NOVEL STOCHASTIC COOLING PICKUPS / KICKERS

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Abstract

This paper presents two novel planar stochastic cooling electrodes: the planar quarter-wave loop and the half-wave slot. The difference mode current gain was measured. A model of the electrodes is developed that closely simulates the measurements. For the mechanical tolerances required at high frequencies, planar structures are much easier to fabricate than 3 dimensional electrodes. The half-wave slot pickup has higher gain per unit length and covers a wider aperture than quarter-wave loops.

Introduction

Traditionally, directional coupled loops have been used for all stochastic cooling pickups and kickers at Fermilab. As cooling frequencies are pushed up to the point where the beam aperture and the pickup dimensions are on the order of a wavelength these devices start to deviate from simple directional coupler theory. The three dimensional nature of these directional coupler structures makes them very complicated to design at high frequencies. This article shall consider two planar structures which can be more easily understood and are certainly easier to fabricate.

For simplicity only pickups will be described in this article. Kicker can be understood by the proper application of reciprocity. The power received from a single pickup is:

\[ P = I_p^2 Z_o, \quad I_p = I_b G \quad (1, 2) \]

Where \( I_p \) is the current a single pickup drives into the receiver, \( Z_o \) is the input impedance the receiver presents to the pickup, \( I_b \) is the beam current, and \( G \) is the pickup current gain.

Consider a Cartesian coordinate system with the beam traveling in the z direction between two infinite conducting planes.

**Figure 1. Coordinate system**

The beam position coordinates are \( x, y \). The pickups lie in the conducting planes centered at \( x=0 \). The sum and difference mode signals of the pickup are:

\[ I_p^{\text{sum}} = I_p^1 + I_p^2 = I_b G^{\text{sum}}, \quad I_p^{\text{diff}} = I_p^1 - I_p^2 = I_b G^{\text{diff}} \quad (3, 4) \]

Where \( I_p^1 \) and \( I_p^2 \) are the top and bottom pickup currents respectively.

General Description

Two types of planar pickups have been measured and modeled. Both were fabricated using standard printed circuit board processes.

**Figure 2. Solid lines are microstrip and dashed lines are slots in ground plane. (a) planar loop geometry, (b) transverse half-wave slot pickup geometry.**

The planar loop, shown in Fig. 2a, is similar to the traditional directional coupler pickup. The usual microstrip line structure is replaced with a coplanar waveguide line made up of the two slots running parallel to the beam. The front and back edges are considered as slits [1]. [2], [3].

A half-wave slot pickup is shown in Fig. 2b. Consider a slot impedance of twice \( Z_o \) and a length \( L_{slot} \). A single charged particle traveling close to the slotline side of the pickup and centered on the microstrip transition induces an image current which creates a voltage pulse across the slot. Half of this pulse travels down the microstrip line to the receiver. The other half splits again into two pulses which travel in opposite directions on the slotline. At the shorted ends of the slot the pulses invert and reflect back toward the microstrip transition. At the microstrip transition the inverted pulses add and travel out the microstrip line. If losses in the slotline are ignored, the signal output is a pulse followed by an inverted pulse of the same amplitude, at time \( L_{slot}/v_{slot} \). This is exactly the same response as the traditional directional coupled loop [4]. The main difference is that the transverse half-wave slot pickup is not directional.

Measurements

These devices were measured using a method described in detail in [3], [6]. The gain \( G^{\text{diff}} \) is measured at \( y = 0.032" \) using a 50 \( \Omega \) air dielectric, microstrip line (the beam simulator). All measurements made in this article were made with \( d/2 \) set to 0.6". The measurements were obtained with a network analyzer (HP-8510B). Time gating was used to remove the influence of connectors [5]. Since the impedance of the beam simulator is 50 \( \Omega \) and \( Z_o \) is 100 \( \Omega \), 3 dB must be subtracted from this data to obtain \( G^{\text{diff}} \).

Prototypes of both pickups were built. They were designed with a \( Z_o \) of 100 \( \Omega \) and were fabricated on 0.031" thick teflon based circuit board \( (e_r = 2.2) \). For this material the 50 \( \Omega \) microstrip lines are 0.094" wide, 100 \( \Omega \) microstrip lines are 0.026" wide and the 200 \( \Omega \) slots are about 0.125" wide.

For a given peak frequency, if the width of a planar loop is decreased the length must decrease. A square planar loop was chosen as a compromise. The dimensions were adjusted for the 2-4 GHz band. (\( W_{loop}, L_{loop} = 0.70" \)). Figure 3 shows the measured frequency and time response with the beam simulator centered under the pickup.

**Figure 4. 0.7" square planar loop measurement for centered beam.**

To obtain a response in the 2-4 GHz band with the half-wave slot, the length of the slot was adjusted to 2.2". Figure 4 shows the measured response.

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Because not every particle travels through the center of the aperture, the response throughout the aperture needs to be understood. The $G_{diff}$ for beams offset in the $x$ direction were measured by moving the pickup from side to side above the beam simulator. Figure 5 shows measurements of both prototypes at different offsets in $x$.

The beam position, impedances, velocities and dimensions of the experimental data shown in Fig. 5 are used as input parameters to the model. The slotline velocity was measured by an independent method and found to be 0.91 c. A linear circuit analysis program (EEsof's Touchstone) calculated the frequency response of the model as shown in Fig. 7.

For computer modeling, the current density is broken into discrete current strips of width $\Delta x$ given by:

$$I_{\Delta x}(x, y) = \frac{1}{\Delta x} \int I(x, y) \, dx = \frac{1}{\pi} \tan^{-1} \left( \frac{y}{x + \Delta x/2} \right)$$

It is assumed that the pickups do not disrupt the current distribution on the ground planes. The transverse slots in the ground plane are modeled by breaking them up into transmission line sections of length $\Delta x$ with a current source between each section. The magnitudes of these current sources are given by Eq. 6. The longitudinal slots in the ground plane have no interaction with the beam and simply serve as transmission lines. The two models for transverse and longitudinal slots are then connected together. With proper phasing for beam delay and knowledge of the position of each current source with respect to the beam, a circuit model is constructed as shown schematically in Fig. 6.
The pickup actually does disrupt the image current distribution given by Eq. 5. Slotlines are not TEM transmission lines. Coupling between adjacent slots in the planar loop model. Radiation from slots. Slot end and corner effects. Microstrip to slotline transition effects [4].

Figs. 8 and 9 show contour plots of $G_{\text{diff}}$ at 3 GHz as predicted by the model. As shown in these figures, the difference mode current gain of the planar loop is much more sensitive to variation of the beam position in the $x$ direction than the half-wave slot pickup. An ideal pickup has all $G_{\text{diff}}$ lines parallel to the $x$ axis. In that case the pickup shows no coupling to the other transverse beam mode.

In the 2-4 GHz band shown in Figs. 5 and 7, the peak of the frequency response shifts as the beam simulator is moved away from the pickup. To understand what causes this frequency shifting, consider the time domain impulse response of the half wave slot pickup as the beam is moved away from the slot. As described above, the time domain impulse response of the half wave slot is an impulse followed by a negative impulse at a time $T = L_{\text{slot}} / v$ later. As the beam is moved away from the pickup, the image current spreads out along the transverse slot. This creates a broadened pulse at the output of the pickup as shown in Fig. 10.

The beginning of the first pulse and the end of the second pulse do not change as function of beam position. So, the peak of the frequency response for very close beam is at $f = 1 / (2 \pi L_{\text{slot}})$ and the peak for far away beam is at $f = 1 / (2 \pi L_{\text{slot}})$.

Consider a planar loop model with $L_{\text{loop}} = 4$ and $W_{\text{loop}} = L_{\text{slot}}$. It is interesting to note that the model predicts the frequency response to be exactly the same as the response of the half-wave slot pickup. Therefore, the half-wave slot model is the limiting case of the planar loop model.

Conclusion

Figure 11 shows the differential mode sensitivity of 4 different 2-4 GHz pickups as a function of $x$ (coverage). These measurements were made at 3 GHz.

The planar loop is similar in performance to traditional 1/4 wave loop pickups. However, for the mechanical tolerances required at high frequencies, the planar loop is much easier to fabricate than the traditional loops. In applications in which directionality is important, 1/4 wave loops are superior to half-wave slots. Unlike 1/4 wave loops, half-wave slots do not have termination resistors. This may cause complications in the design of kicker combiner networks.

For many applications the half-wave slot pickup outperforms 1/4 wave loops. It has the same $G_{\text{diff}}$ at the center as do 1/4 wave loops but has better coverage. As shown in Figs. 8 and 9, the half-wave slot pickup also has better rejection of the unwanted transverse beam mode.

For cooling systems which are limited by signal to noise ratio, the power per unit length of a pickup array is very important. Quarter-wave loop pickups are usually placed about 1/2 wavelength apart. Measurements have shown that slotline pickups can be placed 1/4 wavelength apart with no detectable effect on $G_{\text{diff}}$. Thus, half-wave slot pickups can receive twice the power per unit length than that received by 1/4 wave loops.

References