Beam Position Monitors in the TESLA Test Facility Linac

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Abstract

The transverse position of the beam in the TTF Linac will be measured using two different types of monitors. For the alignment of the quadrupoles a circular cavity was designed because of the desired resolution of 10 μm and the limited longitudinal space. The amplitude of the TM_{110}-mode will be measured in a homodyne receiver, using a signal from the timing system as a reference. Stainless steel prototypes were tested. Furthermore, the single bunch behaviour was measured at the CLIC Test Facility.

Coaxial Striplines will be installed in the experimental area, having a resolution of better than 100 μm. The averaged position of the whole bunch train or the position of an individual bunch will be measured using the amplitude-to-phase conversion.

I. Introduction

In order to establish a technical basis for a superconducting linear collider the TESLA Test Facility is an essential part of the development of injectors, accelerating cavities, cryostat and new diagnostic techniques.

The transverse position of the beam after the injector will be measured using two different types of monitors. For the alignment of the quadrupoles a single circular cavity was designed because of the limited longitudinal space and the desired resolution of about 10 μm in a cold environment (see also [3]). The amplitude of the TM_{110}-mode will be measured in a homodyne receiver, using the seventh harmonic of a 217 MHz timing signal as a reference.

Stripline BPMs will be installed in the experimental area, having a resolution of about 100 μm. For Injector I (bunch spacing of 4.6 ns) the averaged position of the bunch train will be measured using the amplitude-to-phase conversion.

II. TM_{110}-Cavity

The amplitude of the TM_{110}-mode excited in the cavity by an off-center beam yields a signal proportional to the beam displacement and the bunch charge. Its phase relative to an external reference yields the sign of the displacement. Both polarizations of this mode have to be measured to get the displacement in x and y, respectively. For Injector I this system can measure only an average over the bunch train.

A. Prototype Design

The cavity parameters given in Table I were calculated with URMEL, and the measurements were performed on a stainless steel prototype at room temperature (Fig.1). CrNi was chosen as the cavity material to measure individual bunches spaced at 1 μs (Injector II).

After cooling down the structure, the seventh harmonic of 216.7 MHz has to be within the cavity bandwidth to avoid an active tuning system inside the cryostat. The antennae consisting of Kyocera-feedthroughs welded into a special flange, are replaceable to allow a pre-tuning (by adjusting the coupling after welding).

parameter dimension	**at 290 K**	**target**	**sensitivity** $\pm.1$ mm $\triangle$
radius R_0	115.2 mm	114.77 mm	∓ 1247 KHz
length l	52.0 mm	51.80 mm	± 79 KHz
beam pipe	39.0 mm	37.85 mm	∓ 610 KHz
theoret. loss factor $[\frac{\mathrm{V}}{\mathrm{pC}}]$	$k_{110} = 0.242$, $k_{010} = 0.179$		
theoretical unloaded Q	$Q_{110} = 2965$		
measured frequ. [GHz]	$f_{110} = 1.5133$, $f_{010} = 1.04$		
measured coupling	$\beta_{110} = 1.31$, $\beta_{010} = 0.1$		

Table I
Cavity design and measured parameters

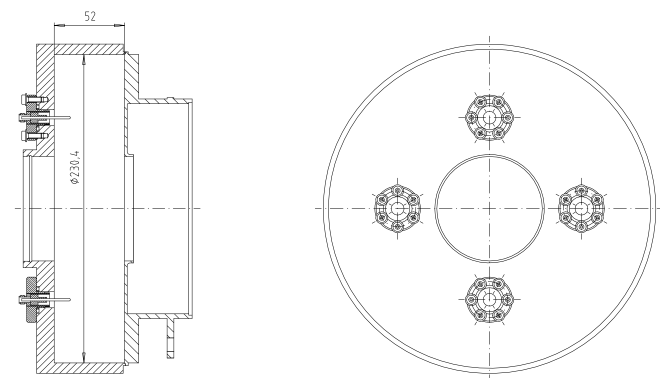


Figure. 1. Cavity BPM

B. 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 of the TM_{110} excited by a beam at a position δ_x vs. the noise voltage can be estimated as

$$\frac{V_{110}(\delta_x)}{V_{\text{noise}}} = \frac{\delta_x \cdot a_{11}}{2J_1^{\max} R_0} \frac{V_{110}^{\max}}{V_{\text{noise}}} = \frac{\delta_x}{J_1^{\max} R_0} \frac{k_{110} \cdot a_{11} \cdot q \cdot \mathrm{T_{tr}}}{\mathrm{NF}\sqrt{Z_0 k_0 \mathrm{TB}}}$$

where a_{11} is the first root of J_1, $\mathrm{T_{tr}}$ the transit time factor, $q = 32$ pC the bunch charge, k_{110} the long. lossfactor and R_0 the cavity radius (Table I). For a noise figure of $\mathrm{NF} = 2$, the S/N-ratio in a bandwidth $B = 10$ MHz at 293 K is about $139 \frac{\delta_x}{\mu\mathrm{m}}$.

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

$$S_1 = \frac{V_{010}(\omega_{010})}{V_{110}(\omega_{110})} = \frac{1}{\delta_x} \frac{\lambda_{110}}{5.4} \frac{k_{010}}{k_{110}} \approx 27 \cdot \left(\frac{\delta_x}{\mathrm{mm}}\right)^{-1}$$

$$S_2 = \frac{v_{110}(\omega_{110})}{v_{010}(\omega_{110})} \approx \frac{1}{S_1} \frac{Q_{110}}{1+2\beta_{110}} \left(1 - \frac{\omega_{010}^2}{\omega_{110}^2}\right) \approx 16 \cdot \frac{\delta_x}{\text{mm}}$$

S_1 gives the required frequency sensitive common-mode rejection - about 69 dB for a displacement of $\delta_x = 10\mu$m. But the minimum detectable signal near the electrical center of the cavity is still limited by residual signals at ω_{110} ($S_2 \leq 1$). With a combination of two antennae in a hybrid one gets a field selective filter and a rejection of unwanted common field components at ω_{110}, limited only by the finite isolation of the hybrid between the Σ- and the Δ-port. Finally, we get a theoretical resolution of less than 6 μm for 20 dB of isolation.

C. Signal Processing

We adopted a homodyne receiver scheme (Fig.2), where the amplitude of the TM$_{110}$ and a reference are mixed down to DC. The reference-signal is generated by mixing a 217 MHz-signal from the timing system and amplifying the seventh harmonic. When the beam is on the right, the system can be set up to give positive video polarity. The signal changes the phase by 180^o when the beam moves to the left, and for a centered beam it becomes zero.

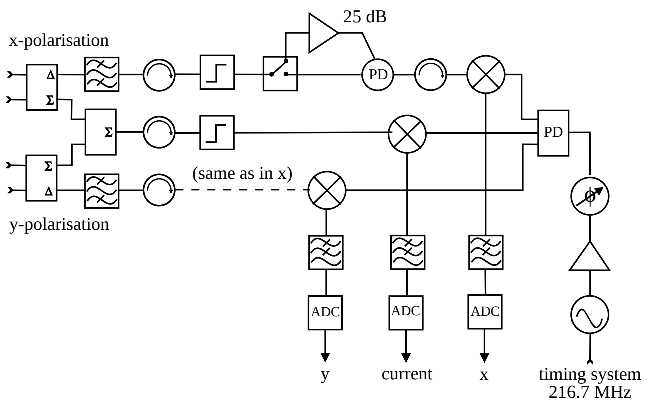


Figure. 2. Signal processing scheme for the cavity BPMs

Due to the limited space, the combination of two opposite antennae was realized outside the cryostat. The tubular bandpass filter has a bandwidth of 100 MHz and a stopband attenuation of more than 70 dB, up to 8 GHz. Together with the hybrid and the coupling factors this gives a frequency sensitive common mode rejection of about 100 dB. Because of the finite isolation of the hybrid and between both polarizations of the TM$_{110}$ (asymmetries in the cavity), the full aperture was divided into two measurement ranges.

The LO-RF-isolation of the mixer determines the dynamic range of the electronics. By using a Quadrature IF Mixer, no additional phase stabilization for the reference would be required. An isolator was inserted between the filter and the mixer to reduce reflections and error signals due to second-time mixing.

After passing a low-pass filter and a bipolar video amplifier, the signal may be either viewed directly on an oscilloscope for adjustment, or digitized and used for the quadrupole alignment. All data of the 12-bit ADC-board can be read out between two bunch trains and the normalization will be done in a computer.

D. Test Results

Bench tests were carried out on a stainless steel prototype to determine the resolution near the center and to test the electronics. Therefore the cavity was excited by an antenna, fed by a network analyzer. A resolution of about 5 μm was measured in the frequency domain (narrowband) and in the time domain (impulse response) by moving the cavity (Fig.3 and Fig.4, see also [3]).

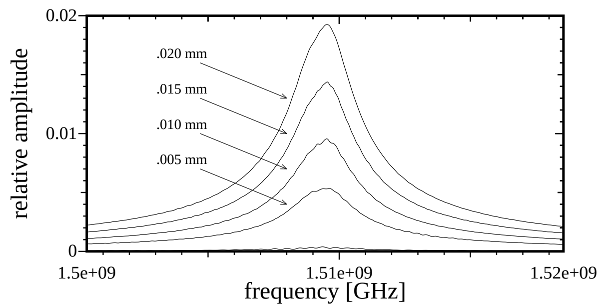


Figure. 3. Bench-test - Narrowband output vs. position

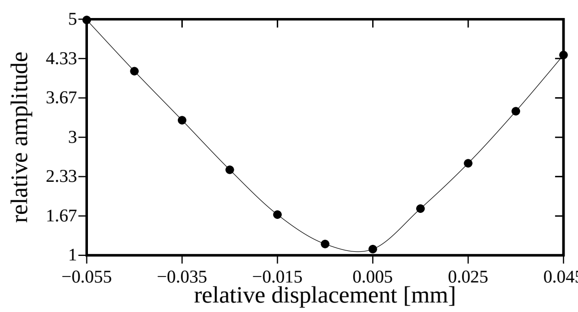


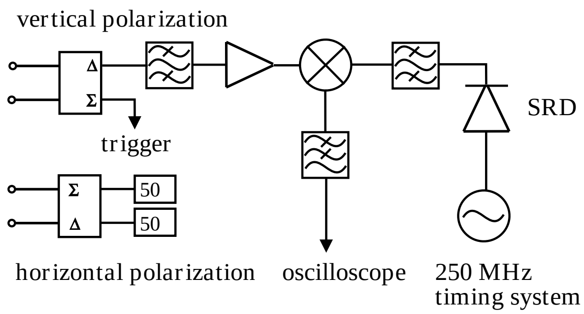
Figure. 4. Bench-test - Impulse response vs. position

To get similar responses in a real time domain measurement and for testing the electronics, a pulser ($t_w \approx 370$ps, amp ≈ 16V) was built to excite the cavity. The filtered $\triangle$-port signal was mixed down to DC and displayed on an oscilloscope triggered by the sum-signal of the hybrid. Since the pulser was not very stable with respect to its amplitude, it was impossible to measure the min. resolution.

In addition, a prototype was tested at the CLIC Test Facility at CERN to demonstrate the principle single bunch response of the monitor and to measure the amplitude of the TM$_{110}$-mode as a function of the relative beam displacement. Therefore, the BPM was installed in the spectro-meter arm and the beam was moved vertically by changing the current of the steering coil.

Since no LO-signal at 1.51 GHz (phase-related to the beam) was available, four different LO-schemes were tested. In one scheme a 250 MHz- signal from the timing system was fed to a step recovery diode and the 6th harmonic was mixed with the Δ-signal. Figure 5 shows the output of the electronics vs. the relative beam position.

Unfortunately, due to the measurement position, the mechanical setup and some machine parameters it was impossible to measure the minimum detectable signal near the monitor center.



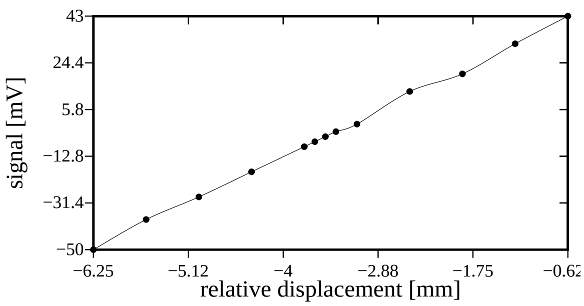


Figure. 5. CTF-test - Output versus rel. position

III. Stripline Monitors

Stripline monitors were selected for the experimental area and a temporary beamline because of the relaxed requirements - 100 μm resolution around the center - and the warm location. All monitors will consist of four 50 Ω coaxial striplines, positioned 90 degrees apart in azimuth (Fig.6). The housing for the one in the dipole arm will be slightly modified due to the elliptical beam pipe.

The BPM body is machined from a single block of stainless steel, and four holes and the beam aperture are drilled (similar to the structure described in [4]). Each electrode is 175 mm long, has a geometrical coupling factor of about 2 % and is shortened at the end. To reduce standing waves on the electrode, the transition from the electrode through the feedthrough into the cable was optimized up to 6 GHz. The main distortion is caused by the feedthrough. A prototype was built by DESY-IfH Zeuthen and is under test.

The signal processing electronics have to measure the Δ-signal and the Σ-signal of two opposite electrodes to calculate the position in one direction. Because of the small charge per bunch and the multibunching, an amplitude-to-phase conversion scheme was adopted. Its basic component is a device which transforms the amplitude ratio of two input signals into a phase difference, usually a $\frac{\pi}{2}$-hybrid. The generation of a normalized output (position versus current) over a wide dynamic range is the main advantage of this system.

Analog electronics will be built by INFN Frascati and a prototype will be tested this summer. The signal coming out of the phase detector may be either viewed directly on an oscilloscope or digitized using a 12-bit ADC-board.

This system will be appropriate to measure individual bunches spaced 1 μs for Injector II, too. Another alternative is to adopt the SLAC-system, where the signals of each electrode are individually stretched, amplified, held at their peak value and than digitized.

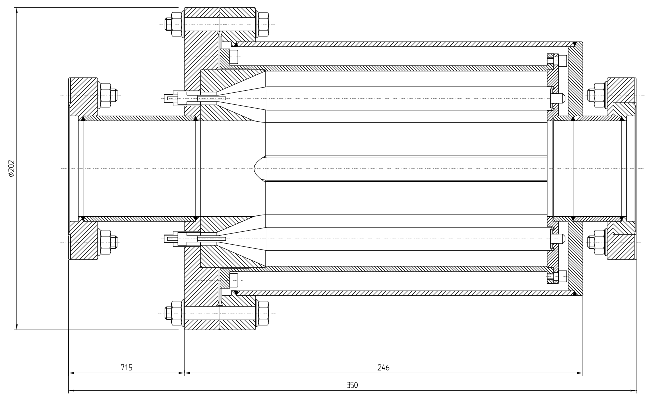


Figure. 6. Stripline BPM

IV. Acknowledgements

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