DESIGN AND TESTS OF A NEW MICROWAVE BEAM POSITION MONITOR FOR THE UNDULATOR OF THE TTF-FEL

T. Kamps, R. Lorenz, W. Riesch, M. Sachwitz,
H.J. Schreiber, R. Steinbecher, H. Thom, F. Tonisch, K.Truetzschler,
DESY Zeuthen, Zeuthen, Germany,
U. Hahn, DESY Hamburg, Hamburg, Germany

Abstract

A new microwave concept is considered to design a BPM capable of detecting beam position with a resolution of a few micrometer. The monitor system is based on ridged waveguides coupling by small slots to the magnetic field accompanying the electron beam . The beam position will be measured in a X-band receiver with a few micrometer resolution. A prototype of this monitor was built and tested on a testbench. In addition, it was tested at the CLIC Test Facility at CERN with single bunches. The paper summarises the concept, the design and test results of the prototype.

1 INTRODUCTION

The Free Electron Laser (FEL) at the TESLA Test Facility (TTF) [1] is designed for a radiation in the spectral band from VUV to soft X-rays. In order to focus the electron beam during the undulator passage, a quadrupole structure is superimposed to the undulator dipole structure. Misalignment of quadrupoles and field errors in the undulator dipoles result in electron orbit deviation and thus disturb the overlap between electron and photon beams. To ensure this overlap, the undulator modules (see Fig.1) will be equipped with Beam Position Monitors (BPM) and correctors. Beside that, diagnostic ports between two adjacent modules are foreseen.

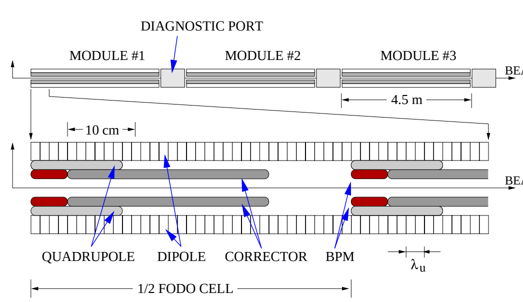

Figure 1: Sideview of the FEL-undulator (top) and zoom into focusing structure (bottom).

For the BPMs inside the undulator modules, the realization of two different system concepts is under way [2]. The new *microwave* BPM is based on ridged waveguides coupling by small slots to the magnetic field accompanying the electron beam. The scope of this paper is to discuss the basic idea, the design, test results, and recent improvements of this structure. Emphasis will be given on model aspects and on comparison of different tests.

2 CONCEPT OF THE MONITOR

2.1 Constraints

The undulator's vacuum chamber consists of a flat slab of aluminium ($12 \times 200 \times 4500$ mm) with a drilled beam hole of 10 mm radius. The chamber plus BPMs have to fit inside the undulator gap of 12 mm; the magnets allow only horizontal access. About 10 BPMs with a resolution of a few micrometer for one bunch (commissioning phase) and averaged for filled bunch trains (experimental phase) are required. Also the BPM system has to be a part of the diagnostics concept for the FEL using beam based alignment to align the electron beam to a straight reference line.

2.2 Basic Idea

The position of a bunched beam can be determined by detecting its accompanying electromagnetic field This field looks like a flat pancake or like the Transverse Electric Magnetic (TEM) field of a coaxial system. Wall currents move parallel to the electron beam and are spread uniformly over the inner pipe surface for a centered beam. When electrons are moving off center this uniformity is disturbed By detecting this perturbation it is possible to obtain information which in terms allows it to reconstruct the beam position. In the microwave concept realized here waveguides are used as a transducer. Since the wall current density is directly proportional to the magnetic field on the inner surface of the beam pipe, small slots can be used to couple a fraction of this field into the waveguide (see Fig.2). With four coupling slots located regularly around

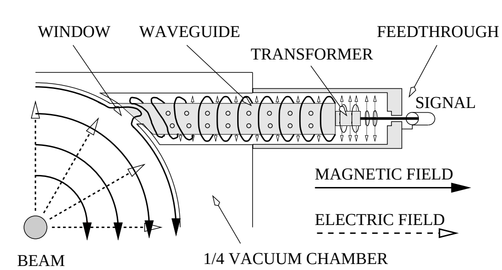

Figure 2: *Sketch of the coupling mechanism.*

the inner duct surface (see Fig.3) and four signals can be extracted to determine the beam position in the monitor plane.

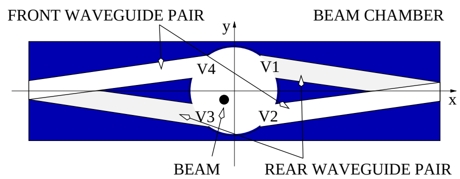

Figure 3: *Profile of the beam chamber with four waveguides building up one BPM.*

2.3 Design Aspects

A special shaped, ridged waveguide was chosen due to severe limitations in vertical space. Another purpose of the ridge is to guide the field lines of the waveguide's magnetic field in a way that there is an overlap between this field and the magnetic field of the electron beam. The upper limit for the first mode is given by the beam pipe cut-off frequency (17.6 GHz). Because of height limitations of the vacuum chamber, the four waveguides of a single BPM were split into two symmetric pairs separated by $5/2\ \lambda_U$ undulator wavelength in beam direction. Waveguide holes and coupling slots can be fabricated by electro discharge machining (EDM). After deciding on a frequency of 12 GHz, size and shape of the waveguide and its ridge have been optimized to get sufficient coupling. The ridge lowers the waveguide cut-off frequency and its shape properly chosen enhances the magnetic field density close to the coupling slot, which results in a sufficient coupling. Transmission to one waveguide port was simulated using MAFIA [3] Scattering Parameter tools. The beam was simulated by a thin conductor creating a coaxial system together with inner pipe surface. A TEM-wave was excited and transmission through the coupling slot into the waveguide was calculated. With this method, the influence of different parameters like slot geometry and wall thickness on coupling have been studied. Finally, the coupling from waveguide to $50\ \Omega$ coaxial system was designed and optimized.

2.4 Expected Performance

The resolution of the monitor is limited by the Signal to Noise Ratio (SNR). Assuming a bunch with charge of $q = 1$ nC, the signal V_i and noise V_N induced into the ith channel and measured in a $Z_0 = 50\ \Omega$-system at an electronic's temperature of $T = 300$ K are

$$V_i = k_i \cdot Z_0 \cdot q \cdot B \quad \text{and} \quad V_N = F \cdot \sqrt{k_b \cdot B \cdot Z \cdot T}. \tag{1}$$

With $k_i = 1\%$ the coupling parameter for the ith channel, $B = 40$ MHz the effective bandwidth of the signal processing electronics, and k_b the Boltzmann constant, the SNR allows to estimate the ideal resolution with

$$\delta x_{ideal} = \frac{b}{2\sqrt{2}} \cdot \frac{1}{\text{SNR}} \tag{2}$$

for a beam pipe with radius b. For beam based alignment, a minimal resolution of $\delta x_{min} = 5\ \mu$m is required. So there is a noise budget for the signal processing electronics of $F = 20$ dB.

Position sensitivities estimated using MAFIA were $S_x = 5.41\ \frac{\text{dB}}{\text{mm}}$ and $S_y = 4.25\ \frac{\text{dB}}{\text{mm}}$ for horizontal and vertical displacements of beam, respectively.

3 TESTS OF PROTOTYPE I

3.1 Measurements in the Laboratory

Coupling parameters k_i measured using a Vector Network Analyser were slightly smaller than expected from simulations. This is due to problems in the EDM process of the waveguide's ridges and due to the welding of the vacuum feedthroughs.

For tests at DESY Zeuthen the prototype was mounted on a wire testbench [2] with two stepping motors to move the BPM. The electrical center was determined by mapping a square in the BPM's transverse plane. Then cross scans around this center were performed to derive the signalfunction V_x, which is proportional to the beam position with a factor $g(x)$ only depending on vacuum chamber and slot geometry with

$$x = g(x) \cdot V_x = g(x) \cdot \frac{(V_1 + V_2) - (V_3 + V_4)}{V_1 + V_2 + V_3 + V_4} \quad . \tag{3}$$

For the vertical plane, an analogous expression exists. The progression of the signalfunctions $V_{x,y}$ is linear in the central region of the BPM. The sensitivities measured in the lab were $S_x = 5.59\ \frac{\text{dB}}{\text{mm}}$ and $S_y = 3.83\ \frac{\text{dB}}{\text{mm}}$. For mapping, data were taken while the wire was moved virtually on a 1 mm^2 around the electrical center with a stepwidth of $10\ \mu m$. Using data from such a scan, various calibration methods have been tested to find out the relation between signalfunction and beam position. In one method, a polynom of 3rd order was fitted to the measured data yielding coefficients for different polynomial terms of $V_{x,y}$. Another method follows an analytical approach calculating the wall charge density induced by a relativistic bunched beam [4]. Here, both beam and coupling slot were viewed as if they were pointlike. Applying this model, the induced wall current for a beam positioned in a cylindrical reference frame at (r, ϕ) on the inner duct radius at position (b, ψ_i) is

$$I_i = K \left[1 + \frac{1}{2} \sum_{n=1}^{\infty} \left(\frac{r}{b} \right)^n \cos[n(\psi_i - \phi)] \right], \tag{4}$$

with the parameter K proportional to the beam current. Here, ψ_i denotes the position of the slot center of BPM channel i and was used as a fitting parameter. This method allows to determine the exact azimuthal position of the coupling slots. Deviations between set and measured virtual wire positions are smaller than $3\ \mu$m for both methods.

3.2 Tests at the CLIC Facility

For measurements at the CLIC Test Facility (CTF, [5]) the prototype BPM was installed in the matching section of the CTF S-band drive beamline. The main purpose was to study the RF-behaviour of the BPM and to measure the signals induced in all four waveguides. The charge of a single bunch was about 2.6 nC, its energy 50 MeV and the repetition frequency 5 Hz. Beam size and optics were optimized at the BPM location to get a round and small beam ($\sigma_{rms} = 1$ mm). The four signals were coupled into 15 m long cables, filtered at 12.0 GHz with $B = 730$ MHz and amplified by 20 dB. Attenuators were inserted at electronics input for matching reasons. A major problem was to obtain a phase-stable reference signal related to the beam, so that most of the measurements were done by by-passing mixer stage, and amplified signals were displayed directly on a Digital Sampling Oscilloscope (see Fig.4). From signals measured for a centered beam, the coupling parameters for all channels were calculated. Tab.1 compares the data obtained at CTF with these obtained in lab at Zeuthen.

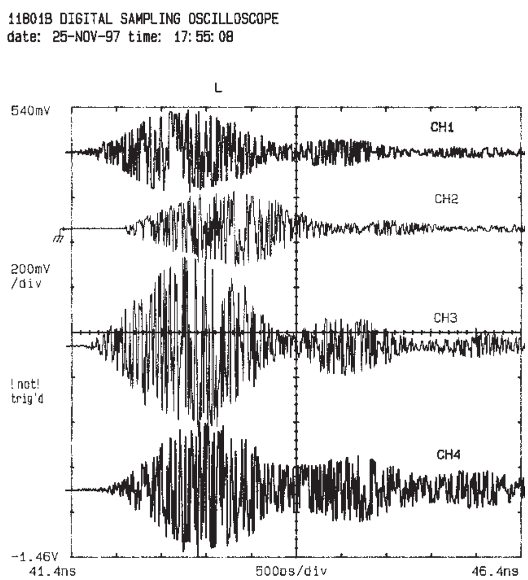

Figure 4: *Signal voltages (peak to peak) measured after 15 m long cables and a bandpass filter for all channels, from top to bottom:CH1 364 mV, CH2 334 mV, CH3 804 mV, and CH4 588 mV.*

Coupling	CH1	CH2	CH3	CH4
k_i [%] at CTF	0.69	1.09	1.96	1
k_i [%] at lab	0.62	1.10	2.09	1

Table 1: *Comparison between coupling parameters obtained at CTF and in lab at Zeuthen. Values are normalised to channel 4 amplitude.*

Also steering experiments have been carried out in order to measure the position sensitivity. Using a pair of correction coils the beam was moved in both transverse directions. After analysis measured values were $S_x = 5.58 \frac{\text{dB}}{\text{mm}}$ and $S_y = 3.86 \frac{\text{dB}}{\text{mm}}$. which differ by less than 5% from wire measurements.

4 CONCLUSION AND OUTLOOK

A new concept for monitoring electron beam inside the undulator of the TTF-FEL has been studied. A prototype was build and tested with wire measurements and with beam. Results derived for coupling parameters and for position sensitivity are consistent.

Recently, a second prototype has been designed and built tackling conceptual and fabricational problems. In order to increase the coupling parameters, geometry of the coupling slot was changed. Furthermore the adapter from waveguide to coaxial system is no longer realized with a $\lambda/4$ coupling at end of waveguide. In the new design, a short piece of rectangular coax line is attached to the waveguide, serving as transformer. Adjacent to the transformer, the round coax system of the vacuum feedthrough follows. Because now all elements are in line, it is possible to decrease the distance between the two waveguide pairs to $3/2\ \lambda_U$. For fabricational aspects, waveguide and ridge will now be manufactured in one step, enabling a better reproducibility.

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