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Test Measurements of a new TESLA Cavity Beam Position Monitor at the ELBE Linac

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Abstract

A new type of a cavity BPM proposed for beam position determination along the TESLA linac was tested at the accelerator ELBE in Rossendorf / Dresden. Measurements using an improved BPM (large and stable cross-talk isolation, significantly less energy dissipation, a novel LO signal generation) were performed in single- and multi-bunch regimes. Agreement with expectations was found. The low bunch charge available allowed for preliminary measurements on sensitivity and position resolution, which extrapolated to TESLA would fulfil the demands for precise bunch-to-bunch position determination. Possible improvements, in particular on the signal processing scheme, are also discussed.

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1 Introduction

The e^+e^- linear collider TESLA [1] is of fundamental importance for the future development of particle physics. The basic difference between TESLA and other designs is the choice of superconducting accelerating structures. TESLA consists of 1752 cryomodules. Each cryomodule, about 17m long, involves 12 9-cell cavities, a quadropole and a beam position monitor (BPM) located in the middle of the structure, as sketched in Fig. 1.

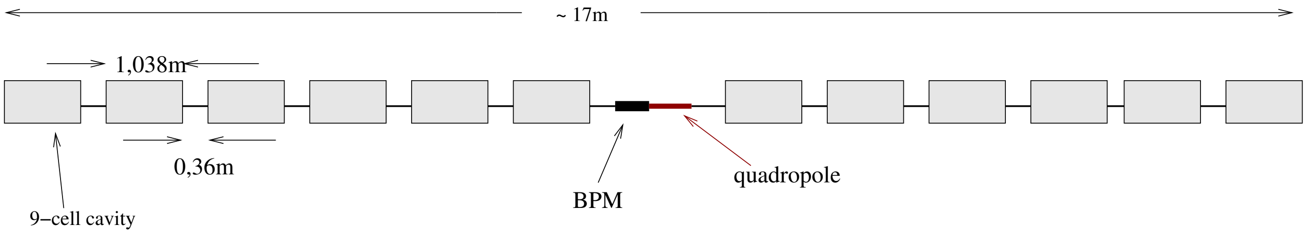

Figure 1: TESLA cryomodule

The main purpose of the BPM is to measure the transverse bunch position with high precision for each bunch with a spacing of 337 ns at E_{CM}=500 GeV. The position resolution requirement on the BPM is 10 μm or better [1].

A predecessor of the monitor with position resolution close to the design value was developed, built and tested [2]. In this paper we discuss a new BPM with significant improvements. In particular, a monitor with significant less energy dissipation on its walls has been designed [3]. Cross-talk, which was found to appear occasionally, is now substantially reduced in a systematic manner [4]. The LO reference signal, stable in amplitude and most of all in phase, is derived from the cavity itself.

The BPM together with the read-out electronics was redesigned and tested first under laboratory conditions. The achieved results were discussed in detail in [3] and encouraged us to test the monitor system (monitor and electronics) with beam at the linear accelerator ELBE in Rossendorf/Dresden.

The paper is organized as follows. In section 2 we present a short description of the new cavity BPM. Theoretically estimated position and time resolutions as well as the scheme for signal processing are also presented here. Test results from the ELBE linac together with their discussion are involved in section 3. Section 4 is devoted to possible improvements of the BPM system. The summary is presented in section 5.

2 The BPM Cavity Prototype

The pick-up station of the prototype BPM is a cylindrical pill-box cavity fabricated from stainless steel (1.4429) with conductivity of $1.33 \cdot 10^6\ \Omega^{-1}\mathrm{m}^{-1}$. Fig. 2 shows the cavity cross section perpendicular to the beam direction. The four black dots indicate the positions of the coupling antennas. The elliptical curves indicate magnetic field lines of the dipole modes TM_{110}^{x} and TM_{110}^{y}, polarized in x- and y- directions, respectively. With two x-directed small cylindrical recesses the polarizations of the dipole modes are forced along these directions. With such a design a stable 40 dB cross-talk isolation between signals from x and y has been achieved. Details about the cross-talk problem, its measurement and the proposed solution are given in [4].

Technical details of the cavity BPM prototype are summarized in Appendices A and B.

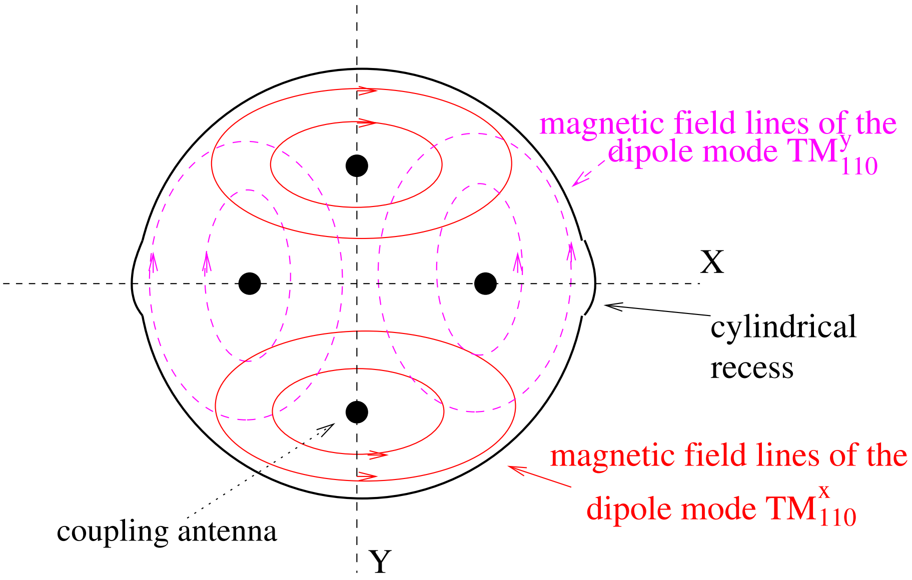

Figure 2: Cross-section of the cavity BPM with magnetic field lines of the TM$^{x}_{110}$ and TM$^{y}_{110}$ modes

2.1 Position and Time Resolutions of the BPM

Important characteristics of a BPM are position and time resolutions. Position resolution is understood as the smallest deflection of the beam which a monitor can sense. Time resolution is the time which a BPM needs to be ready for next bunch detection. If, for example, a bunch to bunch position measurement should be performed, the time resolution has to be smaller than the distance between two consecutive bunches.

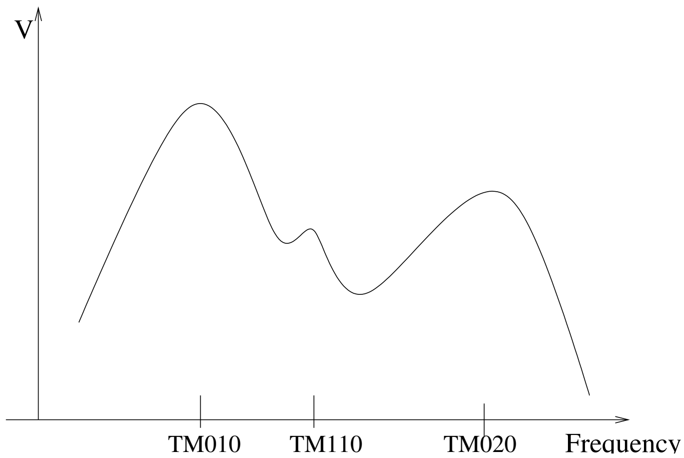

Figure 3: Voltages of the first and second monopole modes together with the TM_{110} dipole mode versus frequency

From all excited modes, the first dipole mode TM_{110} is used for beam position monitoring. Its signal in the beam-pipe region (for bunch velocity $v \approx c$) has a linear dependence on the bunch displacement [3], [5]. In our case, the modes excited by the bunch are coupled from the cavity by four symmetrically arranged feedthroughs (two for x and two for y position detection) into 50 Ω coaxial cables.

The voltage at the dipole mode frequency f_{110} coupled by the antenna and fed into the read-out circuit can be written as

$$V(x) = a \cdot x + n + V_N, \tag{1}$$

where V_N is the termal noise level of the electronics, x the bunch displacement from zero, n a constant due to possible leakage of the dominant first and second monopole modes at the dipole mode frequency as sketched in Fig. 3. The linear term $a \cdot x = V_{110}^{out}(x)$ is the signal of the dipole mode TM_{110} estimated as [6]

$$V_{out}^{110}(x) = \pi f_{110} \sqrt{Z_0 \left(\frac{1}{Q_{ext}}\right) \left(\frac{R_{sh}}{Q}\right)_{110}^{fix}} \frac{x}{x_{fix}} q \equiv a \cdot x \tag{2}$$

with $\left(\frac{R_{sh}}{Q}\right)_{110}^{fix} = 0.047\ \Omega$ the shunt impedance R_{sh} devided by the quality factor Q of the TM_{110}-mode at some fixed offset x_{fix}=1 mm, computed by the computer code GdfidL [7], f_{110}=1.514 GHz, Q_{ext}=998 the external quality factor and q the bunch charge. Z_0 is the 50 Ω impedance of the cable. More details are given in ref. [3].

With a bunch charge of 50 pC at the ELBE linac, the voltage V_{out}^{110} for 10 μm beam displacement is expected to be

$$V_{out}^{110}(x = 10\mu m) = 0.12\mathrm{mV} \tag{3}$$

This value will, however, be further reduced by 18 dB to about 0.015 mV through the 25 m long signal cables to the electronics outside the ELBE tunnel.

The position resolution δx is defined as the value of the beam offset at which the TM_{110} response $V_{110}^{out}(x)$ equals the noise level V_N of the electronics:

$$V_{110}^{out}(\delta x) = a \cdot \delta x = V_N \tag{4}$$

V_N can be computed if the bandwidth (BW) and noise factor (NF) are known. BW and NF of the electronics used are 120 MHz and 12, respectively. Hence, V_N results to

$$V_N = NF \sqrt{4 k_b T \cdot BW \cdot Z_0} \approx 0.12\mathrm{mV}, \tag{5}$$

where k_b=1.38·10^{-23} [JK^{-1}] is the Boltzmann coefficient. Comparing V_N with the 10 μm offset signal of 0.015 mV expected at the input of the electronics, condition (4) is satisfied for δx=80 μm

$$V_{110}^{out}(\delta x = 80\mu m) = V_N \tag{6}$$

Note, the TESLA bunch charge of 3.2 nC (instead of 50 pC) leads to some 64 times stronger TM_{110} signal, so that with the same noise level, a position resolution of 1-2 μm is expected at the TESLA linear collider.

The time resolution of the BPM is defined by the damping time τ_{110}=150 ns of the dipole mode TM_{110}. It is the time after which this mode in the cavity is damped by the factor of $e \simeq$2.72. The damping time can be computed according the following equation

$$\tau = \frac{Q_L}{\pi f} = \frac{1}{\pi \cdot BW_0} \tag{7}$$

where $BW_0 = \frac{f}{Q_L}$ is the bandwidth of the signal in the cavity and Q_L is the loaded quality factor of the cavity for a given frequency f. Besides the dipole mode TM_{110}, also both dominant monopole modes TM_{010} and TM_{020} should be considered for proper time resolution estimation. Damping time values for the TM_{010} and TM_{020} monopole modes are 280 ns and 60 ns, respectively.

2.2 Signal Detection Scheme

The task of the electronics is to detect the 1.5 GHz signal of the dipole mode and reject the monitor response at other frequencies, in particular the strong common mode at 1.1 GHz. The proposed scheme for signal processing is shown in Fig. 4.

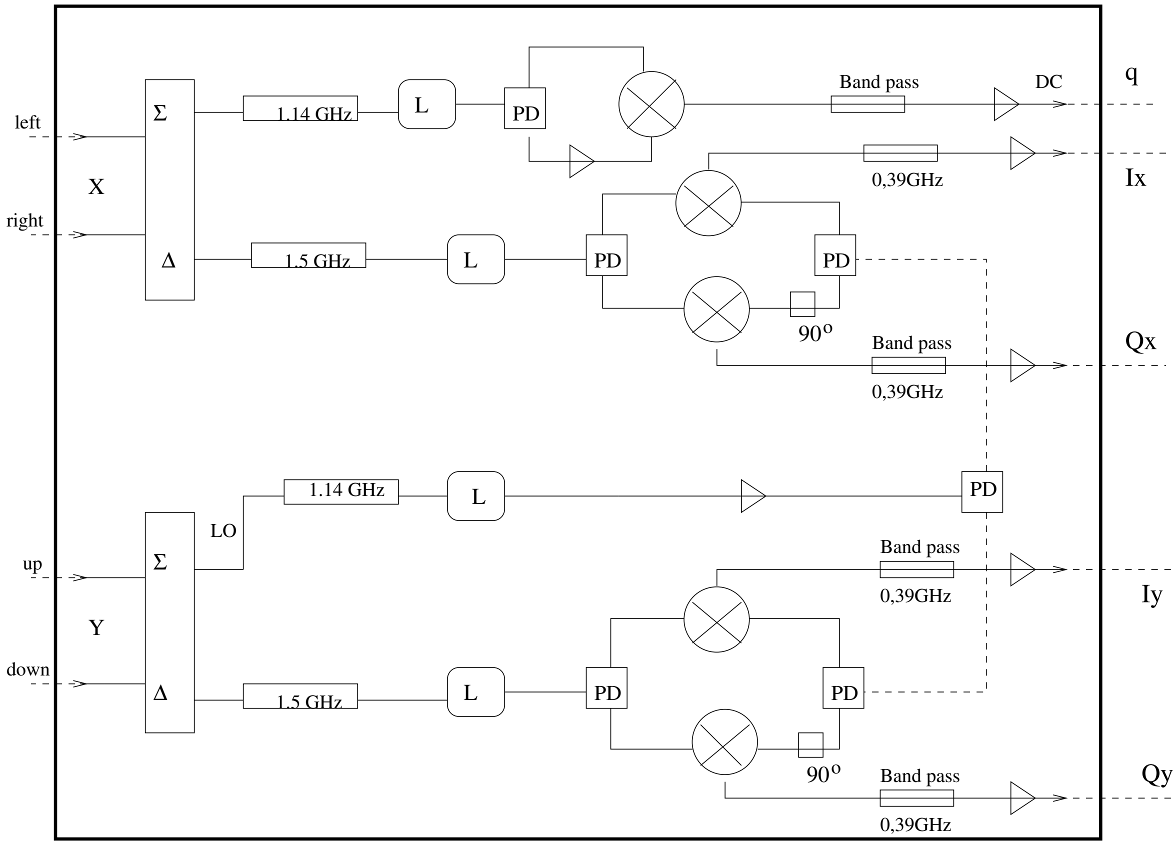

Figure 4: Block diagram of the electronics

The signals from two opposite antennas (left-right as well as up-down) of the cavity are processed together in a homodyne receiver. These signals are combined in a 180^o broadband hybrid circuit, where the common mode power is reduced by 20 dB. The hybrid provides the difference (Δ) and the sum (Σ) signals, which are utilized for x- (and y-) position detection and charge measurement. The Δ-signal is filtered by a bandpass filter having a center frequency of 1.517 GHz and a bandwidth of 120 MHz, so that a rejection of about 60 dB on common mode frequency can be achieved. Passing the limiter (L), which protects subsequent components from exceptional large signal levels, the difference signal is down-converted using an I-Q mixer (with integrated power dividers (PD)) with a reference signal (LO) of 1.14 GHz. This signal is generated by the same cavity and provided by the Σ signal of the y-polarization. With this novel approach a stable and most of all in phase reliable LO-reference signal is obtained. The I-Q mixer supplies two signals, one in phase (I) and one in quadrature (Q), i.e. shifted by 90^o. The resulting IF signals at 400 MHz frequency can be digitized by a fast ADC. Further filtering and amplification in advance might be advantageous. The Σ-channel of the hybrid for x detection is used for bunch charge measurement. After a bandpass filter at the 1.14 GHz common mode frequency the signal is divided and self-downconverted to direct current. A standard ADC can be used for this signal digitization. The signal processing provides five output channels: I_x and Q_x for x-position detection, I_y and Q_y for y-position detection and q for charge determination.

After digitization the resulting voltages in x- and y-direction can be computed as

$$V_x = \sqrt{I_x^2 + Q_x^2}, \qquad V_y = \sqrt{I_y^2 + Q_y^2} \tag{8}$$

and the sign of I_x or Q_x (I_y or Q_y) determines the polarity of the position displacement, i.e. right or left, respectively, up or down beam offsets.

3 Monitor Tests with Beam

For beam test measurements the prototype BPM was mounted at the end of the ELBE beam line as sketched in Fig. 5.

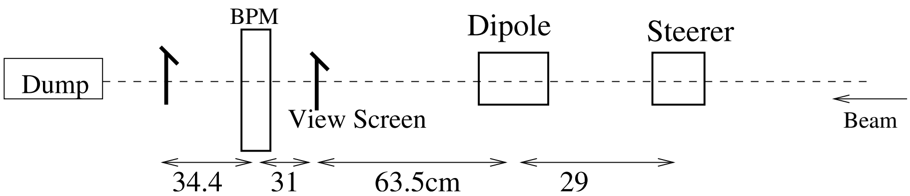

Figure 5: Last part of the ELBE beam line as used for the test

The steerer allowed to deflect the beam in both horizontal and vertical directions. Using distance and steerer current informations, predictions of the beam position within the cavity can be derived. Two view screens at both sides of the BPM provided first position information of the beam. Details of the monitor as mounted in the beam line can be seen in Fig. 6. The beam was damped after passing the monitor.

The hybrids, originally proposed to be located within the read-out electronics, are very sensitive to possible phase differences of the input signals. In order to avoid large phase errors, the hybrids were placed close to the BPM connected by 25 cm long semi-rigid cables rather than the 25 m long cables to the electronic hut.

3.1 Tests without Electronics

At first, the response of the monitor, i.e. the Δ- and Σ-signals of the hybrids are studied without read-out electronics. Thus, no signal filtering and down-mixing are performed. The aim of this measurement is to check whether the BPM cavity itself delivers high quality signals in accordance with expectations, without disturbing influences from the signal processing detector.

The signals of the cavity, passing through the 180^o-hybrids, were fed into a spectrum analyzer, 25 m away from the monitor. A sketch of the set-up as applied for this kind of measurements is shown in Fig. 7.

The following parameters of the beam were used: bunch charge q=50 pC, beam energy E_b=15 MeV and bunch spacing t_b=20 μs, which we denote as single-bunch regime. Transverse beam sizes were approximately 1 mm.

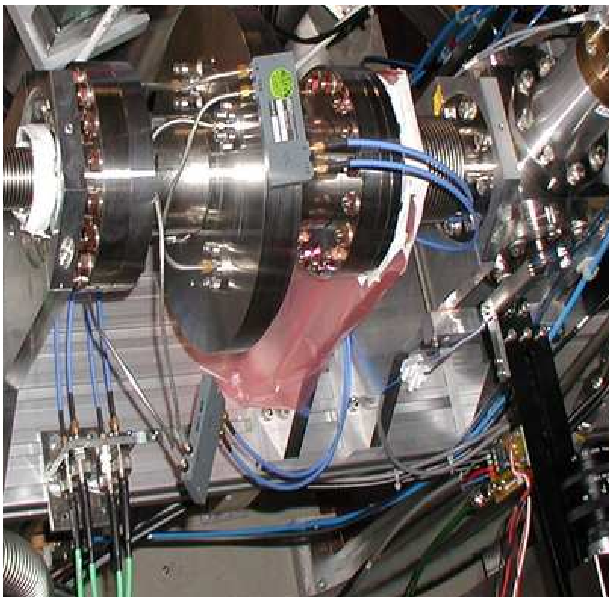

Figure 6: The BPM as mounted in the beam line of the ELBE linac

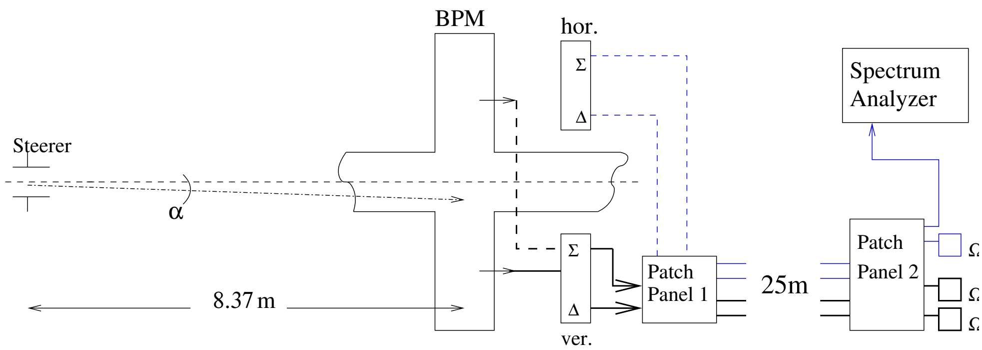

Figure 7: The test setup without electronics

By changing the steerer current, repositioning of the beam within the BPM can be achieved in x- and y-direction, and predicted beam displacements can be compared with measured values.

Fig. 8 displays the BPM Δ-port voltage against vertical beam displacements, for fixed x ($\approx$ 0) position. Each point plotted in Fig. 8 was averaged over $\sim$1000 bunches to eliminate possible beam position and charge fluctuations. The point y=0. is defined as the position with minimum power. Voltages with negative offsets were assigned to be negative in order to obtain a straight line behaviour over the whole displacement range. The position behaviour of the difference signal is basically in agreement with expectations. Apart from a peculiar situation around y=0., the Δ-response is in good approximation linear over more than $\pm$8 mm beam offset.

The sensitivity of the BPM denoted as the slope of the straight line fit over the measured voltages is 2.95 mV/mm, if all data points in Fig. 8 are included. The position resolution is defined as the square root of

$$< \Delta x^2 >= \frac{\sum_{i=1}^{n} (V_i^{fitted} - V_i^{meas.})^2}{K^2} / n \qquad (9)$$

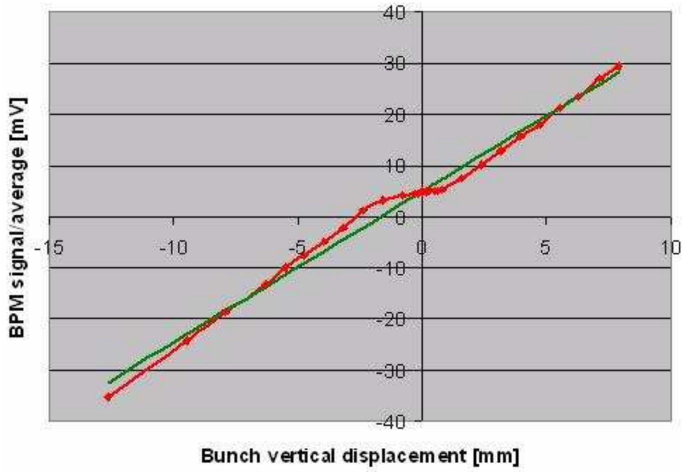

Figure 8: Measured and straight line approximation of the Δ-port voltages as a function of vertical beam displacement at fixed x-position

where K is the slope of the straight line and n the number of measured points. It is the average of mismatches between the measured and fitted voltages in Fig. 8, and results to $\sqrt{<\Delta x^2>}$=593 μm.

Around the center of the monitor at y=x=0., the signal observed is rather insensitive on beam displacements. The very small bunch charge of 50 pC reflects directly the weak power of the TM_{110} dipole mode frequency, which becomes even zero for a centered beam [1]. Here, noise is dominant and precludes position sensitivity. If the straight line fit is repeated without the points $|y| < 1$ mm, the sensitivity and the position resolution become 3.44 mV/mm and 87 μm, respectively.

An analogous procedure has been performed for horizontal displacement of the beam at y≈0. The voltages from the Δ-port and the straight line fit are shown in Fig. 9 against x-position of the beam.

A sensitivity of 5.12 mV/mm has been deduced, and a position resolution of 535 μm was determined. Also here, a rather insensitive region near x=0. can be observed. Improved sensitivity and position resolution of 5.73 mV/mm and 50 μm, respectively, were obtained when data points at $|x| \approx 0$. were discarded.

As can be seen, the sensitivity in the horizontal plane is significantly higher than in the vertical plane. This difference is assigned to a less perfect phase match of the vertical up- and down-signals, which enter the corresponding hybrid.

3.2 Test Measurements of the Complete BPM System

The layout for measurements of the BPM including the read-out electronics is illustrated in Fig. 10. The response of the Δ- and Σ-hybrid ports is transmitted to a simple signal processing detector located 25m away outside of the linac tunnel. The Δ-signal was filtered at 1.5 GHz with a bandwidth of 120 MHz and mixed down to a 400 MHz signal by utilizing the Σ-port of the vertical polarization of the cavity. As no ADC for 400 MHz signal sampling was available, the logarithmic detector AD8313 was used. This detector converts the envelope of the signal to direct current (DC). In this way, only the amplitude of the signal is measured and the phase is

[1]The insensitive region for centered beams will be strongly reduced for the TESLA bunch charge, which is about 64 times larger than the buch charge used.

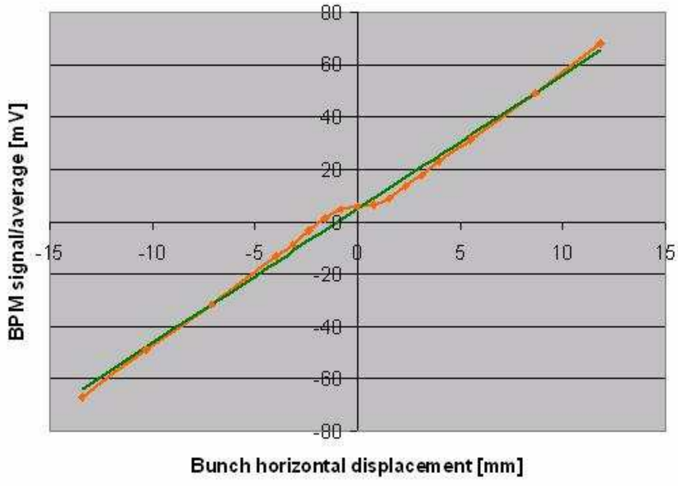

Figure 9: Measured and straight line approximation of the Δ-port voltages as a function of horizontal beam displacement at fixed y-position

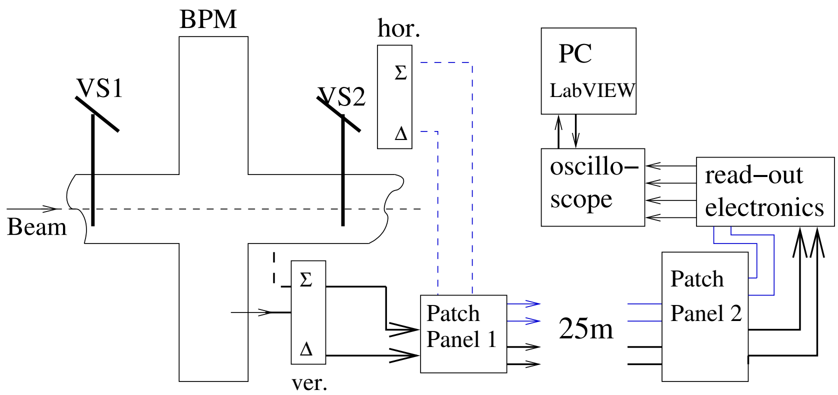

Figure 10: Block diagram of the complete BPM test layout

lost. The logarithmic detector also amplifies the signal to a sufficient level, so that no further IF amplifier is needed. The components used for signal detection are listed in table 1.

A 9-bit oscilloscope was used for analog-to-digital conversion to control the data and adjust the trigger. For the scope trigger, the beam signal itself was taken provided the peak voltage exceeds a predetermined threshold. A LabVIEW application running on a PC was used to control the scope and transfer the data to storage on disk.

In advance of data taking with beam, tests of the electronics were performed using two signal generators. One provided a variable input signal at 1.5 GHz, while the other a 1.1 GHz signal at constant level of 10 dBm for the mixer LO port. An example of the results obtained is shown in Fig. 11, where the output signal (in Volt) of the electronics is shown against the input signal (in dBm). A large linearity range over ∼45 dB is observed.

For this setup, two view screens (VS) were also included into the beam line. One VS was positioned 31 cm upstream of the monitor, while the other 34.4 cm downstream. Beam steering in horizontal and vertical direction was achieved by means of the corresponding steerer current.

At first, single-bunch measurements were performed with beam parameters as given in section 3.1. After centering the beam within the monitor by means of the view screens, the beam was steered in x-direction for y≈0., and along the y-axis for $x \approx 0$.

Indication	Supplier	Label
3dB, 180°-Hybrid	M/A-COM	2031-6331-00
Δ Port		
1.5GHz Bandpass	RLC	BPF-500-1517-120-5-RM
Limiter, 0.5-2GHz	ACC	ACLM-4530
Power divider, 1-2GHz	MCLI	PS2-2
Mixer, 0.5-2GHz, LO 7-13dBm	PARTZICH	DM0052LA2
Σ-Port		
1.1GHz Bandpass	Mid Atlantic	AMPLM970

Table 1: Components used for the signal processing circuit

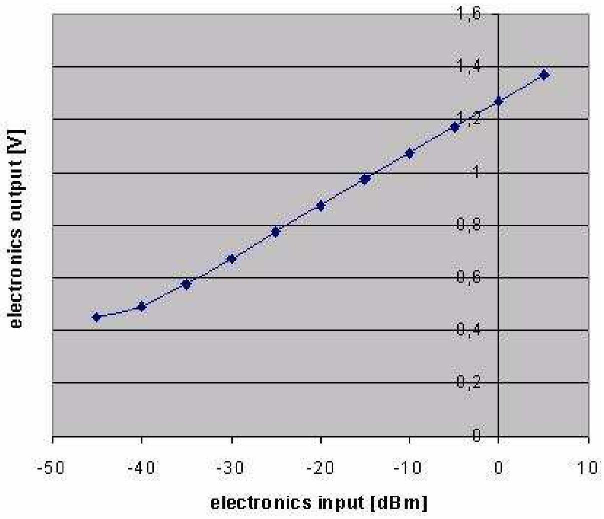

Figure 11: Output voltage of the electronics versus RF input power at 1.5 GHz

As described in the previous section, measured voltages obtained by steering the beam in x-direction and the parameters from straight line fits are used to determine the BPM sensitivity and resolution. We obtained 55.91 mV/mm for the sensitivity and 470 μm for the position resolution.

Measurements performed by steering in vertical direction resulted in a sensitivity of 30.93 mV/mm and a resolution of 1.16 mm. Such a bad position resolution in y-direction can be understood by the low LO signal level from the y-polarization hybrid. A desired level of 10 dBm could not be achieved, only about 3 dBm were attainable. This shortcoming would take place in principle also in x-direction. But here a somewhat higher Σ-signal level exists due to some better phase match of the corresponding input signals, which in turn results in an improved sensitivity and position resolution in x-direction. Repeated y-measurements with an LO signal from a generator of constant 10 dBm level, sent to the I-Q mixer, delivered an increased sensitivity of 41.61 mV/mm and a resolution of 203 μm. So, with an optimal level for the LO signal the BPM resolution can be improved by about a factor of 5, as our exercise demonstrated.

In order to study the monitor response for each bunch within a train as expected at the TESLA linac, the bunch-to-bunch distance was adjusted to 308 ns. Time domain measurements were displayed directly on the oscilloscope, see Fig. 12 as an example. Here, Δ-port voltages at x≈2 mm and y≈0 mm are shown as a function of time. Note that the sweep of the oscilloscope is 200 ns per division. Clear signal periodicity is visible which resembles the time structure of the

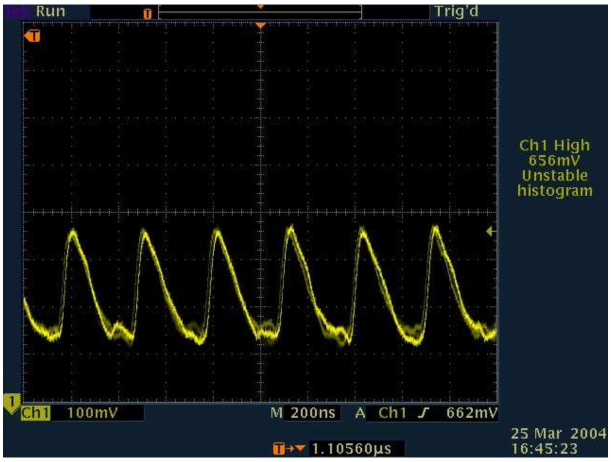

Figure 12: Time domain measurement within a train

bunches within the train. The figure also shows that the cavity damping time is good enough to meet the next bunch with 308 ns delay, without pile-up of signals. Note that for TESLA a 337 ns bunch-to-bunch distance is anticipated.

4 Improvements

According to the results improvements on the monitor and the read-out electronics are needed for optimal application at the TESLA linac.

If the cavity would be copper plated to minimize heat load, damping time is increased and might exceed the 337 ns bunch spacing at TESLA. This increase can be compensated by a stronger coupling to the field. If, as an example, the antennas are positioned 12 mm instead of 9 mm deep into the cavity (in case of copper type RRR=6.9), bunch-to-bunch position measurement is retained. For more details we refer to [3].

Obviously, the mis-match of the signal phases at the 180^o-hybrid has to be eliminated. Including a phase shifter prior to the hybrids provides a simple practical solution. Also, the use of only one instead of two signals from each direction can be helpful. However, larger monopole mode contributions of about 20 dB have to be accounted for in the signal processing scheme, which is also related to some position resolution degradiation of the BPM. If this approach is intended to be realized, further R&D is needed.

We noticed the importance of a stable, high level and well adjusted LO-signal for the I-Q mixer. In order to achieve these demands, the use of a limiting amplifier properly tuned is recommended to maximize the I and Q signals.

5 Summary

A new type of a cavity BPM for the TESLA linear collider was tested at the ELBE linac in Rossendorf/Dresden. The BPM was significantly improved compared to a predecessor. In particular, a stable cross-talk isolation of 40 dB has been achieved, energy dissipation is reduced from 1.1 W to acceptable 0.46 W and an LO signal very stable in amplitude and phase is delivered to the I-Q mixer for down-conversion of the 1.5 GHz displacement signal. Tests with beam, with and without a simple read-out electronics, confirmed a behaviour of the monitor as expected. Due to the low bunch charge of 50 pC at the ELBE linac only preliminary sensitivity and position resolution could be derived. If, however, these results are scaled to TESLA with an anticipated bunch charge of 3.2 nC, position resolutions of 1-2 μm are achievable. The timing behaviour of the BPM was shown to allow for single bunch-to-bunch measurements at the TESLA linac. Improvements of the monitor, especially of the signal processing scheme, are discussed.

6 Acknowledgements

We would like to express our gratitude to H. Henke, A. Liapine, P. Michel and W. Riesch as well as to the operating crew of the ELBE linac in Rossendorf.

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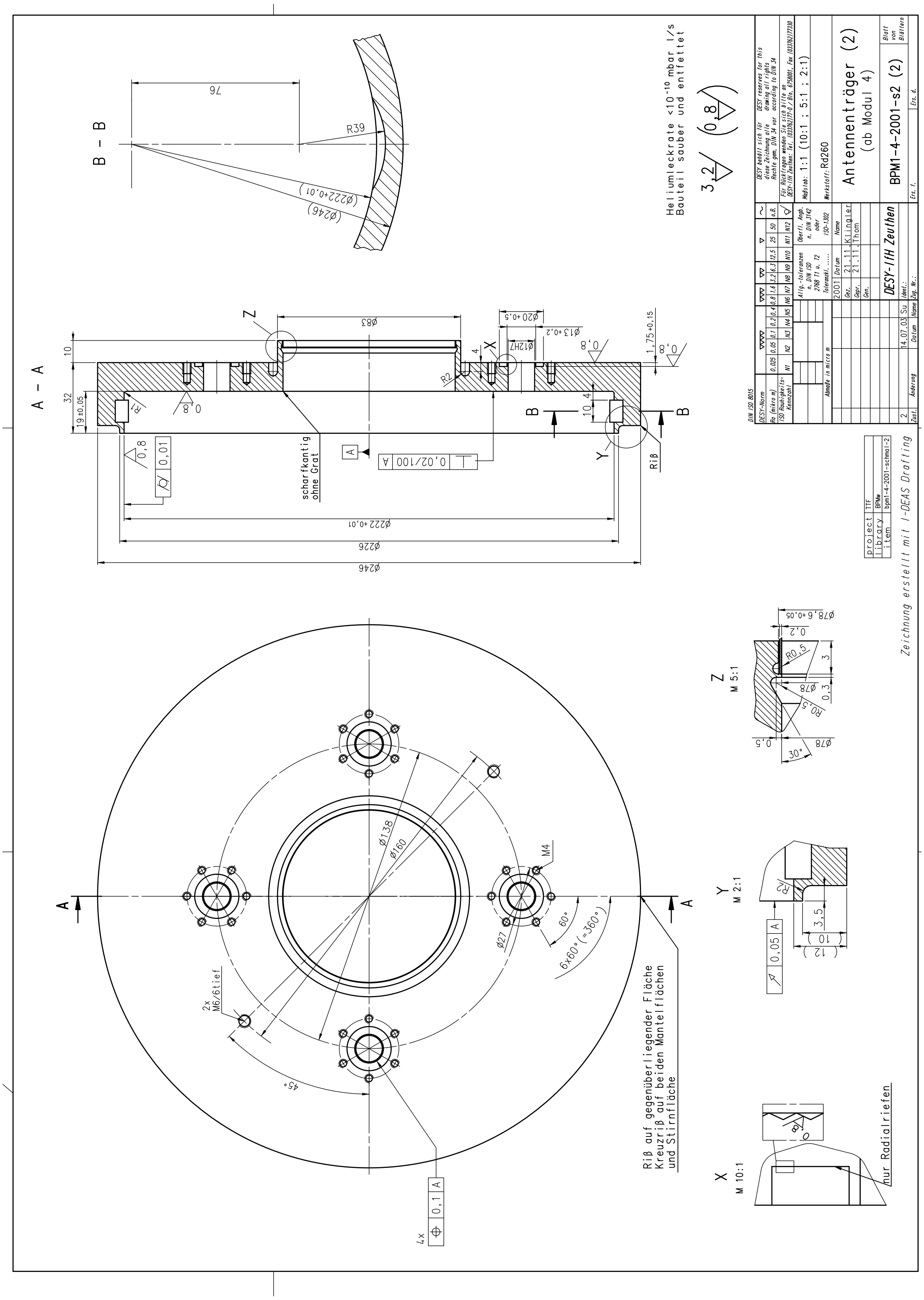
Appendix A: Technical design of the cavity; part I



Appendix B: Technical design of the cavity; part II