Simulation of Slow Particle Beams Using a Microstrip Line Model

H. Borek* and P. Raabe
Institut f. Hochfrequenztechnik
Technische Hochschule Darmstadt
Merckstr. 25, D-6100 Darmstadt

Abstract

The theoretical analysis of a pickup structure containing a microstrip line instead of the particle beam is presented. Dispersion characteristics, coupling efficiency and sensitivity of the pickup device fed via the simulator line are calculated. The usefulness of a microstrip line model simulating a slow beam with $\beta = 0.76$ in the frequency range of ESR stochastic cooling (0.9 -1.6 GHz) is discussed.

1 INTRODUCTION

The simulation of particle beams plays an important role in designing and testing beam-electrode interaction devices, such as pickup and kicker structures for stochastic cooling systems. These high-frequency broad-band coupling components are often designed and constructed before the beam actually exists. Therefore, models of particle beams are under development.

The coaxial wire method is a well-known technique used to simulate electromagnetic coupling between a detector structure and a fast particle beam with β close to unity [1]. In the case of slow beams, the phase velocity of the simulator line has to be reduced to match the required velocity. The aim may be achieved by using dielectric loading, i.e. coating of the wire. Due to the different distribution of the electromagnetic field, however, the ratio of E and H does in general not correspond to that of the slow beam. A different approach to simulate a slow beam with $\beta = 0.065$ is presented in [2], where a set of two kinds of antennas - probes as E-antennas and loops as H-antennas - is reported to give satisfactory measurement results.

In this paper, we present the theoretical analysis of a pickup structure containing an additional microstrip line instead of the particle beam. A microstrip line is one of the simplest and therefore easiest-to-apply models of particle beams for the experimental investigation of pickup devices. The pickup geometry is chosen similar to the high-frequency beam-electrode interaction devices designed for ESR stochastic cooling at GSI [3]. We discuss the usefulness of a microstrip line model destined to simulate a slow beam with $\beta = 0.76$ in the frequency range 0.9 - 1.6 GHz.

Dispersion characteristics, coupling efficiency and sensitivity of this model are studied using a 2D full-wave analysis in frequency domain. The results are compared to the actual electromagnetic beam-electrode interaction that is calculated by means of the computer analysis outlined in [4].

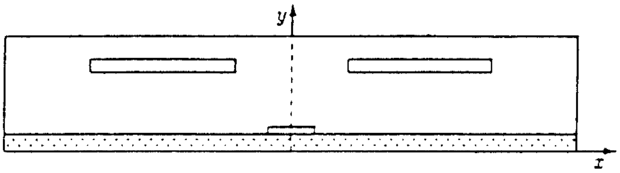

Figure 1: Two pickup electrodes and an additional microstrip line that simulates a slow beam.

2 FIELD-THEORETICAL ANALYSIS

A microstrip line as the model of a slow beam is placed on a ground plane inserted into a pickup device, as shown in Fig. 1. Dielectric permittivity is chosen to match the phase velocity of the transmission line with the velocity of the beam. The electrode structure under consideration is assumed to be infinitely long. It represents half of the electrode-array configuration designed for the ESR stochastic cooling system.

A two-dimensional mode-matching method has been employed for theoretical analysis. At it is a full-wave approach in frequency domain, dispersion of both phase velocity and coupling efficiency is taken into consideration. All quasi-TEM as well as higher-order modes propagating in the shielded structure can be calculated by using this method. One of them - the "microstrip" mode - has the most interesting properties. Its phase velocity can be easily controlled by changing dielectric permittivity. As its electromagnetic field distribution concentrates near the microstrip electrode, this additional transmission line may be considered as the energy carrier and thus shows similarity to a particle beam. The exact simulation of the actual fields of a beam with $\beta < 1$ by means of a transmission line model, however, is not possible.

Due to geometrical symmetry, investigations may be limited to one half of the structure, as depicted in Fig. 2. A vertical magnetic wall has to be inserted at $x = w$ for the analysis of symmetrical modes, such as the "microstrip" mode. Because of the isolated pickup electrodes in Fig. 1, a second symmetrical quasi-TEM mode occurs. Fields of

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*On leave from Institute of Radioelectronics, Warsaw University of Technology, Warsaw, Poland

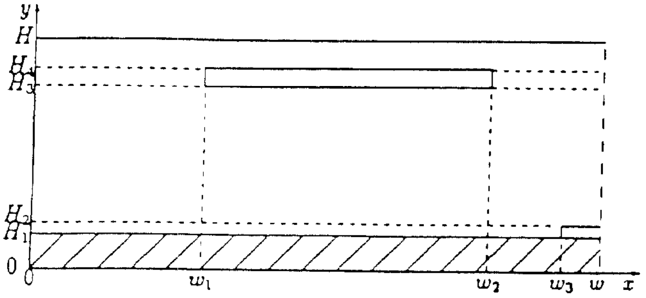

Figure 2: The analyzed structure including a magnetic or electric vertical wall at $x = w$. Dimensions: $H = 25$ mm, $H_4 = 16$ mm, $H_3 = 15$ mm, $(H_2 - H_1) = 0.05$ mm, $w = 75$ mm, $w_2 = 60$ mm, $w_1 = 20$ mm.

this mode as well as fields of the existing antisymmetrical quasi-TEM mode concentrate in vacuum near the detector plates, resulting in phase velocities close to c.

With regard to each quasi-TEM mode, transmission-line currents, voltages, and characteristic impedances are derived for both the microstrip line and the pickup plates. (Strictly speaking, the definitions of current, voltage, and line impedance are unambiguous only for pure TEM-waves.) Thus, signal coupling between the microstrip and the detector can be investigated, particularly in the case of "microstrip"-mode propagation. Only this mode – simulating the slow beam – should be excited in experimental set-ups for testing the performance of pickup devices.

Finally, from a circuit theory's point of view, the structure under investigation – with fixed geometrical length – represents a six-port device, relating the input signals to the output signals of the microstrip and the detector electrodes. In this context, total line currents and voltages have to be decomposed into the above-mentioned waves, propagating in forward and backward direction if reflections are taken into account.

3 RESULTS

3.1 Phase Velocity and Line Impedance

Fig. 3 and Fig. 4 show the phase velocity of the "microstrip" mode as a function of microstrip height (i.e. thickness of the dielectric) for a narrow and a wide microstrip electrode (1 mm and 10 mm, respectively). A dielectric permittivity $\varepsilon_r = 2$ was chosen because of the simulation of a slow beam with $\beta \approx 0.76$. Results are presented for three frequencies (5 MHz, 1 GHz, and 2 GHz).

The corresponding functions of microstrip impedance versus microstrip height are depicted in Fig. 5. As far as frequency dependence is concerned the impedance slightly rises for higher frequency. This is a known effect for microstrip impedance defined as $Z_L = U/I$.

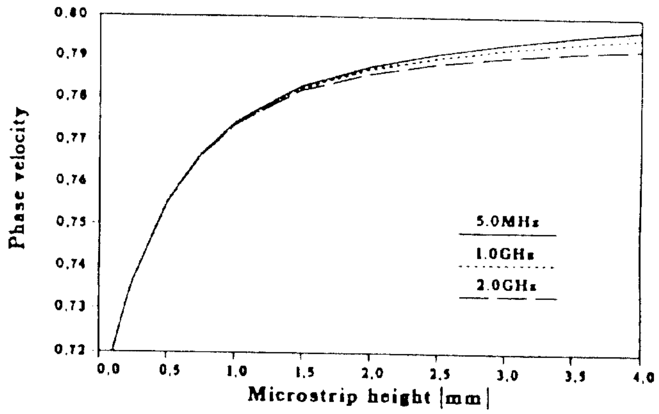

Figure 3: Phase velocity against microstrip height for three frequencies. Microstrip width 1 mm, $\varepsilon_r = 2$.

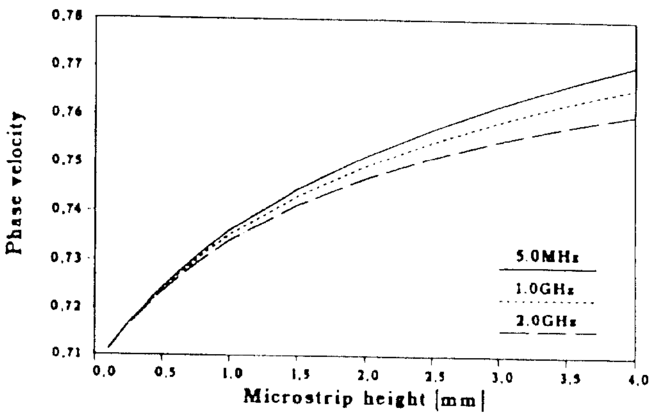

Figure 4: Phase velocity against microstrip height for three frequencies. Microstrip width 10 mm, $\varepsilon_r = 2$.

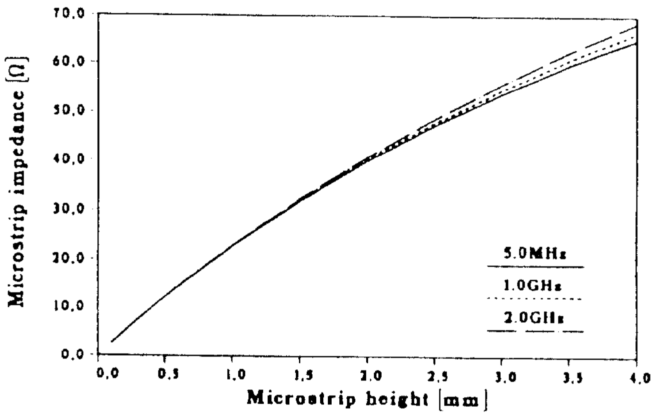

Figure 5: Microstrip impedance against microstrip height for three frequencies. Microstrip width 10 mm, $\varepsilon_r = 2$.

3.2 Dispersion Characteristics

The dispersion of the simulator line should be as small as possible. However, the well-known phenomenon of decreasing the phase velocity (increasing effective permittivity) for higher frequencies in a microstrip line can be observed in Fig. 6. Dispersion is stronger for larger distances between the microstrip electrode and the ground plane, see Fig. 3 and Fig. 4.

3.3 Signal Coupling and Sensitivity

The frequency-dependent coupling of the wide microstrip (10 mm) is shown in Fig. 7 (ratio of electrode current and microstrip current for "microstrip"-mode propagation). The values for the narrow microstrip (1 mm) are about three times as large as for the wide one.

Coupling versus microstrip height is depicted in Fig. 8. From these results, a vertical sensitivity function of the structure under investigation may be derived. The curves are in general nonlinear. In the case of the narrow microstrip, linearity increases if the height of the microstrip is significantly larger than its width.

4 CONCLUSIONS

The investigations have shown the main differences between the performance of the microstrip model and real particle beams: The current induced by a particle beam with $\beta < 1$ decreases for higher frequencies [4]. In the case of microstrip the coupling rises with frequency. The height of the microstrip can be referred to the beam position. The nonlinear coupling characteristics of the microstrip start tangentially to the height axis. This means that the sensitivity of the detector equals zero in the point considered. Coupling is nearly linear and sensitivity is different than zero as far as the particle beam is considered.

It is not easy to choose the best geometry for the microstrip model. On the one hand, it requires a rather wide microstrip to have a suitable characteristic impedance. On the other hand, the narrower the microstrip is the better coupling is achieved. As far as the phase velocity (i.e. dispersion) is considered the microstrip should both be narrow and have small height. A compromise is needed to reconcile such various requirements.

5 REFERENCES

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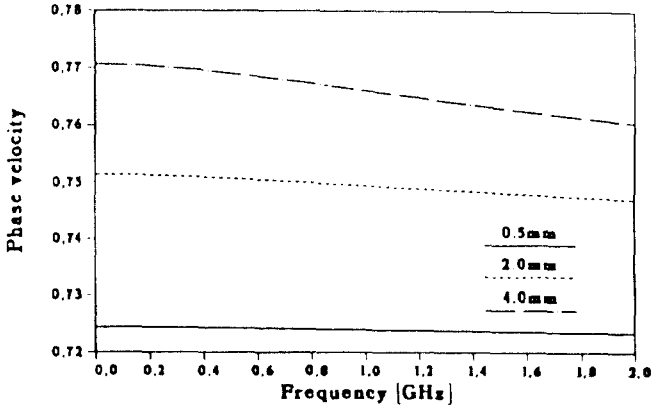

Figure 6: Phase velocity of "microstrip" mode against frequency for three thicknesses of dielectric. Microstrip width 10 mm, $\varepsilon_r = 2$.

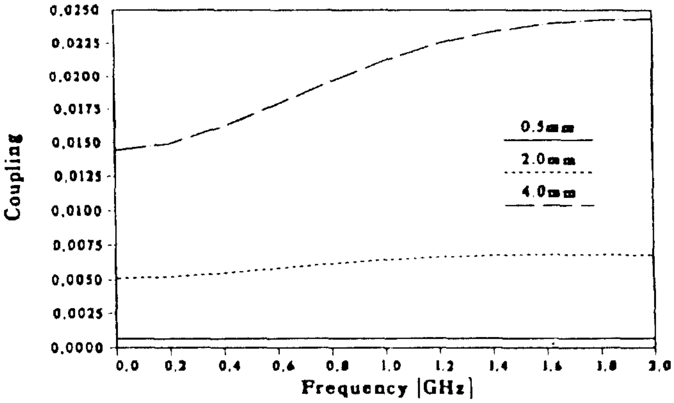

Figure 7: Signal coupling against frequency for three thicknesses of dielectric. Microstrip width 10 mm, $\varepsilon_r = 2$.

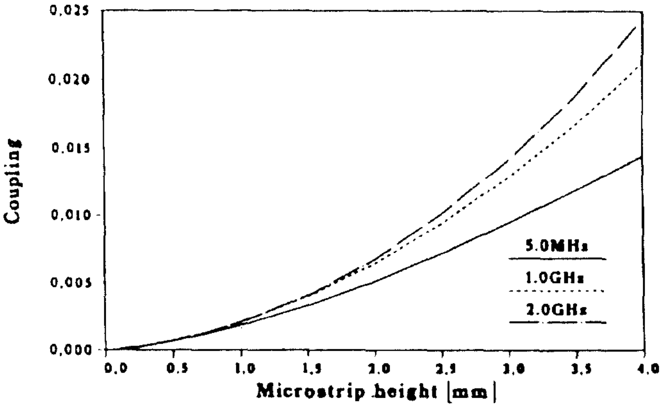

Figure 8: Signal coupling against microstrip height for three different frequencies. Microstrip width 10 mm, $\varepsilon_r = 2$.