Resolution Studies at Beam Position Monitors at the FLASH Facility at DESY

N. Baboi[*], J. Lund-Nielsen[*], D. Noelle[*], W. Riesch[†],
T. Traber[*], J. Kruse[*] and M. Wendt[‡]

[*]DESY, Notkestr. 85, 22607 Hamburg, Germany
[†]DESY, Platanenallee 6, 15738 Zeuthen, Germany
[‡]FNAL, PO Box 500, Batavia, IL 60510, USA

Abstract. More than 60 beam position monitors (BPM) are installed along about 350 m of beamline of the Free Electron LASer in Hamburg (FLASH) at DESY. The room-temperature part of the accelerator is equipped mainly with stripline position monitors. In the accelerating cryo-modules there are cavity and re-entrant cavity BPMs, which will not be discussed here. In the undulator part of the machine button BPMs are used. This area requires a single bunch resolution of 10 μm. The electronics is based on the AM/PM normalization principle and is externally triggered. Single bunch position is measured. This paper presents the methods used to determine the resolution of the BPMs. The results based on correlations between different BPMs along the machine are compared to noise measurements in the RF lab. The performance and difficulties with the BPM design and the current electronics as well as its development are discussed.

Keywords: beam position monitors, resolution, analog electronics
PACS: 41.85.Qg, 41.75.Fr, 41.60.Cr

INTRODUCTION

The Free Electron Laser in Hamburg (FLASH) at DESY yields through the principle of Self-Amplified Spontaneous Emission (SASE-FEL) [1] an intense light with wavelength from 32nm down to 13 nm, recently achieved. The linac was until recently known as the VUV-Free Electron Laser (VUV-FEL) and it is also used as a test facility for the X-ray Free Electron Laser (XFEL) and the International Linear Collider (ILC) study under the name TESLA Test Facility - Phase 2 (TTF2).

Mostly stripline and button beam position monitors (BPM) [2] with single bunch resolution are built in FLASH. Other BPMs, such as cavity BPMs [3], re-entrant cavity BPM [4] and striplines of different make are not discussed here. A resolution of 30μm rms is desired from the stripline BPMs, while the button BPMs with 10mm diameter should have a resolution of 10μm rms.

The resolution of each BPM has been calculated from cross-correlations with the other BPMs. The method is described in detail in the paper.

The electronics for the BPMs is an improved design from the one used in TTF1, and is based on the AM/PM normalization principle, using an external trigger [5]. This TTF2-type electronics has been installed during 2005. During commissioning the resolution of the button BPMs has proved to be unacceptable. The studies made on the button BPMs as well as the reasons for bad resolutions and remedies are discussed. The stripline BPMs have also been investigated.

The FLASH Linac

The layout of FLASH linac is shown in Fig. 1. With the help of a laser sent on the photo-cathode, the gun generates beams with up to 800 electron bunches spaced by 1μs. Eight 1m-long superconducting cavities built in each of 5 cryo-modules accelerate the beam to an energy between 450 and about 700MeV. Two bunch compressors reduce the bunch length. Several collimators are used mainly to protect the 6 undulators, where an intense VUV light is produced through the SASE-FEL process. The electrons are then sent to a dump, while the FEL beam goes further to one of several user beam lines. The bypass line has the role of protecting the undulators during machine studies. The position of about 45 BPMs is also qualitatively shown in the figure. The monitors will be described in the next subsection.

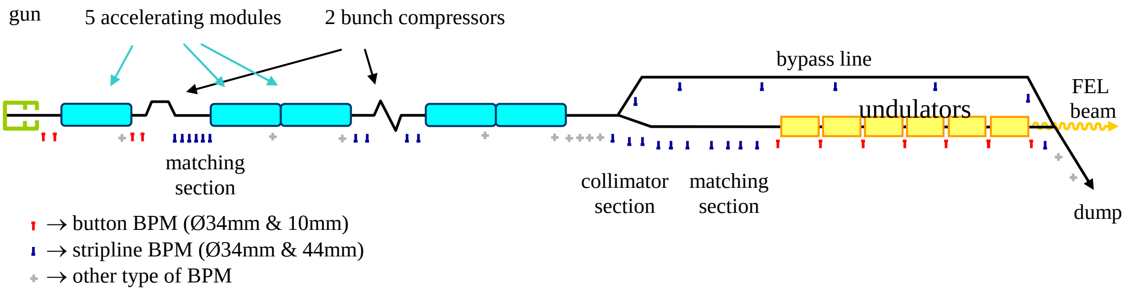

FIGURE 1. Sketch of the FLASH linac.

The matching sections are designed to have periodical optics, as is the case also in the undulator section. However, as a whole, the optics in the linac is non-periodical as it can be seen in Fig. 2. In this figure, the beta function for both transverse planes, for an example of a design optics for 450MeV is shown. The periodic lattices of the matching sections and the undulator area are clearly visible. The regions with large beta function correspond to the accelerating modules and the area between the 5th module and the collimators.

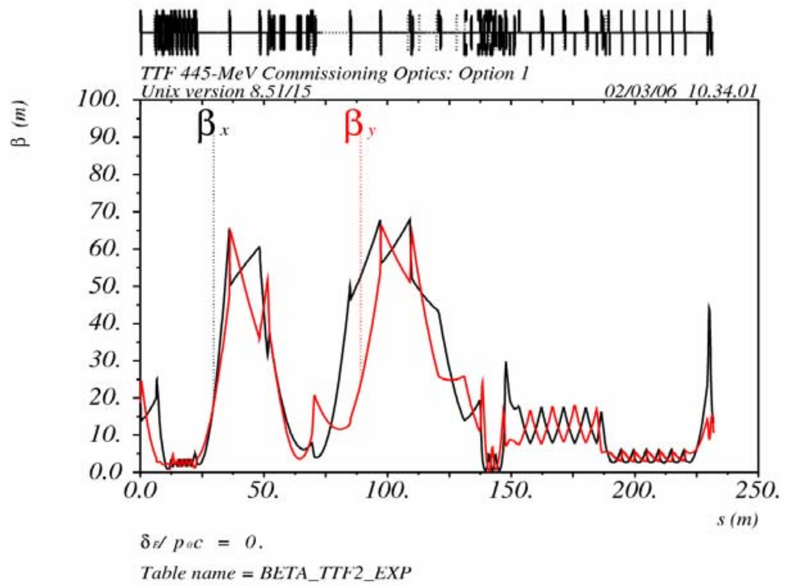

FIGURE 2. Example of design optics for 445MeV (courtesy of N. Golubeva).

Button and Stripline BPMs

As qualitatively shown in Fig. 1, the facility is equipped with many BPMs of various kinds. The injector area contains button-type BPMs of 34mm diameter. Other button BPMs of small cross-section of 10mm diameter are in the diagnostics sections between the undulators. Stripline BPMs with 34mm diameter, and a few with 44mm, are built in most of the rest of the linac. Most stripline monitors are built in quadrupoles. These button and stripline BPMs are the object of this paper. A single bunch resolution of 30μm rms is expected from striplines, while the undulator BPMs should provide 10 μm.

The cryo-modules have cavity BPMs and one re-entrant cavity BPM. The button BPMs built in the undulators themselves have not been commissioned yet. The other monitors are buttons and striplines with a different design or different electronics, generally with relaxed requirements, and will also not be discussed here.

BPM Electronics

The electronics built for the button and stripline BPMs in FLASH/TTF2 is based on the AM/PM normalization principle [5]. Basically the amplitude modulation (AM) of the signals from the pickups, depending on the beam position and intensity, is converted into phase modulation (PM). The signals from two electrodes are normalized, and the result is a signal depending on the beam offset and independent of the beam intensity.

The block diagram of the button BPM electronics is shown in Fig. 3. The signals from two opposite BPM pickups go through Gaussian low-pass (LP) filters and are

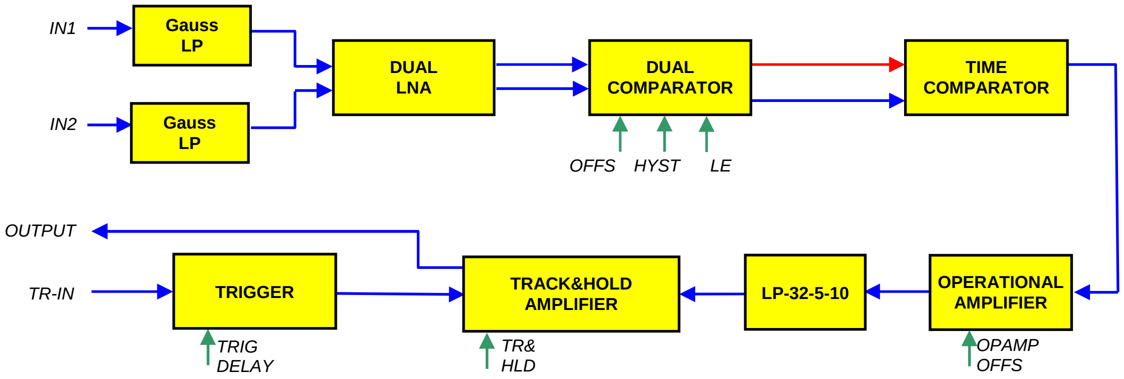

FIGURE 3. Block diagram of button BPM electronics. The stripline electronics is similar.

amplified by a dual low noise amplifier (LNA). A dual comparator detects the zero-crossing of each signal. The following time comparator compares both signals to a nominal pulse. Its area is proportional to the beam displacement. Four such signals are generated for the integration made effectively by the operational amplifier. The pulse is low-pass filtered before having its peak effectively sampled and frozen by the Track&Hold amplifier for 1μs. An external trigger is used, whose delay is adjusted by a trigger module. For the stripline electronics, the main difference is in the first two components, a 375MHz band-pass (BP) filter and a 90° hybrid.

The output signal of the electronics depends on the beam position as atan of the ratio of the two input signals. For small beam offsets the output is proportional to the beam offset.

The signal is further sampled and digitized with AD converters. By help of linear coefficients the values are calibrated into beam offsets. These coefficients are correct for small offsets and for centered beam in the transverse direction. A more accurate calibration is being investigated.

BPM RESOLUTION

The BPM resolution has been measured by correlating the reading of one BPM in one plane against the readings of all other BPMs in the same plane. The classical method is to use pairs or few BPMs which have an appropriate phase advance between them, such that the movement of the beam is seen by the other BPMs equally. In our case measuring the optics is a lengthy process; also, the machine works with various optics and is partially still being commissioned for different energies. However, as mentioned earlier, the optics of the machine is by design non-periodic. Additionally, the real optics in the machine differs from the design, therefore often having additional non-periodicity. We relied on this fact and on the large number of BPMs in the machine when we chose to use correlations against all other position monitors to calculate the resolution.

Calculation of BPM Resolution

In order to correlate BPMs with each other, we use linear regression. The beam position is measured by each monitor for p beam pulses. Now we form a column matrix for the BPM of interest:

$$\mathbf{M} = \begin{pmatrix} x_{1,m} \\ x_{2,m} \\ \cdots \\ x_{i,m} \\ \cdots \\ x_{p,m} \end{pmatrix}, \tag{1}$$

where $x_{i,m}$ is the reading in one transverse plane, horizontal or vertical, for pulse i, for BPM with index m.

The readings of the other BPMs are put in another matrix:

$$\mathbf{B} = \begin{pmatrix} 1 & x_{1,1} & \cdots & x_{1,m-1} & x_{1,m+1} & \cdots & x_{1,n} \\ 1 & x_{2,1} & \cdots & x_{2,m-1} & x_{2,m+1} & \cdots & x_{2,n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & x_{i,1} & \cdots & x_{i,m-1} & x_{i,m+1} & \cdots & x_{i,n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 1 & x_{p,1} & \cdots & x_{p,m-1} & x_{p,m+1} & \cdots & x_{p,n} \end{pmatrix}, \tag{2}$$

where n is the total number of position monitors.

Now we look for the vector **A** which is the solution, in the least square sense, of the equation:

$$\mathbf{M} = \mathbf{B} \cdot \mathbf{A}, \tag{3}$$

with

$$\mathbf{A} = \begin{pmatrix} a_0 \\ a_1 \\ \cdots \\ a_{n-1} \end{pmatrix}. \tag{4}$$

The columns of ones in matrix **B** allows for a free term in equation (3).

After matrix **A** has been obtained, the reading of monitor m can be predicted from the readings of the other BPMs:

$$M_{pred,i} \equiv \mathbf{B}_i \cdot \mathbf{A}, \tag{5}$$

where $\mathbf{B}_i$ is one row from matrix **B**, corresponding to pulse i. M_{pred} contains the correlation of the reading of BPM m to the readings of other BPMs, which occurs through changes in beam position.

The reading of the button BPM in one undulator diagnostics station is plotted against the prediction from the other BPMs in the linac in Fig. 4[1]. About 40 BPMs have been considered. 100 single pulses have been measured.

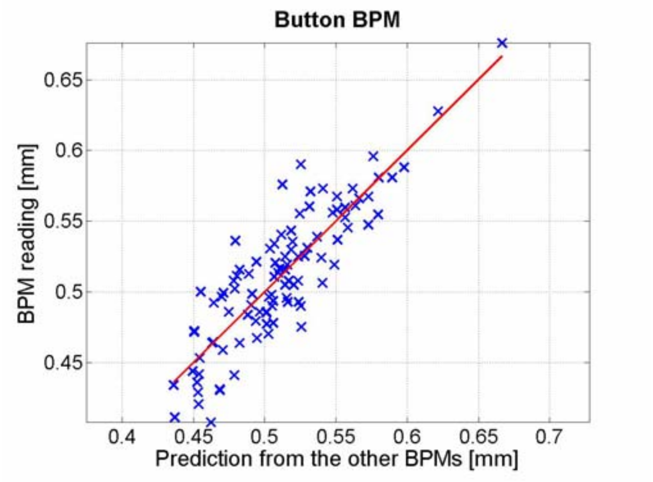

FIGURE 4. Correlation between the reading of one BPM and the readings of all other BPMs in the linac. The uncorrelated part, i.e. the difference between the BPM reading and the prediction from the other BPMs gives the BPM resolution. Here the resolution is 24µm rms; the total rms of the BPM readings is 48µm.

The uncorrelated part of the monitor reading comes from BPM noise and defines the rms resolution of the BPM:

$$\text{BPM resolution} = \sqrt{\frac{1}{p}\sum_{i=1}^{p}\left(x_i - x_{\text{pred},i}\right)^2} \tag{6}$$

BPM Resolution and Beam Jitter

The standard deviation of the BPM readings, or the rms, is given by the beam movement, in our measurements the beam jitter, and the BPM noise. Fig. 5 shows the rms of the BPM readings and the monitor resolution calculated for 100 pulses. For many BPMs the difference between the rms of the reading and the resolution is large. This happens in areas with large beta function (see Fig. 2), e.g. in the accelerating modules around 25m, 50-70m and after about 100m.

Therefore the rms of the BPM reading, or better the jitter of the BPM after removing the contribution from the BPM resolution, reflects qualitatively the optics in the linac. In contrast the BPM resolution, i.e. the BPM reading after removing the correlation to the other BPMs, gives information only about the properties of the monitor. The resolution will be discussed further in the discussion subsection.

---

[1] This data has been taken on February 20, 2006

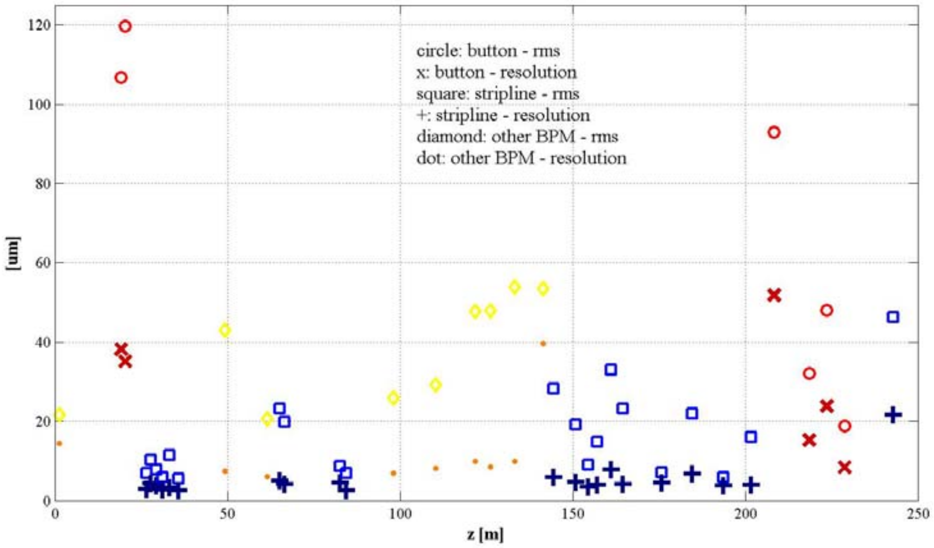

FIGURE 5. rms and resolution calculated over 100 pulses for about 40 BPMs along the linac.

BPM Noise Measurement

The noise of the BPM electronics has been measured in the RF laboratory. Two equal signals have been fed to the inputs of the electronics module, and the output has been displayed on a scope. A peak-peak noise of 20mV has been observed, or about 4mV rms. The constant of the electronics has also been measured in the lab, by feeding signals with various ratios at the inputs, thus simulating the beam offset. The constant for this electronics is 17.3mV/dB. The constant for the monitors in the undulator area is known from electromagnetic simulations with MAFIA to be 6.92dB/mm. These give a total BPM constant of about 120mV/mm. This translates the noise of the electronics of 4mV to about 30µm rms.

Discussion

Button BPMs

The noise measurement made in the laboratory is in good agreement with the measurements made with beam on a button BPM. However Fig. 5 shows different values for various BPMs in the undulator. This is due to the sensitivity of the electronics to the external trigger delay, to the internal delay, to differences in the electronics constant and in the calibration constant in the control system.

The measured resolution for a given BPM is not always reproducible from measurement to measurement, although over short periods of time one gets in general similar values. This has several reasons: The calibration constant is valid only for not too large offsets of the beam. For large offsets, the output of the electronics is by design non-linear with the bunch position, making the calibration constant inaccurate. Also, the beam should be centered in the perpendicular plane, otherwise the calibration constant is again not accurate anymore. The electronics has an additional non-linearity, which is being currently investigated. The non-linearity with beam offset makes the resolution of the BPMs to be dependent on the beam position.

The resolution may also be affected by inappropriate phase advance to the other BPMs; however an error can occur only towards worse resolutions.

The next section discusses the reasons for a resolution worse than designed.

Stripline BPMs

The resolution is relatively constant for the stripline BPMs, being for most of them below 10μm. Therefore the performance of the striplines is better than desired. The reproducibility is also less of a concern since the values are below the design.

The non-linearity of some components in the electronics is also present, and is currently the worst issue with the stripline monitors. However, as with the other problems mentioned with the button BPMs, the impact on the resolution estimation is negligible, though having an influence on the calibration. Also, since the signal from striplines is much longer and relatively constant than for the button case (as will also be shown in the next chapter) the trigger jitter or drift is not a concern.

Correlation to beam charge

The BPM readings are not only correlated through changes in beam position, but also to a small amount through charge variations, due to some residual dependency of the electronics on the beam intensity. Through the same method we looked for correlations between the BPM readings and charge readings from toroids and found that it is very weak. That is, after removing the correlation BPM-toroid, the remaining is almost equal to the rms of the BPM reading.

RF MEASUREMENTS ON THE BPM SIGNALS

Undulator Button BPMs

After the initial installation of the BPM electronics, a large value for the resolution has been observed for the undulator monitors, well above 100μm. The reasons have been investigated in detail. For this a 6GHz, 20GS/s scope has been directly connected to the pickups of one button BPM in the diagnostics station in the undulator area. The scope was controlled remotely from outside of the linac tunnel.

One such measurement is shown in Fig. 6. The lower curve shows the raw signal from a pickup for a bunch of 0.5nC charge. The upper curve represents the signal after the Gaussian LP filter.

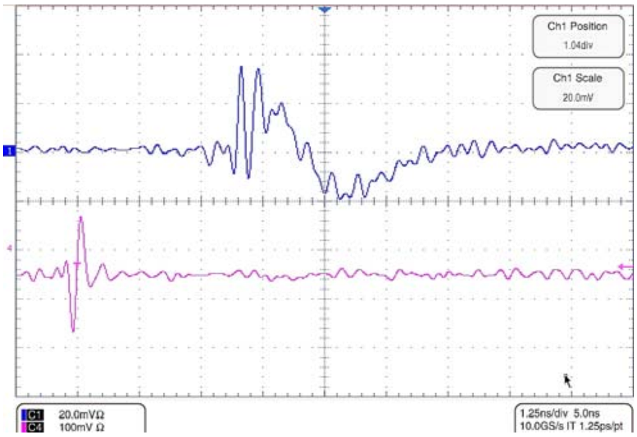

FIGURE 6. Signal from a undulator button-BPM for 0.5nC. Lower curve: raw signal from pickup. Upper curve: signal after Gauss LP filter.

The amplitude of the signal has been found to be too small for the next components of the electronics. In addition the signal is noisy, due to the fact that the filter allows for higher frequencies, in the GHz region to go through. Therefore a high-frequency LP filter, with cut-off at 1GHz, and an additional amplifier have been added immediately after the Gaussian filter. The signal is now much cleaner in the presence of these components as shown in Fig. 7.

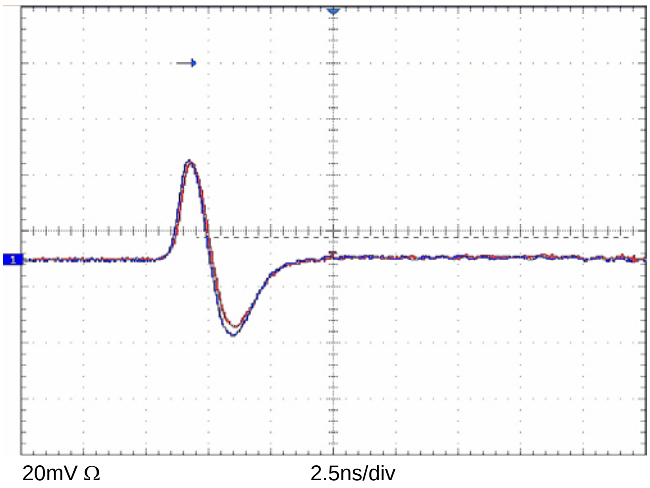

FIGURE 7. Signal from two opposite pickups of an undulator button-BPM for 1nC with high-frequency LP filter (cut-off 1GHz), Gaussian LP filter and amplifier. The beam is centered in the BPM.

The high-frequency LP filter seems also to improve the linearity of the electronics, but more studies are needed in this sense.

In Fig.s 6 and 7 one can see that the length of the filtered signal is on the order of 1ns. Therefore the output signal is sensitive to jitter of the Track&Hold trigger, which was observed to be in some cases hundreds of ps rms.

Stripline BPMs

As mentioned above, the single bunch resolution of the stripline BPMs is better than designed. However, as in the button case, the electronics presents a disturbing non-linearity. The signal from a stripline monitor has been measured with a fast scope and is presented in Fig. 8 for a 1nC bunch. The lower curve shows the raw signal from a pickup, with the direct and reflected signal. The upper waveform is after the BP filter centered on 375MHz. As in the case of the button BPMs, high frequency components are also present.

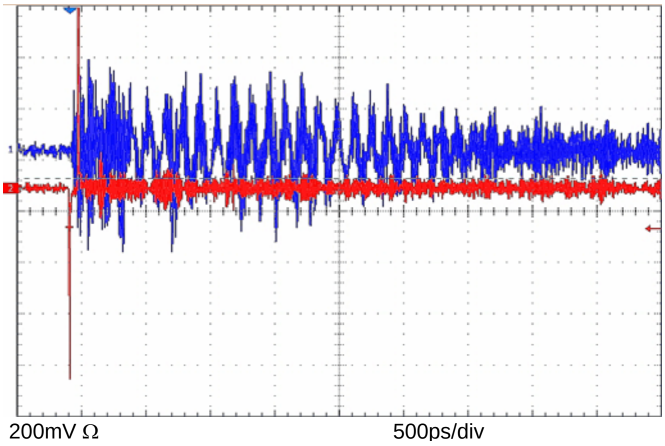

FIGURE 8. Signal from a stripline BPM (Ø34mm) for a 1nC bunch. Lower curve: raw signal from pickup. Upper curve: signal after BP filter.

The waveform is cleaned by using a high-frequency LP filter, with cut-off at about 500MHz. Figure 9 shows the signal in the presence of such a LP filter.

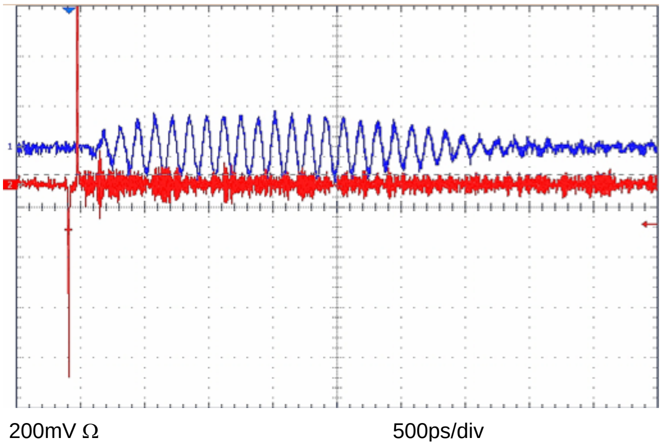

FIGURE 9. Signal from a stripline BPM for a bunch with 1nC. Lower curve: raw signal from pickup. Upper curve: signal after high-frequency LP filter and BP filter.

In Fig.s 8 and 9 one can also see that the pulse length is of the order of a few ns and relatively flat. This explains why the stripline electronics is much more stable against trigger jitter than for the button BPMs.

OUTLOOK

The calculation of the BPM resolution can be refined by using the method of singular value decomposition. This method has the potential of not only giving the resolution of the BPM, but also to show the sources of beam jitter.

The studies on the BPM electronics are on-going, depending on available beam time at FLASH/TTF2. We are investigating currently the non-linearity of the electronics, the dynamic range of beam charge and a more accurate calibration in the control system. A new master oscillator to be installed in the future shall provide for a more stable trigger. Also, there are several ideas for improvement of the electronics, which could be implemented as patches. We believe that all these will provide for the required resolution also in the undulator BPMs.

ACKNOWLEDGMENTS

We thank our colleagues from the MDI group who contributed to building the position monitors and their electronics and to the ZE department for testing the electronics for the button BPMs. We had many fruitful discussions on the resolution calculation with many colleagues, of which we would like to mention P. Castro, H. Schlarb, C. Gerth, K. Wittenburg. Last but not least, we thank the TTF operational team for its support with the studies at the linac.

REFERENCES

1. V. Ayvazyan et al., *Eur. Phys. J.* D **37**, 297–303 (2006)
2. D. Noelle and M. Wendt, Proc. of LINAC 2004, Lübeck, Germany, 2004, pp. 435-437.
3. R. Lorenz, Proc. of PAC97, Vancouver, Canada, 1997, pp.2137-2139
4. C. Simon et al., these proceedings
5. M. Wendt, Proc. DIPAC 2001, Grenoble, France, 2001, pp. 63-65