New Microwave Beam Position Monitors for the TESLA Test Facility — FEL

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Abstract. Beam-based alignment is essential for the operation of the SASE-FEL at the TESLA Test Facility Linac. In order to ensure the overlap of the photon beam and the electron beam, the position of the electron beam has to be measured along the undulator beamline with a high resolution. Due to the severe space limitations, a new microwave concept is being considered. It is based on special ridged waveguides coupling by small slots to the magnetic field of the electron beam. The four waveguides and slots of each monitor were split into two symmetric pairs separated in beam direction. All waveguides are about 35 degrees apart in azimuth from the horizontal axis and will be fabricated using electro-discharge machining (EDM). Waveguide-to-coax adaptors were designed to couple the signal of each waveguide into a coaxial cable. The goal is to measure the averaged position of a bunch train in a narrowband receiver with a center frequency of 12 GHz. A prototype of this monitor was built and tested on a testbench, as well as at the CLIC Test Facility at CERN. The paper summarizes the concept, the design, and further improvements of the waveguide monitor.

INTRODUCTION

The construction of a free-electron laser (FEL) based on the self-amplified spontaneous emission mechanism (SASE) is under way at DESY [2]. The goal is to get a coherent, very bright beam of photons with wavelengths tunable between 6 and 20 nm. The high-intensity electron beam needed to drive the undulator will be delivered by the TESLA Test Facility Linac (TTFL, [1]). Some parameters for the FEL operation of the TTFL are listed in Table 1.

TABLE 1. Parameters for the TTFL-FEL.

Bunch length (FWHM) for Phase I / II	250 μm / 50 μm
Bunch charge and repetition rate	1 nC , 10 Hz
Bunch spacing	1 μs – 111 ns
Number of bunches (pulse length 800 μs)	1 – 7200

The position of the electron beam might vary inside the undulator, mainly because of field imperfections in the dipole and quadrupole magnets. Since a precise overlap of the electron and the photon beams is essential for the FEL operation, the position of the electron beam has to be measured and corrected along the undulator beamline. About 10 beam position monitors (BPMs) with a resolution of less than 5 μm averaged over the bunch train are required for the beam-based alignment of each undulator module. The same resolution has to be reached for single bunches during commissioning.

In Phase I the undulator consists of three modules, each containing a 4.5 m long vacuum chamber having a rectangular profile. These chambers, made of aluminum, will be equipped with an alternating arrangement of correction coils and monitors. All mechanical parts of the pickups have to fit inside the undulator gap of 12 mm; the magnets allow only horizontal access. The realization of two different monitor concepts is under way: an electrostatic pick-up and a microwave monitor (see also [3]). The scope of this paper is to discuss the idea and the concept of the latter. Since the signals are coupled into waveguides, we will call this structure a waveguide monitor. Emphasis will be on analytical and numerical aspects of the design, as well as on measurements and tests.

CONCEPT OF THE WAVEGUIDE MONITOR

Basic Idea

If a beam of charged particles is centered in a circular, conducting beam pipe, then there is a uniformly distributed electromagnetic field accompanying the beam. The closer the velocity of the beam is to the velocity of light, the more this field looks like a transverse electromagnetic (TEM) wave. An off-center beam produces a 'distortion', and the TEM-fields are no longer uniformly distributed. The wall current density of a beam at a position (r, ϕ, t) is given by [4]

$$i_w(r, \phi, t) = \frac{-I_b(t)}{2\pi R_0} \left[1 + 2 \cdot \sum_{n=1}^{\infty} \left(\frac{r}{R_0} \right)^n \cos\left(n(\phi - \theta)\right). \right] \quad (1)$$

$I_b(t)$ is the beam current, R_0 the beam pipe radius, (r,θ) the beam position and ϕ the angular width on the inner surface of the beam pipe.

BPM systems mainly consist of four subsystems: the transducer close to the beam, transmission lines, the electronics and the software. Most of the transducers used in BPM systems detect the electric and/or the magnetic field around the beam pipe. Short (buttons) or long electrodes (striplines) are often used for this purpose. Their signals are detected and subtracted in the electronics or in a computer to measure the 'field distortion'. Because of the limited space inside the undulator gap and the extremely short bunches expected for Phase II, waveguides are used in the transducer for the microwave concept realized here (Fig. 1a). Since the wall current density is proportional to the magnetic field on the inner surface of the beam pipe, small slots can be used to couple this field into the waveguide. Therefore, Equation (1) can be used to describe the behavior of this new structure.

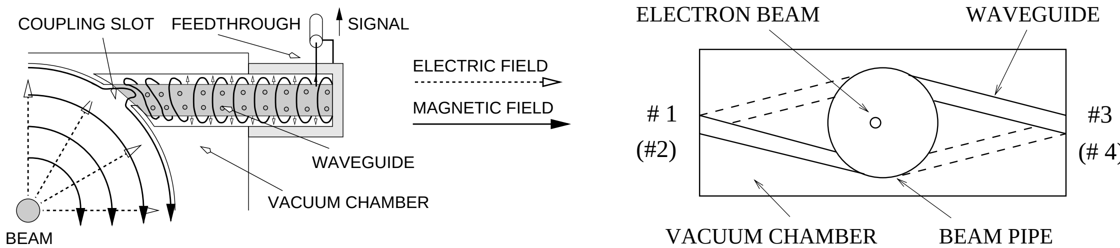

FIGURE 1. a) Principle sketch of the coupling mechanism; b) cross-section of the monitor. The waveguides #2 and #4 (dashed lines) are behind #1 and #3.

Fundamental Design Aspects

The design frequency should be as high as possible so that a waveguide fits into the vacuum chamber, and to get a reasonable coupling. Its upper limit is given by the cutoff frequency of the beam pipe (about 17 GHz). A compromise was $f_0 = 12$ GHz, the same frequency as used for the cavity monitors to be installed in the diagnostic sections [3]. This offers the possibility of developing both electronics in parallel. Another advantage is that the frequency band is used commercially (e.g., TV-sat, DBS).

The height of the vacuum chamber limits the flange size at each side and leads to a design in which the waveguide is in the middle of the flange. The result is that the four waveguides must be split into two symmetric pairs, separated in beam direction. Since the coupling slots are positioned at ± 34 degrees with respect to the horizontal plane, there is a slight angle for each waveguide. After the frequency f_0 was chosen, the size and the shape of the waveguide were studied (MAFIA 2D/3D, [5]). The goal was to have f_0 well above the fundamental waveguide cutoff frequency, but below the next higher cutoff. The special waveguide shape came out during the numerical 3D design: the ridge lowers the cutoff frequency and its shape enhances the magnetic field close to the slot, which results in a larger coupling.

The transmission to a waveguide port was calculated by using the S parameter macros of MAFIA. A 'beam' was simulated by a thin conductor in the beam pipe, thus forming a TEM line excited on one side. This method was used to estimate the coupling through a slot (depending on its size, its position/orientation and the wall thickness) and to study tolerances. In addition, the position of the inner conductor ('beam') was changed to estimate the sensitivity. Finally, the coupling from the waveguides into a 50-Ω system was designed and optimized.

Expected Signals

Let us assume a charge q in the center of the beam pipe. The signal V_s at the output port of each waveguide can be estimated by

$$V_S = k \cdot Z_0 \cdot q \cdot B = k \cdot 50\ \Omega \cdot q \cdot B. \qquad (2)$$

Z_0 is the impedance and B the bandwidth of the external circuit. The coupling factor k contains the coupling to the beam and from the waveguide into a 50-Ω system. For small displacements δx and δy from the center, the beam position in terms of voltages can be calculated for the structure in Figure 1 from

$$\delta x = \frac{1}{S_x} \cdot \frac{(V_{S_1} + V_{S_2}) - (V_{S_3} + V_{S_4})}{(V_{S_1} + V_{S_2} + V_{S_3} + V_{S_4})}, \qquad \delta y = \frac{1}{S_y} \cdot \frac{(V_{S_2} + V_{S_3}) - (V_{S_1} + V_{S_4})}{(V_{S_1} + V_{S_2} + V_{S_3} + V_{S_4})}. \quad (3)$$

S_y and S_y are signal functions depending on the monitor geometry. The reason for this complex form is that the angle between the slots is not 90^0. Neglecting this, the resolution δx can be estimated by the relations for electrode monitors [4]:

$$\delta x = \frac{V_N}{V_S} \cdot \frac{R_0}{2} \cdot \frac{1}{\sqrt{2}} = \frac{F \cdot \sqrt{k_b \cdot B_e \cdot Z_0 \cdot T}}{V_S} \cdot \frac{R_0}{2} \cdot \frac{1}{\sqrt{2}}. \quad (4)$$

F is the electronics noise figure, k_b the Boltzmann constant, and T the temperature. The linearity error estimated from Equation 1 is less than 1% for a beam position within ± 0.5 mm from the electrical center.

DESIGN AND TESTS OF PROTOTYPE I

Design

A first prototype [3] was built in 1997, its design is shown in Figure 2. The waveguide holes and the ridges of the waveguides were fabricated by electro-discharge machining (EDM). According to MAFIA-calculations, the coupling factor of a single slot is about 0.5% at 12 GHz. The right part of this figure shows the ridge, which has to be inserted into the hollow waveguide, together with a coaxial adapter containing a standard commercial vacuum feedthrough from KAMAN Corp. The whole piece is flange-mounted, and the SMA-connector is parallel to the beam.

The coupling factor k, measured using a Vector Network Analyzer, is slightly less than that expected from MAFIA simulations. This is probably due to problems in the fabrication of the coax-adapters: all feedthroughs were welded into the flange with an (unexpected) angle and the couplings into 50 Ω are not matched.

Test Results

Measurements in the Laboratory

For tests at DESY Zeuthen, the prototype was mounted on a system of two stepping motors and a 125 μm tungsten wire was stretched through the structure. By moving the BPM block instead of the wire, high frequency wire oscillations are minimized. With this assembly it was possible to move the structure under test with a precision of less than 1 μm. The whole setup is shown in Figure 3a.

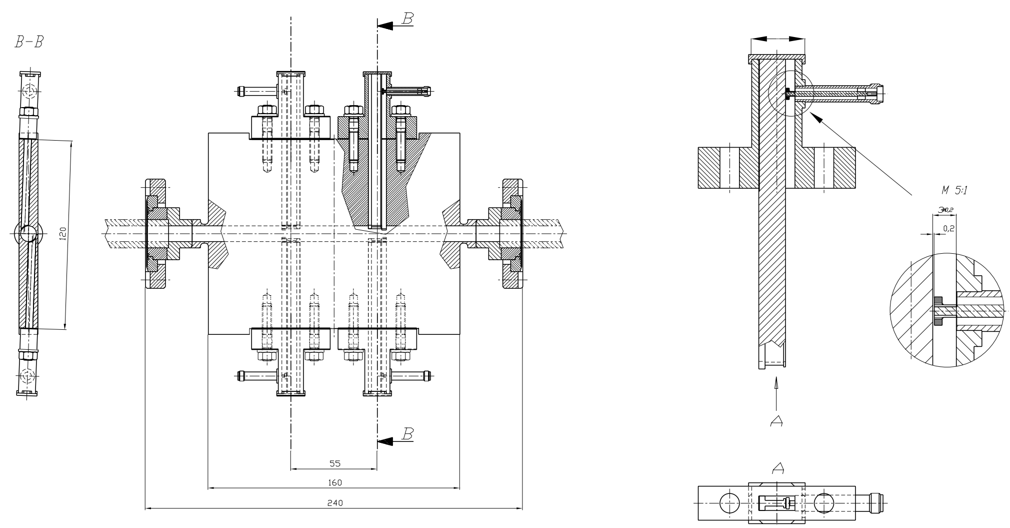

FIGURE 2. Design of prototype I. Both planes are separated in beam direction by 55 mm.

A cw signal of 12 GHz was induced by a signal generator into this coaxial system (wire and inner beam pipe surface). Impedance transformers were placed in front and behind the BPM to minimize rf reflections caused by impedance mismatches. The output signals of all four channels are amplified, filtered, and measured in a power meter. All components are controlled by a PC running a Labview application.

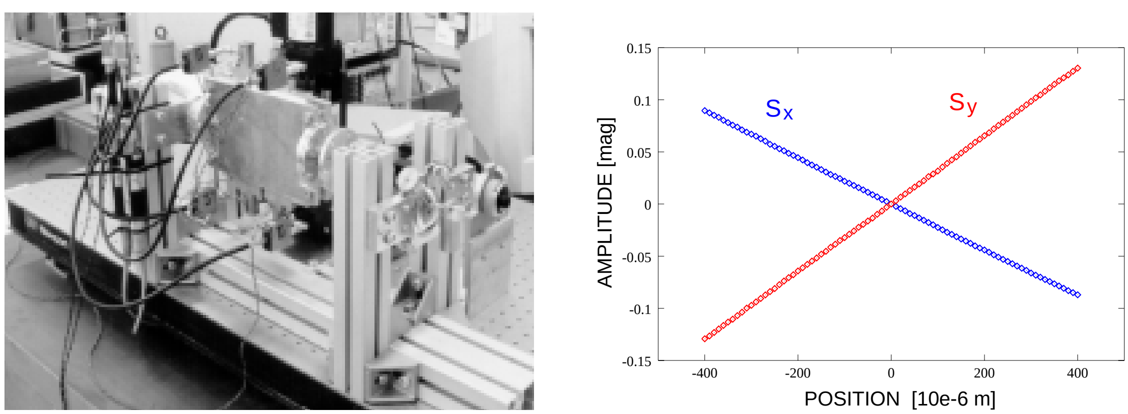

FIGURE 3. a) Prototype test at DESY Zeuthen; b) measured signal functions S_x, S_y.

First, the wire was moved on a 1 mm square around a point close to the electrical center with a stepwidth of 10 μm. With these data, three calibration algorithms were tested to obtain the signals functions S_x and S_y in Equation (3). The results for a range of ± 400 μm from the electrical center are shown in Figure 3b).

In the first method, the wire position is approximated on a sub-grid around the first guess of the position value by interpolation. The iteration stops when a reasonable value of convergence is reached. The other methods assumes a polynomial relation between the wire position and the signal function. With the knowledge of the signal functions the 'beam' position can be predicted better than 3 μm within a radius of 500 μm around the electrical center. The method following Equation (1) gives an estimation for the angular position of each of the coupling slots. The results obtained have to be further investigated by mechanical measurements, since this may offer a method to check 'real' structures after fabrication.

The slope of the curve in the linear part around the center is directly proportional to the sensitivity of the BPM. All calculated, simulated, and measured sensitivities are summarized in the last section (Table 2).

Tests at the CLIC Facility (CTF) at CERN

For measurements at the CLIC Test Facility (CTF) at CERN [6] the prototype BPM was installed in the beamline of the CTF structure's drive beam. The main purpose of this test was to study the rf behavior of the BPM and to measure the signals induced in the waveguides. The charge of a single bunch was about 2.6 nC, its energy 50 MeV and the repetition frequency 5 Hz. Some beam parameters were optimized for this test, especially the beam size at the BPM location.

The signals of the four channels were coupled into 15 m long cables, filtered at 12.0 GHz ($B = 730$ MHz; see Fig.4 b) and amplified. Additional attenuators were inserted at the electronics input for matching reasons and to avoid nonlinearities in the mixers and amplifiers. A major problem was to obtain a phase-stable reference signal related to the beam. Therefore, most of the measurements were done by bypassing the mixer stage and by displaying the amplified signals directly on a digital sampling oscilloscope (Tektronix 11801B).

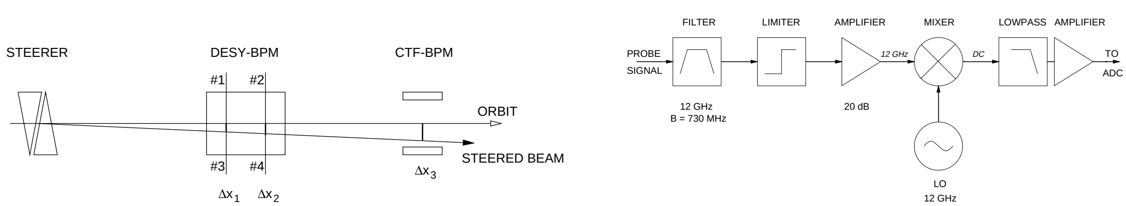

FIGURE 4. a) Installation/steering at the CTF; b) signal processing for the CTF tests.

The voltages of all four channels measured on the scope were $400 - 1100$ mV (peak-to-peak), they differ roughly by a factor of 2. The largest voltage was measured on port #3, the lowest on port #1. This might be caused by two factors: the coupling factors k are not the same for all waveguides, and the beam was not centered in the monitor. Using Equation (2) and taking into account all attenuations (cables, attenuators, filters, limiters), the coupling factors are estimated to be $0.5 - 1.5\%$. For steering experiments, the electron beam was centered by quadrupole scans. Then it was steered in both transverse planes, and the output signals of every channel were detected on the oscilloscope. From these data the sensitivities in both planes were calculated.

SUMMARY

It has been demonstrated that this new waveguide monitor can be built. All the test results obtained are in reasonable agreement with analytical estimations and with MAFIA simulations. The signals coupled into a 50-Ω system and measured on a scope are large enough that the desired resolution can be reached.

The slope of the curve in the linear part around the center is directly proportional to the sensitivity of the BPM. All calculated, simulated, and measured sensitivities are summarized in Table 2. A reason for the lower horizontal sensitivity measured at the CTF might be the detection method and an offset from the real center position.

TABLE 2. Summary of all calculated and measured sensitivities.

Method, Measurement	**Sensitivity [dB/mm]**		**Remarks**
	horizontal	**vertical**	
Theory	5.67	3.89	wall current, Eqn. (1)
Simulation (Mafia)	5.41	4.25	slightly other structure
Laboratory (DESY)	5.59 / 5.6	3.83 / 3.89	before/after CTF tests
Tests at the CTF	4.3	3.96	

Further Developments

Recently, a new prototype of the waveguide monitor has been built, which will be tested soon. In Figure 5 one clearly sees that the waveguides are now completely fabricated by EDM. Further improvements include

- a higher coupling factor for each slot, now more than 0.9 %;
- a coupling into the 50-Ω system which is transverse to the beam direction, having a higher bandwidth and leading to a more compact design; and
- a separation of both planes by 41 mm (3/2 of the undulator wavelength).

In addition, the realization of a heterodyne receiver is under way. The signal of each waveguide will be filtered, amplified in a low-noise amplifier, and down-converted to less than 50 MHz in two stages. 12-bit ADCs will be used to detect the resulting signals.

According to MAFIA calculations one can design a BPM having a similar geometry and the same electronics frequency even for a reduced undulator gap width of 8 mm. Another interesting point is that the angle between two opposing waveguides can be further increased up to 45°. This would improve the linearity, reduce the position calculation algorithm in Equation (3) and simplify the electronics, too.

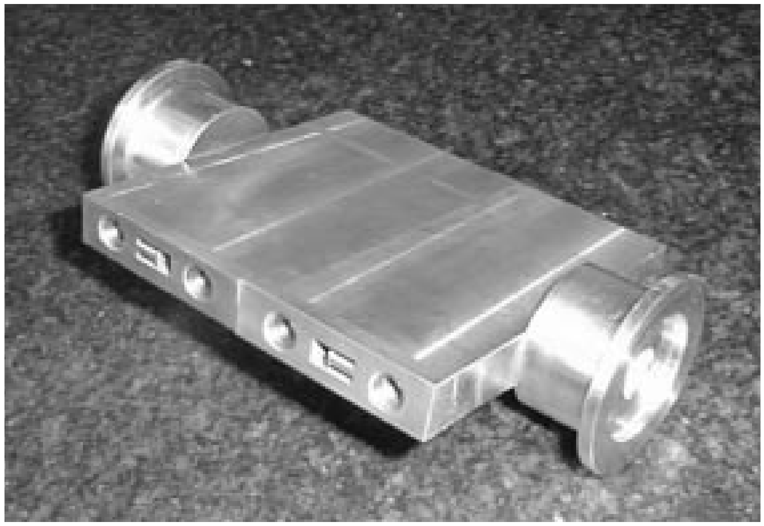

FIGURE 5. New Prototype fabricated by EDM.

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