BPMs with Precise Alignment for TTF2

D. Noelle, G. Priebe, M. Wendt, and M. Werner

Deutsches Elektronen Synchrotron DESY*, Notkestr. 85, D-22603 Hamburg, Germany*

Abstract. Design and technology of the new, standardized BPM-system for the warm sections of the TESLA Test Facility phase II (TTF2) are presented. Stripline- and button-BPM pickups are read-out with an upgraded version of the AM/PM BPM-electronics of TTF1. The Stripline-BPMs are fixed inside the quadrupole magnets. A stretched wire measurement was used to calibrate the electrical axis of the BPM wrt. to the magnetic axis of the quadrupole.

INTRODUCTION

The control of the beam orbit is essential for the operation of linear accelerators for future linear colliders (LC), as well as for free electron laser (FEL) drive linacs. Beam position monitors (BPM) with high resolution and single-bunch, single-pass measurement capability are mandatory. The transport of the beam, by preserving its low emittance, requires a precise measurement of the beam orbit with respect to the magnetic axis of the quadrupoles. As a beam based alignment procedure is not always applicable (common quadrupole power supplies), or sometimes may not give satisfactory results (shot-to shot beam jitter), a stretched wire alignment measurement for quadrupole and BPM pickup can be used as an alternative or add-on.

THE TESLA TEST FACILITY PHASE II

In phase II of the TESLA Test Facility (TTF2), currently under commissioning at DESY, the beam accelerated up to 1 GeV/c by the use of 5 (6) TESLA cryo-modules (Fig. 1.). The task of the TTF2 facility is twofold:

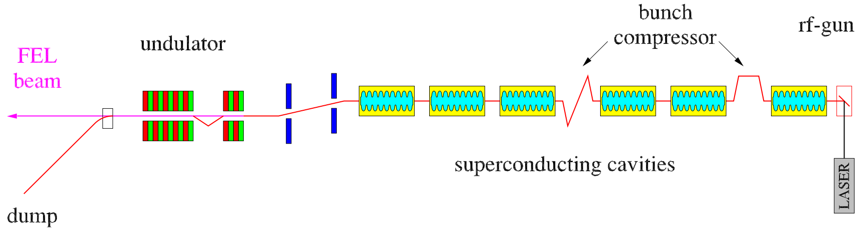

FIGURE 1. Schematic overview of TTF2 (bypass beamline not shown).

CP732, *Beam Instrumentation Workshop 2004: Eleventh Workshop,*
edited by T. Shea and R. C. Sibley III

- Linac test facility for beam test of high-gradient superconducting L-Band cavities and subsystems in terms of linear collider development.
- Drive linac for a 30 m long VUV (wavelength 6 nm) SASE-FEL user facility [1].

TABLE 1. Parameters of the TTF2 electron beam.

max. beam energy	=	800 MV (1 GeV)
max. rep. rate f_{rep}	=	10 Hz
macro pulse length t_{pulse}	=	800 μs
max. # of bunches per pulse	=	7200
bunch spacing Δt_b	=	110 ns or 1 μs
N_e per bunch	=	0.5...4 nC (typical 1 nC)
bunch length σ_z	$\approx$	50 μm
norm. emittance ε_{norm}	<	2 mm mrad
rms energy spread	=	0.1 %

Table 1 gives an overview of the TTF2 electron beam parameters. In order to establish standard components to improve operational and maintenance aspects we limit to the following BPM types:

- $\approx$ 30 *button* BPMs located in the injector, bunch-compressors and in and between the FEL-undulator sections.
- $\approx$ 30 *stripline* BPMs in all other "warm" parts of the machine.
- 4 *resonant* and one *re-entrant cavity* BPMs in the accelerating modules.

For a compact design the stripline BPMs are mounted inside the corresponding quadrupole magnets. With a proper mounting this allows to align and to fix the BPM and the magnetic axis of the devices with respect to each other. Due to the absence of the synchrotron radiation power, this is much easier for LINAC drive devices compared to storage rings.

Standardized read-out electronics, based on the *AM/PM normalization* principle, are used for all button- and stripline BPMs. Although this analog signal processing seems to be today somewhat "conservative," it matches best to the TTF data acquisition system.

THE STRIPLINE BEAM POSITION MONITOR

Principle

The impulse response of a stripline electrode of length l, terminated at both ends in its characteristic impedance Z_0, is given to:

$$z(t) = \frac{Z_0}{2}\left[\delta(t) - \delta(t - \frac{2l}{c_0})\right] \tag{1}$$

The characteristic impedance Z_0 of the "semi"-coaxial tube-electrodes of the TTF2 stripline BPMs are matched to the usual 50 Ω impedance of rf and microwave equipment.

The *Fourier* transform of (1) is the transfer impedance:

$$Z(\omega) = j Z_0 e^{-j\frac{\omega l}{c_0}} \sin\left(\frac{\omega l}{c_0}\right) \tag{2}$$

The magnitude of (2) has a maximum at frequencies where the length is an odd multiple of the quarter-wavelength:

$$f_{\text{center}} = \frac{c_0}{4l}(2n-1) \tag{3}$$

Usually the stripline pickup operates at the first "lobe" (n=1). Its 3dB-bandwidth exceeds an octave:

$$f_{\text{lo}} = \frac{1}{2} f_{\text{center}} \qquad\qquad f_{\text{hi}} = 3\, f_{\text{lo}}$$

The physical length of the stripline electrodes in TTF2 is fixed to $l = 20$ cm, which leads to $f_{\text{center}} = 375$ MHz $(n = 1)$.

The signal voltage delivered by a BPM electrode (stripline, button) is:

$$V_{\text{electrode}}(\omega, x, y) = s(x,y)\, Z(\omega)\, I_{\text{beam}}(\omega) \tag{4}$$

which is proportional to the current $I_{\text{beam}}(\omega)$ of the passing beam and to the beam-to-electrode distance (x,y) (transverse beam displacement) or coupling, which is described by a sensitivity function $s(x,y)$. Because of the short TTF2 electron bunches the frequency spectra of $I_{\text{beam}}(\omega)$ is of no concern; for the BPM system the bunches behave like *Dirac* impulse excitation signals. $s(x,y) = \Phi(x,y)$ is evaluated by analyzing the 2-dimensional cross-section geometry of the stripline BPM, applying *Laplace*'s equation $\Delta\Phi = 0$ with help of a numerical electromagnetic solver, e.g., *MAFIA*, *EM Studio*, etc. For a centered beam the coupling to a TTF2 stripline electrode is $s(0,0) = k \approx 0.065$.

The TTF2 Stripline BPMs

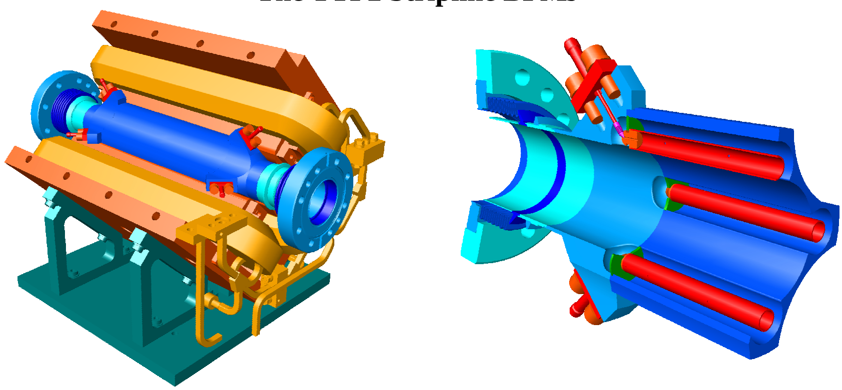

FIGURE 2. TTF2 stripline BPM (*type B*: 44 mm beam-pipe diameter, 8 mm electrode diameter), inside quadrupole installation and sectional view.

In order to save space and for alignment purposes the cross-section of the TTF2 stripline monitors are matched to the poles of the corresponding quadropole magnets (Fig. 2). The gold-plated stainless-steel tube electrodes provide high mechanical stiffness. They are fixed with ceramic spacers to the monitor body, which is shaped by an EDM process. A micro-bellow keeps the electric contact between the spherical shaped electrode-end and the pin of the SMA UHV feedthrough. Because of the high gradient superconducting cavities at TTF2 dust or particle emission has to be avoided. Thus the stripline BPM production had to fulfill cleanroom class 100 conditions.

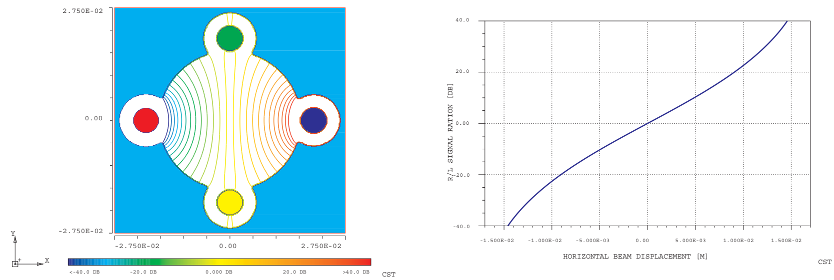

FIGURE 3. Equipotentials of the horizontal stripline electrodes (logarithmic scaled for $s(x,y)$ and $s(x,0)$).

The 4 electrodes are arranged orthogonally, along horizontal and vertical planes. One channel of the read-out electronics processes the signals of two opposite electrodes, e.g.:

$$\text{normalized hor. beam displacement} = \frac{V_{\text{right-electrode}}(x,y)}{V_{\text{left-electrode}}(x,y)} \tag{5}$$

with $V_{\text{right-electrode}}(x,y) = V_{\text{left-electrode}}(-x,y)$. This *normalization* procedure results in an intensity independent beam position signal, which also reduces the nonlinearities of $s(x,y)$ of a single electrode. Fig. 3 shows this normalized equipotential pattern for the horizontal electrodes. The sensitivity around the center is $\approx$ 2 dB/mm.

Currently 30 stripline BPMs of two different apertures (34 mm and 44 mm beam pipe diameter) are installed in TTF2. Further stripline BPMs are foreseen for SASE-FEL seeding upgrade. Advantages of stripline BPMs, compared to the more simple, lower cost button BPMs, are:

- High signal levels, already at moderate frequencies (here: 375 MHz), simplify the read-out electronics (no downconversion) and results in a good S/N-ratio. Button BPMs have a high-pass behavior and forces for complicated high frequency read-out electronics.
- A resistive 50 Ω source impedance (button BPMs: capacitive source impedance) minimizes reflection effects between BPM pickup and read-out electronics and therefore resolves single bunches in a better way.

PRECISION ALIGNMENT OF STRIPLINE BPM AND QUADRUPOLE MAGNET

The stripline BPM is fixed tightly at both ends with the quadrupole magnet, so they form a rigid mechanical unit. A stretched wire setup is used to measure both:

- The magnetic center of the quadrupole magnet.
- The electric center of the stripline BPM.

and calibrate them without using an external reference. This idea [2] was already adapted for a few stripline BPM-quadrupole units, used at the S-Band Test Facility linac [3], and is now applied under cleanroom conditions for larger quantities in the frame of TTF2 beam instrumentation.

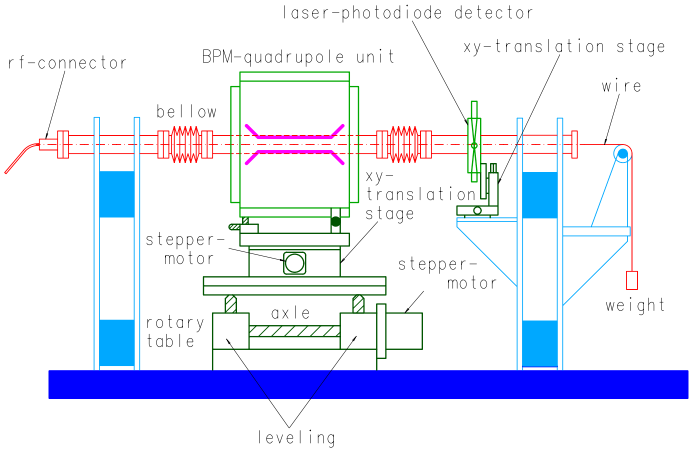

FIGURE 4. Schematic view of the stretched wire alignment setup.

Fig. 4 shows a schematic view of the stretched wire test bench with its basic elements. An aluminium plate carries the BPM-quadrupole unit on a stepper-motor movable xy-translation stage. Two rigid pillars fix the beam-pipe sections, which adapt to the movable BPM pipe in the center via bellows. A 130 μm diameter, copper-beryllium wire is stretched in the center of the beam pipe and forms a coaxial transmission line. Pulse-resp. rf-signals are feed from the upstream N-connector for calibration of quadrupole or BPM axis. A laser-photodiode detection system is located on the downstream pillar for calibration of the magnetic center. The distance between this detector and the end of the wire has to be longer than the half of the magnet length, in order to separate original and reflected signals. Other parts of the test bench are a defined weight to stretch the wire and mechanical elements to compensate a tilt between BPM-quadrupole and wire. The detector can also be moved by a manual xy-translation stage.

The calibration procedure is done in two steps:

Calibration of the Magnetic Center of the Quadrupole

A method to measure the effect of a magnetic field on a stretched wire, excited with a strong, but short pulse of charge Q is described in [4], [5]. The *Lorenz* force accelerates the part of the wire, on which the magnetic field B acts, in transverse direction. This displacement of the wire

$$x(z_0,t) = \frac{Q}{2\,\mu\,c}\int_{z_0}^{z_0-ct} B(\tilde{z})\,d\tilde{z} \tag{6}$$

moves with the wave velocity $c = \sqrt{T/\mu}$ towards upstream and downstream fixpoints of the wire and can be detected at a location z_0 behind the magnet (μ is the weight per unit length of the wire, T is the tensile force to which the wire is stretched).

Before starting the calibration procedure the magnet was cycled using a bipolar power supply. Then the magnet was powered with 25% of its nominal current ($\approx$ 100 A). A pulse of 400 V, 20 A and 10 μs length was feed into the stretched wire. The magnet was then moved in a way that the signal from the wire gets zero. This reading of course defines the magnetic axis of the quadrupole.

The movement of the the BPM-quadrupole unit was done by computer controlled stepper motors with a resolution of 5 μm (hor.) resp. 0.6 μm (vert.) Being close to the magnetic center also the tilt between wire and magnetic axis was minimized.

From this *reference position* – set micrometer gauges and step counter to zero – we started the second step of the procedure:

Calibration of the Electrical Center of the Stripline BPM

A Δ-signal of two opposite electrodes of the stripline BPM was produced by wiring well calibrated, phase-stable semi-rigid coaxial cables and a *M/A-COM H-9* 180^0 broadband hybrid. With a network analyzer a frequency-domain $|S_{21}(f)|$ measurement was setup between stretched wire input and Δ-signal output. We didn't care about the reflections in the not terminated stretched wire beam-pipe, as the measurement was performed for a single frequency (zero-span mode). By moving the BPM-quadrupole unit with the stepper motors and appropriate settings of the network-analyzer ($f_{\text{center}} = 180$ MHz, $f_{\text{RBW}} = 100$ Hz, $t_{\text{sweep}} = 5$ s) it was simple to minimize $|S_{21}|$ down to the -100 dBm noise level. The signal minimum could be identified clearly within a single step in the horizontal (step size: 5 μm) and 2..3 steps in the vertical plane (step size: 0.6 μm).

When both planes show a minimum of the Δ-signal transfer, the stretched wire was in the electrical center of the stripline BPM. The *xy-offset* between magnetic center of the quadrupole and electrical center of the stripline BPM was evaluated by counting the driven steps, cross-checking with the micrometer gauge readings.

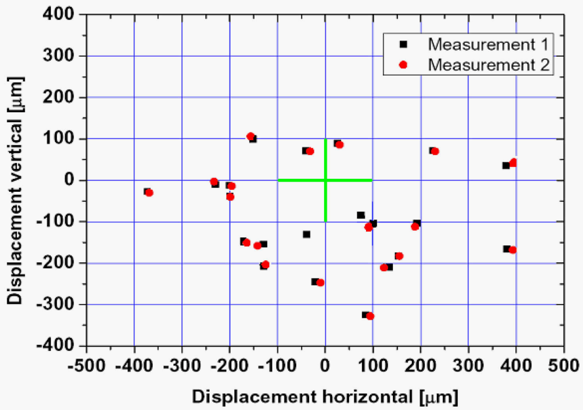

FIGURE 5. Results of the stretched wire alignment procedure.

Results

23 BPM-quadrupole units were calibrated with the stretched wire alignment setup. Each measurement was performed twice, the setup was de-adjusted and partially demounted between individual measurements. The result are shown in Fig. 5. As expected 200...300 μm offsets typical for mechanical construction show up. While the resolution to identify the BPM center is in the range 1...2 μm, the identification of the magnetic center is limited to 10...20 μm, dominating the the resolution of the complete setup. This is due to several facts, like stray fields, wire diameter, laser focussing, mechanical vibration, etc. and, in the horizontal plane, the rather large step size.

BPM READ-OUT ELECTRONICS

A set of standardized read-out electronics has been developed, which applies the AM/PM-principle for normalization to the signals of two opposite BPM electrodes (5). Let us simplify the electrode signals to to stationary sine-wave voltage functions v_A and v_B:

$$v_A(t) = \hat{a}\, e^{j\omega t} \qquad v_B(t) = \hat{b}\, e^{j\omega t}$$

of the same frequency and in phase, but with different amplitudes $\hat{a}$ and $\hat{b}$ due to the beam displacement. At the outputs C and D of the hybrid-with-delay circuit the signals:

$$v_C(t) = \mathscr{A} \arctan\left[\frac{\hat{a}\sin(\omega t) + \hat{b}\cos(\omega t)}{\hat{a}\cos(\omega t) - \hat{b}\sin(\omega t)}\right] \qquad v_D(t) = \mathscr{A} \arctan\left[\frac{\hat{a}\sin(\omega t) - \hat{b}\cos(\omega t)}{\hat{a}\cos(\omega t) + \hat{b}\sin(\omega t)}\right]$$

have the same amplitude $\mathscr{A} = \sqrt{\frac{\hat{a}^2+\hat{b}^2}{2}}$, but the amplitude-ratio of A and B is converted into a phase-difference:

$$\Psi_{C-D} = 2\,\mathrm{arccot}\left(\frac{\hat{a}}{\hat{b}}\right) \tag{7}$$

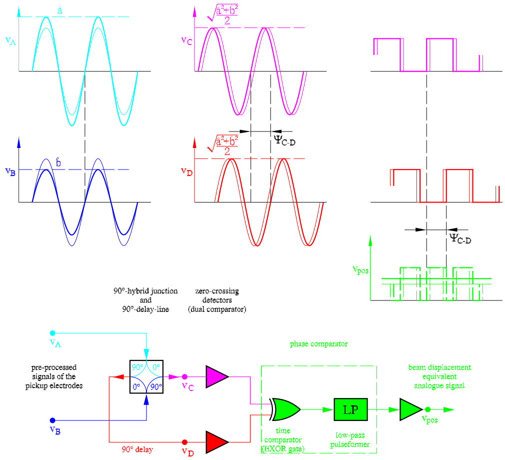

FIGURE 6. AM/PM-principle for normalization of the BPM electrode signals.

The phase (time) detection and further signal processing results in beam intensity independent position signal (Fig. 6).

The TTF2 BPM read-out electronics is realized on a VXI mainboard housing a set of 9 rf-modules. Button BPMs are processed with a broadband "monopulse" technique, which was already successfully operated on the FEL-undulator button BPMs during the TTF1 run [6]. By changing the input low-pass towards "ringing" band-pass filters and a few other modifications the same board is capable for processing the stripline BPM signals. In this case the measurement (integration) time is longer: $\approx$ 80 ns, instead of 12 ns for the monopulse technique.

The expected single-bunch resolution for a complete setup – BPM-pickup and read-out electronics – is in the range 10...30 μm.

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