are the following: 40.5 Ω for the odd mode and 50 Ω for the even mode, whereas the striplines are terminated by resistors of 50 Ω.

For stripline kickers, both the electric and magnetic fields contribute to kick the beam, and the electric and magnetic contributions to the deflection angle are generally considered to be equal [2]. In the case of the stripline kicker for beam extraction from the CLIC DRs, the total required deflection angle is 1.5 mrad, and therefore, the deflection produced by the electric and the magnetic fields have historically been assumed to be 0.75 mrad each. However, the impedance mismatch between the striplines and the terminations, in the odd mode, has an impact upon the magnetic field contribution to the kick angle. To theoretically study this, the deflection angles have been calculated for an electrostatic case (α_E) and for an AC magnetic case (α_B) at 500 kHz, as a function of the odd mode characteristic impedance, for 50 Ω terminations: the change of impedance is modelled by modifying the inside radius of the striplines beam pipe.

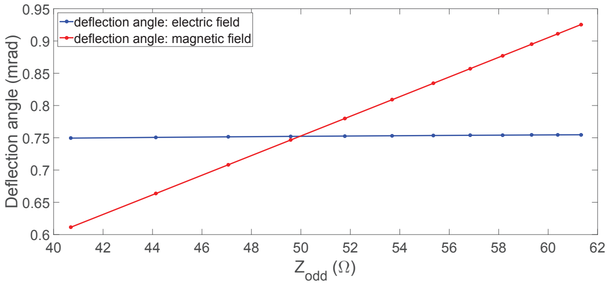

Figure 6: Deflection angle versus the odd mode characteristic impedance of the striplines, at 500 kHz, for 50 Ω terminations: the current through the striplines is ±250 A.

Figure 6 shows the electric and magnetic deflection versus the odd mode characteristic impedance of the striplines, at a frequency of 500 kHz. The deflection due to the predicted electric field barely changes; however, the deflection due to the predicted magnetic field changes significantly, increasing in proportion to the characteristic impedance, for a given magnitude of current. Both deflection angles are equal only when the odd mode characteristic impedance of the striplines has the same value as the termination impedance, which is 50 Ω.

At 500 kHz, the ratio between the deflection angle due to the electric and magnetic fields is equal to the ratio between the termination impedance Z_L and the odd mode characteristic impedance, as shown in Eq. (1):

$$\frac{\alpha_E}{\alpha_B} = \frac{Z_L}{Z_{odd}} \tag{1}$$

Hence, for a stripline kicker not perfectly matched in the odd mode, the electric and magnetic field magnitudes and their contribution to the kick angle are no longer equal.

Figure 7 shows the magnetic field contribution to the deflection angle (also plotted in Fig. 3) and the magnetic contribution to the deflection angle calculated using Eq. (1). In this equation, α_E = 0.75 mrad, Z_L = 50 Ω, and the Z_{odd} values are taken from the data shown in Fig. 1. Thus Eq. (1) is valid only at relatively high frequencies (from approximately 300 kHz).

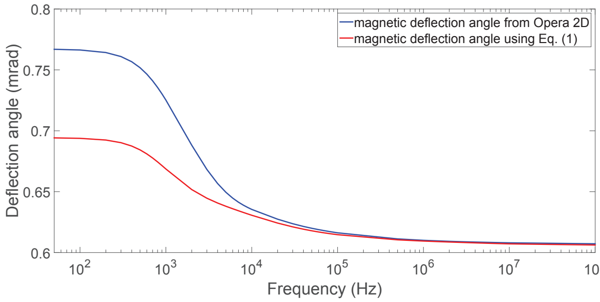

Figure 7: Comparison of the deflection angle due to the magnetic field, versus frequency, calculated with Opera2D and also by scaling the odd mode impedance shown in Fig. 1 using Eq. (1).

In order to achieve the required deflection angle of 0.75 mrad for the magnetic field, given the relatively high frequency content of a pulse, the odd mode characteristic impedance of the striplines must be matched by the termination resistance. A method has been shown in [2] to match the even mode impedance to 50 Ω and the odd mode impedance to 40.5 Ω, by connecting a resistance of 425 Ω between the output of the electrodes. However the output current to be supplied by the inductive adder [4] will be increased from 250 A to approximately 310 A.

CONCLUSIONS

The influence of the odd mode characteristic impedance upon the contribution of each field component, electric and magnetic, to the deflection angle has been studied. In addition, the variation of the characteristic impedance and field homogeneity with frequency have been presented. Results show that odd mode impedance matching is required in order to have the same electric and magnetic contribution to the kick angle at high frequencies: hence the proposed matching network shown in [2] will be implemented. In addition, studies of the deflection angle and field homogeneity along different arc radii, at the centre of the striplines aperture, have been carried out and good preliminary results obtained. Transient simulations, to study the time dependence of the magnitude of the magnetic field pulse, are planned: the required output pulse shape from the inductive adder, to compensate the frequency dependence, will be derived. In addition a study of the field homogeneity and the magnetic deflection throughout the pulse will be carried out.

REFERENCES

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