Beam Position Monitors for the TESLA Test Facility

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Abstract

For the TESLA Test Facility beam position monitors with a precision of about 10 μm are required. This has to be achieved for several bunch charges. A circular cavity excited in the TM_{110}-mode by the off-axis beam provides a signal strong enough for the bunch charges under consideration. Expected signal to noise ratios and the theoretical resolution are estimated for a designed structure. First measurement results on a brass model are presented. Since the resolution is limited by the excitation of common modes a coaxial combiner was designed.

Beam position monitors with a lower impedance might be required for the operation of a Linear Collider. Therefore, it is also foreseen to test other monitors behind the injector. Resonant buttons, two coupled cavities and a monitor using a re-entrant cavity are briefly described here.

1 Introduction

For the alignment of the quadrupoles in the TESLA Test Facility (TTF) beam position monitors with a precision of about 10 μm are required. This has to be achieved for several bunch charges ([1]). The monitors are located behind a cavity module and are attached to the quadrupoles within 50μm mechanical alignment precision. Because of the desired precision and the limited space we designed a TM_{110}-excited circular cavity. The resonant frequency f_{110}=2.1667GHz was chosen to avoid interferences from the accelerating cavities.

name, comments	particles/bunch	frequency f_b	bunch separation
1b	$5.0 \cdot 10^8$	72.2 MHz	13.8 ns
1b, with a subharmonic buncher	$1.6 \cdot 10^8$	216.7 MHz	4.6 ns
2, for TESLA	$5.0 \cdot 10^{10}$	1.0 MHz	1.0 μs

Table 1: Injectors proposed for the TTF and TESLA

But for the operation of a Linear Collider it might be necessary to have BPM's with a lower impedance or to measure individual bunches. That's why it is also forseen to measure the linearity, stability and precision of different BPM's behind the injector and to test the electronics. Three structures - resonant buttons, two coupled coaxial cavities and a re-entrant cavity - are briefly described in this paper. More detailed design studies and some proposals to measure individual bunches with a resonant device will be published later.

In this paper we denote 'resolution' as 'precision limited by electromagnetic interference and circuit noise'.

2 TM$_{110}$-Excited Circular Cavity

The simplest microwave BPM-structure is a circular cavity with a central beam hole excited in the TM_{110}-mode by an off-axis beam. The amplitude of this mode yields a signal proportional to the beam displacement; and to obtain the sign, the phase has to be measured approximately.

Advantages

* the amplitude of the TM_{110}-mode yields the desired signal directly; it is stronger than the signal given by other monitors
* the cavity can be machined within micrometer tolerances
* the structure itself does the subtraction - in principle no additional combiners, less cable drift and unbalances
* the amplitude of the fundamental mode yields a signal proportional to the bunch charge

Problems

* the resolution is limited by the finite Q ([4]); it can be easily increased by combining two symmetrical outputs in a hybrid
* a common mode rejection of about 100 dB with respect to the TM_{110} will be required for signal detection
* an appreciable amount of power (common modes) might be extracted from the beam and stored in the cavity (could cause wakefield or temperature problems)
* the strong signal change requires a very wide dynamic range in power for the electronics; special problems arise for the first beam or in the case of a beam break-up

2.1 Estimated Resolution

The resolution of such a cavity-BPM is limited by:

* the power out - signal to noise ratio due to the thermal noise of the electronics.
* the expected signal ratio due to the finite Q-values for all modes in the cavity.

To estimate both limits we need the maximum voltage of the TM_{110} excited by a beam with a displacement δ_x ([3])

$$V_{110} = \frac{J_1'(0)}{J_1^{max}} \frac{a_{11} \cdot \delta_x}{r} V_{110}^{max} = \frac{J_1'(0)}{J_1^{max}} \frac{a_{11} \cdot \delta_x}{r} \cdot 2qk_{110} \qquad (1)$$

with the Bessel function J_1, its first root a_{11}, the cavity radius r and the longitudinal lossfactor k_{110} of the TM_{110} excited at one of its maxima.

The thermal noise from the first stage of amplification may be estimated with the Boltzman Constant k_0 and a bandwidth $B = 10\text{MHz}$ as

$$P_{noise} = 4 \cdot k_0 \cdot T \cdot B \approx 10^{-13}\text{W} \quad = -100\text{dBm}$$

Expected Power in the Dipole Mode

The power in the TM_{110} extracted from the beam can be estimated using impulse excitation of an equivalent circuit

$$P_{110} = \frac{V_{110}^2}{4 \cdot k_{110} \cdot T_p} = \delta_x^2 \cdot \frac{q^2}{T_p} \cdot \frac{k_{110}}{4} \cdot \left(\frac{a_{11}}{J_1^{max} \cdot r} \right)^2$$

T_p is the time for the power to decay, q the bunch charge.
With k_{110}=$\omega/4 \cdot (R/Q)_{110}$, N the number of particles per bunch, the R/Q for a cavity without beam pipes and Q_L=2000, f_{110}=2.1667 GHz, r=78.2mm, length l=40mm we obtain

$$P_{110} \quad = \quad \delta_x{}^2 \cdot (Ne\omega)^2 \cdot \frac{Z_0 \cdot l \cdot a_{11}}{4\pi \cdot r^3 \cdot Q_L \cdot J_0^2(a_{11})} \qquad \frac{P_{110}}{\mathrm{W}} = \left(\frac{\delta_x}{\mu \mathrm{m}} \right)^2 \cdot 1.31 \cdot 10^{-16} \cdot N^2$$

$$\text{for} \qquad N = 5 \cdot 10^{10} \qquad \frac{P_{110}}{\mathrm{W}} \approx 3.4 \cdot 10^{-7} \left(\frac{\delta_x}{\mu \mathrm{m}} \right)^2$$

$$\text{for} \qquad N = 1.6 \cdot 10^{8} \qquad \frac{P_{110}}{\mathrm{W}} \approx 3.4 \cdot 10^{-12} \left(\frac{\delta_x}{\mu \mathrm{m}} \right)^2$$

With numerical results (Table 2) for the R/Q of a cavity with beam pipes and assuming a coupling factor β=1 we get for one bunch of injector 2

$$P_{out} \approx 2 \cdot 10^{-7} \mathrm{W}/(\mu \mathrm{m})^2 = \text{- } 43 \text{ dBm}/(\mu \mathrm{m})^2$$

This is much more than the expected thermal noise from the first stage of amplification.

cavity length	Mode	frequency	Q-value	$\frac{R}{Q}$ in Ω	k_0 in $\frac{V}{pC}$
20 mm	TM_{010}	1.74 GHz	1493	48.0	0.131
20 mm	TM_{110}	2.18 GHz	1780	68.2	0.230
40 mm	TM_{010}	1.63 GHz	2422	79.5	0.203
40 mm	TM_{110}	2.16 GHz	2627	91.5	0.311
geometry: cavity radius r=78.2mm , beam pipe radius a=39mm material: ring and endplates - CrNi					

Table 2: MAFIA-results for a cavity with beam pipes (without electrodes or coupling slots)

Excitation of Common Modes

W. Schnell ([3], confirmed in [4]) estimated the voltage ratio of the beam driven TM_{010}/TM_{110}

$$S_1 = \frac{V_{010}(\omega_{010})}{V_{110}(\omega_{110})} \approx \frac{5.4}{\lambda_{110}} \cdot \delta_x \cdot \frac{k_{010}}{k_{110}}$$

For the spectral densities at ω_{110} he obtained

$$S_2 = \frac{v_{010}(\omega_{110})}{v_{110}(\omega_{110})} \approx S_1 \cdot Q_{110} \cdot \left(1 - \frac{\omega_{010}^2}{\omega_{110}^2} \right) \tag{2}$$

where λ_{110} is the wavelength, Q_{110} the Q-factor of the TM_{110}. Including numerical results we obtain a displacement of $\delta_x \approx 45\mu$m for $S_2 = 1$, Q_L=2000.

With a symmetry-reduction (combination of 2 outputs by a hybrid) we can get another 30 dB, which is limited by the finite isolation of a standard hybrid.

2.2 Design-study for the TTF

TM_{110}-cavity

The number of modes trapped in the cavity should be as small as possible. This can be achieved with a short cavity and shifting the resonant frequency of the TM_{020} above the beam pipe cut-off. The resonant frequency f_{110}=2.1667 GHz was chosen to avoid interferences from the accelerating cavities (RF and HOM - stop-band: 1.9 GHz - 2.38 GHz) and to have only two trapped modes. It is the 10th harmonic of f_b for injector 1b with a subharmonic buncher (SHB; see Table 1). Since it is foreseen to measure individual bunches with the second injector Q_L has to be less

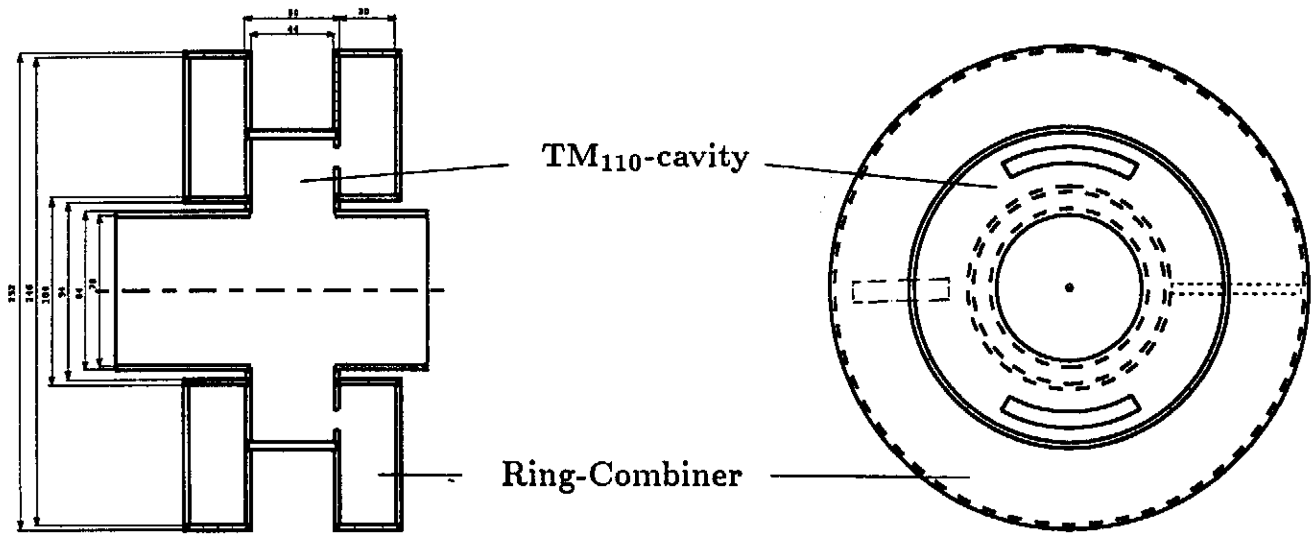


Figure 1: Cavity with a coaxial ring-combiner

than 2000. Hence the material was chosen as CrNi. First measurements on a brass model confirmed the theoretical resolution of 10μm for brass (see also Appendix A). An improvement of the measurement accuracy is expected with a new experimental set-up.

Ring-Combiner

Since the theoretical resolution for our design is limited by the common-mode excitation we designed a ring-combiner to reject these modes (Fig.1; also [5]). For $f_{110} = 2.1667 GHz$ the magnetic field of the dipole mode adds whereas for the common modes it subtracts. We expect a symmetry rejection of more than 30 dB for the TM_{010} with respect to the TM_{110}.

One problem is to avoid standing waves. We designed a coupling to a ridged waveguide via a slot in z-direction, but it might be necessary to realize a stronger coupling (selective coupler).

The TM_{010} will be used as a reference and for measuring the bunch charge. We investigate a selective coupler located at a point where the magnetic field of the TM_{110} (in the hybrid) will be zero. The combiner can be machined with micrometer tolerances, too.

However, the prototype for the first module uses four electrodes and a standard hybrid instead of the ring-combiner (as shown in Fig.2)

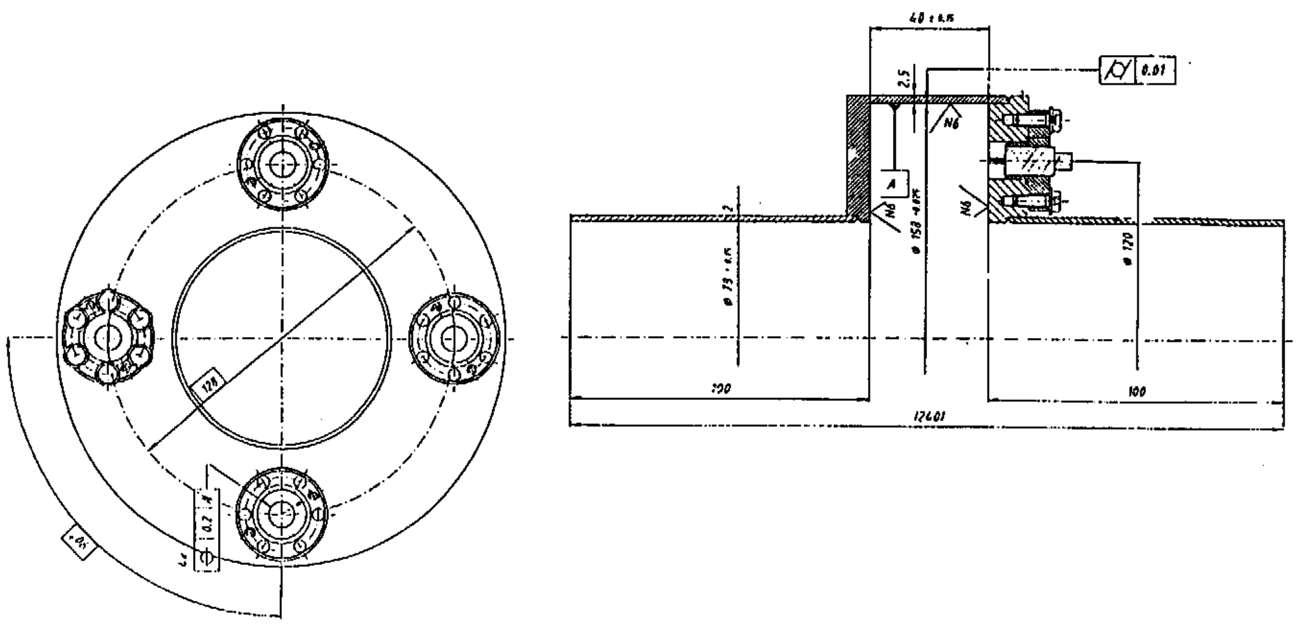


Figure 2: Cavity-prototype for the first TTF-module

2.3 Signal-Detection

We plan to realize two different schemes and to compare some important parameters (e.g. resolution, stability, costs):

a) with a heterodyne receiver, no damping

In a heterodyne receiver the frequencies of the dipole mode and a reference (smaller than or

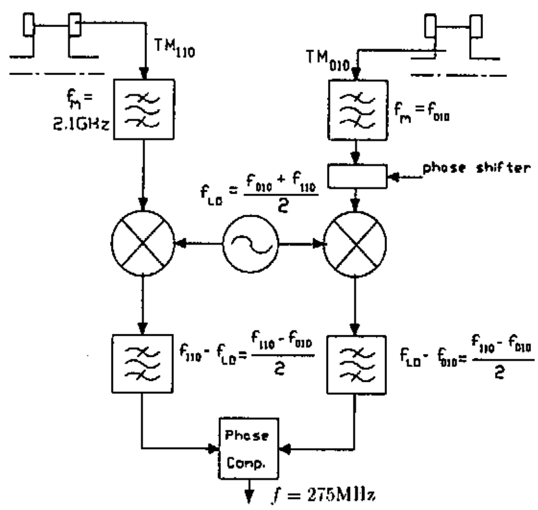


Figure 3: Signal detection using a heterodyne receiver

equal to the dipol mode frequency) are mixed down to an IF. Due to the difference between both frequencies we need only one stage, with an LO at $f_{LO}=\frac{f_{010}+f_{110}}{2}$. But the very high dynamic range in power (N=$5 \cdot 10^{10}$: -17dBm for δ_x=10μm, 55dBm for δ_x=39mm) required for the mixers causes problems. Step attenuators or limiters in a parallel scheme could solve this problem.

b) with selective couplers and several filters

The problem mentioned above could be solved with a filter, rejecting all other modes except the TM_{110}. At the end log-amplifiers at 2.17GHz will be used to get the desired dynamic range. A possible scheme which requires several filters to get more or less than 100 dB rejection is given in Fig.3 (see also [6]).

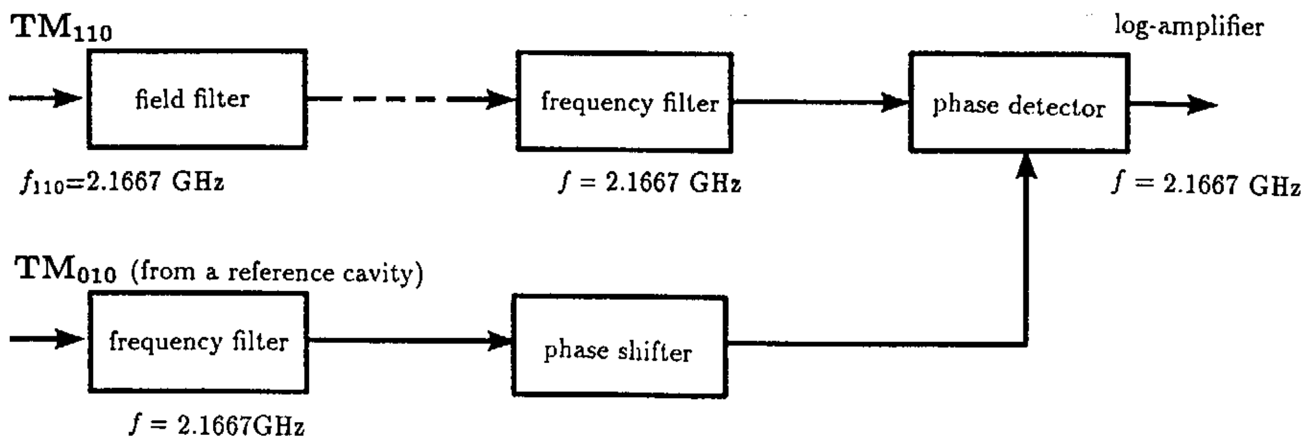


Figure 4: Signal detection using different filters

3 Low-Impedance Resonant BPMs

Due to the longrange wakefields and because of the required resolution it might be necessary to have resonant BPM's with a lower impedance.

3.1 Resonant Button Pickups

A button pickup consists of four similar electrodes (round plates with small diameters, see Fig. 5a) in the wall of the beam tube. For small buttons is the signal V_e with field theory developed and the result is shown in Fig.6a. The device behaves as a pure capacitance.

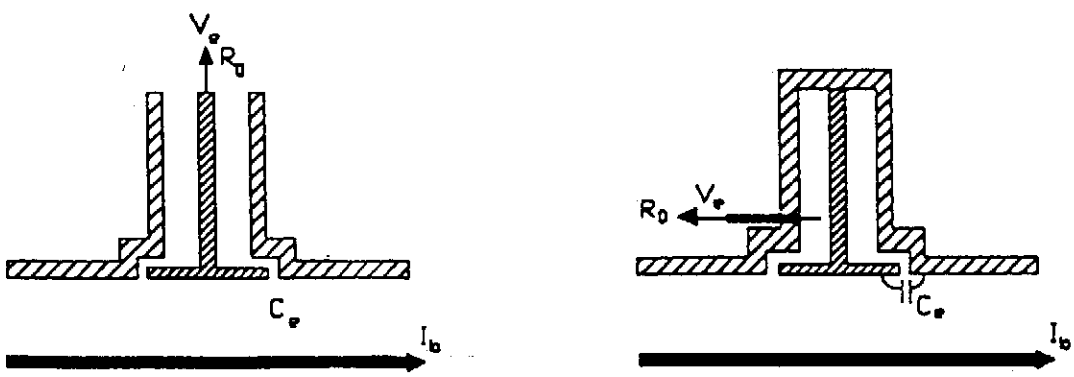


Figure 5: a) Capacitive button pickup b) Resonant button pickup

The signal we get with capacitive buttons is not strong enough, hence we can not reach a resolution of a few μm. To get a stronger response, the button is made resonant by placing a)

b)

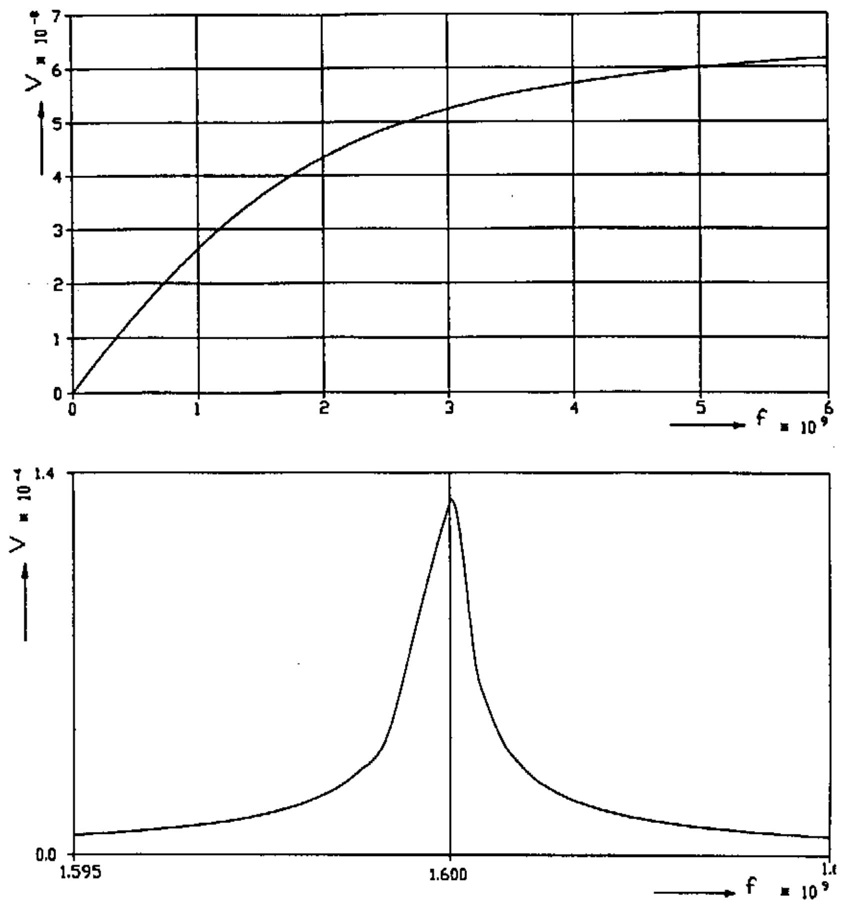


Figure 6: Signal versus frequency on a) a capacitive button b) a resonant button

an inductor in parallel with the capacitance. Fig.5b shows a possible realisation with a short-circuited feed and Fig.6b the frequency dependence. Theoretically, with resonant buttons one can reach a resolution of 10 μm for $5 \cdot 10^{10}$ particles per bunch and a noise power of 10^{-12} W.

The difference signal of two opposite electrodes has a linear deviation dependence and the sum signal is constant. The ratio difference to sum, which is shown in Fig.7 for three different positions in perpendicular direction, has a linear deviation dependence, too.

3.2 Coupled Zero-Mode Monitor

In another arrangement proposed by W. Schnell [3] the signal is superimposed as a modulation. Two identical cavities are weakly coupled to the beam by coupling slots. If the beam passes through the centre both cavities start oscillating at equal amplitudes and in phase with each other. The oscillation decreases in a smooth exponential. If the beam is displaced to the right, the left cavity will be given less energy than the right. A modulation by $f_\delta = f_0 - f_\pi$ (f_0 is the zero-mode and f_π the π-mode frequency) will be superimposed to the exponential decay of the output signal. Its amplitude yields the beam displacement, while the starting phase determins the sign.

However, the arrangement originally proposed is complicated and not very favourable for machining at micrometer tolerances. We investigated coaxial cavities as shown in Fig.4 and estimated the coupling between a coaxial cavity and the beam to get the power in the desired mode. For our design and N=$5 \cdot 10^{10}$ particles/bunch we expect a resolution of about 12μm.

The coupling between the cavities and hence the modulation frequency has been increased with additional slots in the common walls between the cavities. The whole BPM consists of two

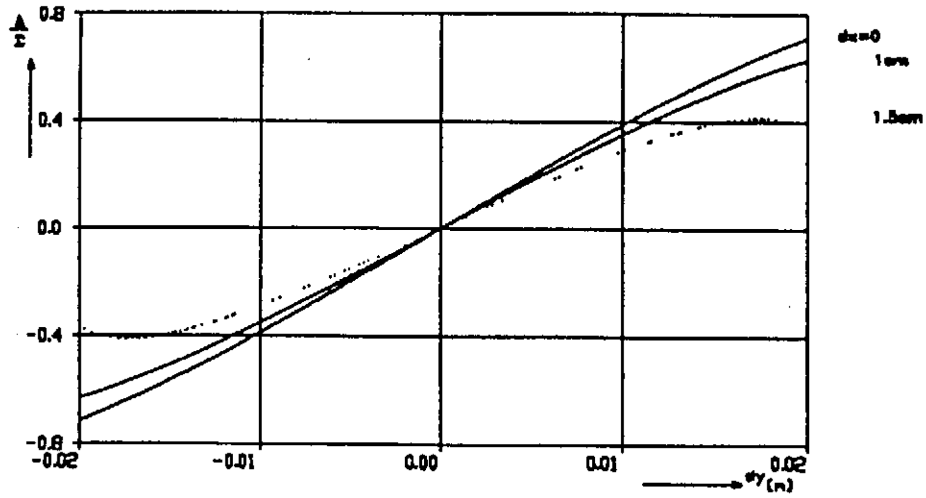


Figure 7: Ratio difference to sum for resonant buttons

such cavities for x- and y-direction, respectively, and a reference cavity to get the starting phase.

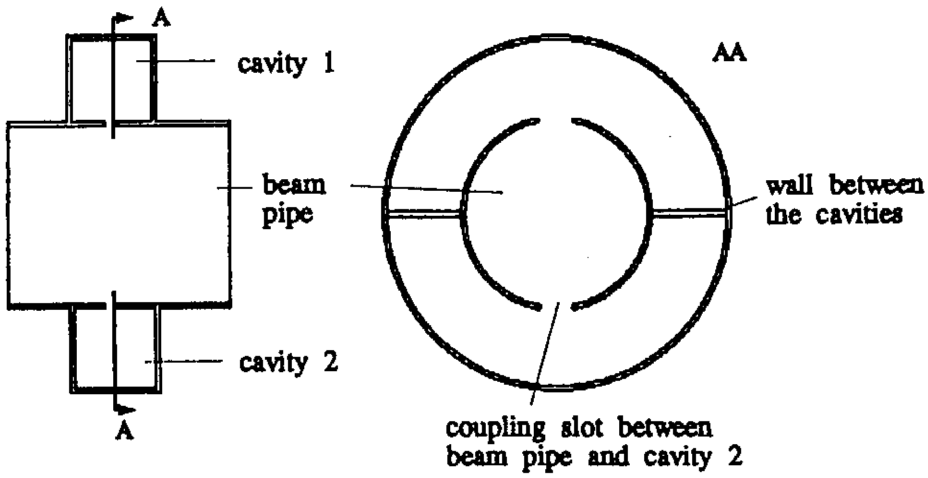


Figure 8: Coaxial coupled zero-mode monitor

Advantages

* simple device, can be machined with μm-tolerances

* the coupling to the beam is much weaker than for the TM_{110}-cavity, lower wakefields even with high Q-factors

Problems

* f_0 and f_π are much closer than the frequencies in the cavity (using (8) we can estimate the spectral densities)

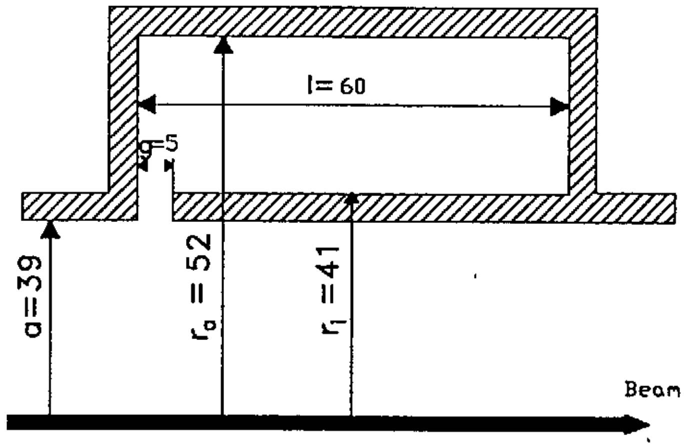
* less power per μm displacement, smaller sensitivity

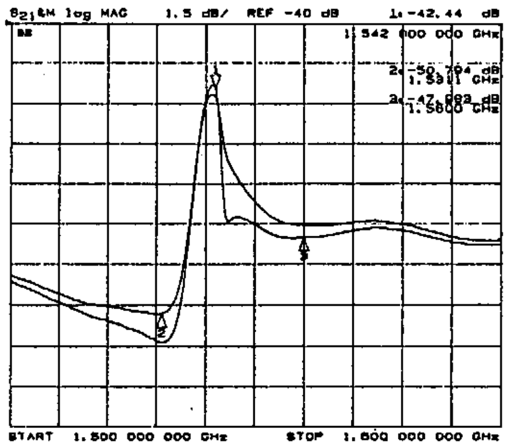
* impossible to measure 10μm with injector 1b

3.3 BPM Using a Re-entrant Cavity

This principle structure was proposed by R.Bossart and the operation of a broadband monitor is described in [2]. Since 1975 eight of these monitors with a resolution of less than 0.004 times the beam pipe radius have been working in the CERN-SPS.

The bunched beam excites the TE_{111}-mode in a re-entrant coaxial cavity. Other modes as the fundamental TEM are excited, too. A broadband monitor below the resonance provides more signal and a better time resolution. But due to the required resolution we designed a resonant monitor (only for injector 2). The resonant frequency $f_{TE_{111}}$=1.6 GHz was chosen to avoid unwanted interferences (first stop-band).





displacement $\delta x \approx 50\mu m$

Figure 9: a) BPM using a re-entrant cavity b) Measurements on a brass model

Some parameters can be seen in Fig.9a and a measurement plot on a brass model for a displacement of 50 μm in Fig.9b. In our first measurements we also found other resonances (slot modes, resonances in the coupling system ?). We are planning to repeat these measurements with a better coupling and using another experimental set-up.

Advantages

* the cavity can be machined within μm-tolerances
* smaller beam-impedance than for the TM_{110}-cavity
* gives a good isolation between the 70K- and the 1.8K-point

Problems

* less power per μm displacement, less sensitivity with respect to the TM_{110}-cavity
* difficult to measure 10 μm with injector 1b
* resolution is also limited by the four antennas and feedthroughs

References

[1] Workshop on the TESLA Test Facility, at DESY Hamburg, 24-26 February, 1993

[2] R. Bossart, *Microwave Beam Position Monitor Using A Re-Entrant Coaxial Cavity*, CERN PS 91-59 (LP)

[3] W. Schnell, *Common-mode rejection in resonant microwave position monitors for linear colliders*, CLIC note 70, CERN-LEP-RF/88-41

[4] J.P.H. Sladen et al., *The effect of finite Q on the precision of resonant beam position monitors*, CLIC note 185, 1993

[5] H. Hayano et al., *Submicron Beam Position Monitor for the Japan Linear Collider*, presented at LINAC 92, Ottawa, 1992

[6] V. Vogel, *BPM for VLEPP*, presented at the ECFA-workshop on e^+e^- Linear Colliders LC 92, Garmisch-Partenkirchen, 25 July - 2 August 1992

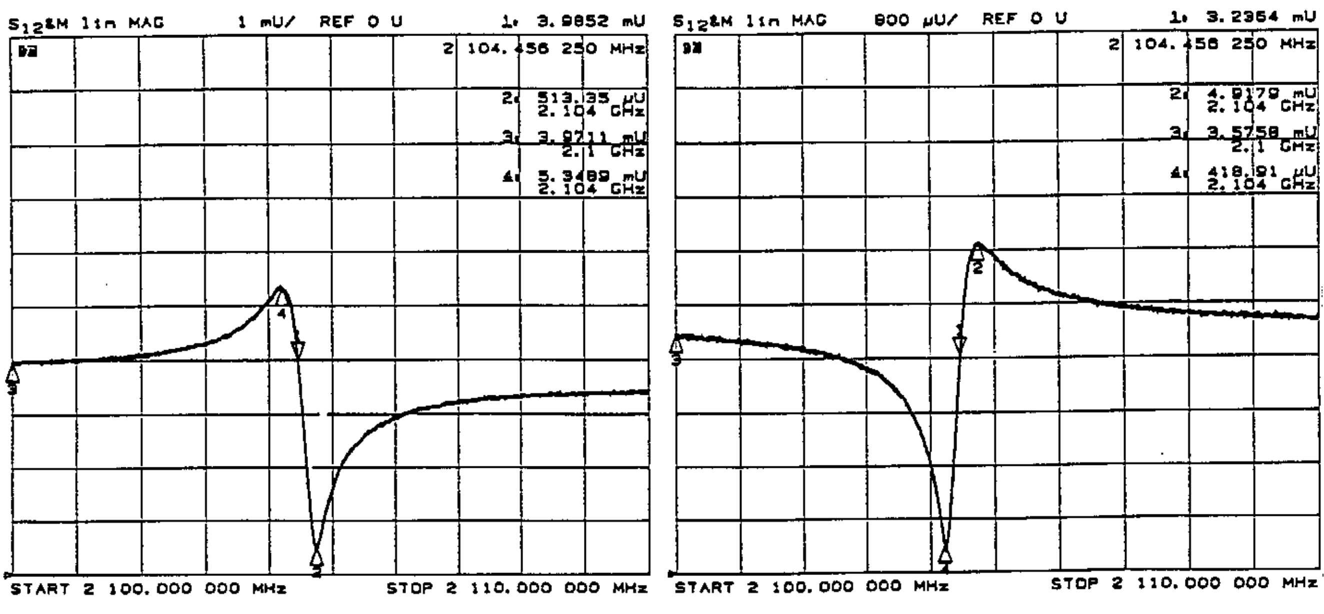
Appendix Design-study for the TM_{110}-BPM

The number of modes excited by the beam and trapped in the cavity should be as small as possible. This can be achieved with a short cavity and shifting the resonant frequency of the TM_{020} above the beam pipe cut-off.

Operating frequency	2.1667 GHz
Frequency of the TM_{010}	1.63 GHz
thermal expansion coefficient	$\approx 16 \cdot 10^{-6} \frac{1}{K}$
expected expansion, cavity radius	$\approx$ -370 μm
expected expansion, cavity length	$\approx$ -200 μm

Dimension	Target (mm)	Sensitivity (1/100 μm)	Tolerance (μm)
cavity radius r	78.2 mm	2.4 MHz	$\pm$ 10
cavity length l	40	- 35 KHz	$\pm$ 150
beam pipe radius a	39	400 KHz	$\pm$ 100

Table 3: Design values and mechanical tolerances



displacement $\delta x = \pm 10 \mu m$

Figure 10: Measurements on a cavity model