CAVITY-TYPE BPMs FOR THE TESLA TEST FACILITY FREE ELECTRON LASER

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Abstract

For measurements of the beam position at the undulator section of the TESLA Test Facility (TTF) at DESY cavity-type beam position monitors were developed, installed and brought into operation. Apart from some theoretical aspects results of in-beam measurements at the TTF are presented and the pros and cons of this monitor concept are discussed.

INTRODUCTION

For a successful operation of a Free Electron Laser (FEL) [1] working in a self-amplified spontaneous emission mode an overlap between the electron beam and the photon beam over the entire length of the undulator is required. Therefore a ”beam based alignment” is fundamental. This requires beam position monitors (BPMs) with a resolution of a few μm. To meet these requirements the TTF-FEL with three undulators was equipped with high-precision BPMs [2] and correction coils within the undulators. Additionally, diagnostic stations containing a cavity-type BPM and a wirescanner at the entrance, the exit and between two adjacent undulator modules [3 - 5] were installed.

PRINCIPLE

Because [6] gives a detailed theoretical background on cavity-type BPMs only a few relevant aspects are summarized as follows. A charged particle passing a cavity generates a superposition of an infinite sum of rf modes. In a circular cavity predominantly the common modes TM_{010} and TM_{020} and the less distinct dipole mode TM_{110} are excited. Fig. 1a shows a sketch of the field lines of the electrical field of the TM_{010} and TM_{110} modes, Fig. 1b the corresponding amplitudes as a function of the frequency.

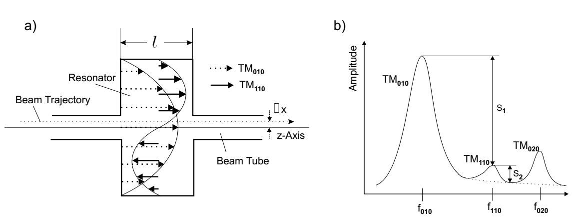

Figure 1: a) Excitation of the TM_{010} and TM_{110}-modes, b) Amplitudes of the TM_{010}, TM_{110} and TM_{020} modes as a function of frequency

Transversal beam displacement is measured using the detection of the TM_{110} (12.025 GHz) mode. The amplitude of this mode scales with the bunch charge and the beam offset, i.e. it disappears for a centered beam. The common mode TM_{010} can be used for measuring the bunch charge. For small displacements its amplitude is nearly independent of the position.

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EXPERIMENTAL SETUP

The cavity-type BPM consists of a cupreous cavity body integrated into the diagnostic station, pickup antennae, cables for the output signals and electronics for signal processing.

For the horizontal and vertical beam displacements two separate circular cavities were used. ”Nose cones” close to the beam pipe were integrated to reduce interferences. Each cavity was connected to the beam pipe. In order to define horizontal and vertical directions waveguides were arranged radially in opposite directions (see Fig. 2). The microwave signals are transmitted via antennae into coaxial cables. The signals from two opposite antennae were

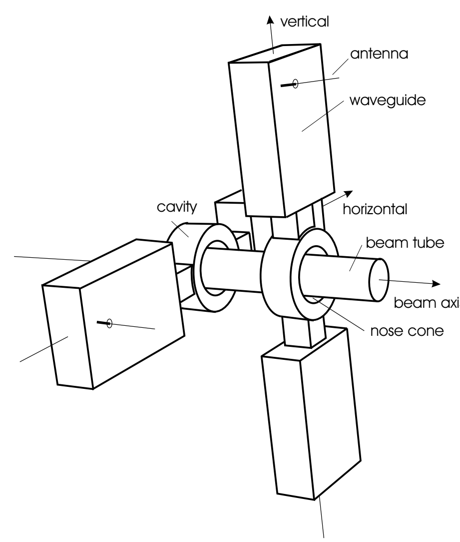

Figure 2: Sketch of the cavity BPM consisting of the beam tube, cavities with nose cones, waveguides and feedthroughs with antennae

combined in a 180^o hybrid circuit. The resulting difference signal was mixed by an I-Q-mixer with a reference signal of 12.025 GHz. The resulting I (in-phase) and Q (in quadrature) were finally converted by a fast 14-bit ADC at a preselected sample time. The beam displacement can be detected using $S = \sqrt{I^2 = Q^2}$, the left-right ambiguity is resolved by the phase information $\phi = arctan\frac{Q}{I}$.

For the beam charge measurement the sum signal, representing the common mode with a frequency of 7.5 GHz, is splitted by a direction coupler and mixed by an I-Q mixer in the same way.

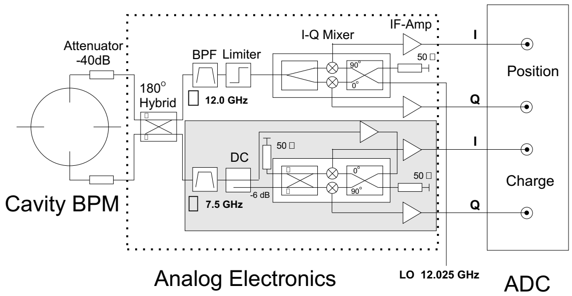

Figure 3: Layout of the electronics with the band pass filter (BPF), the direction coupler (DC), the amplifier (IF Amp), the analog-to-digital converter (ADC) and the terminal resistance (50Ω). Marked in gray is the part optionally used for charge measurements

RESULTS

Before upgrading the TTF-linac to TTF Phase II in-beam tests of the BPMs were performed. For the measurements two BPMs (before and after the first undulator) were selected (in the following denoted as 0UND1 and 0UND2).

The data taken can be divided into two types:

1. Measurements of the bunch charge detecting the TM_{010} mode at a fixed position.

2. Measurements of x- and y beam displacements for a given bunch charge.

In all measurements, the correction coil settings used for SASE operation defined the 'ideal' beam orbit. The corresponding beam position was denoted as x=y=0. Based on these settings beam steering was done symmetrically in horizontal and vertical directions. The data were taken in a single-bunch regime of 1 MHz. Each point represents an average of 20 bunches.

In Fig. 4 the signal representing the common mode as a function of the bunch charge for the SASE correction coil settings of monitor 0UND1 is shown. Linearity between -94 dBm until -10 dBm can be observed.These boundaries are limited by the noise power and the 1 dB-compression point, resp.

Fig. 5 shows the signals representing the dipole mode of the monitors as a function of the beam displacement of both x or y directions for both monitors and a bunch charge of 1 nC. A fairly good linearity can be derived. From these measurements the sensitivity and the resolution of the BPMs can be deduced. Table 1 summarizes the slopes of the signal voltages $dS/dx|dy$ of Fig. 5 (denoted also as sensitivity) and the deduced resolutions σ for horizontal and vertical directions.

If a beam passes the center of a cavity, the amplitude of the dipole mode will go through zero and the phase will

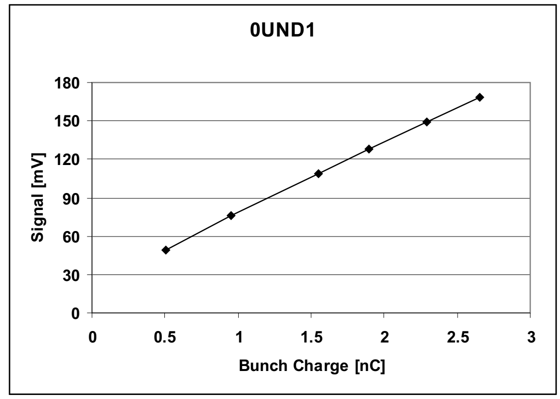

Figure 4: Signal from the $\sum$-port against the bunch charge. The bunch charge was measured by a toroid monitor.

shift by 180^o, i.e. the measured signal will change its sign. As can be seen in Fig. 5c, just in one case (0UND2/horiz.) such a phase shift could be observed. Monitor responses at $x \approx 600$ and $800\mu m$ in Fig. 5c were reflected at the zero line. One might deduce that either the SASE setting parameters provide a significant beam off-set in the monitors or the BPMs have an a priori off-centered position due to installation misalignments. Also, residual common mode leakage of the TM_{010} mode through the band pass filter might cause an electrical zero-point shift. We expect that all effects contribute and cause substantial off-sets between the ideal beam orbit and the center of the BPMs.

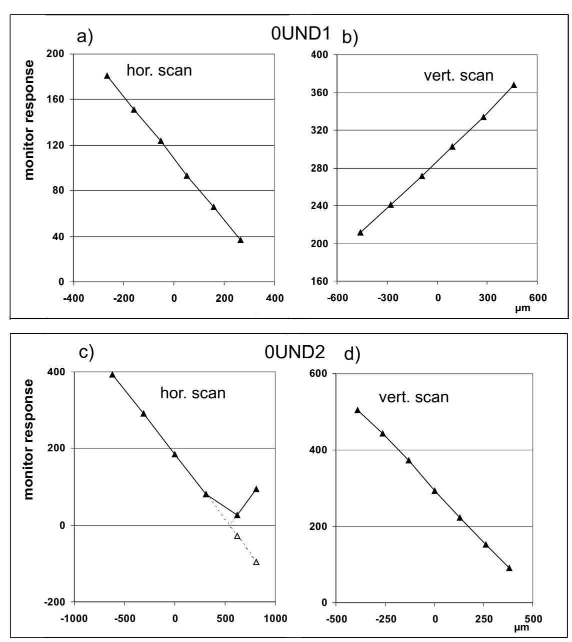

Figure 5: Horizontal and vertical scans of BPMs 0UND1 and 0UND2 for 1 nC bunch charge

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

COMPARISON BETWEEN LO AND TM_{110} FREQUENCY

Inevitable inaccuracies during the fabrication of the monitors cause differences of the TM_{110} mode frequency between individual BPMs. 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. 6 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 18 MHz 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) is independent on Δf and (not visible in fig. 6) on the phase difference assumed. 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. 6 and derive $\Delta f = 6.5$ MHz for the worst case. Deviations of the design cavity radius result to TM_{110} frequencies which can easily exceed this boundary. MAFIA simulations have shown that an alteration of the cavity radius of $10\mu m$ causes a frequency shift of 6 MHz. Consequently, fabrication of the cavity has to be done very carefully.

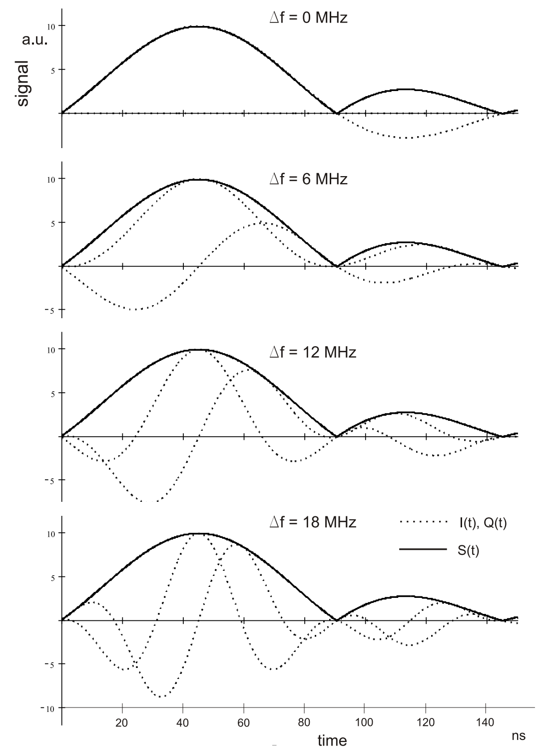

Figure 6: Simulated time variations of S, I and Q for various frequency differences between LO and the resonance frequency

CONCLUSION

In order to realize the severe requirements of a "beam based alignment" in the TTF-FEL it was decided to use cavity-type BPMs within the diagnostic stations before, behind and in between the undulator modules.

Arguments in favour of this choice 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.

Also, some disadvantages can be listed:

– a lot of care has to be taken over the fabrication of the cavities,

– for a centered beam the dipole mode, i.e. the beam displacement signal, disappears.

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