NOVEL STOCHASTIC COOLING PICKUPS / KICKERS

J. Petter, D. McGinnis and J. Marriner
Fermi National Accelerator Laboratory *

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[5]. 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. Kickers can be understood by the proper application of reciprocity. The power received from a single pickup is:

$$P = I_p^2 Z_o , \quad I_p = I_b G \qquad (1), (2)$$

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.

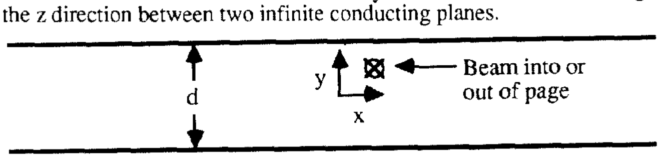


Figure 1 Coordinate system

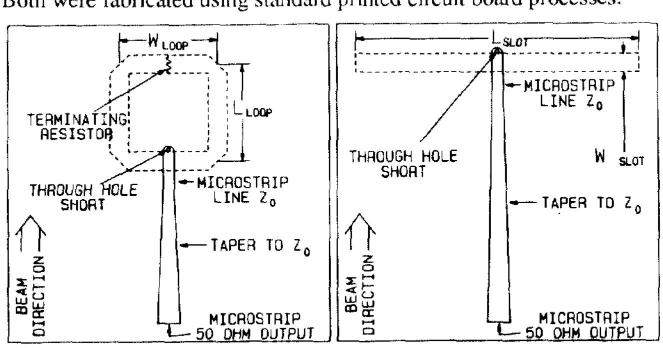
The beam position coordinates are x, y. The pickups lie in the conducting planes centered at x=0. The sum and difference mode signals of the pickup are:

$$I_{p\,sum} = I_{p1} + I_{p2} = I_b\, G_{sum} , \quad I_{p\,diff} = I_{p1} - I_{p2} = I_b\, G_{diff} \qquad (3), (4)$$

Where I_{p1} and I_{p2} 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.



(a) (b)

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 slotlines [1], [2], [3].

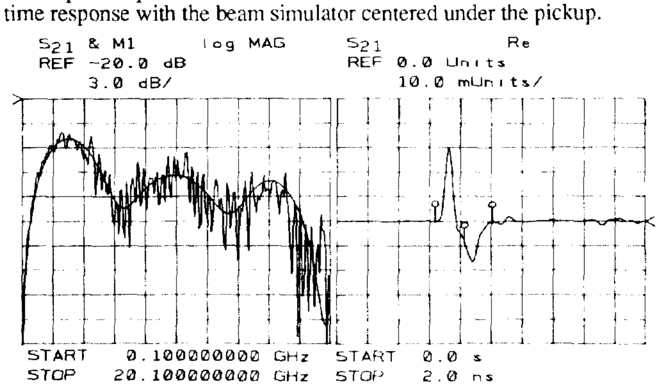
A half-wave slot pickup is shown in Fig. 2b. Consider a slot impedance of twice Z_o and a length L_{slot}. A single charged particle traveling close to the slotline side of the pickup and centered on the microstrip transition induces an image current which creates a voltage pulse across the slot. Half 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 [5]. 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 [5], [6]. The gain G_{diff} is measured at y = 0.043" using a 50 Ω, 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 Ω and Z_o is 100 Ω, 3 dB must be subtracted from this data to obtain G_{diff}.

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

For a given peak frequency, if the width of a planar loop is increased 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.

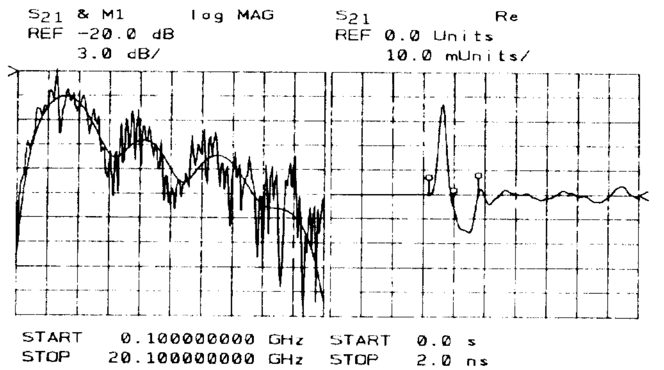


(a) (b)

Figure 3 0.7" square planar loop measurement for centered beam. G_{diff} = measurement - 3 dB. (a) gated and ungated frequency response. (b) impulse response, markers show time gate window.

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.

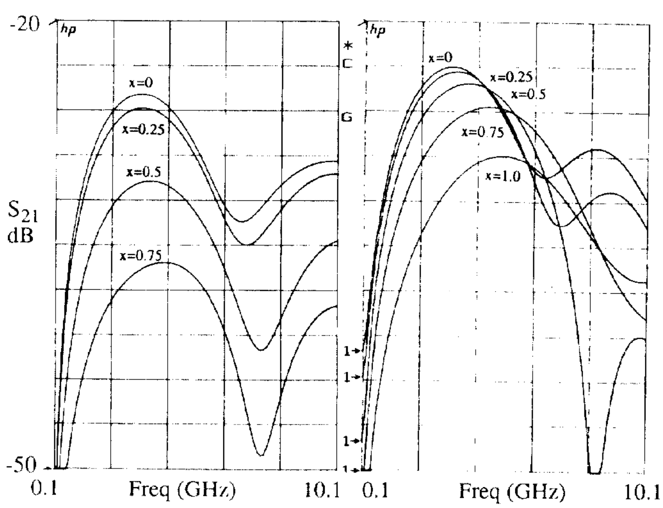
* Operated by the Universities Research Association under contract with the United States Department of Energy.



(a) (b)

Figure 4 *2.2" half-wave slot measurement for centered beam. G_{diff} = measurement - 3 dB. (a) gated and ungated frequency response. (b) impulse response, markers show time gate window.*

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.



(a) (b)

Figure 5 *(a) 0.7" square planar loop measurement at x = 0", 0.25", 0.5" and 0.75". (b) 2.2" half-wave slot pickup measurement at x = 0", 0.25", 0.5", 0.75" and 1.0". G_{diff} = measurement - 3 dB.*

Planar Pickup Model

The measurement technique used above only measures G_{diff} for small y. If y is much larger, the pickup couples too much energy out of the beam simulator. This makes the impedance and velocity of the beam simulator hard to predict, making interpretation of the measurements much more complex. A good model must be developed to predict G_{diff} for larger y as well as G_{sum}. In addition, this model could then be used to design pickups of different slot configurations, different frequency bands, and different apertures.

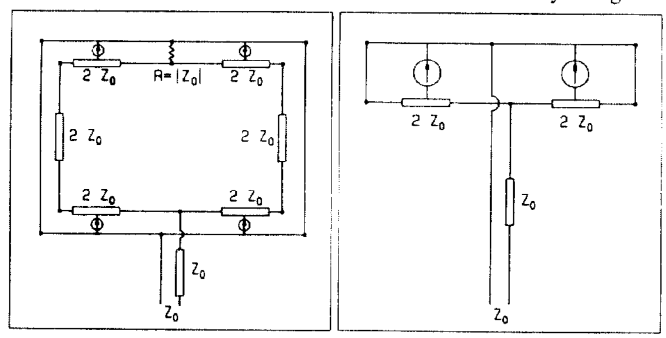
The image currents induced in the ground planes are a function of x. The surface current density at x=0 on the upper plane as a function of beam position (x, y) is given by:

$$J_s(x, y) = \frac{I_b \sin \pi \left[\frac{y}{d} + \frac{1}{2}\right]}{\cosh\left[\frac{\pi x}{d}\right] - \cos \pi \left[\frac{y}{d} - \frac{1}{2}\right]} \qquad (5)$$

For computer modeling, the current density is broken into discrete currents strips of width Δx given by:

$$I_{\Delta x}(x, y) = \int_{x-\frac{\Delta x}{2}}^{x+\frac{\Delta x}{2}} J_s(x, y)\, \partial x = \frac{I_b}{\pi} \tan^{-1} \left[\frac{e^{\frac{\pi x}{d}} - \sin \frac{\pi y}{d}}{\cos \frac{\pi y}{d}}\right]_{x-\frac{\Delta x}{2}}^{x+\frac{\Delta x}{2}} \qquad (6)$$

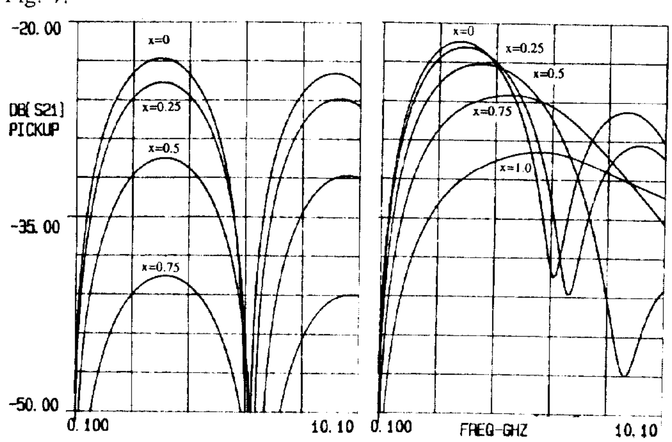
It is assumed that the pickups do not disrupt the current distribution on the ground planes. The transverse slots in the ground plane are modeled by breaking them up into transmission line sections of length Δx with a current source between each section. The magnitudes of these current sources are given 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.



(a) (b)

Figure 6 *Schematic representation of pickup models. Each transmission line with current source is actually a 10 section distributed current transmission line. (a) planar loop schematic. (b) half-wave slot schematic.*

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.



(a) (b)

Figure 7 *(a) 0.7" square planar loop modeled frequency response for x = 0, 0.25, 0.5 and 0.75. (b) 2.2" half-wave slot pickup modeled frequency response for x = 0, 0.25, 0.5, 0.75 and 1.0 (scaled same as Fig. 5).*

The frequency response of the measurement and the model share the same general characteristics. Thus, this simple model can be used to contrast the two types of planar pickups. The difference between the model and the measurements might be due to:

- 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_{diff} at 3 GHz as predicted by the model. As shown in these figures, the difference mode current gain of the planner 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_{diff} lines parallel to the x axis. In that case the pickup shows no coupling to the other transverse beam mode.

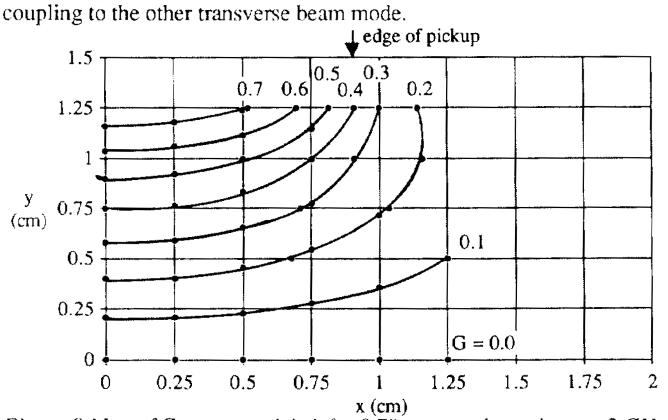


Figure 8 Map of G_{diff} as modeled for 0.7" square planar loop at 3 GHz.

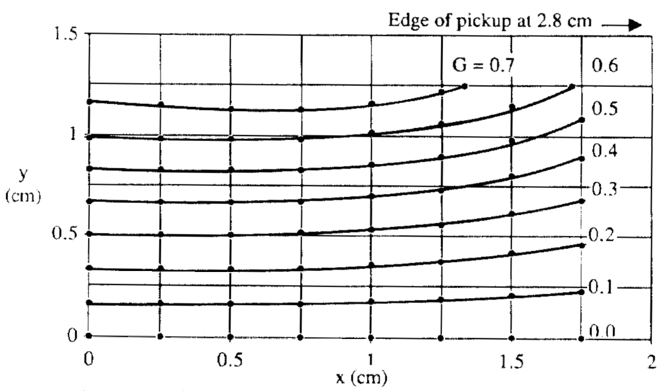


Figure 9 Map of G_{diff} as modeled for 2.2" transverse half-wave slot pickup at 3 GHz.

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 $T = L_{slot} / v$ 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.

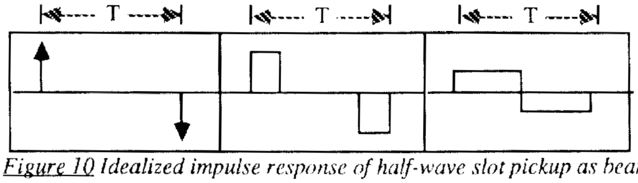


Figure 10 Idealized impulse response of half-wave slot pickup as beam is move away.

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 $f = 1 / (2\,T)$ and the peak for far away beam is at $f = 1 / T$. For the case of the half-wave slot pickup measured in Fig. 5b, T equals 204 pS. Thus, for close beam the peak is expected at 2.45 GHz and for far beam 4.9 GHz. These trends are in agreement with the measurements shown in Fig. 5b. The same kind of frequency shifting happens to a lesser extent in the planar loop.

Consider a planar loop model with $L_{loop} = 0$ and $W_{loop} = L_{slot}$. 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.

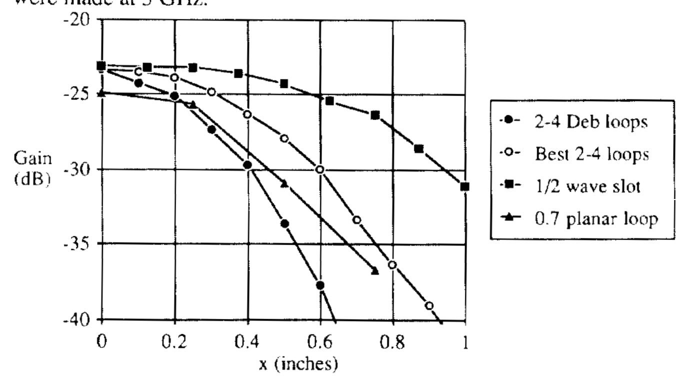


Figure 11 Differential mode coverage measurement of 4 different pickups at 3 GHz. " 2-4 Deb loops" are the pickups currently used in the Fermilab Debuncher betatron cooling system. "Best 2-4 loops" are loops designed using the technique described in [5]. " 1/2 wave slot" is the half-wave slots described here. "0.7 planar loop" is the planar loop described here. (G_{diff} = measurement - 3 dB)

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_{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_{diff}. Thus, half-wave slot pickups can receive twice the power per unit length than that received by 1/4 wave loops.

References

[1] D. Boussard, Evaluation of slotline pick-up sensitivity, CERN/SPS/ARF Note 85-9, September 1985, Unpublished.

[2] F. Caspers, Planar Slotlines, Pick-ups and Kickers for Stochastic Cooling, CERN/PS85-48 (AA), Aug. 1985-June 1986. Unpublished

[3] F. Caspers, Planar Slotline Pick-ups and Kickers for Stochastic Cooling, IEEE Trans. on Nuclear Science, Vol. NS-34, 1987, pp. 1866-1868.

[4] B. Schuppert, Microstrip/Slotline Transitions: Modeling and Experimental Investigation, IEEE Trans. Microwave Theory Tech., vol. 36, NO. 8, August 1988, pp. 1272-1282.

[5] D. McGinnis, J. Petter, J. Marriner, J. Misek , S. Y. Hsueh, Frequency Response of 4-8 GHz Stochastic Cooling Electrodes, Presented elsewhere in these proceedings

[6] J. Petter, D. McGinnis, J. Marriner, J. Misek, New 4-8 GHz Core Cooling Pickups and Kickers for the Fermilab Accumulator, Presented elsewhere in these proceedings