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INVESTIGATION OF PLANAR PICK-UP AND KICKER ELECTRODES FOR STOCHASTIC COOLING

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The success of stochastic cooling crucially depends on the interaction between the beam and high frequency devices for detection (pick-up electrodes) and deflection (kicker electrodes). This contribution shows the theoretical investigation of a planar electrode to be used for stochastic cooling of secondary particles with a beta of 0.83. The coupling to the beam is realized by a slotline. Transition networks are added to extract the signal. The detailed investigation is performed via a numerical electromagnetic field analysis. The longitudinal kick of the deflectors is calculated as a function of the beam position and scaled to the applied voltage. According to the Panofsky-Wenzel theorem the transverse kick is obtained simultaneously. The electromagnetic properties of the discussed electrode are compared to existing ones as currently in use in the ESR storage ring (GSI, Darmstadt).

1 INTRODUCTION

Stochastic cooling [1] is a very efficient method to decrease the phase space of a coasting (or even bunched) beam. Electrodes are used in stochastic cooling to detect a signal, which gives information about the beam position (pick-up), as well as to change the beam momentum with an amplified pick-up signal (kicker). The interaction of the electrodes and the beam is realized by coupling of electromagnetic fields. Normally pick-up and kicker electrodes are constructed in the same manner, and thus obey the reciprocity theorem described in Section 2.

One typical design of such electrodes is a so called ”quarter-wave loop electrode” [2], [3] as currently used in the ESR storage ring at GSI, Darmstadt. The quarter-wave loop performance is well known, but the construction is mechanically complicated. Hence it is desirable to find a kind of electrode which is easy to build up and shows competitive electromagnetic characteristics. For that purpose a planar structure as shown in Figure 1 is discussed. While the quarter-wave loop performance can still be predicted with theoretical approximations, the discussed electrode must be designed and investigated with numerical tools. How to perform a detailed investigation via a three-dimensional fullwave analysis is exemplified in this paper.

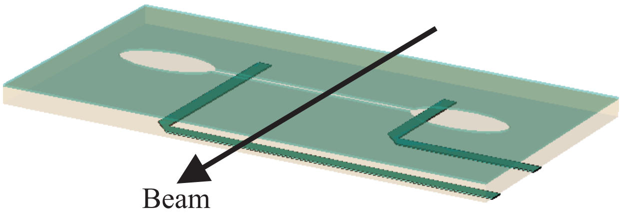

Figure 1: Planar Pick-Up/Kicker electrode with a microstrip/slotline transition using quarter wave transformers.

2 PICK-UPS AND KICKERS

Pick-Up and kicker characteristics are related to each other by the reciprocity theorem of electromagnetic field theory [5]

$$U_{PU} = -\frac{Z_L}{2U_{in}} \int_V \vec{E}_k(\vec{r}) \cdot \vec{J}_s(\vec{r}) dV \quad . \qquad (1)$$

It states that the pick-up output voltage U_{PU} excited by a current density $\vec{J}_s$ of the beam is directly related to the input voltage U_{in} applied to a kicker which generates the field $\vec{E}_k$. Z_L is the line impedance of the input and output line respectively. In (1) and the following all values are magnitudes of complex numbers. It must be kept in mind that equation (1) only holds if no travelling wave passes the boundaries of the part of the beam tube considered. Since pick-ups and kickers are related to each other, only one analysis is needed to determine the characteristics of both. In this paper only the kicker characteristics will be presented.

The longitudinal momentum change of a particle passing an electric field is described by

$$\triangle p_l(x,y) = \frac{q}{v} \int E_z(\vec{r})\, e^{jkz} dz \quad , k = \frac{\omega}{v} \qquad (2)$$

assuming that v is constant over the whole integration path [2]. According to the Panofsky-Wenzel theorem [6] the transverse component can be described by

$$\triangle \vec{p}_t(x,y) = -\frac{v}{j\omega} \text{grad}_{\,t}(\triangle p_l) + C \quad . \qquad (3)$$

where the constant C vanishes if no electric field exists at the boundaries of the integration path. As main consequence, the transverse momentum change is fully described

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by the transverse gradient of the longitudinal momentum change [6]. Thus, it is sufficient to find the so called longitudinal kicker voltage

$$U_k(x, y, \omega) = \int E_z(\vec{r})\, e^{jkz} dz \qquad (4)$$

to know the transverse and longitudinal performance of the kicker.

As sensitivity, we introduce the relation of the kicker voltage U_k and the input voltage applied to a kicker U_{in}.

$$S(x, y, \omega) = \frac{U_k(x, y, \omega)}{U_{in}(\omega)} \qquad (5)$$

From (2) and (3), the sensitivity must be maximized to gain the largest momentum change. Because of the need to build up a series of pick-up or kicker electrodes, the actual figure of merit is the integrated scaled sensitivity

$$S' = \frac{\int S df}{L} \quad , \quad f = \omega/2\pi \qquad (6)$$

where L denotes the physical length of the pick-up or kicker structure in the beam direction. The limits of the integration are given by the desired application bandwidth, which is typically limited by the bandwidth of the amplifier. In case of the quarter-wave loop, the simulated value of S' is 28.37 GHz/m.

3 PLANAR ELECTRODE DESIGN

The design of the planar electrode is based on the idea of using a slotline as coupling device, which has already been described in [4]. A transition as proposed in [7] is added to convert a microstrip mode pattern into a slotline mode pattern.

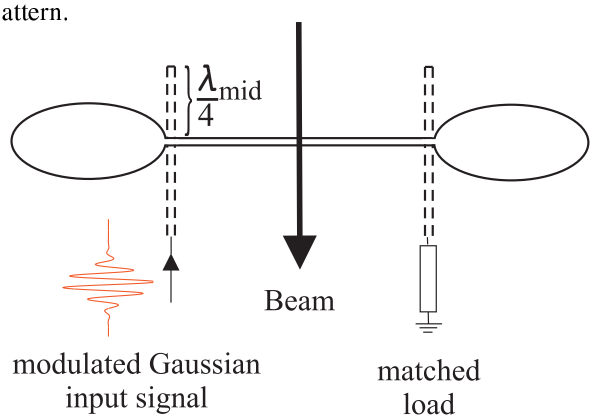

Figure 2: Principle of the Pick-Up/Kicker structure.

On the lower side of a substrate there are two microstrip lines (dashed) with an open end (Figure 2). The upper side of the substrate is coated with metal except the area surrounded by the solid line. This represents a slotline with open ends at both sides. The length of the overlapping open ended microstrip line is $\lambda_{mid}/4$ where λ_{mid} is the medium specific wave length of an electromagnetic wave propagating on this microstrip line. Due to the length of the overlapping line the open end is transformed into a virtual short, which connects microstrip and slotline. One of the microstrip lines serves for excitation while the other is terminated with a resistor matching the line impedance. The structure is crossed by the beam above the slotline.

For optimization of this design there are three parameters, the radii of the slotline open, the width of the slotline and the length of the overlapping microstrip line. The width of the microstrip line is not used for optimization purposes, because it is adjusted to 50 Ω. However, in principle the optimization could also be extended to this width. All optimization parameters are primarily modified to achieve a small reflection coefficient at the input line.

4 SIMULATION APPROACH

The numerical analysis is performed using the commercial software tool CST Microwave Studio [8]. This package is based on the Finite Integration Technique (FIT) [9]. The most efficient approach for this problem is solving the three dimensional electromagnetic field in the time domain. Here, a broadband solution is obtained in one run, after a Fourier Transform has been applied to the time signals.

The structure is excited by a microstrip mode pattern with a Gaussian modulated amplitude. Additionally the lines are terminated with their specific line impedance. The fields are monitored in the whole computational domain for one or more predefined frequencies again by use of a Discrete Fourier Transform, now applied to field components.

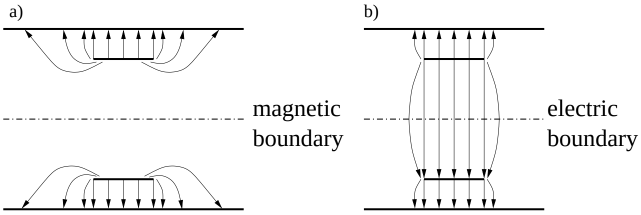

Figure 3: a) Electric field pattern of the even mode. b) Electric field pattern of the odd mode.

In Figure 3 the electric field pattern of the quarter-wave loop example for different excitation modes are shown. As becomes evident, the electric field of a kicker in even mode shows a symmetry which can be described by a magnetic wall. The electric field pattern in odd mode shows an electric wall-like symmetry. Thus, the structure to be calculated can be reduced to only one pick-up/kicker electrode by use of these symmetry conditions. The calculation domain is then terminated with absorbing boundary conditions and one magnetic or electric boundary condition, respectively. In the following, we focus the analysis on the even mode.

For this example the computing time is about 18 minutes on a PC (2 × 1 GHz, 256MB RAM), while the mesh contains 129,895 grid points. The integration which is needed for U_k and S' is finally performed in the postprocessing within a few seconds.

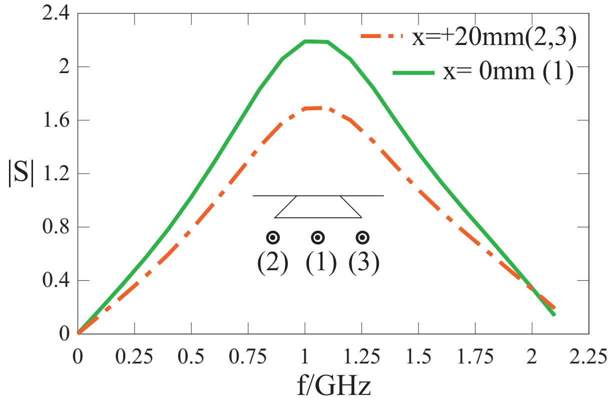

Figure 4: Simulated sensitivity magnitude at different coupling points for a single quarter-wave loop electrode.

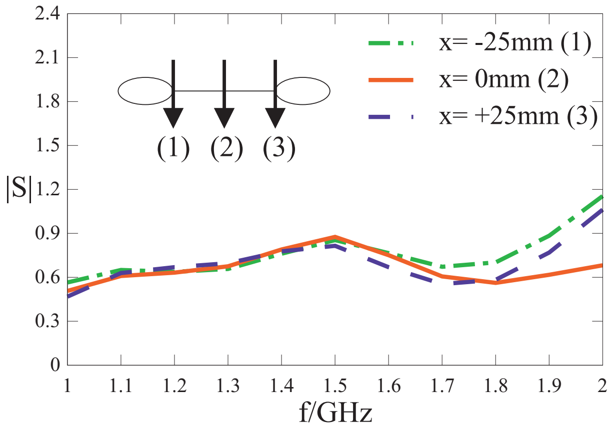

Figure 5: Simulated magnitude of the sensitivity at different coupling points for the planar design.

5 NUMERICAL RESULTS

To validate the simulation approach, it is tested with the well known sensitivity of a quarter-wave electrode. The performance of $|S|$ dependent on the frequency is shown in Figure 4 for different horizontal positions of the beam. The vertical beam/electrode distance remains 10 mm. The results are sinusoidal which agrees with the theoretical predictions in [2] and [10].

The magnitude of the sensitivity of the planar design is shown in Figure 5 for $\beta = 0.83$. Again the curves denote different horizontal positions of the beam and the vertical distance is 10 mm. As can be seen, the frequency response of the magnitude of the sensitivity is nearly constant over the frequency range 1-2 GHz and there is only a weak dependence on the horizontal position of the beam. A second sensitivity calculation with a $\beta = 0.97$ shows almost the same results. Therefore the structure can be applied to different β in this frequency range without significant change in its performance. However, the magnitude of the sensitivity is lower compared to the quarter-wave loop electrode, which can be qualitatively explained by the different electromagnetic coupling mechanisms. In principle, in the quarter-wave electrode the coupling takes place twice — at each edge of the structure. In case of the planar design there is only one coupling interface —at the slot.

In the first design stage a sensitivity of $S' = 14.7$ GHz/m has been achieved, and there are still several possibilities of improvement left. For instance, the length can be minimized by bending the open stub of the transition network. Additionally it is possible to make use of the signal propagation to both ends simultaneously, yielding an increase of the effective S' by a factor of $\sqrt{2}$.

6 CONCLUSION

In this paper, a planar electrode design for pick-ups and kickers is discussed, which is mechanically robust. The device is investigated by a fullwave analysis in time domain using the Finite Integration Technique. As could be seen, the planar design still has to be optimized to be competitive with the familiar quarter-wave loop electrode. However, the new device can be used with different β. Further steps will be the simulation and simultaneous measurements of a beam simulation model. On this basis the simulation results of the pick-up/kicker electrode will be compared to measurements.

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