RF 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. A circular cavity excited in the TM_{110}-mode by the off-axis beam provides a signal strong enough for various injectors. Expected signal to noise ratios and the theoretical resolution are estimated for a designed structure. A coaxial combiner was designed for common mode rejection. It is also foreseen to test different low-impedance monitors behind the injector. A structure using two coupled cavities is briefly described.

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 will be attached to the quadrupoles within 50μm mechanical alignment precision. Because of the desired precision and the limited

name	particles/bunch	frequency	bunch separ.
1b	$5 \cdot 10^8$	73 MHz	14 ns
2	$5 \cdot 10^{10}$	1 MHz	1 μs

Table 1: Injectors proposed for the TTF and TESLA

space we designed a TM_{110}-excited circular cavity. The resonant frequency f_{110}=2.1GHz was chosen to avoid interferences from the accelerating cavities. In this paper we denote 'resolution' as 'precision limited by electromagnetic interference and circuit noise'.

Since monitors with lower impedances might be required for a multibunch Linear Collider it is also foreseen to test other structures like resonant buttons or a re-entrant cavity (see also [2]) behind the injector. A structure using two coupled coaxial cavities is briefly described here.

2. TM_{110}-Excited Circular Cavity

The simplest microwave BPM-structure is a circular cavity excited in the TM_{110}-mode by an off-axis beam.

Advantages

* the TM_{110}-amplitude 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
* by measuring the amplitude of the fundamental mode we get a signal proportional to the bunch charge

Problems

* the precision is limited by the finite Q ([4]); it can be increased by combining two symmetrical outputs in a hybrid
* a common mode rejection of more than 120 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
* 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 (electronics).
* the expected signal ratio due to the finite Q-values.

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.

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

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

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 and (1) we get

$$P_{110} = {\delta_x}^2 \cdot (Ne\omega)^2 \cdot \frac{Z_0 \cdot l \cdot a_{11}}{4\pi \cdot r^3 \cdot Q_L \cdot (J_0(a_{11}))^2} \qquad (3)$$

With Q_L=2000, f_{110}=2.1GHz, r=81mm, length l=44mm this yields for N=$5 \cdot 10^{10}$

$$\frac{P_{110}}{\mathrm{W}} = (\frac{\delta}{\mu\mathrm{m}})^2 \cdot 1.31 \cdot 10^{-16} \cdot N^2 \approx 3.3 \cdot 10^{-7} (\frac{\delta}{\mu\mathrm{m}})^2 \qquad (4)$$

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With numerical results (Table 2) for the $\frac{R}{Q}$ of a cavity with beam pipes and assuming a coupling factor β=1 we obtain

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

This is much more than the expected thermal noise from the first stage of amplification ($P_{noise} \approx 10^{-12}$W).

length	Mode	$\frac{frequency}{GHz}$	Q	$\frac{R/Q}{\Omega}$	$\frac{k_0}{V/pC}$
l_1	TM_{010}	1.66	1901	48.60	0.127
l_1	TM_{110}	2.12	2537	71.83	0.237
l_2	TM_{010}	1.55	3989	86.62	0.209
l_2	TM_{110}	2.11	5471	100.70	0.332
geometry: r=81mm , a=39mm, l_1=20mm, l_2=44mm material: ring - Cu , endplates - CrNi					

Table 2: MAFIA-results for a cavity with beam pipes

Excitation of Common Modes

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

$$S_1 = \frac{V_{010}(\omega_{010})}{V_{110}(\omega_{110})} \approx \frac{5.4}{\lambda_{110}} \cdot \delta_x \cdot \frac{k_{010}}{k_{110}} \qquad (5)$$

For the spectral densities at ω_{110} he obtained

$$S_2 = \frac{v_{010}(\omega_{110})}{v_{110}(\omega_{110})} \approx S_1 \cdot Q_{110} \cdot (1 - \frac{\omega_{010}^2}{\omega_{110}^2}) \qquad (6)$$

λ_{110} is the wavelength, Q_{110} the Q-factor of the TM_{110}. Including numerical results we obtain $\delta_x \approx 30\mu$m.

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 hybrid.

2.2. Design-study for the TTF

The prototype consists of the cavity itself and a coaxial ring-combiner to reject common modes.

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}=2.1GHz was chosen to avoid interferences from the accelerating cavities (stop-band: 1.9 GHz - 2.38 GHz).

Since it is foreseen to measure individual bunches with the second injector Q_L has to be less than 2000. Hence the material was chosen as CrNi. First measurements on a brass modell confirmed the theoretical resolution of 10μm for brass. 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 (see results above) we designed a ring-combiner to reject these modes (Fig.1; also [5]). For $f_{110} = 2.1GHz$ 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.

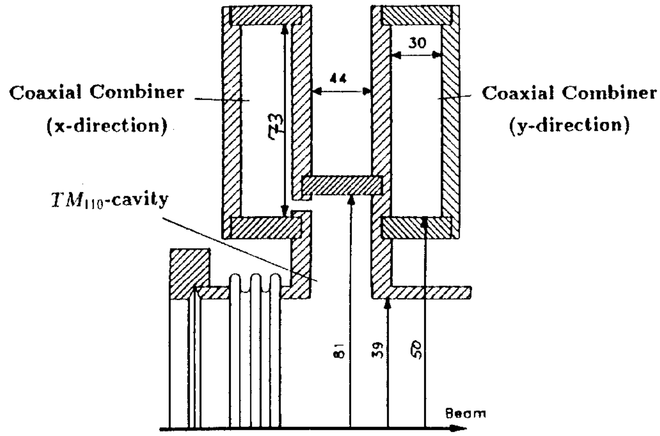

Figure 1: Cavity and coaxial ring-combiner

One problem is to avoid standing waves. We designed a coupling to a ridged waveguide via a slot in z-direction. However, it might be necessary to realize a stronger coupling with a 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 micrometre tolerances, too.

2.3. Signal-Detection

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

a) with a superheterodyne receiver, no damping

In a superheterodyne receiver the frequencies of the dipole mode and a reference (smaller or equal 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 required for the mixers causes problems.

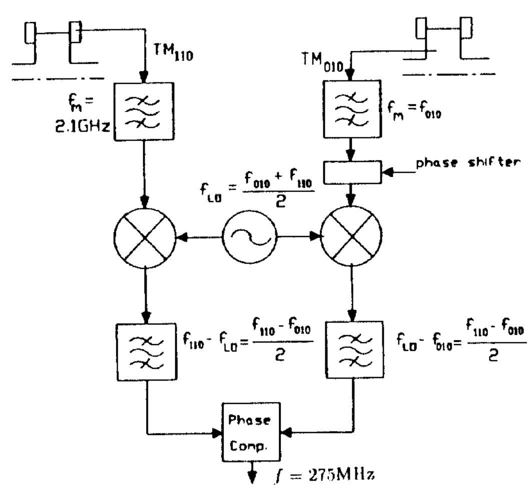

Figure 2: Signal detection using a heterodyne receiver

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 2.1GHz will be used to get the desired dynamic range. A possible scheme which requires several filters to get more or less than 120 dB rejection is given in Fig.3 (see also [6]).

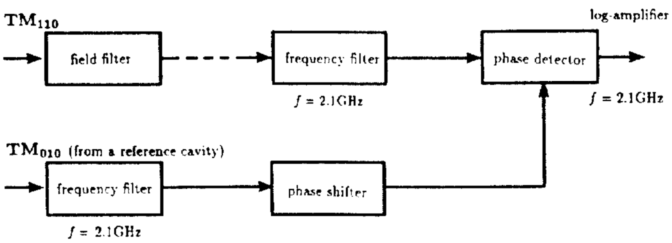

Figure 3: Signal detection using different filters

3. Coupled Zero-Mode Monitor

It might be necessary for the operation of a multibunch Linear Collider to use monitors with a lower impedance. We investigated three different structures, which are resonant to get the desired resolution. Resonant buttons, a monitor using a re-entrant cavity and measurements on prototypes are discussed in detail in [7]. Theoretically, with resonant buttons one can get a resolution of $10\mu m$ for N=$5{\cdot}10^{10}$ ($P_{noise} \approx 10^{-12}$W).

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 originally proposed arrangement is complicated and not very favourable for machining at micrometre 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 $5{\cdot}10^{10}$ particles per bunch we expect a resolution of about $12\mu m$ (see also [7]).

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

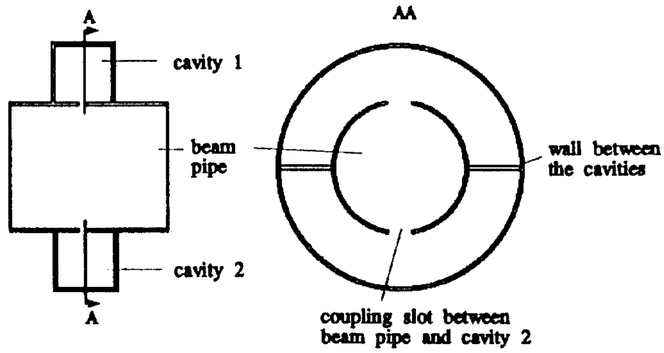

Figure 4: Coaxial coupled zero-mode monitor

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 $10\mu m$ with injector 1b

5. Acknowledgements

The advice and help of H. Henke for the analytical calculations and helpful discussions is gratefully acknowledged.

References

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