Beam Position Monitor Developments for TESLA

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Abstract

A programme to develope beam position monitors for the TESLA 500 is under way. The goal is to design a low-impedance BPM with an accuracy of better than 50 μm and a resolution of less than 10 μm. Two different structures using resonant buttons and a ridged waveguide to combine two opposite buttons are briefly described. Brass models were built and measurement results will be discussed. The measured resolution is better than 30 μm.

1 INTRODUCTION

Beam position monitors with a resolution of about 10μm near the axis are required for the quadrupole alignement in the TESLA Linear Collider study. This has to be achieved in a cold environment, measuring single bunches with a charge of 8 nC spaced 1 μs. A TM_{110}-cylindrical cavity has been designed for the TESLA Test Facility and test results on a prototype will be discussed elsewhere ([1]). But due to the longrange wakefields monitors with a lower impedance might be required, having the same resolution and a reliable behaviour at lower temperatures ([3]). In this paper we discuss two different button monitors and present measurements on brass models. Another structure using two coupled cavities where the signal is superimposed as a modulation has been described previously ([2]). This structure can be machined within μm-tolerances and a reliable behaviour in a cold environment is expected.

2 RESONANT BUTTON PICKUPS

A button pickup usually consists of four round electrodes in the wall of the beam pipe. The response of such a capacitive pickup can be calculated for two opposite buttons using field theory. For small buttons at $y = \pm b$ and the geometry shown in Fig.1a this yields

$$V^{\pm}(\delta_x, \delta_y) \approx \frac{Z_0 k_0 a_1 d I_b \cos(\frac{\pi\delta_y}{2b})}{4b(1 \mp \sin(\frac{\pi\delta_y}{2b}))} \cdot \left(\frac{\pi^2(a_1^2 + 4\delta_x^2)}{32b^2(1 \mp \sin(\frac{\pi\delta_y}{2b}))} - 1\right) \cdot \frac{H_0^{(1)}(\xi) + \rho H_0^{(2)}(\xi)}{H_1^{(1)}(k_0 a_1) + \rho H_1^{(2)}(k_0 a_1)} \qquad (1)$$

with

$$\rho = \frac{j\frac{Z_s}{Z_0} H_1^{(1)}(\xi) - H_0^{(1)}(\xi)}{H_0^{(2)}(\xi) - j\frac{Z_s}{Z_0} H_1^{(2)}(\xi)} \qquad \frac{Z_s}{Z_0} = \frac{2\pi \cdot d_a \cdot ln\frac{d_a}{d_i}}{d(2\pi + j\omega C_e Z_0 ln\frac{d_a}{d_i})}$$

$H_{0,1}^{(1),(2)}$ are the Hankel functions, $\xi = k_0 d_a = \frac{2\pi d_a}{\lambda_0}$
C_e is the electrode capacitance, $Z_0 = 377\Omega$
δ_x is the horizontal and δ_y the vertical beam position

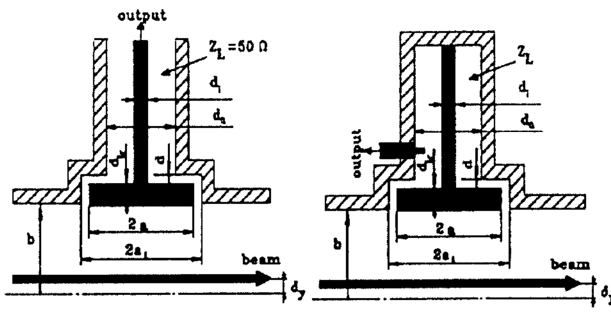

Figure 1: a) Capacitive button b) Resonant button

In Fig.2a, eqn.(1) is plotted for the parameters given in Table 1 and N=5 $\cdot$ 10^{10} particles/bunch.

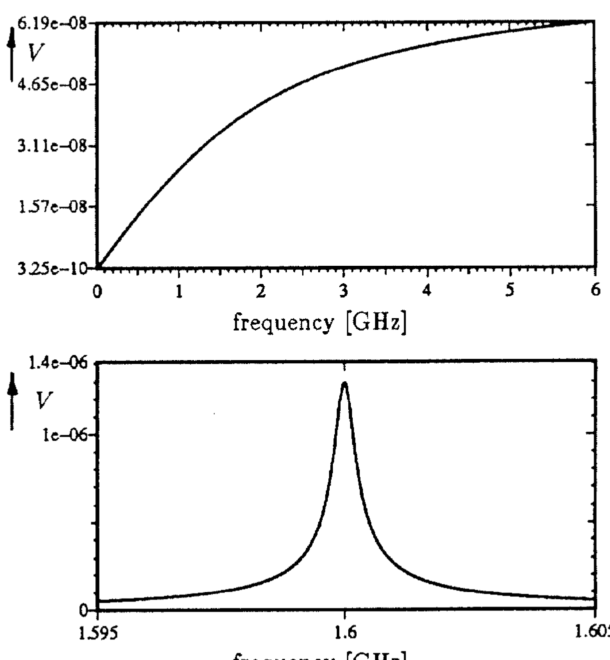

Figure 2: Response of a a) capacitive b) resonant button

The theoretical resolution limited by the thermal noise of the electronics can be estimated using eqn.(1)

$$\frac{\Delta}{\Sigma} = \frac{V^+ - V^-}{V^+ + V^-} \approx \frac{\pi}{2}\frac{\delta}{b} = \frac{V_{\text{noise}}}{V_{\text{signal}}} = \frac{1}{\text{S/N}}$$

This yields a S/N-ratio of ≥ 2500 to detect a displacement of $10\mu m$. Since the bandwidth of the electronics has to be $\geq$ 1MHz (to measure single bunches), one has to increase the signal voltage to get the required S/N-ratio.
Making the buttons resonant, one increases the detector output power density by a factor of $\frac{Q}{2}$ for the same displacement (Q is the quality factor of the resonant circuit, [4]). A simple realisation is a shorted button, as shown in Fig.1b. In the equivalent circuit, an inductor was placed in parallel with the capacitance. For this structure one gets similar results for $V^{\pm}$, but with a different impedance:

$$Z_s = \frac{2\pi d_a Z_L \tanh((\alpha + j\beta)l)}{d(1 + j\omega C_e Z_L \tanh((\alpha + j\beta)l))}$$

where α is the attenuation constant and β the phase constant of the 50Ω coax-cable. The voltage coupled out by a loop or a probe is plotted in Fig.2b, assuming a coupling factor of 1.

dimension	a	a_1	d	d_k	d_i	d_a	b	l
value [mm]	7	9	1	1	1.5	6.5	39	16.9

Table 1: Parameters for a resonant button brass model

2.1 Measurement Results

A brass model with two opposite resonant buttons was built and measured at room temperature using an antenna and a network analyzer. The mechanical parameters are given in Table 1. Fig.3 shows the resonant behaviour of the two buttons, with a measured Q-value of about 400 for both buttons. Hence, the required S/N-ratio (to detect 10 μm) decreases down to 13.

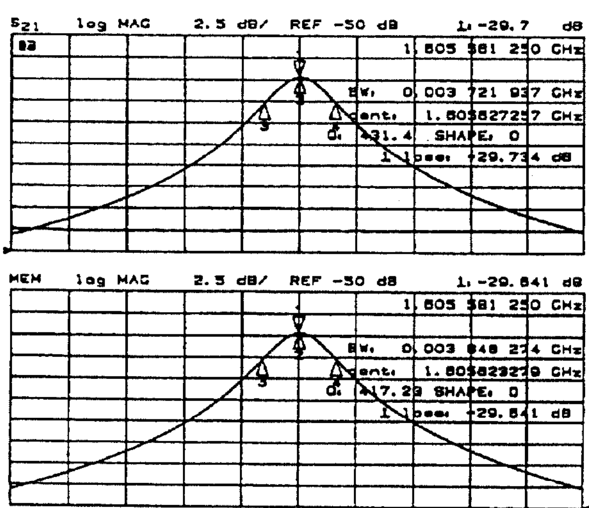

Figure 3: Measured response of two resonant buttons

Then, the structure was woved within 50 μm steps with respect to the antenna. The signals of both buttons were measured and the $\Delta/\sum$-ratio was calculated. Fig.4 shows

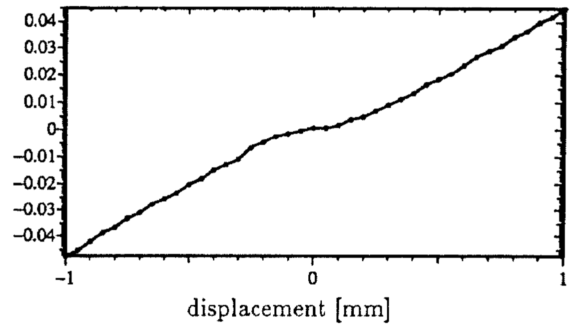

Figure 4: Response to a movement within ± 1 mm

the results for a movement within ± 1 mm from the center. Note that the magnitude is given in relative units.
The main problem is to build two identical buttons having the same resonant frequency and Q-value. Although it is possible to tune the buttons at room temperature, we expect problems to maintain this behaviour in a cold environment. Another important parameter is the coupling to the external load, which has to be almost identical for two opposite buttons. Therefore, other coupling structures than the tested probe are under investigation.

2.2 Signal Processing

For signal processing we adopted a narrowband technique, succesfully used in many accelerators for beam position monitoring ([5]). In this AM/PM method (shown in Fig.5), the amplitude ratio of two opposite electrodes is coverted in a $\frac{\pi}{2}$-hybrid into two signals having the same amplitude and a phase difference of

$$\psi = 2\arctan(\frac{V^+}{V^-}) - \frac{\pi}{2}.$$

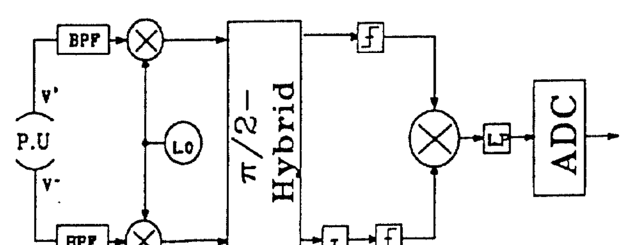

Figure 5: Signal processing scheme

The two signals coming out of the hybrid are clipped to a constant amplitude (hard-limiter) and the phase difference is measured in a phase detector. After the lowpass filter, the remaining dc-signal is proportional to

$$v_{out} = 2k_{pd} \cdot \arctan(\frac{V^+}{V^-}) \quad \Rightarrow \quad \delta_y \approx \frac{b}{\pi}\left(\frac{v_{out}}{k_{pd}} - \frac{\pi}{2}\right)$$

k_{pd} is the transfer characteristic of the phase detector.

This method avoids the problem of transmitting very tiny Δ-signals. Furthermore, it gives the normalized position and it allows a large dynamic range. The hard limiters usually restrict the system performance because of their high frequency limit, phase shift and dynamic range.

3 RIDGED WAVEGUIDE

Another processing method for deriving the normalized position signal is the difference-over-sum method ([5]). Therefore, in a narrowband system a hybrid is often used two combine the signals of two electrodes and to obtain the Δ and the $\sum$.

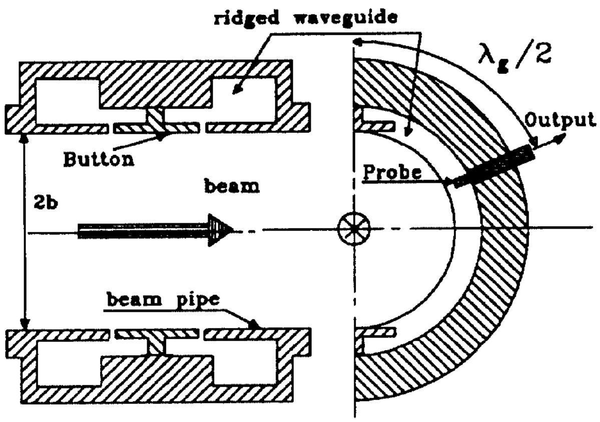

Figure 6: Ridged waveguide combining two buttons

Instead of using a standard hybrid, a ridged waveguide around the beam pipe was designed combining two opposite buttons (Fig.6). The signal is coupled out by a probe at a distance of $\frac{\lambda_g}{2}$ from the upper button. At that point, the signals coming from the upper and the lower button have the same amplitudes but opposite phases for the frequency

$$f_g = \frac{c_0}{\lambda_g} = \frac{c_0 \cdot 3}{2\pi a}$$

where λ_g is the wavelength in the ridged waveguide and a is the mean radius.
In principle, the field pattern is similar to that of the TE_{311}-mode in a coaxial resonator. Hence, the output signal is proportional to the beam position (difference between both signals) and the beam intensity.

A brass model was built and measured using an antenna and a network analyzer. Some of the results are shown in Fig.7. The difference between both traces corresponds to a movement of the structure with respect to the antenna of 50μm. A Q-value of about 400 has been measured. Hence, the S/N-ratio again has to be $\geq$ 13 to detect a displacement of 10μm (similar to the estimation described above). In Fig.8 the displacement is plotted versus the readout at $\frac{\lambda_g}{2}$. We missed the center position since the structure was moved only in one direction.

For signal processing it is forseen to use a homodyne system, where the signals and a reference are mixed down to DC to get the envelope. The beam current has to be measured elsewhere to normalize the signals in a computer. Unfortunately, this gives the beam position only for one plane. Hence, two such structures are required to detect the position in x and y.

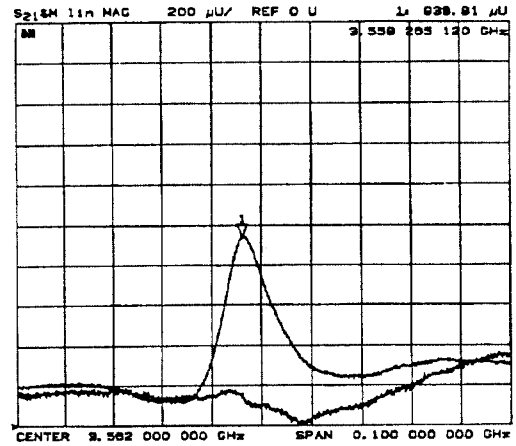

Figure 7: Measurements on a brass model

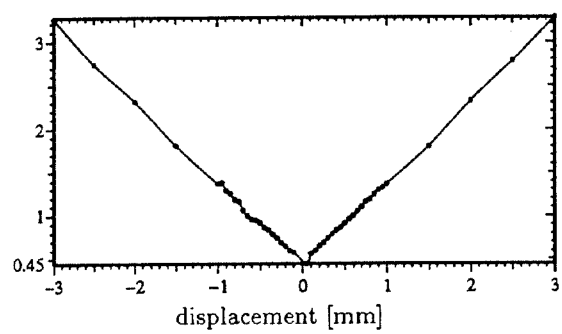

Figure 8: Response of a ridged waveguide structure

4 ACKNOWLEDGEMENTS

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5 REFERENCES

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