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HIGH-PERFORMANCE BUNCH ARRIVAL TIME MONITORS WITH fs PRECISION AT DESY

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Abstract

Pump-probe experiments at Free-Electron Laser facilities depend heavily on the relative timing precision of the pump and the probe, which determines the resolution of the observed ultrafast phenomena. The DESY's Bunch Arrival Time Monitors (BAM) are state-of-the-art sensors based on an electro-optical detection principle, that delivers information on the bunch timing with unprecedented femtosecond-level precision. Timing synchronization at machine level is achieved through a complex system of arrival time sensors, stabilized optical distribution, and feedback controls. Major advances in the performance, construction, and operation of the BAMs are discussed in detail. Integration of the sensor into the synchronization system, and important global optimization and interplay are mentioned as well. These improvements enabled a synchronization of the electron beam with a world-leading precision of less than 3 fs at European XFEL.

BAM SYSTEM OVERVIEW

The BAMs are electro-optical sensors that measure arrival time of electron bunches relative to a timing signal [1]. The Coulomb field of an electron beam is sensed by two or four 40 GHz pick-ups, combined to produce a single voltage signal. A laser based synchronization system [2] delivers precise laser pulses over stabilized, polarity-maintaining links. A lithium niobate Mach-Zehnder amplitude modulator front-end, located as close to the beam line as possible, receives the RF voltage signal and modulates the amplitude of the passing laser pulses with it [3]. The amplitude-modulated laser pulses are transferred to the back-end via fiber optics and read out with dedicated back-end MicroTCA electronics. The front-end (Fig. 1) is enclosed in a custom-built box (Fig. 2) that provides power, monitoring, biasing voltage, and a temperature-controlled environment for a compartment in which the modulator with an optical laser chain is located. The back-end electronics processes the digital signal and provides the result over an optical link to a low-level RF station upstream.

ACHIEVING OPERATION STABILITY

The BAM system underwent a significant improvement in operability and stability. Previously, an expert would spend ≈ 20 minutes after each system reset, and up to an hour after HW interaction, setting up a station, yielding partially non-reproducible configurations. Machine setup changes that produced offsets in arrival time had to be adjusted manually

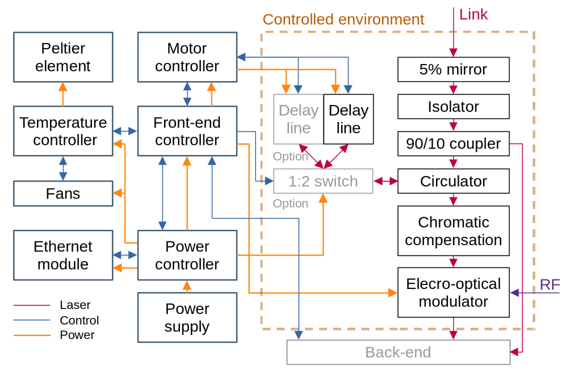

Figure 1: The block diagram shows the main building blocks of the BAM front-end electronics.

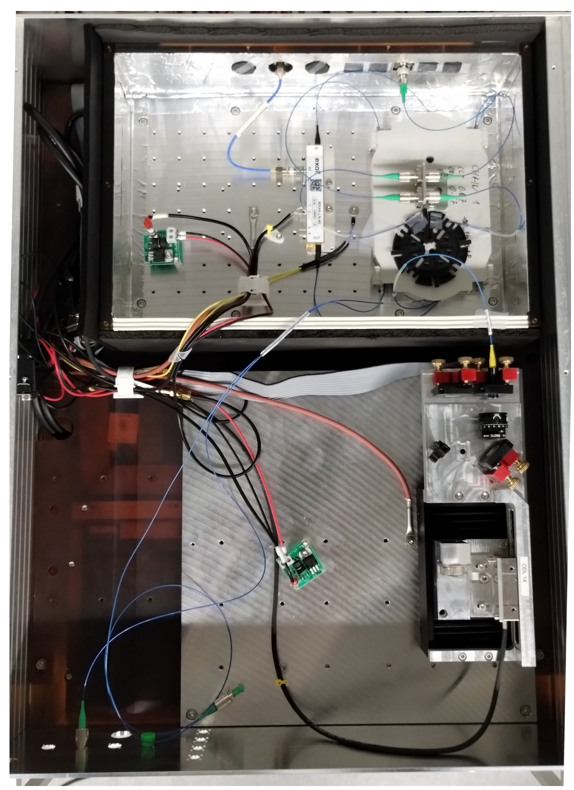

Figure 2: Photo of the top level of the BAM front-end electronics. The controlled environment compartment is located at the top, and houses the optical chain, with an optical delay line being placed outside of it in this version (right bottom). Humidity and temperature sensors are seen as well.

by an expert. A periodic adjustment of system drifts during longer-term operation was required to prevent drifting away from the configured operation point or degradation of res-

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olution. Currently, the system calibration provides reliably reproducible results and is fully automated, which allows an ordinary accelerator operator to prepare the whole system, of 10 or 7 stations at EuXFEL or FLASH respectively, for operation with a single control element click within minutes. Stability is unlimited as long as the machine parameters do not change abruptly or significantly. In practice, recalibration is carried out after each machine setup or after an issue occurred.

System Engineering

The first step in achieving operational stability was to analyze the entire system, from hardware to the high-level control system, in order to identify and correct all possible issues that prevent stable operation. Indeed, power supply short circuits and incorrect I/O voltage levels were identified in the electronics, degrading its performance. Uncontrolled clock phases produced by an on-board PLL were causing non-reproducibility of the electronics configuration and a slipping of the trigger signal. The firmware was overhauled to improve the precision of the mathematics computation, to provide a stable timing closure, and the number of clock domain crossings was reduced to a well-defined minimum. The firmware was re-based on the standard DESY FPGA firmware framework FWK [4]. Pattern encoders and decoders were built into the firmware on multiple levels to allow a deterministic offline check of the functionality of the electronics. Devices with, for example, damaged FMC connectors that produced errors in pattern tests, were replaced. System complexity was decreased while conserving functionality. Motor controls operating at the back-end on a dedicated card were integrated onto the existing front-end controller, removing the necessity of long cabling and eliminating one type of electronics card from the system. Reception of the machine timing was moved from software to firmware, increasing reliability. The control server was ported to a new software framework ChimeraTK [5], and its architecture was adapted to closely match the needs of the hardware and firmware. Operation habits and goals were discussed with the machine operators; the control system server and its user interface were adapted to suit them as well.

Automation

All calibration routines that were processed manually by an expert are now automated. This includes finding several clock phases, identifying ADC sampling phase, amplifier gain, locating the modulator working point (Fig. 3), calibrating time, finding laser overlap with short and long optical delay lines, and locating the bunch trigger. The firmware was adapted to allow for the automation. Calibration algorithms that scan and identify working points were developed in Python and tested extensively under operational conditions. Once matured, the algorithms were ported into the standard DOOCS control server. Feedback loops were established for sources of drift in the system (e.g. EOM biasing or dynamic range optimization).

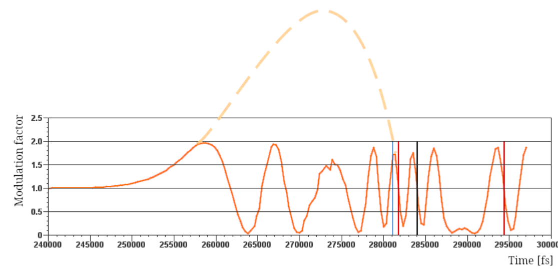

Figure 3: Voltage signal generated by a bunch, as a function of time. The voltage signal (dashed) rises and falls. Its amplitude is larger than V_π of the EOM, thus several over-rotations are observed as the laser signal (orange) is modulated. An automation algorithm uses a probabilistic approach to identify possible working points (signal crossing unity, marked with vertical lines), from the most probable (light red) to the least probable (black). The previous working point is also shown (blue). The performance has proven itself reliable under various beam conditions.

PERFORMANCE IMPROVEMENT

The resolution of the BAM depends on internal and external conditions. Bunch charge and length influence the modulation RF amplitude and bandwidth (steepness). Laser amplitude and phase noise contribute significantly. Internal sources of noise are front-end and back-end electronics noise, injection losses, laser amplification, polarization degradation, and pulse elongation. Keeping the external parameters constant, improved performance results from electronics and laser chain optimization or improved EOM sensitivity.

Optimization

Focusing on the primary mission and removing auxiliary functionality has already resulted in substantial performance improvement. The two-channel system with 40 GHz and 20 GHz parallel EOMs was simplified to a single 40 GHz channel. The removal of several monitoring and unused laser splits decreased injection losses to the level where the internal laser amplification chain, the source of amplitude noise and pulse elongation, could be removed. Conversion from connectorized optical components to splicing additionally improved the injection loss, polarization maintenance, and decreased susceptibility to dust.

Hardware Upgrades

The incoming optical links are compensated for chromatic dispersion, but the front-end optical chain lies outside of this compensation. Its length was reduced to 4 meters. Such a length translates to approximately 200 fs of laser pulse elongation due to chromatic dispersion, which is significant when sampling a signal in the order of 2 ps. Polarization-maintaining chromatic dispersion compensation was added to the internal front-end chain to compensate. A different model of EOM was selected to improve V_π, bandwidth, and sensitivity to the biasing voltage.

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Performance

The noise level is measured within a band window, in which influence on the feedback loops is expected, and which is accessible with the available data. The ADCs sample at 216.666 MHz and a 1024-sample-wide raw buffer is available; the usually accessible bunch repetition rate is 2.25 MHz with hundreds to thousands of bunches. The latest BAM builds consistently reach noise levels at 1.2 fs both at ≈500 kHz - 108 MHz, and 100 kHz - 1.12 MHz windows, under standard EuXFEL conditions (250 pC). The measurement precision, together with the laser source and fast feedback loop [6], translates into the achievable synchronization level. EuXFEL can reproducibly reach 2.55 fs RMS within several thousands of consecutive macropulses of 10 Hz repetition rate (Fig. 4).

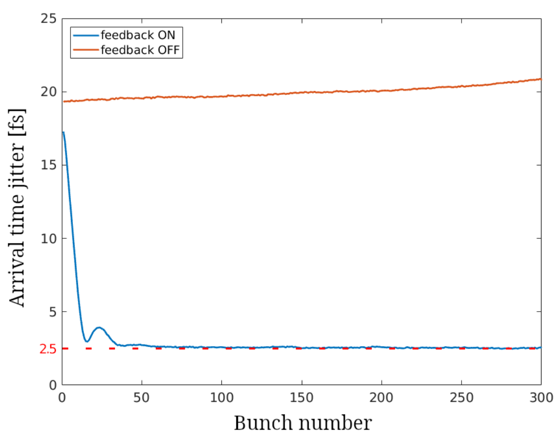

Figure 4: Per-bunch in-loop arrival time jitter with fast feedback disabled and enabled, EuXFEL, 250 nC, 3680 macropulses.

CONCLUSION

As a result of the work presented, DESY operates a reliable, and low-noise bunch arrival time measurement devices that deliver data for fast and slow machine stabilization, and open the possibility to conduct more precise time critical measurements. The BAM resolution approaches 1 fs level at 250 pC, the reproducible accelerator synchronization reaches 2.55 fs. System engineering with emphasis on the primary mission, design optimization, careful integration, automation, hardware upgrades, and controlled working practices led to achieving the goal. The design is not DESY-specific and can, and is, being adapted by other institutes.

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