DEVELOPMENT OF A MODIFIED SIX-PORT DISCRIMINATOR FOR PRECISE BEAM POSITION MEASUREMENTS*

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Abstract

For the European XFEL, new energy beam position monitors (EBPM) based on planar transmission lines where designed for energy measurements in the dispersive section of bunch compressor chicanes. The EBPM consists of transversely mounted stripline pickups in a rectangular beam pipe section and a signal detection scheme which measures the phases of the pulses at the ends of the pickup [1]. It allows simultaneous measurements of the beam energy and arrival-time. The EBPM needs a high dynamic range over the sensor length of 183 mm and high resolution of less than 20μm. Both, the dynamic range and the resolution depend on the operation frequency. Due to phase ambiguity, a low frequency is required for the high dynamic range whereas a high frequency is needed for the high resolution.

This paper presents the development of a RF readout electronic based on a modified six-port discriminator as a low-cost alternative to the readout electronics based on the MTCA.4 platform for the EBPM [2]. Based on the six-port, the beam position can be determined by means of the phase difference between the received signals from both ends of the transmission line pickup.

The six-port discriminator is a linear passive component, first developed in the 70's for accurate measurements of complex reflection coefficients in microwave network analysis [3]. It typically consists of two hybrid couplers and two power dividers or one Wilkinson power divider and three -3dB hybrid couplers. For the measurement of the difference of two signals excited from a single source one of the hybrid coupler can be omitted. The advantage of the six port is the fact that accurate phase measurements can be performed at microwave and millimeter wave frequencies only by amplitude measurements. This paper shows the principle of operation, developed prototype, and first test results.

INTRODUCTION

The rapid increase of computational power in the last decades made various possibilities of digital measurements available. As a result of this development well developed analog measurement techniques are only of minor importance today. For some applications, there is a more simple solution in the analog domain that is worth to be considered. This paper evaluates whether phase difference measurements are realizable using a analog six-port reflectometer circuit and determines the achievable phase resolution.

The six-port reflectometer, first mentioned in publications in the 1970's by Engen [3], never became commonly spread although many possible application fields exist. Application fields are amongst others measurement devices , communication receivers or sensors in automotive radar systems. This diversity comes from the relatively simple circuit design and the ability to scale the six-port circuit to almost any frequency [4]. The name already implies that the device has six connections whereof two are input ports and four are output ports. The superposition of the two input signals is internally phase shifted in the reflectometer. As a result four different powers at the outputs can be measured and further processed. Phase shifts can be realized by different types of couplers which makes the six-port reflectometer a relatively large but completely passive circuit structure.

One advantage of the six-port reflectometer is the direct application in the RF frequency range. Many applications like the MTCA.4 platform use signals in the RF range and down-convert them to an intermediate frequency for processing purposes [2]. In contrast the six-port reflectometer only needs one ADC for every output which is twice as many as a common receiver structure with I/Q-circuit has. A drawback using a reflectometer is the necessity of narrow bandpass filters for the RF signals, that can be easier realized at intermediate frequencies.

COPLANAR WAVEGUIDE ENERGY BEAM POSITION MONITOR

The operation of the European XFEL will require multiple special diagnostic tools to study the properties of the electron bunch. For the longitudinal properties Energy Beam Position Monitors (EBPMs) are utilized at three different locations along the European XFEL LINAC. Here the EBPM consists of two transversely mounted striplines and signal detection system, which measures the phases of the pulses emerging from both ends of the pickup in the dispersive section of a bunch compressor chicane [5]. The bunch energy can be determined from the phase differences that are directly proportional to the beam position by the formalism of the bunch compressor [6]. The principle of operation is visualized in Fig. 1 that shows a realized EBPM utilized with transversely mounted open coaxial lines in FLASH. The phase difference between the measured phases on the left and right side is direct proportional to the bunch position. The measurement resolution is defined by the minimum detectable phase-difference between both pulses. The phase of the pulse is defined by the phase constant of the transmission line. Without any distortions on the transmission line the phase constant is directly proportional to the fre-

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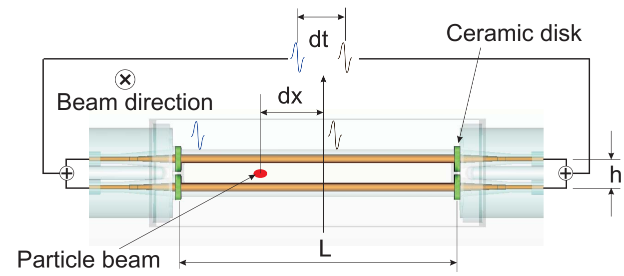

Figure 1: CAD model of the EBPM installed in the second bunch compressor at FLASH.

quency of operation and thus the phase-difference between both ends of the line. The measurement resolution is limited by the maximum operation frequency of the pickup, the limitations of the detection electronics and the length of the active sensor region which imposes the wavelength, below which the phase detection will be no longer unique [2]. The mechanical and electrical requirements for future EBPMs at the European XFEL differs significantly from the ones at FLASH. The opening of the rectangular beamline section is increased from L = 183 mm, H = 8 mm for FLASH to L = 400 mm, H = 40.5 mm for XFEL and at the same time the minimum detectable bunch charge is reduced from 1 nC for FLASH to 20 pC for XFEL. First results of planar transmission line pickups as a baseline for the XFEL EBPM monitor were presented in [7]. A possible upgrade of the EBPM by a quasi-grounded coplanar waveguide that combines the advantages of microstrip transmission lines and coplanar waveguide structures is shown in [1]. Compared to the microstrip design the grounded CPW line is the more complex design and even more difficult to mount within a vacuum environment. To make the CPW approach applicable for usage in accelerators, the CPW structure needs to be adapted to fulfill the vacuum requirements. In the proposed structure, the vias are exchanged by two metallic walls. Furthermore the metallic walls are shifted to the edge of the ground strips on the top layer as shown in Fig. 2. For

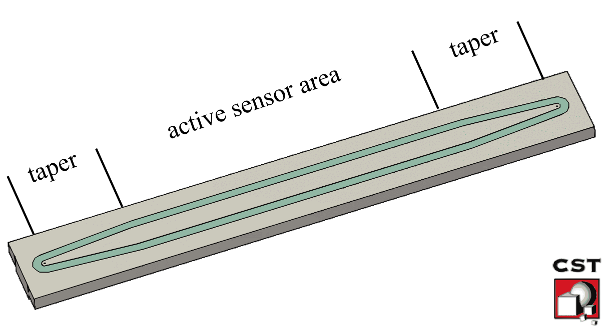

Figure 2: Simulation model of the quasi-grounded CPW structure.

maintaining the 50 Ω geometry, the gap between the line and the ground layer was increased slightly compared to a standard grounded CPW line. To match the wave impedance for the smaller line width, either the gap needs to be reduced for a constant substrate thickness or the thickness needs to be reduced for a constant gap. The matching to the transition is performed by a tapered reduction of the substrate thickness due to the parasitic effects in the transition section.

SIX-PORT REFLECTOMETER DESIGN

There are different possible implementations of a six-port reflectometer. The selected design is based on the measurement configuration from Engen [8], depicted in Fig. 3 in black and Grey color. It consists of a directional coupler, a rat-race coupler and three branch line couplers. For the

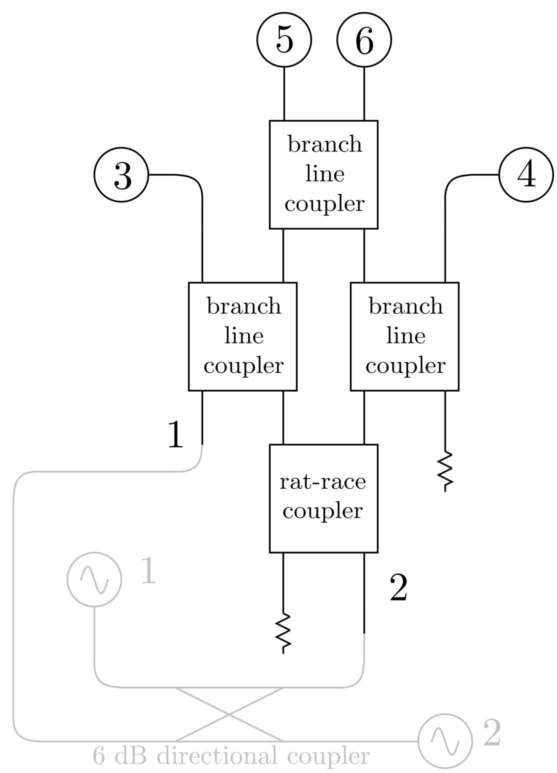

Figure 3: General circuit design for measurement purposes (Grey), and modified circuit design (black).

direct measurement of the signal difference of two signals, the structure can be simplified. The directional coupler at the input (grey color) can be omitted. The output values can be calculated from the input signals. The parameter a describes the amplitude of the incoming wave from port 1, while b is the amplitude for the wave from port 2.

$$\text{Port 1} : 2a \tag{1}$$

$$\text{Port 2} : 2b \tag{2}$$

$$\text{Port 3} : \frac{\sqrt{3}}{2}a - \frac{\sqrt{3}}{\sqrt{2}}b \tag{3}$$

$$\text{Port 4} : \frac{\sqrt{3}}{2}a \tag{4}$$

$$\text{Port 5} : \frac{\sqrt{3}}{2\sqrt{2}}a + \frac{\sqrt{3}}{2}b - j\frac{\sqrt{3}}{2\sqrt{2}}a \tag{5}$$

$$\text{Port 6} : \frac{\sqrt{3}}{2\sqrt{2}}a - j\frac{\sqrt{3}}{2\sqrt{2}}a - j\frac{\sqrt{3}}{2}b \tag{6}$$

It is visible that every output port has a different phase, which is a necessary criterion for the function of the six-port reflectometer. It can be seen that port 4 is only dependent on the incoming wave a, so that it can be used as a reference port.
The simulation of the circuit models were done with *Agilent Advanced Design System*, afterwards the ADS layouts were used to build 3D models in *CST Microwave studio*. The model is depicted in Fig. 4

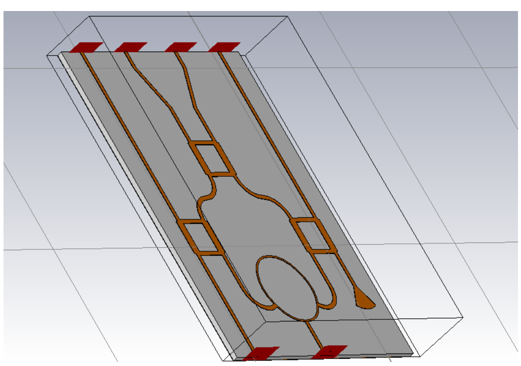

Figure 4: 3D model of the Six port reflectometer.

In order to proof the functionality, a phase shifter was added to input port 2 to obtain a phase sweep from 0° to 360° in 5° steps. The goal was to find a range were the detected power is as high as possible and second the power should vary as much as possible, to enable a more precise measurements. A suitable solution is the range of about 50° to 80°, as shown in Fig. 5.

As a substrate, *Rogers RT/duroid 6010* with a relative permittivity $\epsilon_r = 10.8$ and a thickness of 1.28 mm was chosen. A high relative permittivity is necessary to keep the dimensions of the circuit small. The connection to the circuit is done using SMA connectors with a flat and short pin that has a width that matches the line width of the six-port. For a stable connection a metal frame was build and the circuit board has been soldered onto it. Figure 6 shows a photo of the finished six-port reflectometer.

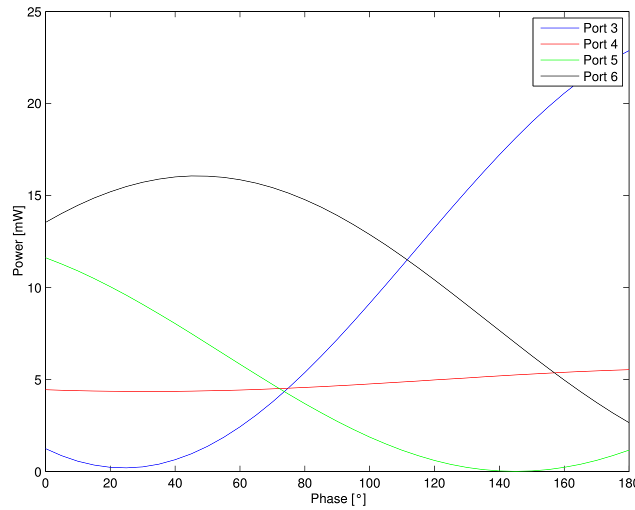

Figure 5: Output power versus phase difference of the six-port reflectometer.

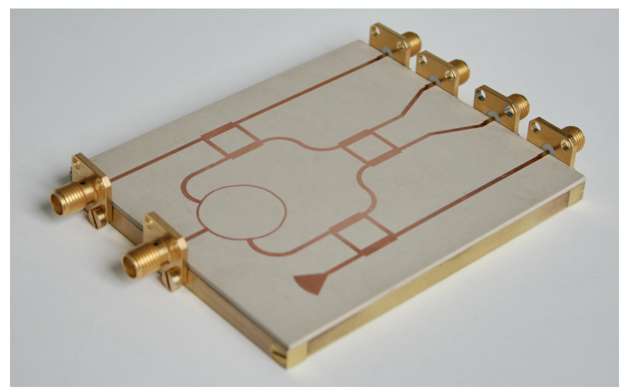

Figure 6: Photo of the six-port reflectometer design.

IMPLEMENTATION

In the application, the six port has to deal with pulses rather than single frequencies. This can be achieved applying band pass filters for the desired frequency range to its inputs which will make the superposed signals in the reflectometer less distorted. A direct processing in the RF domain

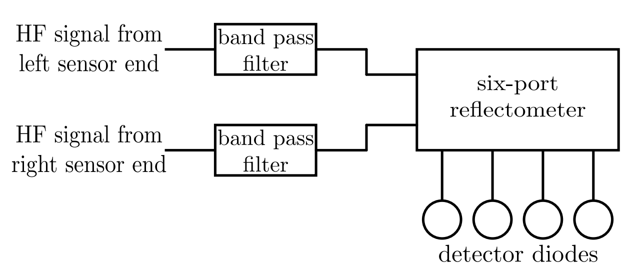

Figure 7: block diagram of the approach.

makes downconversion to an intermediate frequency range redundant and the signal can be directly led into the input ports of the six-port circuit. At every output a detector diode or a comparable circuit is installed to read the power level. This approach is depicted as a block diagram in Fig.7. For

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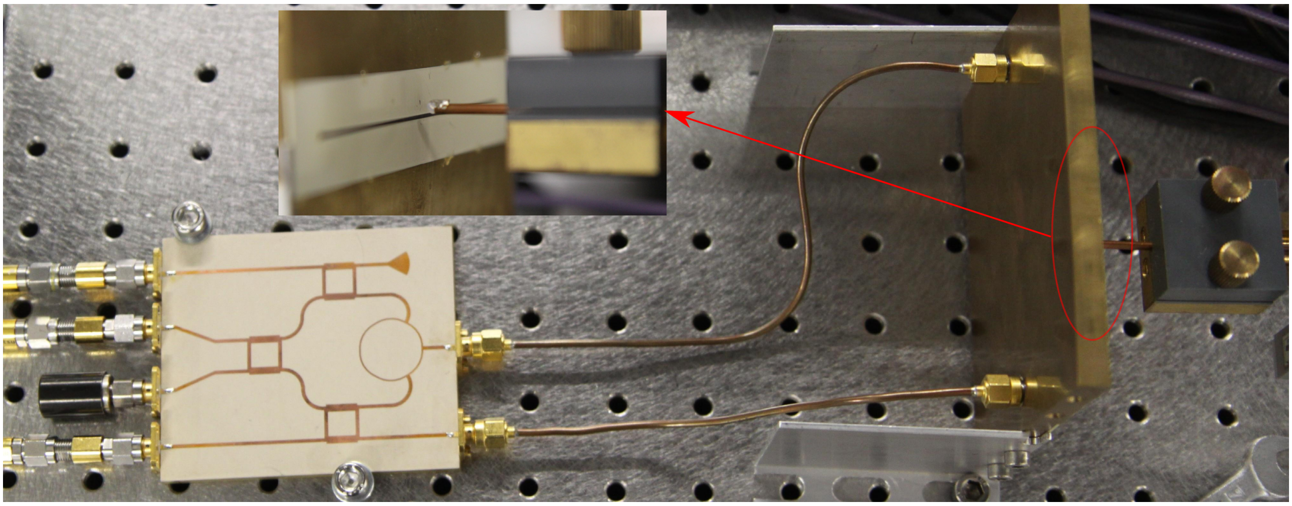

Figure 8: Measurement setup.

single-bunch measurements in multibunch operation mode, which will be the standard operation mode of the XFEL, the beam induced sensor signal shaped is a derivation of Gaussian bunches. This makes a instantaneous measurement necessary. A six-port reflectometer has the ability to detect these pulses, if the time resolution of the overall system is small enough [9]. Especially the detector circuit and plays an important role here.

PHASE DIFFERENCE MEASUREMENTS

The phase difference at both output ports of the sensor originates from the beam induced signal at the transmission line sensors. Since the particle beam only covers a small part of the sensor's width the induced signal is primary induced at a single point along the transmission line. As a result, electromagnetic waves propagate to both ends of the sensor where K-connectors are positioned. If the particle beam is not centered, the propagation time to the ends will differ, which leads to a phase mismatch, that can be detected with the six-port reflectometer.

An important information is the maximal phase difference that is achieved when the particle beam is near one of the sensor's terminations. The total length to both connections is about 183 mm. The propagation speed of the wave in the transmission-line substrate c depends on its electromagnetic properties of the used Rogers RO3010 substrate. It has a relative permittivity $\epsilon_r = 10.2$.

$$c = \frac{c_o}{\sqrt{\epsilon_r \mu_r}} = \frac{2.998 \cdot 10^8 \mathrm{m\,s^{-1}}}{\sqrt{10.2 \cdot 1}} \approx 93.87 \cdot 10^6 \mathrm{m\,s^{-1}} \quad (7)$$

Using the equations

$$\Delta t = \frac{\Delta l}{c} \quad (8)$$

and

$$\Delta t = \frac{\Delta \phi}{\omega} = \frac{\Delta \phi}{2\pi f} \quad (9)$$

the phase difference for a non-centered particle beam can be calculated.

The measurement setup to test the six-port reflectometer is shown in Fig. 8.

The beam induced excitation is modeled with a small coupling loop in the vicinity of the transmission line. The coupling loop is mounted A 3D Micropositioner to adjust the induced signal with μm precision. Due to the limited adjustable range, less than a quarter of the sensor length could be measured. The obtained results are shown in Fig. 8 Evaluating port 4, it can be clearly seen that the transmission line sensor is not fully matched to the six-port reflectometer. The reflections cause a power variation of more than 3dBm. Nevertheless a change in detected power of more than 15dBm for port 3 and 35dBm for port 5 could be observed.

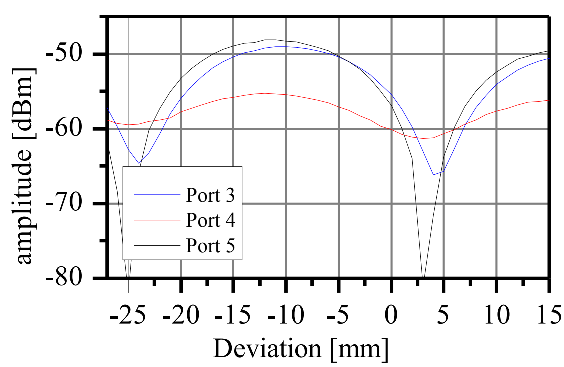

Figure 9: Detected power versus beam offset for ports 3,4 and 5 at a 3GHz.

The investigation of the minimum detectable phase shift and thus beam position requires a much lower step size in lateral direction. Figure 10 shows the measurement results obtained with a step size of 100μm. The amplitude variation for port 4 is less than 1dBm, for port 3 8dBm and port 5

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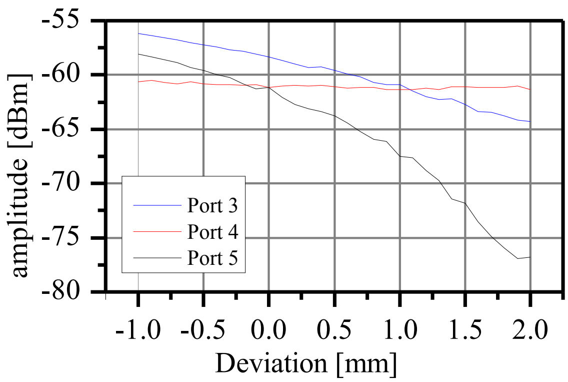

Figure 10: Detected power versus narrow beam offset for ports 3,4 and 5 at a 3GHz.

more than 20dBm for a beam offset of 3mm. This results in a sensitivity of more than 5dBm/mm taking into account a quadratic behavior.

CONCLUSION

A simple and passive read out scheme the EBPM Pickup structures for energy measurements of free-electron lasers such as FLASH or XFEL was introduced. The EBPM needs a high dynamic range over the sensor length of 183 mm and high resolution of less than 20μm. Both, the dynamic range and the resolution depend on the operation frequency. Due to phase ambiguity, only the readout scheme for high resolution was simulated using Agilent ADS as well as CST Microwave studio. For validating the obtained simulation results a prototype was build and a series of measurements were conducted with a non-hermetic prototype of a EBPM Pickup structure.

The proposed design provides a sensitivity of more than 5dBm/mm beam offset for a mean value of -60dBm for the non hermetic test setup. For the high resolution of less than 20μm a sensitivity of 0.1dB at the given power level is sufficient. A standard power meter fulfills this requirements typically down to -70dBm.

Although a measurement of all four output ports was not possible at the same time, it could be confirmed, that the six-port reflectometer enables precise measurements of phase and amplitude differences.

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