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Cavity-type Beam Position Monitors for the SASE FEL at the TESLA Test Facility

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Abstract

Cavity-type beam position monitors were developed to measure the beam alignment at the undulator section of DESY's TESLA Test Facility (TTF). This paper describes some theoretical aspects and the experimental setup. The results of some in-beam measurements at the TTF are presented and pros and cons of the monitor concept are discussed.

1 Introduction

A successfull operation of a Free Electron Laser (FEL) [1] working in a self-amplified spontaneous emission regime (SASE) requires stringent overlap between the electron beam and the generated photon beam over the entire length of the undulator which were segmented into three sections. For a proper FEL operation a beam based alignment is fundamental. This requires a resolution of beam position monitors (BPM) of a few micrometer. Therefore sufficiently precise diagnostic devices along the beamline - especially inside and between the undulators - are obligatory. For that reason the beamline inside each undulator module of the TESLA Test Facility (TTF) was equipped with high-precision BPM's [2] and correction coils which were located between the BPM's and allowed for horizontal and vertical steering of the beam. In addition, diagnostic stations with a cavity-type beam position monitor and a wirescanner were installed at the entrance, the exit and between two adjacent modules, see fig. 1 [3]. A non-destructive cavity monitor within the diagnostic stations was developed and brought into operation for precise beam position measurements. An overview of the concept as well as some details of the diagnostic blocks are shown in fig. 2. More information can be found in [4], [5]. Also, some other facilities were equipped with cavity-type BPM's as a successful tool for beam position measurements (see eg. [7], [6]).

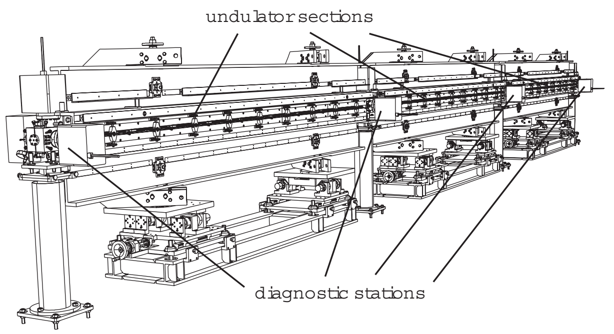

Figure 1: Sketch of the undulator region consisting of three undulators with four diagnostic stations.

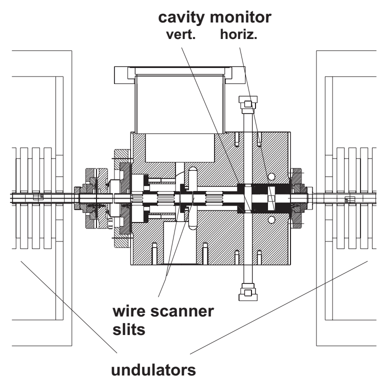

Figure 2: Cross section through a diagnostic station. It houses a wirescanner and a cavity-type monitor.

2 Some theoretical aspects

Since some detailed theoretical background on cavity BPM's can be found e.g. in [8], here we only summarize few aspects relevant to this study.

A particle with charge q passing a cavity generates radio-frequency (rf) oscillations which can be represented by an infinite sum of modes. In a pill box-like cavity predominantly the common modes TM_{010} and TM_{020} and in addition the less distinct dipole mode TM_{110} are excited. The amplitude of TM_{110} yields a signal proportional to the beam displacement δx and charge q, and its phase relative to an external reference gives the sign of the displacement. Both TM_{110}-polarisations have to be measured to obtain the beam offsets in x and y directions. Fig. 3 shows the shape of these modes within the cavity and their amplitudes as a function of the frequency.

With the geometrical design parameters of the proposed cavity BPM as presented in section 3, we get for the voltage V_{110}^{in} induced in the TM_{110} mode within the cavity by a charge q

$$\frac{V_{110}^{in}}{\delta x} \approx 1115 \cdot q \left[\frac{mV}{\mu m}\right].$$

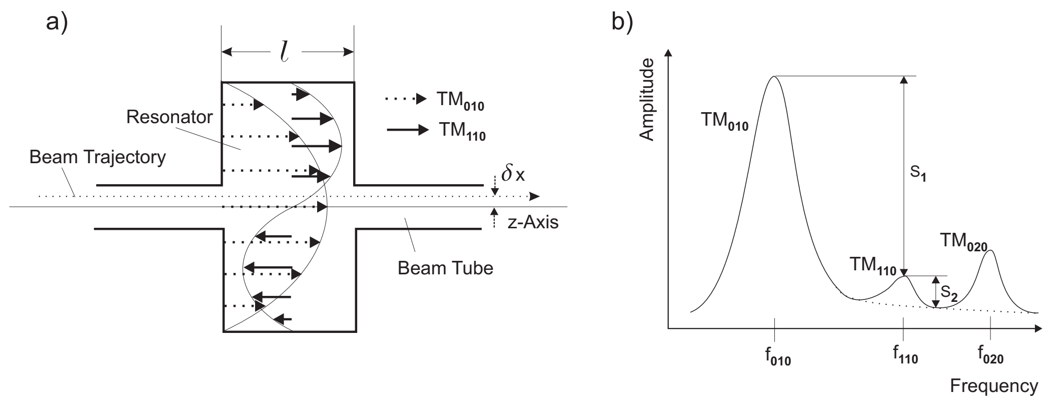

Figure 3: a) Excitation of the TM_{010} and TM_{110} -modes,
b) Amplitudes of the TM_{010} , TM_{110} and TM_{020} modes as a function of frequency

For a loaded Q value of $Q_L = 1000$, the bandwidth results to about 12 MHz . If the voltage is coupled into a 50 Ω-system the output voltage for the monitor discussed in this note is reduced to

$$\frac{V_{110}^{out}}{\delta x} \approx 7.4 \cdot q \left[\frac{mV}{\mu m}\right] \tag{1}$$

if a bunch of particles of charge $q[nC]$ passes the cavity.

Due to attenuation components between the monitor and the electronics like feedthroughs, cables and additional attenuators (of about -40 dB in our case) the sensitivity (the voltage per unit length) at the entrance of the signal processing electronics was expected to be about $0.08 mV/\mu m$ which corresponds to approximately -78 dBm.

3 Experimental aspects

Basically, the described monitor system consists of the cavity body integrated in a diagnostic station (see fig. 2), the pickup antennae, cables for the output signals and the signal processing electronics.

3.1 Monitor design

Each diagnostic station contained two separate circular cavities for horizontal and vertical displacement measurements. They were connected to the beam tube via "nose cones". These cones were introduced to reduce interferences between the electromagnetic field inside the cavity and those of subsequent bunches. The use of two independent cavities, one for each direction separated by 24 mm in beam direction, reduced substantially any cross talk which would otherwise lead to a deterioration of the output signals. The cavities were made of copper. For each resonator two waveguides (WR-90) were positioned radially in opposite directions. These two waveguide systems were arranged by 90^o to each other so that x and y directions were defined. The coupling apertures between the cavities and the waveguides were designed for a coupling factor of 2.5, resulting in a loaded Q of about 1000. This allowed to resolve single-bunch detection at the TTF with currently 1 μs bunch-to-bunch spacing. The waveguides were matched into 50 Ω. An ultra-high vacuum microwave feedthrough with an antenna transmitted the microwave signal into coaxial cables.

Fig. 4 shows a schematic view of the complete monitor system: two cavities, beam tube with nose cones, waveguides and feedthroughs. Design parameters of the BPM are given in fig. 5 and tab. 1. According to the parameters chosen, the dipole and the common mode frequencies resulted to 12.025 and 7.5 GHz, respectively. Tab. 1 also indicates frequency shifts of the common and the dipole modes due to mechanical changes and thermal expansions.

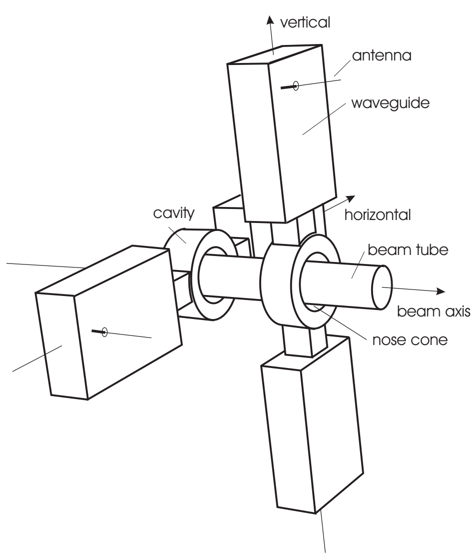

Figure 4: Sketch of the cavity BPM consisting of the beam tube, cavities with nose cones, waveguides and feedthroughs with antennae

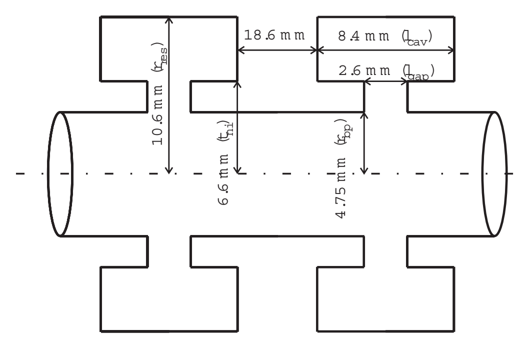

Figure 5: Internal dimensions of the cavity monitor (not scale-preserving)

dimension	design $[mm]$	sensit. $[MHz/100\mu m]$ TM$_{010}$	TM$_{110}$	Δ dim. $[\mu m/K]$	Δ frequency$[kHz/K]$ TM$_{010}$	TM$_{110}$
radius r_{res}	10.6	-78.9	-63.0	0.170	-134.1	-107.1
radius r_{in}	6.60	2.1	-52.3	0.106	2.3	-55.4
length l_{cav}	8.40	-47.1	-36.8	0.134	-63.1	-49.3
length l_{gap}	2.60	103.7	47.5	0.042	43.6	20.0
radius R_{bp}	4.75	47.1	-25.4	0.076	35.8	-19.3
$\sum$ $[kHz/K]$					-115.5	-211.1

Table 1: Some design parameters and calculated frequency shifts for the common and dipole modes due to mechanical changes and thermal expansion, $\alpha_{Cu} = 16 \cdot 10^{-6} K^{-1}$.

As can be seen, most important for achieving the design TM$_{110}$ resonance frequency are mechanical parameters. Temperature changes within the expected range would result to small and acceptable frequency shifts. Therefore, mechanical tolerances for the critical dimensions were specified to be within few micrometers.

3.2 Electronics

The signals from two opposite antennae of each cavity were processed together in a homodyne receiver. After passing semi-rigid and CELLFLEX cables with a total length of about 30 m, these two signals were combined in a 180^o broadband hybrid circuit. The difference signal was filtered by a bandpass filter having a center frequency of 12.0 GHz and a bandwidth of less than 300 MHz, resulting in a TM$_{010}$ common mode rejection of more than 60 dB. After this bandpass a limiter protected the subsequent active components from signal levels above a certain threshold. The resulting signal was mixed by an I-Q mixer with a reference signal of 12.025 GHz, generated by the TTF linac. The I-Q mixer provided two signals: one in-phase (I) and one in quadrature (Q), i.e. shifted by 90^o. Details about these devices are described in [9], including calibration procedures. The resulting I- and Q-signals were finally converted by a fast ADC with a 14-bit resolution at a preselected sample time [10].

In principle[1], the beam displacement can be calculated by

$$S = \sqrt{I^2 + Q^2}, \tag{2}$$

and the left - right ambiguity is resolved by means of the phase information

[1]This is true only for a perfect I-Q mixer. In practice, additional parameters obtained from a calibration procedure have to be included.

$$\varphi = \arctan\left(\frac{Q}{I}\right). \tag{3}$$

The hybrid also provided a sum signal to extract the common mode for beam current or bunch charge measurements. The optionally processed sum signal was splitted by a direction coupler (DC). One port was fed to a limiting amplifier thus yielding the LO signal to mix down the signal of the second port by an I-Q mixer.

The signal processing scheme for the proposed cavity BPM is shown in fig. 6, and the components used for the electronics are listed in tab. 2.

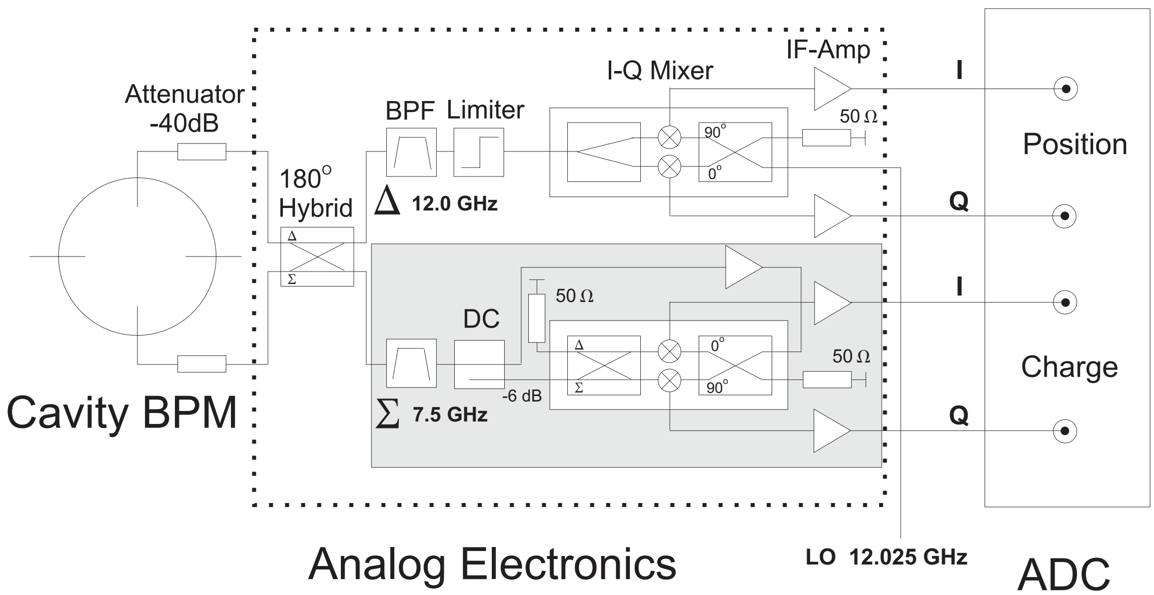

Figure 6: Layout of the electronics with the band pass filter (BPF), the direction coupler (DC), the amplifier (IF Amp), the analog-to-digital converter (ADC) and the terminal resistance (50Ω). Marked in gray is the part optionally used for charge measurements

3.3 Resolution of the monitor

The BPM resolution is defined as the minimal beam shift which can be detected by the electronics. It is limited by several terms which have to be considered additionally to the dipole TM_{110} voltage:

$$V_{cav} = V_{110}^{out}(\delta x) + V_{0n0} + V_{110}(x') + V_n + V_{jit} \tag{4}$$

Indication	Supplier	Label
3dB, 180^o-Hybrid	M/A - COM	PN 2031 - 6335 - 00, (0.5 - 12.4 GHz)
	Δ PORT	
12 GHz Bandpass	developed by DESY (S. Sabah)	12 GHz/08, bandwidth 150 MHz attenuation 2 dB
Limiter	Advanced Control	ACLM - 4533C3
I-Q Mixer		
Power Divider	M/A - COM	PN 2089 - 6204 - 00, (8 - 12.4 GHz)
Mixer	Watkins-Johnson	MC2710
3dB, 90^o - Hybrid	narda	Model 4035C, (7 - 12.4) GHz
IF - amplifier	developed by DESY (R. Lorenz)	32 dB
50 Ω load	Suhner	Type: 6500.19.A, SMA
	$\sum$ PORT	
7.5 GHz Bandpass	developed by DESY (R. Lorenz)	7.5 GHz/SN02, bandwidth 300 MHz attenuation 2.5 dB
Direction Coupler	M/A - COM	PN 2020-6620-08, (7.0 - 12.4 GHz)
Amplifier	DBS Microwave	DBS - 0513N210 / 9724, gain 22dB
I-Q Mixer		
3dB, 180^o - Hybrid	M/A - COM	PN 2031-6335-00, (8 - 12.4 GHz)
Mixer	Watkins-Johnson	MC10616LA
3dB, 90^o - Hybrid	M/A - COM	PN 2030-6376-00, (6.5 - 16 GHz)
IF - amplifier	developed by TU Berlin (R. Schroeder)	13 dB
50Ω load	Suhner	Type: 6500.19.A, SMA

Table 2: Components used for the analog electronics

$V_{110}^{out}(\delta x)$ is the beam displacement dependent signal of interest, V_{0n0} is caused by the leakage of the monopole modes, $V_{110}(x')$ is due to the beam angle, V_n is the thermal noise in the electronics and V_{jit} is a signal jitter caused by the sampling time uncertainty in the ADC. The signals V_{0n0} and $V_{110}(x')$ are 90^0 out-of-phase from the dipole mode TM_{110} or the beam current signal.

As already mentioned the signals from opposite antennae of a cavity are combined in the 180^o-hybrid circuit (see fig. 6), and the signal for displacement measurements is taken from the difference port Δ. However, also some leakage of the common modes occur at this port whose rejection is limited by the finite isolation power between the Δ- and $\sum$-ports of the hybrid, i.e. by the cross-talk from the $\sum$- into the Δ-port. The rejection of this common mode leakage signal is typically 25 dB for standard hybrids as used in our electronics.

The $V_{110}(x')$ voltage due to inclined particles (see fig. 7) fakes a beam displacement which can be estimated as

$$\delta x = 2244.5 \cdot \frac{l_{cav}^3}{r_{res}} \cdot \frac{1}{\lambda} \cdot \frac{1}{sin\frac{\pi l_{cav}}{\lambda}} \cdot x' \approx 15.435 \cdot \frac{l_{cav}^3}{r_{res}} x'. \quad (5)$$

For a typical drift path of 1 m and a beam pipe radius of 5 mm, the angle x' of inclined particles is less than 1 mrad. With the dimensions of the monitor shown in fig. 5, it follows that the displacement fake $\delta x_f < 5.4 \quad \mu m$. Since x' being usually a small fraction of 1 mrad, δx_f can be neglected in most cases. For more details on non-zero beam angle effects we refer to [8].

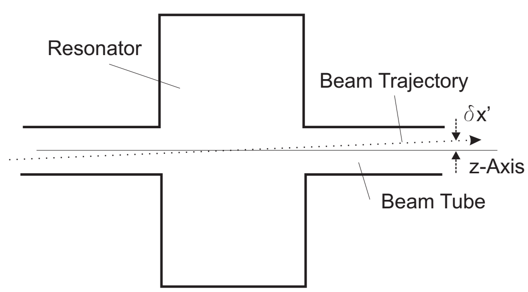

Figure 7: Sketch of the beam angle

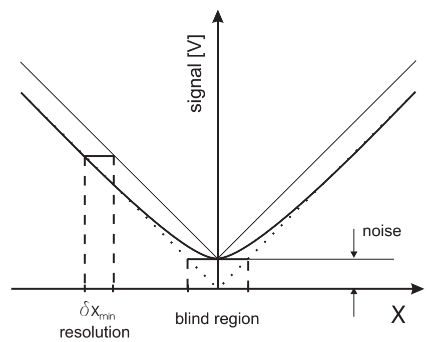

Figure 8: Resolution of a cavity-type monitor

Since the common mode leakage signal and the inclined beam signal are phase shifted by $\pi/2$ to the dipole mode, both signals can in principle be further rejected by using a synchronous demodulator.
According to expectations for V_{0n0} and $V_{110}(x')$ we conclude that the resolution of the cavity BPM is essentially limited by the electronic noise, whose effect to the beam offset is indicated in fig. 8. Noise variations of the signal are directly projected to the beam position resolution, and the blind region at the center of the cavity is about twice the monitor resolution.

3.4 Choice of the TM_{110} frequency

In the following, reasons which led to the choice of the design frequency will be discussed.

First, one has to consider mechanical constraints due to like the beam pipe diameter and available space in transverse as well as in longitudinal direction. This results to upper limits possible for the cavity diameter and its length.

The resolution depends on the cavity radius in a way that a smaller cavity leads to a higher voltage per micron displacement. Thus, to achieve few micrometer position reduction an upper limit for the radius of the cavity is fixed. Some minimum cavity radius is mainly determined by the following arguments: Cavity excited fields leak into the beam pipe and any mechanical distortions could excite additional rf fields which cause reactive effects. Also, fields excited elsewhere in the linac with frequencies below the cutoff frequency of the beam pipe can propagate into the cavity, especially in cases when their origin is near the cavity. Disturbing effects from these fields in the cavity should be minimized which is best achieved when the cavity radius is significantly larger than the beam pipe radius, i.e. the TM_{110} dipole mode frequency is substantially smaller than the beam pipe cutoff frequency of ≈ 18 GHz. Finally, the choice for the LO frequency in phase-correlation with the accelerator

and the electronics was a very important aspect. Commercially available electronic components should be used as much as possible to minimize the costs. Especially, the frequency band around 12 GHz is worldwide used for consumer satellite receivers. Since a heterodyne receiver with a low IF frequency had been envisaged (or even a homodyne), 12.025 GHz had been chosen for the LO frequency, which in turn led to a design frequency for the dipole mode of 12.025 GHz.

4 Beam test results

Before upgrading the TTF-linac to TTF Phase II in-beam tests of the 12 GHz cavity BPM's were performed.

4.1 Setup and experiments

Due to problems during fabrication and resulting electrical properties only two out of the four installed monitors were selected for measurements (see sect. 5). These monitors are denoted as 0UND1 and 0UND2 in the following. The measurements can be basically divided into two types: (a) measurements of the cavity response (voltage) as a function of the beam charge q for fixed beam position and (b) I and Q measurements versus x- and y- displacements of the beam, for a given bunch charge. In all measurements, the correction coil settings suitable for the SASE process defined the 'ideal' beam orbit and the corresponding positions of the beam in the BPM's were denoted as $x = y = 0$. Beam steering was done symmetrically in the horizontal and vertical directions with respect to the predefined SASE correction coil settings. The data taking was performed in a single-bunch regime of 1 MHz and each point measured is the average over 20 bunches.

	0UND1			0UND2		
	$dS/dx\|dy$ $[mV/\mu m]$	σ $[\mu m]$	V_n $[mV]$	$dS/dx\|dy$ $[mV/\mu m]$	σ $[\mu m]$	V_n $[mV]$
x	-0.27	3.3	0.88	-0.34	2.0	0.68
y	0.169	5.2	0.88	-0.55	1.3	0.72

Table 3: The slopes, the resolutions σ and the 1-standard deviation noise signals V_n of the monitors 0UND1 and 0UND2.

4.2 Measurements as a function of bunch charge

The induced voltage is proportional to the bunch charge [8]. This proportionality has been found to be valid, see fig. 9, where $S = \sqrt{I^2 + Q^2}$ of the common mode is shown as a function of q for the SASE correction coil settings of monitor 0UND1, as an example. This result demonstrates linearity of the whole read-out signal-processing chain from -94 dBm determined by the noise power until -10 dBm which is fixed by the 1-dB-compression point. Nonlinearities due to saturation and/or distortion of amplifiers were not detected. Thus, the dynamic range of the cavity BPM electronics meets the requirements for FEL operation, namely being linear for bunch charges in the range of 0.5 to 3 nC.

4.3 Measurements as a function of beam displacements

If the beam was steered horizontally and/or vertically, the charge-normalized dipole mode response of the monitor $S_{x|y} = \sqrt{I^2_{x|y} + Q^2_{x|y}}$ is deduced from the digitized I and Q signals. Also the corresponding phase information was exploited according to eq. (3). The responses are shown in fig. 10 as functions of x or y for both monitors and a bunch charge of 1 nC. Here, the point $x = y = 0$ is defined by the SASE correction coil currents. Non-zero (x,y) beam positions were obtained by increasing/decreasing these currents and, using a beam-based alignment procedure, horizontal and vertical displacements were calculated in a controlled manner. These measurements allow to derive the sensitivity and resolution of the BPM's. Tab. 3 summarizes the slopes of the signal voltages $dS/dx|dy$ of fig. 10 (denoted also as sensitivity) and the deduced resolutions σ for horizontal (x) and vertical (y) directions. The resolutions presented correspond to the 1-standard deviation noise signals of the electronics, V_n, without beam, including the sensitivity ds/dx respectively ds/dy. The measured sensitivities are consistent with theoretical expectations from eq. 1, including attenuation of the signals between the monitor and the electronics and margin tolerances of all components of the monitor.

If the beam passes the center of a cavity, the amplitude of the TM_{110} mode should go through zero, and the phase jumps by 180^0. Consequently, the measured signal

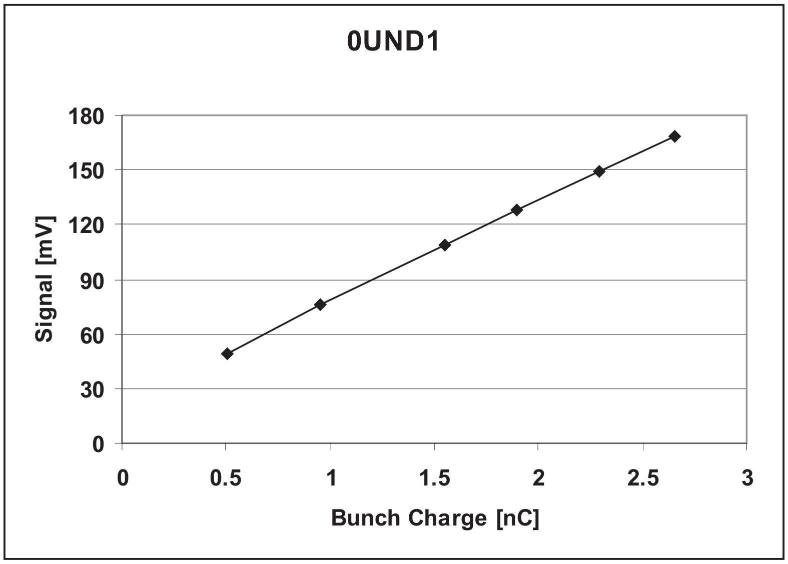

Figure 9: Signal from the $\sum$-port against the bunch charge. The bunch charge was measured by a toroid monitor.

would change its sign, so that a differentiation between positive and negative beam displacement is possible. In our steering measurements such a phase shift has only been observed in one case, namely for the horizontal beam steering in monitor 0UND2. The monitor responses at $x \approx 600$ and $800\mu m$ in fig 10c which occur after the 180^0 phase shift were just reflected at the zero-line (△→ ▲), so that S_x is positive definite, as it should be. From the measurements of fig. 10 one might deduce that either the SASE setting parameters provide a significant beam off-set in the monitors 0UND1 and 0UND2 or the BPM's have an a priori off-centered position due to installation misalignments. We expect that both effects contribute and cause substantial off-sets between the ideal beam orbit and the center of the BPM's.

5 LO versus TM_{110} frequency

Due to inevitable inaccuracies during fabrication of the monitors, differences of the TM_{110} dipole mode frequency between individual BPM's are expected.
We have studied consequences of this problem by calculating the behaviour of the I and Q signals in the time domain, including an I-Q mixer with an LO frequency of 12.025 GHz and, for simplicity, a zero-degree phase difference. Fig. 11 shows the calculated I and Q values as a function of time for four dipole frequencies with differences of $\Delta f = 0$, 6, 12 and $18MHz$ relative to the LO frequency.
We note that within the simulation the cavity response function $S(t) = \sqrt{I^2(t) + Q^2(t)}$ which involves the beam displacement (solid line in fig. 11) is independent on Δf

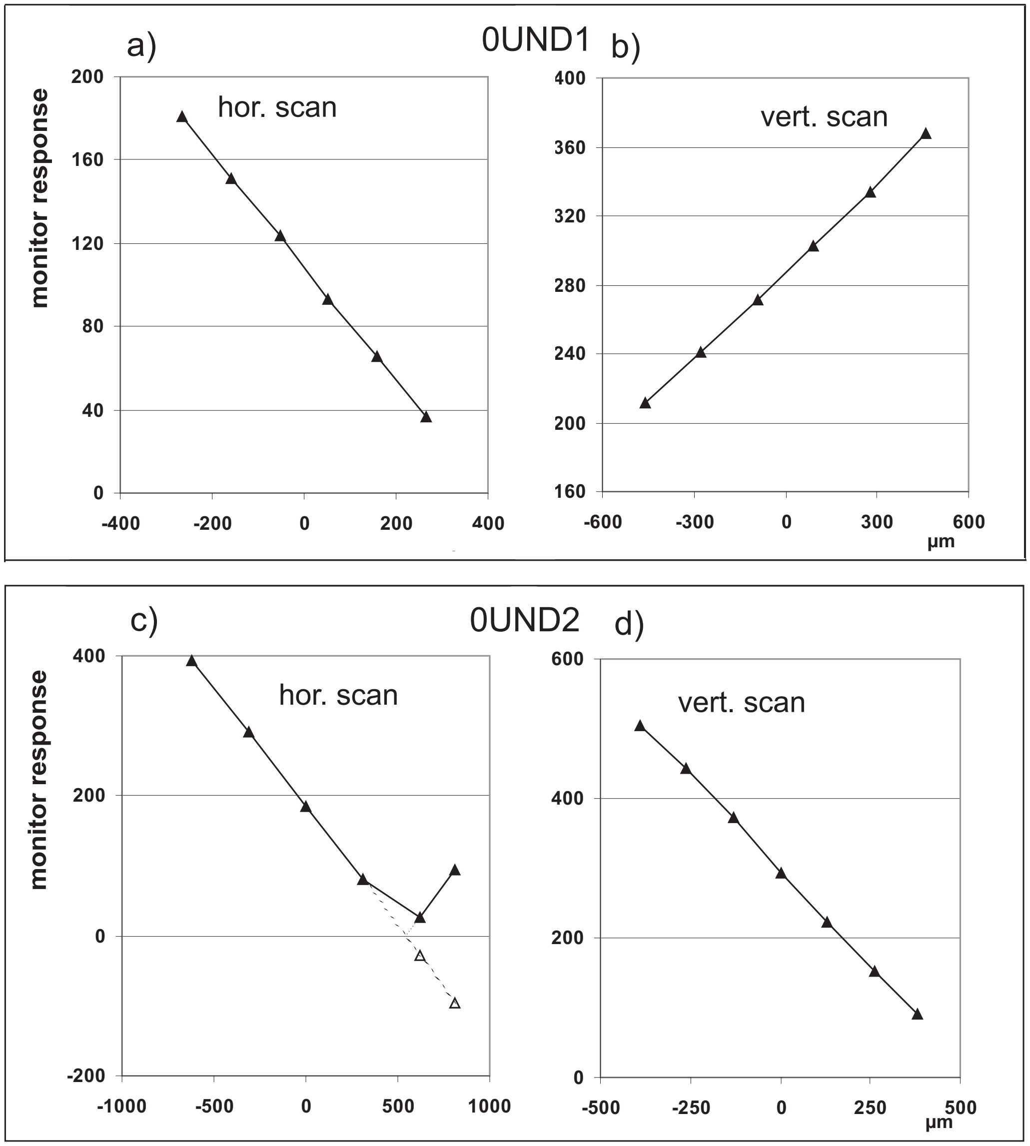

Figure 10: Horizontal and vertical scans of BPM 0UND1 and 0UND2 for 1 nC bunch charge

and (not visible from fig. 11) on the phase difference assumed. Now, unavoidable time jitter within the sampling time uncertainty of about 1 ns (due to external clock signal variation of the ADC's, time-dependent analog electronics and the ADC itself) causes independent time variations of I and Q which become more important as larger Δf is. In order to determine the maximum of Δf allowed for e.g. a resolution of 5 μm, we rely on the I and Q time-behaviour in fig. 11 and derive $\Delta f = 6.5MHz$ for the worst case. If such a frequency difference can be achieved, relative small time variations of I and Q are then expected and a stable data acquisition situation would exist.

Deviations of e.g. the cavity radius from its nominal value result to TM_{110} frequencies which can easily exceed the 6.5 MHz value. MAFIA simulations have shown that e.g. an alteration of the cavity radius by only 10 μm causes a frequency shift of 6 MHz. Therefore, fabrication of the cavity and the coupling aperture have to be performed with high precision and, in particular, radius tolerances have to be within a few micrometers. One of the monitors has a frequency difference of $\Delta f \simeq 85MHz$ so that its use for systematic measurements was excluded a priori.

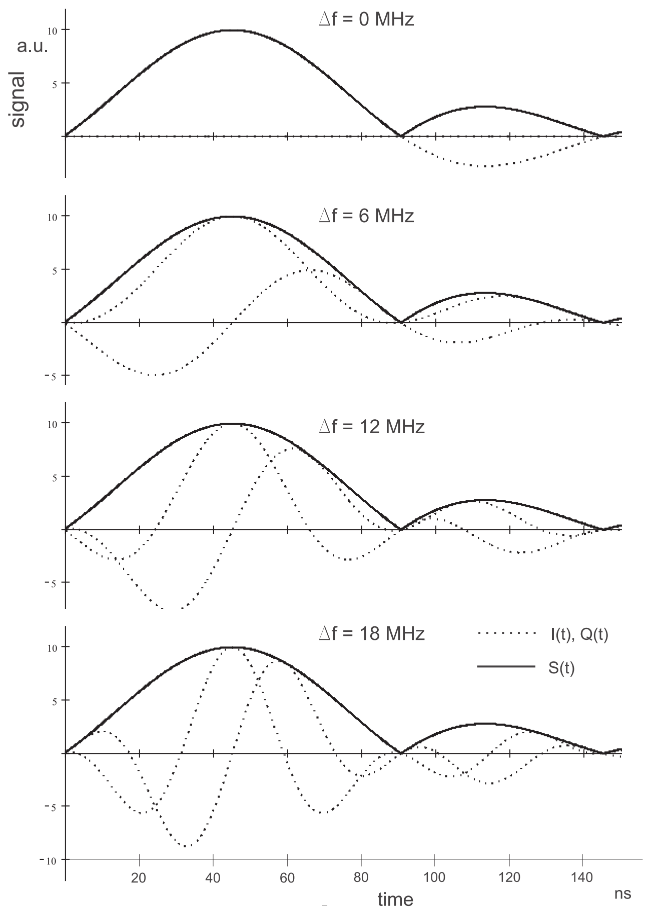

Figure 11: Simulated time variations of S, I and Q for various frequency differences between LO and the resonance frequency.

Some characteristics of the two monitors used are summarized in tab. 4.

	x-plane					y-plane				
	TM_{110}			TM_{010}		TM_{110}			TM_{010}	
	f[GHz]	Δf[MHz]	Q	f[GHz]	Q	f[GHz]	Δf[MHz]	Q	f[GHz]	Q
BPM1 (0UND1)	12.0496	+24.6	815	7.505	2736	12.0073	-17.7	900	7.523	3026
BPM2 (0UND2)	12.0131	-11.9	966	7.428	2498	12.010	+12.9	751	7.506	-

Table 4: Some properties of the cavity BPM's used: f: resonance frequency, Δf: difference to the LO frequency of 12.025 GHz, Q: quality factor for the dipole and the common modes.

6 Discussion and conclusion

The requirements on beam position monitors for TTF FEL operation are very stringent. In order to meet these requirements it was decided to use cavity BPM's within the diagnostic stations which were installed before, behind and in between the undulator modules. A pair of cavities resonant at 12.025 GHz was designed for each diagnostic station allowing for precise beam position measurements in x and y. Arguments in favour of this choice of BPM's were

- large signals for off-centered beams enabling high position resolution
- simple fabrication with high precision due to cylindrical geometry
- simultaneous beam charge measurement through the common mode TM_{010} signal allowing for charge-independent beam position measurements.
- strong (x,y) cross talk suppression since the two cavities are well separated in longitudinal beam direction.

The signal processing electronics consists of a 180^o-hybrid circuit which provides sum and difference signals from opposite antennas and a heterodyne receiver. The resulting I and Q signals are converted by a fast 14-bit ADC. The signals are normalized and therefore perform a beam intensity independent beam position measurement.

Results of in-beam measurements presented in this paper allow to draw the following conclusions.

Sensitivities of the BPM's are in agreement with theoretical expectations (eq (1)). The values are in the order of some hundreds $\mu V/\mu m$. Together with attenuation between the monitor and its ADC, electronic noise and time jitter, this determines the beam position resolutions to a few micrometer in x and y. Since the measured resolution involves some residual beam position jitter, this should be considered as an upper limit of the position resolution. Cavity response measurements as a function of the bunch charge for the SASE correction coil settings possess good linearity over a range of 0.5 to 3.0 nC. Thus, all results together meet the basic requirements on beam position monitoring for TTF FEL single bunch operation.

Very tight fabrication tolerances have to be retained in order to achieve small differences between the dipole and the LO frequencies. If this difference exceeds some limit, I and Q measurements vary strongly within the ~ 1 nsec sampling time uncertainty which in turn lower significantly the position resolution. Two out of four BPM's used for the analysis had frequency differences between 12 and 26 MHz, while one had a difference of about 85 MHz and was therefore not included in the analysis.

As critical points of this type of monitors we consider the stringent mechanical tolerances of a few micrometer in order to coincide with the LO frequency within a few MHz. Also, for centered beams the displacement TM_{110} signal disappears in a region estimated to be about twice the position resolution so that beam based alignment procedures are somewhat restricted. Consequently, beam position information (modulus and sign) cannot be determined. Wether cavity-type monitors cause unacceptable effects on the beam due to wakefields has, however, to be studied for each application separately.

7 Acknowledgement

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