PERFORMANCE STUDY OF HIGH BANDWIDTH PICKUPS INSTALLED AT FLASH AND ELBE FOR FEMTOSECOND-PRECISION ARRIVAL TIME MONITORS

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Abstract

At today's free-electron lasers, high-resolution electron bunch arrival time measurements have become increasingly more important in fast feedback systems for a timing jitter reduction down to the femtosecond level as well as for time-resolved pump-probe experiments. This is fulfilled by arrival time monitors which employ an electro-optical detection scheme by means of synchronised ultrashort laser pulses. Even more, at FLASH and the European XFEL the measurement has to cover a wide range of bunch charges from 1 nC down to 20 pC with equally sub-10 fs resolution. To meet these requirements, recently a high bandwidth pickup electrode with a cut-off frequency above 40 GHz has been developed. These pickups are installed at the macro-pulsed SRF accelerator of the free-electron laser FLASH and at the macro-pulsed continuous wave SRF accelerator ELBE. In this paper we present an evaluation of the pickup performance by direct signal measurements with high bandwidth oscilloscopes and by use of the electro-optical arrival time monitor.

INTRODUCTION

FLASH at the Deutsches Elektronen-Synchrotron is a free-electron laser with pulsed superconducting RF acceleration. Beam energies of up to 1.25 GeV correspond to FEL wavelengths down to 4.2 nm. THz sources and an optical laser are provided for pump-probe experiments. In addition, with the second FEL beamline, FLASH 2, the facility offers the possibility to apply or test different seeding schemes, i.e. HGHG, EEHG and HHG [1, 2]. Recently, increasingly more often user experiments demand for short FEL pulse lengths down to few 10 fs duration, which is achieved by decreasing the bunch charge well below 100 pC. Thus, the charge operation regime of FLASH now expands from a few 10 pC up to 3 nC.

ELBE at the Helmholtz-Zentrum Dresden-Rossendorf is a superconducting electron accelerator with a quasi-continuous wave (quasi-CW) mode of operation achieving beam energies up to 40 MeV. Bunches with up to 1 nC, after the next upgrade, and durations down to 200 fs are accelerated and transported to different beamlines, where they are used for various purposes, e.g. FEL pump-probe experiments, THz generation or for experiments with Thomson back-scattering, with positron or neutron radiation [3, 4].

At both facilities, all of the diverse applications rely on stable beam conditions, which concerns electron bunch parameters such as charge, energy, compression and arrival time.

Arrival time drift and jitter are imprinted onto the electron bunch from instabilities in the electron source and from RF field fluctuations in the accelerating modules.

Besides delivering information to experiments, bunch arrival time monitors (BAMs) with femtosecond resolution also offer the possibility of feedback systems to actively stabilise the arrival time at different locations of the facility.

At FLASH e.g., such a beam-based feedback system has been implemented and has already proven a jitter reduction within the MHz repetion rate bunch train to below 20 fs (RMS) at a moderate bunch charge of 200 pC [5].

Bunch Arrival Time Monitor

At both facilities, the same basic layout of the arrival time monitor is implemented. Making direct use of timing-stabilised laser pulses, which are provided by an optical synchronisation system [6], the BAM measures the electron bunch timing with an electro-optical detection scheme by means of integrated-optics devices.

For this, a broadband RF pickup delivers a transient beam-induced voltage signal, which is transported through phase-stable cables to the electro-optical modulator (EOM). In this Mach-Zehnder type EOM the voltage magnitude is translated into an amplitude modulation of the laser pulses, depending on the relative timing between optical and electrical signal. The optical, amplitude modulated signal then is detected and processed in high-speed, FPGA-based electronics. The arrival time is derived from an according time calibration showing a sensitivity of the monitor in the range of a few 10 fs per percent of amplitude modulation, which offers the possibility of sub-10 fs resolution [7].

In order to extent this high resolution operation of the BAMs also to low bunch charges, a broadband, cone-shaped pickup has recently been developed in coorperation with the Technical University of Darmstadt [8]. The RF feedthrough part has been produced by Orient Microwave and the mechanical vacuum parts were designed and built by DESY.

At FLASH and at ELBE, these new pickups with a cut-off frequency above 40 GHz have been installed lately.

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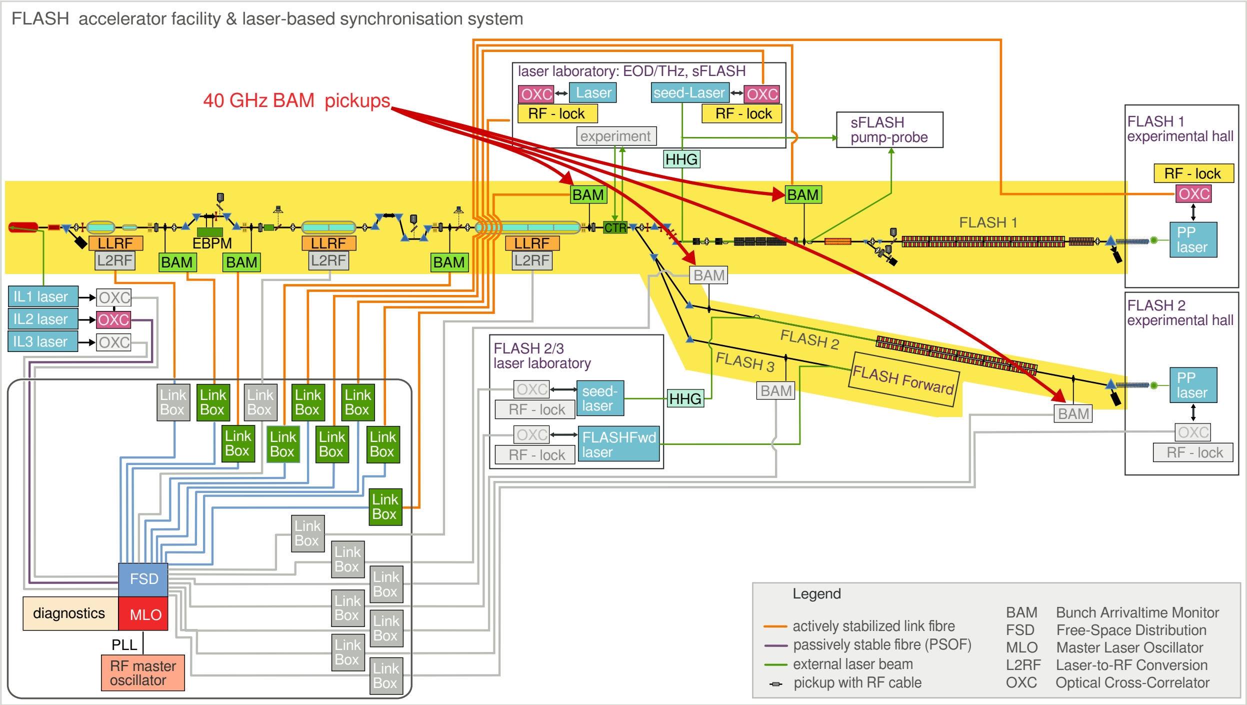

Figure 1: Infrastructure of the laser-based synchronisation system at FLASH. From 9 installed fibre-links, 7 are in permanent operation from which 4 connect to BAMs. The positions of the new, 40 GHz BAM pickups are pointed out. For the presented measurements, the BAM directly behind the last acceleration module has been used.

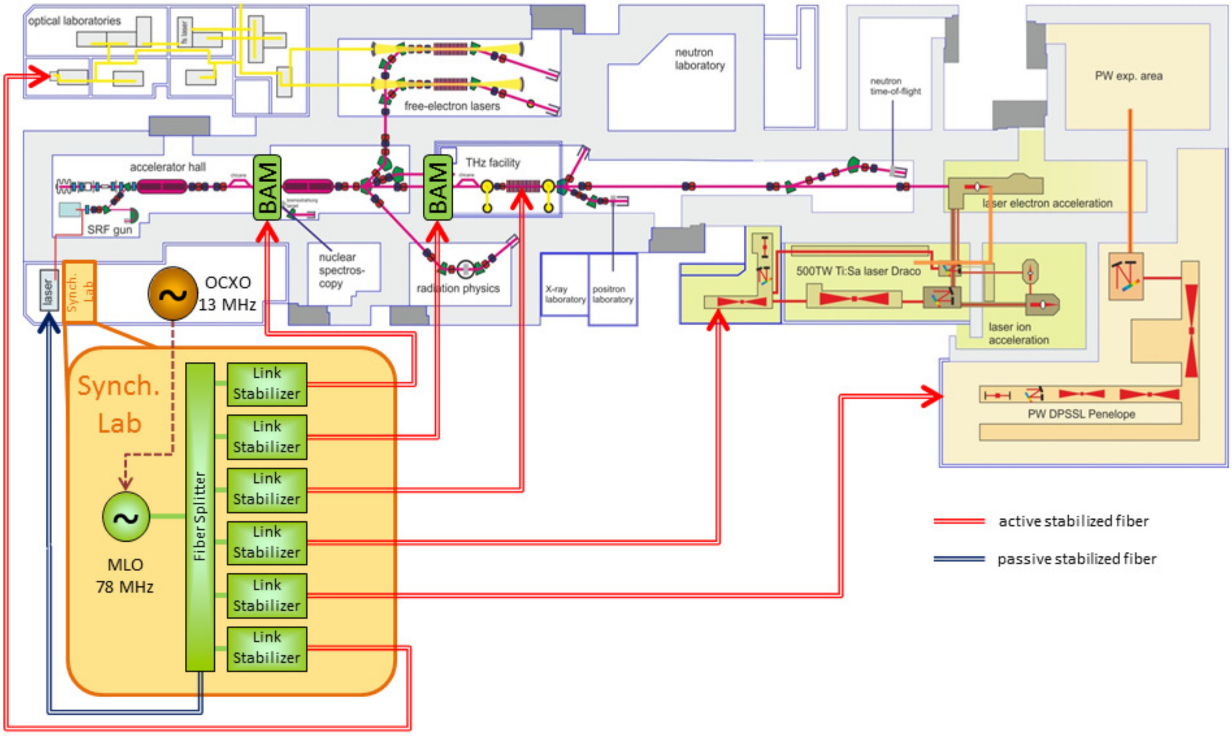

Figure 2: Infrastructure of the laser-based synchronisation system at ELBE. In total, 6 length-stabilised fibre-links will be installed (4 commissioned yet), from which 2 connect to BAMs, both being equipped with the 40 GHz pickups. One BAM is located downstream of the first bunch compressor, directly in front the second accelerating module, and the other is located between the CTR station and the THz undulator.

In this paper, we present first results from an extensive performance evaluation at both facilities. Two different approaches have been chosen, on the one hand a direct sampling of the RF signal with broadband oscilloscopes and on the other hand signal scanning by use of the electro-optical BAM setup.

BAMs at FLASH

At FLASH, the laser-based synchronisation system with individually length-stabilised fibre links has been in permanent operation since 2008 and, currently, serves 10 end stations [9]. From the 7 BAMs at FLASH, 4 locations are already equipped with the new high-bandwidth pickups (Fig. 1), each with a set of 4 pickups arranged symmetrically around the beampipe, aligned to in the horizontal and vertical plane. The pickup evaluation presented here, was performed at the BAM location directly behind the last accelerating module.

BAMs at ELBE

At ELBE, a pulsed optical sychronisation system has been implemented in 2012 in cooperation with DESY, and is now being extended to six remote stations [10,11]. Figure 2 gives an overview of the synchronisation system infrastructure, pointing out the locations of the BAMs, which are connected via individual, length-stabilised fibre-links. One BAM is located behind the bunch compressor, directly in front of second accelerating module, the other is installed between the CTR station and the THz undulator.

The arrival time information will be used to enable a feedback on phase and amplitude values in the low-level RF control to continuously minimise deviations in the accelerating RF fields benefitting from the quasi-CW operation mode.

MEASUREMENTS AT FLASH

The RF pickup signals were connected through short (2 m) phase-stable RF cables (Phasemaster 160, Teledyne-Storm Microwave) to a Tektronix DSA8300 sampling oscilloscope with a 80E10 electrical sampling module, using an attenuation of 30 dB for an over-voltage protection. In addition, the device was covered with lead to be protected from radiation.

In this setup, we simultaneously measured the voltage signals from a single pickup on channel 2 and a combined singal from two opposing pickups in the horizontal orientation on channel 1. The signal from the remaining single pickup (vertical, top) has been low-pass filtered to trigger the oscilloscope, compare Figure 3.

For a thorough performance evaluation, extensive scans of electron bunch parameter have been performed, including various bunch compression settings, charge sweeps from 20 pC up to 250 pC and beam orbit scans.

As can be seen from Figure 4, the amplitude (corrected for the level of attenuation) shows the expected linear dependence on the total bunch charge, with up to 1 V peak at 25 pC. This includes losses through 2 m of high quality RF cable and connector losses.

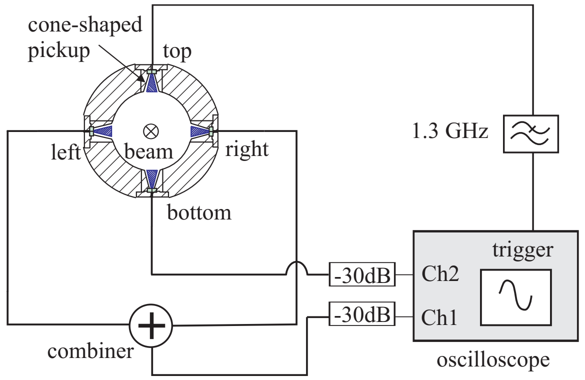

Figure 3: Measurement setup at FLASH with a sampling oscilloscope.

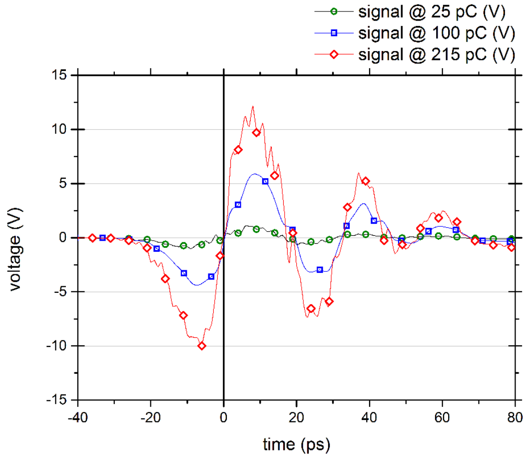

Figure 4: Voltage signals from the single pickup measured at 3 different bunch charges.

Simulations during the pickup design process indicated a linear scaling of voltage amplitude with bunch charge, while a peak voltage of 1 V has been expected for a charge of 20 pC [8], and has now been measured to 1.1 V at 25 pC.

The plots in Figures 5 and 6 reveal the orbit dependency of the linear signal slope (around the zero-crossing between the first two peaks), recorded at a fixed bunch charge of 150 pC.

In Fig. 5, the signal from the single pickup (lower vertical position) reflects the expected behaviour of a linear response to beam orbit changes in the vertical plane: with decreasing distance between bunch and pickup, the magnitude of the induced signal increases, thus the slope increases as well.

In Fig 5, a remaining orbit dependency of about 20 % in total can be seen. However, the slope values from the other measurement channel, clearly displays the benefit of a signal combination in terms of a reduced sensitivity to orbit changes.

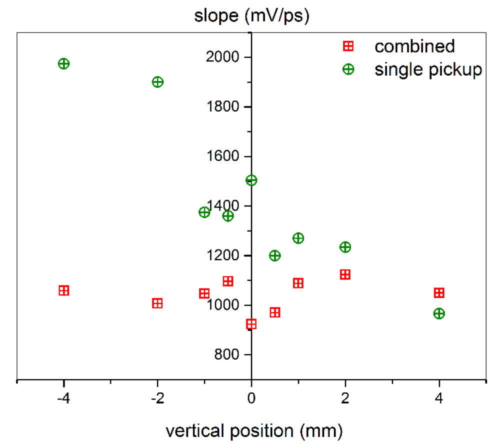

Figure 5: Variation of signal slopes under vertical beam orbit scans, at a bunch charge of 150 pC.

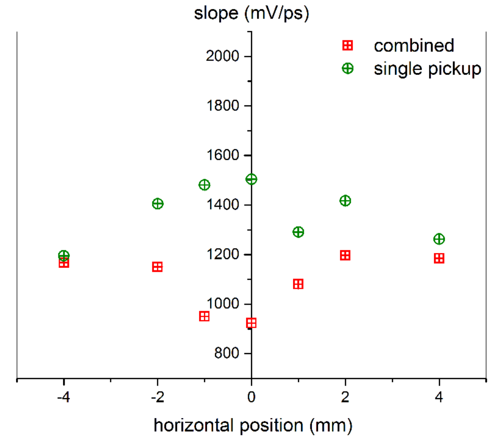

Figure 6: Variation of signal slope under horizontal beam orbit scans, at a bunch charge of 150 pC

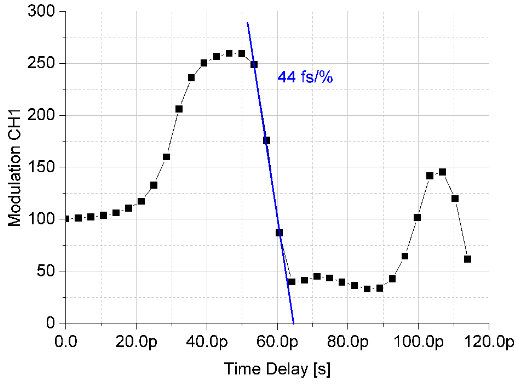

Figure 7: Calibration curve of the BAM signal at a charge of 50 pC. The time calibration of 44 fs/% yields the opportunity to achieve the targeted sub-10 fs resolution in the low charge regime down to 20 pC.

Any remaining orbit dependency can be removed from the arrival time data by using feedback from beam position monitors, ideally mounted in direct vicinity of the BAM pickup. This has been shown for the lower bandwidth BAMs in [12].

Due to this, at FLASH and also at the European XFEL, it is foreseen to install high-resolution bunch position monitors directly behind the BAM pickup mount. The signals will be transmitted through low-latency links to the BAM electronics and will be processed online in the FPGA-based board firmware.

MEASUREMENTS AT ELBE

At ELBE, the pickup performance has been evaluated in two different ways. The RF signal quality was verified in a similar setup as at FLASH, but a high bandwidth, real time oscilloscope Agilent Infiniium 90000 Q-Series has been used, which provides two 63 GHz channels at a sampling rate of 160 GS/s. With bunch charge sweeps between 5 pC and 95 pC the behaviour of amplitude and slope has been examined to prove the exptected linearity.

The voltage slope at 20 pC bunch charge was measured with 380 mV/ps and thus complies with the results at FLASH and with simulations.

The data presented here, has been recorded with the BAM setup, which makes use of a 35 GHz semiconductor-based EOM (U2T, MZMO 2130). The combined signal from opposing RF pickups is transmitted through SiO_2 cables (Anritsu, with 35 GHz bandwidth), and fed into the modulation input of the EOM, including an RF limiter (Agilent N9355F) protecting the EOM against high peak voltages.

Using an optical delay line, the laser pulse timing has been scanned relative to the electron bunch timing, to obtain the transmission curve through the EOM depending on the input RF modulation voltage. Figure 7 shows the percentage amplitude modulation of the laser signal. The time calibration, thus sensitivity of the BAM, is given by the inverse linear slope around the operation point around 100 %, and was calculated to 44 fs/%.

This curve reveals the potential to achieve femtosecond-precise arrival time measurements also at lower bunch charges. With high quality electronics, which offer an amplitude detection with a noise level below 0.1 %, this BAM yields an achievable detection resolution of below 5 fs at a bunch charge of 50 pC.

CONCLUSION

Presented in this paper, as well as in former published studies, it has been shown that for achieving femtosecond-precise electron bunch arrival time measurements using the described monitor, several conditions must be met:

- a broad-band pickup with a voltage slope higher than 350 mV/ps for the envisioned lowest bunch charge regime,

- low-loss, high bandwidth RF transmission line with components which meet the bandwidth of the pickups
- a suitable, broad-band EOM with an E/O bandwidth similar to the RF components, and low V_π for a modulation depth close to 100 % over the full region of the linear voltage slope
- a high-precision, low-noise laser amplitude detection in analogue and digital electronics.

With the sensitivity of the BAM setup in the range of few 10 fs/%, we are convinced to reach the envisioned sub-10 fs resolution in the bunch charge regime of below 50 pC. With the optimised RF part of the BAM, the measurement accuracy itself is now predominantly limited by the overall amplitude noise in the system.

A more thorough evaluation of the obtained data from the extensive studies is in preparation, underlining the very good agreement with signal simulations, and showing that the design values of the cone-shaped, broadband RF pickup design are met.

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REFERENCES

[1] B. Faatz, N. Baboi, V. Ayvazyan, et. al., “FLASH II: a Seeded Future at FLASH”, IPAC’10, Kyoto, Japan, 2010, TUPE005 (2010), `http://www.JACoW.org`

[2] J. Bödewadt, C. Lechner, “Results and Perspectives on the FEL Seeding Acitvities at FLASH", FEL2013, New York, NY, USA, 2013 WEPSO02 (2013) `http://www.JACoW.org`

[3] J. Teichert, A. Arnold, H. Büttig, et al., Nuclear Instruments and Methods in Physics A 743(2014), 114-120

[4] M. Gensch, B. Green, S. Kovalev, et al.,”THz Facility at ELBE: A Versatile Test Facility for Electron Bunch Diagnostics on Quasi-CW Electron Beams“ IPAC’14, Dresden, Germany, TUZA02 (2014) `http://www.JACoW.org`

[5] Ch. Schmidt, M.K. Bock, S. Pfeiffer, et al.,“Feedback Strategies for Bunch Arrival Time Stabilizationat FLASH Towards 10 fs” FEL’11, Shanghai, China THPA26 (2011), `http://www.JACoW.org`

[6] F. Löhl, V. Arsov, M. Felber, et al., Physical Review Letters 104, 144801 (2010)

[7] M.K. Bock, M. Bousonville, M. Felber, et al., “Benchmarking the Performance of the Present Bunch Arrival Time Monitors at FLASH”, DIPAC’11, Hamburg, Germany TUPD28 (2011) `http://www.JACoW.org`

[8] A. Angelovski, A. Kuhl, M. Hansli, et al., Physical Review Letters Special Topics – Accelerators and Beams 15, 112803 (2012)

[9] S. Schulz, M. Bousonville, M.K. Czwalinna, et al.,“Past, Present and Future Aspects of Laser-Based Synchronization at FLASH”, IBIC’13, Oxford, UK, 2013, WEPC32 (2013) `http://www.JACoW.org`

[10] M. Kuntzsch, A. Buechner, M. Gensch, et al.,“Status of the Femtosecond Synchronization System at ELBE” BIW’12, Newport News, VA USA, MOBP03 (2013) `http://www.JACoW.org`

[11] M. Kuntzsch, S. Findeisen, M. Gensch, et al.,“Electron Bunch Diagnostic at the Upgraded ELBE Accelerator: Status and Challenges” IBIC’13, Oxford, UK, MOBL3 (2013) `http://www.JACoW.org`

[12] M.K. Bock, “Measuring the Electron Bunch Timing with Femtosecond Resolution at FLASH”, DESY-THESIS-2013-008 (2013) `http://www-library.desy.de/`

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