THE EUROPEAN XFEL BEAM POSITION MONITOR SYSTEM

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Abstract

The European XFEL is an X-ray free electron laser user facility that is currently being built in Hamburg by an international consortium. The BPM system of the XFEL is developed by a collaboration of PSI, DESY, and CEA/Saclay/Irfu. Cavity BPMs will be used in all parts of the E-XFEL where highest resolution and lowest drift is required, e.g. in the undulators and some locations in the beam transfer lines. In the cryostats of the superconducting 17.5GeV main linac, 2/3rds of the BPMs will be buttons, while 1/3rd will be re-entrant cavities that promise higher resolution than buttons. The transfer lines will also be equipped with cost-efficient button BPMs. The BPM electronics is based on a modular system concept, with a common FPGA-based digital back-end design for all BPMs and pickup-specific analog RF front-ends. This paper introduces the design concepts and reports on the project status and measurement results of BPM pickup and electronics prototypes.

INTRODUCTION

The European XFEL (E-XFEL) [1] has a superconducting 17.5GeV main linac that will provide trains of up to 2700 bunches, with 0.1-1nC bunch charge, 600µs train length, ≥222ns bunch spacing, and 10Hz train repetition rate. A kicker/septum scheme can distribute fractions of the bunch train to two main SASE undulator lines followed by "secondary undulators" for spontaneous or FEL radiation. The E-XFEL will provide SASE radiation down to 0.1nm wavelength and supports arbitrary bunch patterns within a bunch train.

The E-XFEL is presently under construction in Hamburg, with first beam scheduled for 2014.

BPM SYSTEM OVERVIEW

BPM Types and Specifications

Table 1 gives an overview of the BPM types in the E-XFEL. The "standard BPMs" in the superconducting ("cold") main linac and "warm" beam transfer lines use button pickups and should have <50µm single-bunch resolution at ±3mm measurement range. The "precision BPMs" for the undulators and some locations in the beam transfer lines have dual-resonator cavity pickups and should achieve (sub-)micron single-bunch resolution in the undulators at ±0.5mm range. The precision BPMs in the warm beam transfer lines have less stringent resolution requirements than the undulator BPMs, with the exception of the four sub-micron BPMs with dedicated electronics (not discussed in this paper) for the transverse Intra-Bunchtrain Feedback (IBFB) [2]. Measurement ranges larger than the values in Table 1 will also be supported, but at reduced resolution.

Table 1: Quantities and Types of E-XFEL BPMs

BPM Type	#	Inner Beam Pipe Diameter	Single Bunch Resolution@ 0.1-1nC	Range For Max. Resolut.
"Cold" Standard BPM (Button, Re-Entrant Cavity)	101	78mm	50µm	±3mm
"Warm" Standard BPM (Button)	228	40.5mm	50µm	±3mm
Precision BPM (Cavity)	117	10mm	1µm	±0.5mm
Precision BPM (Cavity)	12	40.5mm	10µm	±1mm

The long-term (weekly) position drift should be smaller than the nominal resolution. The short-term (hourly) drift should be ~5-10 times better as required by beam-based magnet and trajectory alignment where the average position over the bunch train (that should be ~5-10 times better than the single-bunch resolution) will be used.

Modular BPM Electronics Concept

The E-XFEL BPM electronics will consist of RF front-end (RFFE) modules that are specific for the BPM type, and a generic FPGA carrier board ("GPAC" = Generic PSI ADC Carrier). The GPAC provides a generic interface to control, timing and machine interlock system. It carries two ADC mezzanine modules to digitize and process the RFFE output signals.

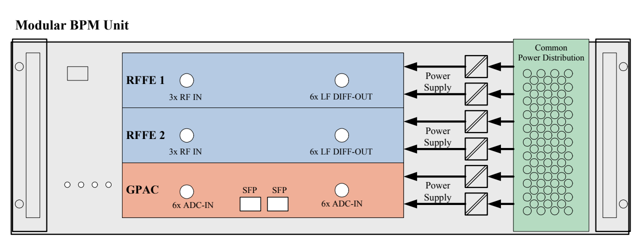

Figure 1: Modular BPM electronics unit (simplified), with 2-4 pickups-specific RF front-ends, and a generic FPGA-based digital back-end with 2 ADC mezzanines.

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RFFEs and GPAC are plugged into a common housing (MBU = Modular BPM Unit) that contains e.g. power supplies, fans, and a rear IO module with digital and multi-gigabit fiber optic IOs. Each MBU contains one GPAC with two ADC mezzanines, and either two cavity RFFEs, two re-entrant RFFEs, four button RFFEs, or a mix of these RFFE types.

Collaboration Partners

The BPM pickups are developed by DESY (buttons, cavities) and CEA (re-entrant cavities). The modular BPM electronics, firmware and software for all BPMs is developed by PSI, with the exception of the "cold" re-entrant cavities in the superconducting linac where the RFFE is provided by CEA/Saclay/Irfu.

CAVITY BPMS

Pickups

The "precision" BPMs of the E-XFEL will have cavity pickups [3] that are based on an SCSS design [4]. Each pickup has a "dipole" resonator that provides a signal proportional to the product of beam position and charge, and a "reference" resonator to measure and normalize out the beam charge. Mode-selective couplers in the dipole resonator suppress modes that might degrade the resolution.

Two pickup versions have been designed and fabricated: One with 10mm inner beam pipe diameter for the undulators and one with 40.5mm diameter for the warm beamlines. Choosing the same frequency of 3.3GHz for both resonators of both pickups allows to use the same electronics for both pickup types and reduces frequency-dependent temperature drift effects in the RFFE. The low-Q pickup is optimized for "mass production", without need for mechanical tuners.

In order to perform tests of BPM pickups and electronics, a BPM pickup test section with one 40.5mm and three 10mm cavities and a 2D mover system has recently been installed at FLASH. A similar test section will shortly be installed at the SwissFEL test injector at PSI, in addition to a single 10mm cavity pickup prototype that was already installed in the SLS linac in 2009.

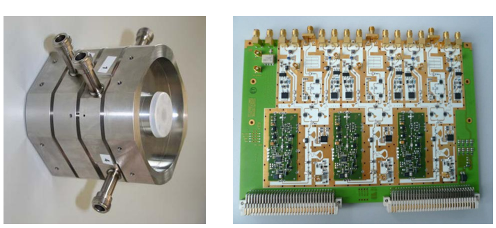

Figure 2: 3.3GHz E-XFEL undulator cavity pickup (left) and RF front-end electronics (right) prototypes.

Electronics

The right hand side of Fig. 2 shows the first 3.3GHz cavity BPM RFFE prototype designed by PSI. It performs IQ demodulation of the bandpass-filtered 3.3GHz cavity signals to baseband, using individual, digitally tuneable PLLs for the reference and the two dipole resonator signals. The present prototype has one input gain range for 0.1-0.3nC and one for 0.3-1nC bunch charge. The RFFE also generates the clock signal for the ADC mezzanines on the GPAC.

The left hand side of Fig. 3 shows the 6-channel 16-bit 160MSPS ADC mezzanine module designed by PSI that is used to digitize the differential IQ output signal pulses of the RFFE. The ADC clock and PLLs are locked to the machine RF, with programmable frequency and phase.

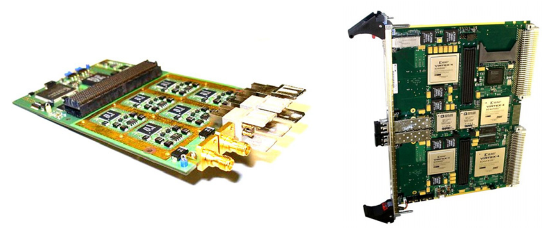

Figure 3: Cavity BPM ADC mezzanine module (left) and IBFB FPGA mezzanine carrier prototype (right).

The right hand side shows the predecessor of the GPAC, the "PDC" board that was designed by PSI as prototype ADC/DAC mezzanine carrier board for the E-XFEL IBFB. GPAC and PDC have compatible mezzanine connectors, thus allowing tests of mezzanines and FPGA firmware on the PDC while the GPAC was still under development. While the PDC was intended for low-volume high-performance feedback applications, the cost-optimized GPAC targets high-volume applications like BPMs. Two Virtex-5 FXT FPGAs ("BPM FPGAs", one per mezzanine) on the GPAC have direct LVDS connections to six 16-bit ADCs (for cavity and re-entrant BPMs) or eight 12-bit ADCs (for button BPMs) per mezzanine. These FPGAs contain BPM-specific firmware/software. A third Virtex-5 FXT FPGA ("System FPGA") contains generic firmware/software, e.g. the control system interface and a Linux server for remote maintenance.

For the E-XFEL, two multi-gigabit SFP transceivers on the GPAC front panel will serve as control system and maintenance interfaces (e.g. via 1000Base-X Ethernet or customized protocols). The GPAC backplane connectors are used for power, RFFE control, and access to trigger and interlock IOs on the rear side of the MBU. In addition to this standalone operation mode, the GPAC has optional VME64x (250MByte/s) and VXS (4+4 GByte/s) interfaces, e.g. for BPM electronics tests at the VME-based PSI accelerators. The VXS connector also allows interfacing the GPAC to 8 optional multi-gigabit SFP transceivers on the rear side of the MBU, e.g. for data exchange with beam-based feedbacks. A first prototype of the GPAC is presently being soldered.

Measurement Results

In order to determine the noise of the cavity electronics prototypes, the signals of a 10mm undulator prototype pickup installed in the SLS linac were split to two RFFEs, with one ADC mezzanine and FPGA carrier board per

RFFE. The (uncorrelated) RMS noise of the electronics was estimated by calculating the beam positions for each electronics from the ADC data, taking the difference of the positions (that should ideally be constant and nearly zero), and dividing the RMS variation of this difference by sqrt(2). The resulting single-bunch position resolution is 0.35µm for 300µm beam offset at the higher end of the RFFE gain range (corresponding to 0.9nC/0.3nC at the E-XFEL with/without input attenuator) and 0.75µm for 600µm offset at the lower end (0.1nC/0.3nC). Among other improvements, the next RFFE revision will have a more flexible gain range scheme and a better IF amplifier to improve especially the low-charge noise performance.

BUTTON BPMS

Pickups

About 2/3rds of the "cold" BPMs and most BPMs in the "warm" beam transfer lines will use cost-efficient button pickups. Cold prototype button pickups [5] have been installed and successfully tested at FLASH. An array of 3 warm prototypes has also recently been installed at FLASH and will also be installed a PSI's SwissFEL test injector for electronics noise correlation measurements.

Electronics and Test Results

The button BPM RFFE prototype that is currently being designed uses low-pass filtering, pulse shaping, and peak detection, with four input channels supporting both individual processing of all four pickup signals as well as time-domain signal multiplexing (a.k.a. Neumann principle). The RFFE input lowpass filter is followed by a notch filter at the 1.3GHz main machine RF and a variable gain stage. A balanced peak detector employs a biased microwave diode. An integrated test pulse generator allows in-situ calibration to suppress nonlinearities and drift effects. A variable droop rate of the peak detector allows operating in two modes: a) High droop rate prevents signal pile-up without using active discharging; b) low droop rate allows jitter-insensitive sampling but requires a discharge pulse. For self triggering the BPM during accelerator commissioning, mode a) can be used. For higher performance, mode b) is selected after aligning the discharger pulse timing. First lab tests of a simplified discharger-based circuit have shown a performance close to the requirements.

The digitizer mezzanine board for the button RFFE output signals has eight 12-bit ADCs with differential inputs, each with ~10 effective bits, >1GHz bandwidth, and up to 500 MSPS. A first prototype has been built and successfully tested.

RE-ENTRANT BPMS

Pickup

The re-entrant cavities in the cold main linac have potential for good resolution. So far, a prototype achieved 4µm resolution at ± 12 mm range [6]. The stainless steel parts of the pickup are welded together by an electron beam. Operation close to 4K temperature in the main linac cryostats requires mounting in a clean room. One re-entrant BPM prototype has been mounted in an XFEL prototype cryomodule (see Fig. 4, left side).

Electronics and Test Results

The re-entrant BPM electronics applies single stage down conversion to obtain Δ/Σ. The difference Δ and sum Σ signals are obtained from a hybrid close to the cryomodule that is connected to the RFFE in the MBU. The Δ channel uses in-phase/quadrature-phase (I/Q) demodulation while the Σ signal has a diode detector. The digitizer, digital back-end and MBU for the re-entrant BPMs will be provided by PSI, using the same 16-bit 160MSPS digitizer as the undulator BPMs.

First lab test results of a RFFE PCB board (see Fig. 4, right side) achieved ~0.6µm RMS noise on the X and ~0.91µm on the Y channel. These values might degrade in the real accelerator environment e.g. due to environmental noise. The RFFE is currently being adapted to the new reference frequency of 216MHz.

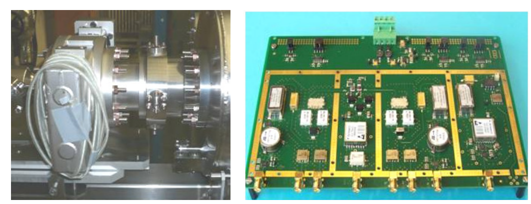

Figure 4: Re-entrant BPM pickup (left) and RFFE board (right)

SUMMARY AND OUTLOOK

The design of the E-XFEL BPM system is well advanced. Prototypes for many subsystems have already been tested in the lab or with single pickups at FLASH or PSI accelerators. Noise correlation tests with arrays of 3-4 pickups at FLASH and PSI are planned in order to investigate the impact e.g. of pickup fabrication or alignment tolerances, mechanical vibrations or environmental noise on the BPM performance.

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