Rigorous Computer Analysis of High-Frequency Pickup and Kicker Devices for ESR Stochastic Cooling*

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Abstract

Beam-electrode interaction devices for the ESR stochastic cooling system at GSI are investigated by computer analysis. The full-wave approach in frequency domain that is presented here holds for arbitrary values of particle velocity. It takes into account parasitic electromagnetic effects such as fringing fields and mutual coupling of signal electrodes. 3D calculations consider the excitation of higher-order waveguide modes caused by the three-dimensional electrode geometry. Results are presented on the coupling efficiency of high-frequency beam-electrode interaction and on the scattering behaviour of quarter-wavelength loop-couplers.

1 INTRODUCTION

The pickup and kicker devices represent key components in stochastic cooling systems. In order to reduce experimental optimization efforts, system design demands for a detailed theoretical investigation of these high-frequency broad-band coupling structures. With increasing frequency of operation (e.g. 0.9-1.6 GHz at GSI's experimental storage ring ESR [1]), pickup and kicker electrodes working as quarter-wave loop-couplers become relatively short. Therefore, well-known two-dimensional approaches and quasi-static approximations do not hold any more, since device performance is significantly affected by fringing fields, mutual coupling and electrical scattering [2]. Additionally, beam-pipe dimensions reach the wavelength's order of magnitude, i.e. the structures investigated become overmoded.

Two different methods have been applied for analysis: Using a modified mode-matching technique we calculated both the basic electromagnetic 2D beam-electrode interaction and the electrical transfer characteristics of the electrode array under consideration.

A full-wave 3D finite-difference approach includes additional parasitic effects caused by the three-dimensional electrode geometry, such as electrical scattering and the excitation of waveguide modes inside the beam pipe.

2 MODELLING AND CALCULATIONS

2.1 Model of the Interaction Devices

ESR coupling devices for stochastic cooling consist of electrode arrays in a rectangular beam pipe as depicted in Fig. 1. No vertical electrodes are used because of rf-stacking after stochastic beam cooling. Each electrode works as a quarter-wavelength directional loop-coupler. Its ends are bent towards the beam pipe wall and tapered in order to form a smooth transition to the feeding lines.

Fig. 2 shows the longitudinal shape of the superelectrode model used in our analysis. At the expense of bandwidth, a superelectrode device provides higher beam-electrode coupling at midband than two single loop-couplers.

2.2 Two-Dimensional Analysis

Taking into account slow particle beams ($\beta_{\mathrm{ESR}} \approx 0.76$), significant longitudinal electric fields exist in the pickup structure. Deriving the geometrical pickup sensitivity from a two-dimensional electrostatic model (conformal mapping) would neglect the resulting displacement current at high frequencies. Additionally, the amplitudes of the induced conductive currents become frequency dependent for $\beta < 1$. In this case, the static image-current approach has to be replaced by a 2D full-wave analysis.

Our computer code calculates the two-dimensional electromagnetic field distribution in frequency domain utilizing a special mode-matching technique [3]. We assume longitudinal beam propagation $\sim \exp[j(\omega t - k_z z)]$ with $k_z = \omega/(\beta c)$ inside a perfectly conducting pickup structure of infinite length. The excited fields are analytically expanded into the well-known eigenfunctions of the waveguide structure, which is subdivided into areas of rectangular shape. Integration of the tangential magnetic field yields the conductive currents of electrodes and inner wall. Coupling efficiency and sensitivity of the electrode array are derived as functions of beam position, frequency and pickup geometry.

Because of the spatial proximity of the electrode plates, the influence of fringing field capacitances on mutual cross-talk and on transmission line impedance is not negligible. Therefore, operating a symmetrical electrode array in different TEM-modes (even-even $\begin{pmatrix} + & + \\ + & + \end{pmatrix}$, odd-even $\begin{pmatrix} + & - \\ + & - \end{pmatrix}$ and even-odd $\begin{pmatrix} - & - \\ + & + \end{pmatrix}$) results in different characteristic line impedances $Z_{L_{ee}}$, $Z_{L_{oe}}$ and $Z_{L_{eo}}$, respectively. With regard to electrical matching, this effect is of particular interest for kicker applications because of the high power levels. Hence, the two-dimensional electrode array has to be characterized as a system of coupled transmission lines.

In the case of TEM signal propagation, plate currents and voltages are related by $(I) = c(C')(U) = (Y_L)(U)$.

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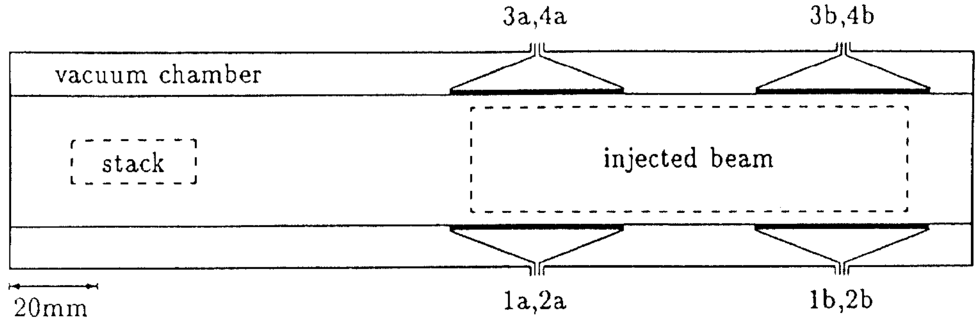

Figure 1: Simplified cross-section of ESR vacuum chamber

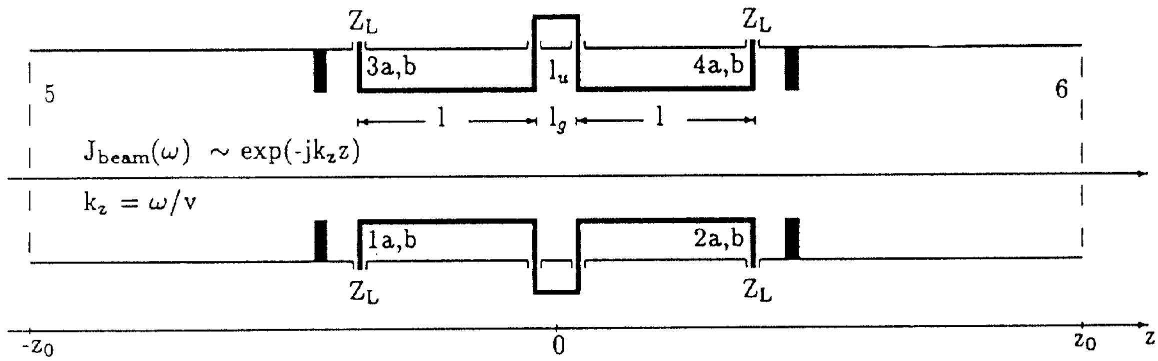

Figure 2: Longitudinal shape of superelectrode model

The coupling capacitances per unit length C'_{ij} and the resulting admittance matrix (Y_L) are calculated by solving the two-dimensional Laplace equation in the transverse plane of the electrode array.

The 2D theoretical analysis of pickup devices assumes the total conversion of the beam-induced plate currents into TEM-waves at the electrical input and output ports of the electrodes. Finally, taking into account external termination networks, the transfer characteristics and frequency response of a pickup electrode array with fixed geometrical length can be calculated using the common theory of electrical transmission lines.

2.3 *Three-Dimensional Analysis*

The systematic 2D analysis neglects additional parasitic end-effects caused by the three-dimensional electrode geometry, such as longitudinal field fringing and the excitation of higher-order waveguide modes. The electrical transitions between the signal electrodes and their feeding lines, however, represent 3D transmission-line discontinuities, see Fig. 2. They may cause undesired reflections of TEM-waves due to electrical mismatch. At high frequencies, waveguide modes will be excited resulting in electrical loss by radiation. Furthermore, energy conversion from TEM to higher-order waveguide modes (and vice versa) may affect operation of superelectrodes and other combined electrode structures due to additional longitudinal coupling.

The 3D field-theoretical analysis presented here accounts for these parasitic electromagnetic effects. We employ a full-wave finite-difference approach [4]. It yields the generalized scattering matrix of the device including the non-evanescent higher-order modes inside the beam pipe. Regarding kicker operation, the three-dimensional electromagnetic field distribution is calculated in the frequency domain. Beam-electrode interaction can be derived by evaluating the Lorentz force along the particle path for various beam positions and velocities.

3 RESULTS

The amplitudes of beam-induced plate currents change significantly with varying frequency and particle velocity, see Fig. 3. Therefore, maximizing the pickup output signal at midband requires a single-electrode length shorter than $\lambda/(2(1+1/\beta))$. Due to the special arrangement of plates, the geometrical sensitivity curves are nonlinear.

Mutual coupling of electrodes results in different line impedances of the TEM transmission-line system, particularly at high impedance levels, see Fig. 4.

The longitudinal kick of the 3D superelectrode array under investigation (Fig. 2) is shown in Fig. 5. The frequency behaviour differs substantially from simple directional-coupler theory [5,6] that predicts a $\sin(\varphi)\cos(2\varphi)$-law, $\varphi = \pi/2 \cdot f/f_0$, with $f_0 = 1.25$ GHz being the midband frequency. In the upper frequency range, beam-electrode interaction is strongly affected by parasitic effects.

Fig. 6 shows the corresponding scattering behaviour of the device. With increasing frequency, electrical reflexion and transmission become more and more nonideal, including sharp resonances at the cut-off frequencies of higher-order TE-modes. With regard to kicker operation, undesired excitation of these waveguide modes is significant, if the input signals of upper and lower electrodes have opposite phase.

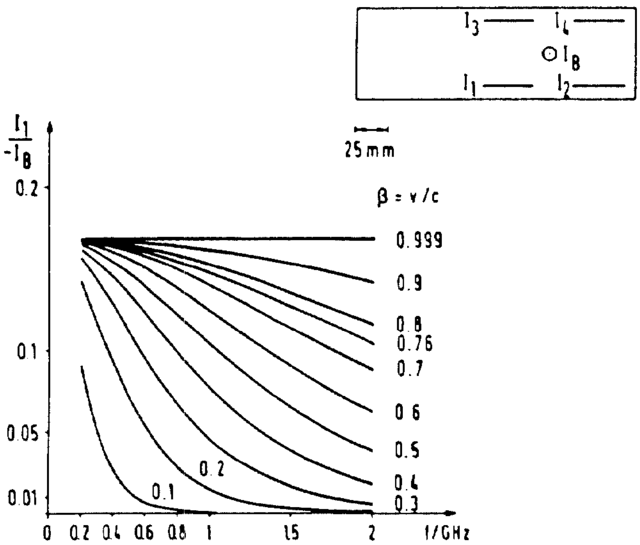

Figure 3: Signal coupling as a function of frequency

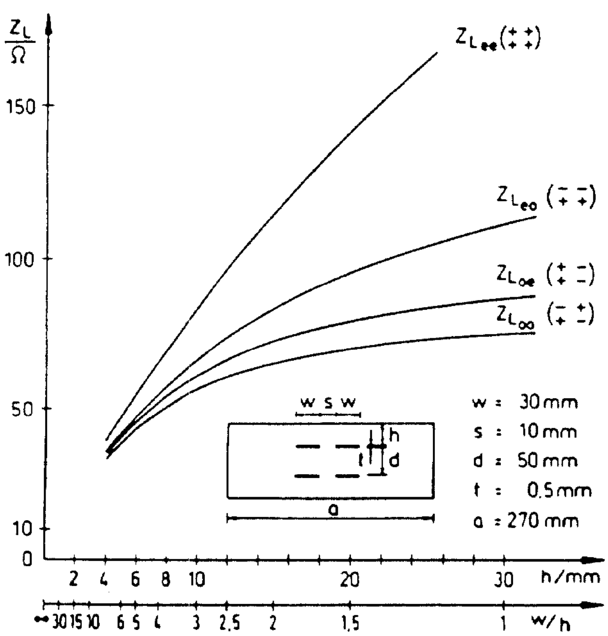

Figure 4: Line impedances of different TEM-modes

The numerical simulations carried out demonstrate the particular influence of parasitic high-frequency effects on the electrical characteristics of the coupling devices. Therefore, optimization requires additional measures such as electrical damping inside the beam pipe.

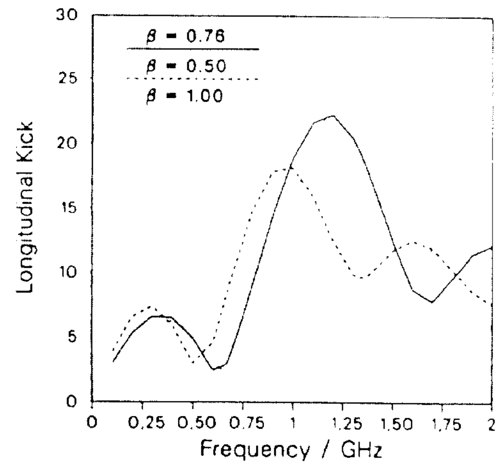

Figure 5: Longitudinal kick $K_z = U_K/\sqrt{1\mathrm{W}\ Z_L}$ at a central beam position between the superelectrodes. U_K denotes the longitudinal kicker voltage. 1W input power supplied at each port 2a, 2b, 4a, 4b; $Z_L = 47\Omega$.

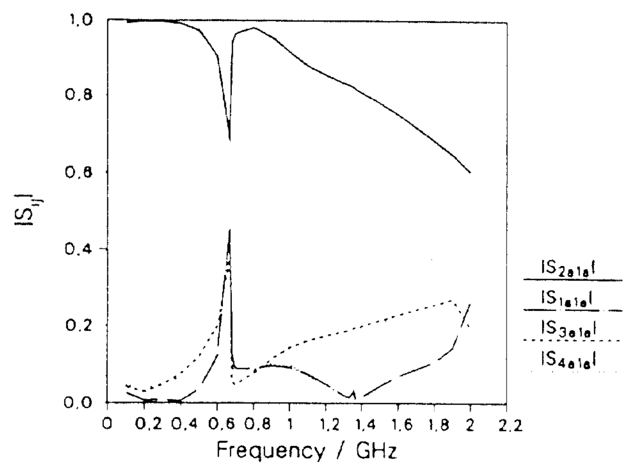

Figure 6: Scattering behaviour of the superelectrode array versus frequency ($f_{c,\mathrm{TE}_{10}} = 0.681$ GHz, $f_{c,\mathrm{TE}_{20}} = 1.363$ GHz).

4 REFERENCES

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