Test Results on a Beam Position Monitor Prototype for the TTF

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Abstract

A beam position monitor using a cylindrical cavity excited by the beam in the TM_{110}-mode has been developed for the first modul of the TESLA Test Facility. The cavity design and the signal processing scheme are briefly described, the expected signals are estimated. A stainless steel prototype and the electronics were tested. Therefore, the cavity was excited by an antenna, fed by a network analyzer or a pulser. To achieve the measured resolution near the electrical center of better than 10 μm two symmetrical outputs were combined in a hybrid.

1 INTRODUCTION

Beam position monitors with a resolution of less than 10 μm near the electrical center are required for the alignment of the quadrupoles in the TESLA Test Facility TTF. This has to be achieved in a cold environment and for two different injectors with 800ms long macro pulses:

injector 1a	charge/bunch 32 pC	bunch spacing 4.6 ns
injector 2	charge/bunch 8 nC	bunch spacing 1 μs

Because of the desired resolution and the limited longitudinal space, a single circular cavity was designed. These monitors are also under investigation for other linear collider studies ([2],[3],[4]). The amplitude of the TM_{110}-mode excited by an off-center beam is proportional to the beam displacement and the bunch charge. The phase relative to an external reference yields the sign of the displacement. Both polarizations have to be measured to get the displacement in x and y.

2 PROTOTYPE DESIGN

The cavity design parameters given in Table 1 were calculated with URMEL, and the measurements were performed on a stainless steel prototype (shown in Fig.1) at room temperature. To avoid interferences from the accelerating cavities, the cavity was designed for a resonant frequency of $f_{110} = 1.517$ GHz.

One of the main mechanical problems was to reduce asymmetries caused by welding. CrNi was chosen as the cavity material to measure individual bunches spaced 1 μs and to have a good thermal isolation between an accelerating cavity and a quadrupole. The antennas are replaceable, consisting of Kyocera-feedthroughs welded into a special flange. This allows a pre-tuning by adjusting the coupling at room temperature.

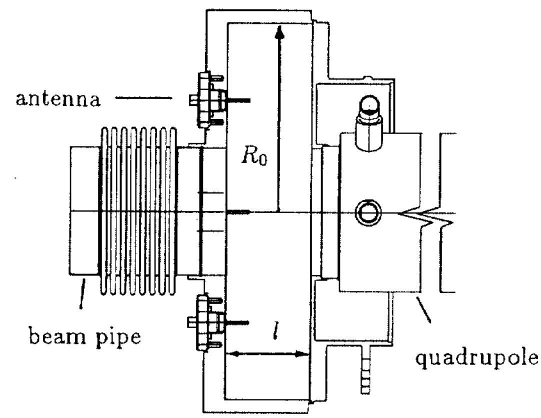

Figure 1: Design of the BPM-Prototype

dimension	at 290 K	target	sensitivity $\pm.1$ mm Δ
radius R_0	115.2 mm	114.77 mm	$\mp$1247 KHz
length l .	52.0 mm	51.80 mm	$\pm$79 KHz
beam pipe Ø	78.0 mm	77.70 mm	$\mp$610 KHz
theoretical loss factor $[\frac{V}{pC}]$		$k_{110} = 0.242$, $k_{010} = 0.179$	
theoretical unloaded Q		$Q_{110} = 2965$	
measured frequency [GHz]		$f_{110} = 1.5133$, $f_{010} = 1.04$	
measured coupling		$\beta_{110} = 1.31$, $\beta_{010} = 0.1$	

Table 1: Cavity design and measured parameters

3 ESTIMATED SIGNALS

The resolution near the electrical center of the cavity is limited by the thermal noise of the electronics and the excitation of common modes. For a cavity without beam pipes, the voltage in the TM_{110} excited by a beam at a position δ_x can be estimated as

$$V_{110}(\delta_x) = V_{110}^{max}\frac{\delta_x \cdot a_{11}}{2J_1^{max}R_0} = \delta_x \frac{k'_{110}a_{11}q}{J_1^{max}R_0} \approx 0.417\cdot\delta_x \frac{\text{mV}}{\mu\text{m}}$$

where a_{11} is the first root of the Bessel function J_1 and $k'_{110} = 0.228$ V/pC is the longitudinal lossfactor of the geometry in Table 1 (but without a beam pipe).

Assuming a noise figure of NF = 6 dB, the S/N-ratio in a bandwidth $B = 100$ MHz at $T = 290$ K is given by

$$\frac{V_{signal}}{V_{noise}} = \frac{0.417\text{ mV}}{\text{NF}\cdot\sqrt{Z_0\cdot k_0\cdot T\cdot B}}\frac{\delta_x}{\mu\text{m}} \approx 47\cdot\frac{\delta_x}{\mu\text{m}}$$

Since the field maximum of the common modes is on the cavity axis, they will be excited much stronger by a beam near the axis than the TM_{110}. The voltage of the TM_{010} with respect to the TM_{110} and the ratio of the spectral densities at ω_{110} ([1]) can be estimated as

$$S_1 = \frac{V_{010}(\omega_{010})}{V_{110}(\omega_{110})} = \frac{1}{\delta_x}\frac{\lambda_{110}}{5.4}\frac{k_{010}}{k_{110}} \approx \frac{0.027}{\delta_x}$$

$$S_2 = \frac{v_{110}}{v_{010}} \approx \delta_x \frac{1}{S_1}\frac{Q_{110}}{1+2\beta_{110}}\left(1-\frac{\omega_{010}^2}{\omega_{110}^2}\right) \approx 16000\cdot\delta_x$$

S_1 gives the required frequency sensitive common-mode rejection - about 69 dB for a displacement of $\delta_x = 10\mu m$ (for the parameters in Table 1). But the minimum detectable signal is still limited by residual signals at ω_{110}. For a single antenna, this can be estimated using $S_2 = 1$, which yields $\delta_x^{min} \approx 62\ \mu m$. With a combination of two antennas in a hybrid one gets a field selective filter, which gives a rejection of unwanted common field components at ω_{110} of more than 20 dB. Hence, the theoretical resolution near the electrical center of the cavity is $\leq 6\ \mu m$.

4 SIGNAL PROCESSING

For signal processing, we adopted a synchronous detector scheme (Fig.2), where the amplitude of the TM_{110} and a reference are mixed down to DC. The phase of the reference signal can be adjusted to maximize the mixer output. When the beam is to the right, the system can be set up to give positive video polarity. The signal changes the phase by 180^0 when the beam moves to the left, and for a centered beam it becomes zero.

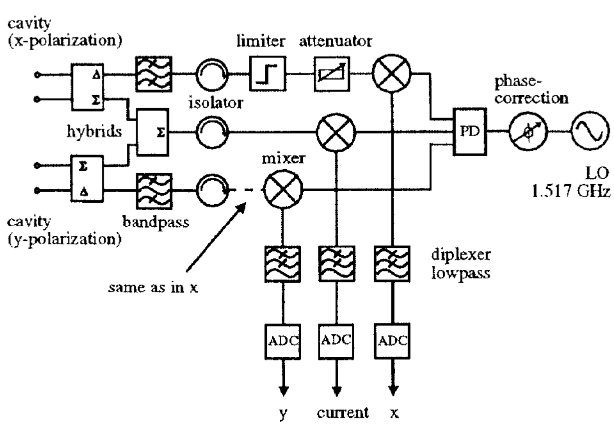

Figure 2: Signal processing scheme

Due to the limited space, the combination of two opposite antennas has to be realized outside the cryostat. The isolation of standard (broadband) hybrids is about 25dB, which limits the resolution. The tubular bandpass filter has a bandwidth of 100 MHz and a stopband attenuation of more than 80 dB, up to 8 GHz. Together with the hybrid and the different coupling factors this gives a common mode rejection of more than 100 dB.

Because of the finite isolation of the hybrid and between both polarisations the full aperture was divided into two measurement ranges:

$0\cdots 300\ \mu m$, normalization from the hybrid sum

$0.3\cdots 39$ mm, normalization from current monitors

The LO-RF-isolation of the double-balanced mixer determines the dynamic range of the electronics. About 45dB is required, due to the displacement and differences in the bunch population. An isolator was inserted between the filter and the mixer to reduce reflections and error signals due to second-time mixing. A low-pass filter removes the residual LO-signal and the sum-signal of both mixer inputs. The signal passes through a bipolar video amplifier to the 12-bit flash ADC. Its trigger is generated by the sum-signal of the hybrid, with a delay of 85 ns. All data can be read out between two bunch trains and the normalization will be done in a computer.

We are planning to test a Quadrature IF Mixer, too. When its two outputs are applied to an oscilloscope, a polar display is produced. The vector radius is proportional to the amplitude of both signals and the angular displacement to the phase difference between both inputs. This system does not need an additional phase shifter for the reference signal, and a signal proportional to the phase difference might be usefull in a PLL.

5 MEASUREMENT RESULTS

Bench tests were carried out on a stainless steel prototype to measure the resolution near the center and to test the electronics. The cavity was excited by an antenna, fed by a network analyzer or a pulser.

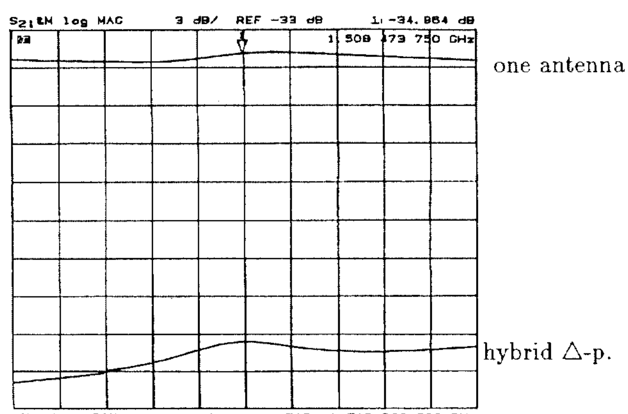

Figure 3: Measured common mode rejection

First, we measured the common-mode rejection due to the combination of two antennas in a 180^0 stripline hybrid. Therefore, the antenna was fed by a network analyzer and moved in x- and y-direction until a minimum was found. The upper trace in Fig.3 shows the output of one antenna and the lower trace the signal at the Δ-port of the hybrid. The difference between both traces corresponds to the isolation of the hybrid, about 23 dB.

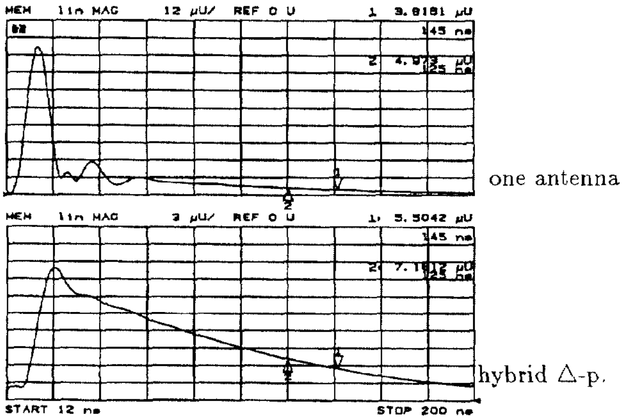

Figure 4: Impulse response of the cavity

To measure the impulse response of the cavity and the electronics, the frequency was swept over a wider range and the inverse Fourier transform was used (t-domain bandpass mode). The equivalent pulse width was about 350 ps. An amplifier was inserted to compensate for the high insertion losses. The upper trace in Fig.4 was measured using a single antenna, whereas the lower trace shows the response at the Δ-port of the hybrid. The oscillation on both traces corresponds to the impulse response of the bandpass filter (inserted after the antenna and the hybrid, respectively).

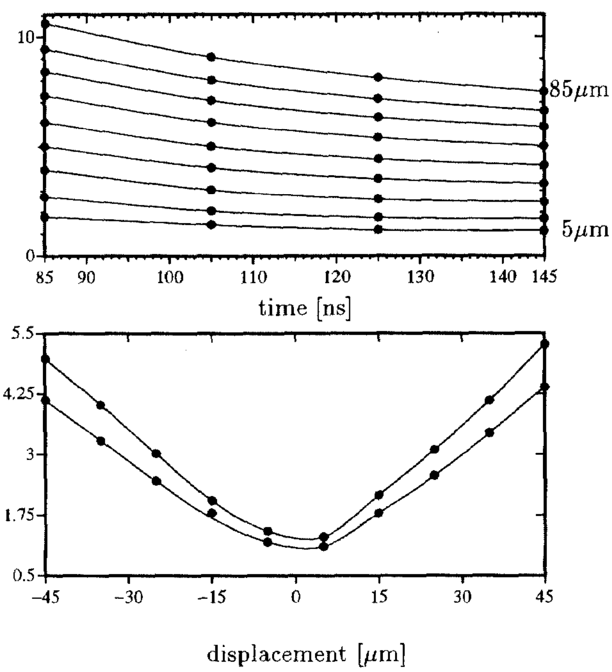

Figure 5: Resolution in the t-domain (impulse response)

Then, four markers spaced 20 ns were placed on the curve and the cavity was moved within 10 μm steps only in the x-plane. All marker-readouts are plotted in Fig.5a for different cavity positions. The shape of all curves shows the exponential envelope of the TM_{110}-amplitude, whereas the difference between two traces corresponds to a movement of 10 μm. The lowest trace gives the response for a position of about 5 μm from the electrical center of the cavity. Fig.5b shows the readout of two markers, plotted versus the relative position. We missed the center position since the cavity was moved only in one direction. Note that the magnitudes are given in relative units.

To get similar responses in a real time domain measurement and for testing the electronics, a pulser with a pulse width of 370 ps and a variable repetition rate (up to 5 MHz) was built to excite the cavity. The filtered Δ-port signal was mixed down to DC and displayed on an oscilloscope (upper trace in Fig.6). The oscilloscope was triggered by the sum-signal of the hybrid, similar to the scheme shown in Fig.2. Again, the oscillation on top of both signals corresponds to the filter impulse response. Since the pulser was not very stable with respect to its amplitude, it was impossible to measure the parameters mentioned above (resolution, min. detectable signal etc.).

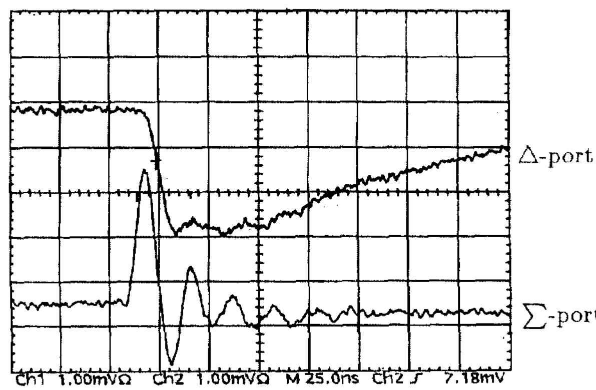

Figure 6: Cavity response to a pulser

6 ACKNOWLEDGEMENTS

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