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CURRENT STATUS OF ELETTRA 2.0 eBPM SYSTEM

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Abstract

In the last years, there has been a growing interest in using the pilot-tone technique for long-term stabilization of electron beam position monitors in synchrotrons. At Elettra, after an internal development, the effectiveness of this approach was proven with tests in the laboratory and on the storage ring. The pilot-tone scheme will be adopted for the eBPMs that will equip Elettra 2.0, the low-emittance upgrade of the present machine. In order to support the development, industrialisation and production of the overall system, a partnership with Instrumentation Technologies has been signed. With the extensive experience with the Libera instruments, the company will be engaged in improving the BPM system developed by Elettra and getting it ready for serial production. This paper presents the current status of the BPM system, with an emphasis on the efforts done to improve the key performances of the system and to address its weaknesses (e.g. enhancing single bunch response and low currents sensitivity) within the industrialisation process, with the goal to get to a reliable system, easy to maintain and that meets the multiple project requirements for the new storage ring, the booster, the pre-injector and the transfer lines.

INTRODUCTION

Elettra 2.0 will be the new diffraction limited storage ring that will start serving the users at the end of 2026, replacing the current machine (Elettra). Even if the lattice length will remain more or less the same, the number of beam position monitors (BPMs) will increase to 147 [1]. In order to reduce costs and optimize resources, the same electronics will be used in preinjector, transfer lines, booster and storage ring. Thus, different operation modes are required for a correct behaviour: single pass (first turn) mode, gated mode, close orbit mode.

As a consequence of the excellent results obtained during the development of the overall prototype [2], the machine will be equipped with BPM controlled by electronics based on pilot tone. A modular approach was chosen, with analog front ends detached from the digital part (Figure 1). The front ends will be placed in machine tunnel, powered and controlled via Ethernet links, while the analog-to-digital conversion and processing unit will remain in accelerator service area (radiation safe), with sufficient computing power to manage two BPMs each. The required connections to machine infrastructure will be optical (e.g., 10 Gb Ethernet link for global orbit feedback data) or copper-based (interlock, synchronisation).

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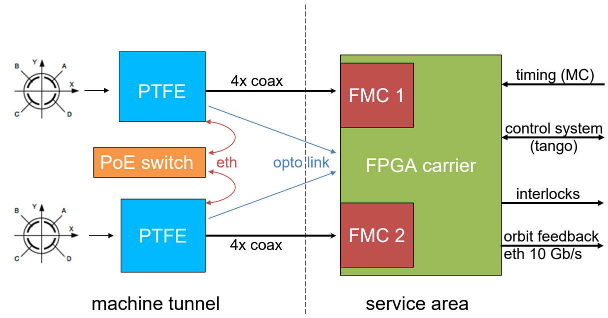

Figure 1: Block diagram of the system.

The process of building such a system for a high number of units (about 200 for the analog front ends, 100 for the digital platform) is not straightforward. Many aspects have to be considered, especially whose related to manufacturing, maintenance and reliability. For this reason, a partnership was signed with Instrumentation Technologies after a tender procedure, in order to industrialize and produce all the components of the system. In this way, Instrumentation Technologies' long-term experience in manufacturing diagnostic tools for particle accelerators will be combined with Elettra's knowledge of the overall aspects of a light source. This collaboration is already making improvements over the original prototype, and these results will be discussed in the following sections.

PILOT TONE FRONT END

The analog front end has been presented already at IBIC 2016 [3]: it consists of an RF analog processing chain with pilot tone injection. Compared to the first working prototype, we have made improvements on various aspects, both in terms of performance improvement and in terms of reliability and the production process.

Radiation Sensor

In order to compensate the overall signal path, the front end has to be installed in the machine tunnel, as near as possible to the pick-ups. This area presents unavoidable and unpredictable ionizing radiations due to multiple sources, that can damage the electronics and cause malfunctions. So, special care must be taken in correct positioning of the electronics, preferring low radiation zones. For this reason, a commercial radiation sensor (Teviso BG51 [4]) has been integrated in the front end (Figure 2). It is capable to detect beta radiation, gamma radiation and X-rays, in a measurement range of dose rate from 0.1 µSv/h to 100 mSv/h. The pulse count rate is about 5 cpm for 1 µSv/h, and the energy response ranges from 50 keV to above 2 MeV. Its output

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is directly connected to the internal microcontroller of the front end, that keeps track of the integrated dose over programmable time windows (last minute, entire life of the device or custom time window).

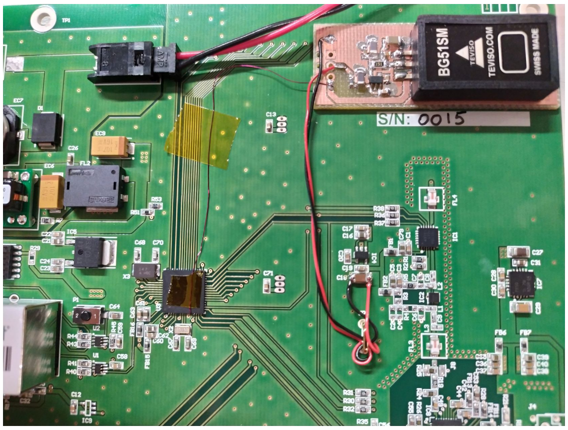

Figure 2: Radiation sensor on front end.

After a test at Elettra Radioprotection laboratory with Cs-137 and Co-60 radioactive sources, that confirmed the performances stated in the datasheet, the front end was installed in the machine, about 1 m below a BPM block. Figure 3 shows the radiations level reported by the sensor during a machine run of about one week, during three different operation modes: machine physics, 2.4 GeV with 150 mA and 2.0 GeV with 310 mA. As expected, the higher the current, the higher the radiation is. However, this addition is not intended to replace a beam loss monitor, but as a useful diagnostic tool to check the device health.

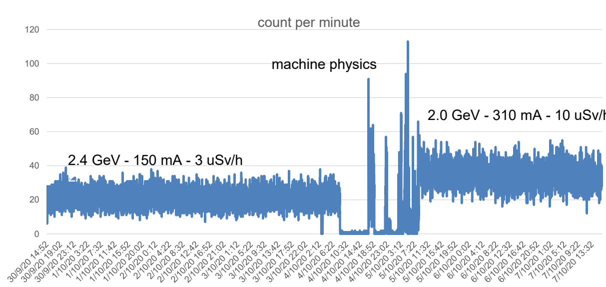

Figure 3: Detected radiation over a one week machine run.

Signal Conditioning Improvements

Glitch Trigger The procedure of changing the gain of the digital attenuators can require a significant amount of time, with a settling time of microseconds. During this time, glitches and spikes can occur on the output (Figure 4). These artefacts will reflect directly on the position calculated by the digital interface. Even if we proved that pilot tone compensation can greatly reduce them, a fiber optic phototransmitter (POF) has been added in order to communicate the gain switching event through a fiber optic link directly to the FPGA. The latter will tag the calculated positions during the switching phase, giving the user the possibility to decide whether to discard them or not.

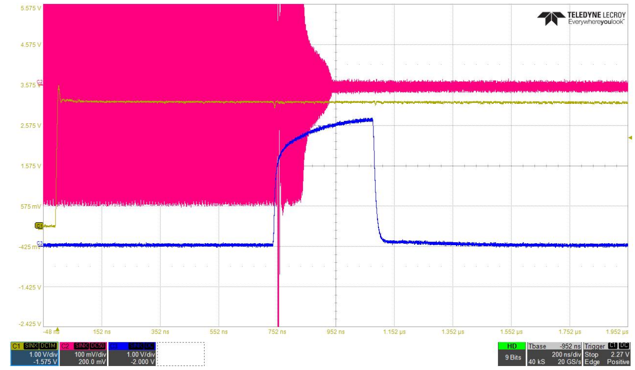

Figure 4: Attenuator spikes. Purple trace: RF signal output, blue trace: glitch trigger to phototransmitter.

Extra Gain Stage The overall gain of the filters, attenuators and amplifiers chain of the prototype front end, can be adjusted between −28 dB and +35 dB at 500 MHz frequency. With low currents (e.g. below 1 mA) and multibunch filling pattern, a resolution of 1 µm was measured. For this reason, we added an extra gain stage of 20 dB: the aim is not only to enhance performances at low currents, but also to ease the future commissioning of Elettra 2.0, where low currents will be injected in the initial stages.

Switchable filters The LC bandpass filter at 500 MHz was chosen for its frequency flatness over its 10 MHz bandwidth. This is essential to guarantee the proper operation of pilot tone compensation. Obviously, a wide bandwidth means a short impulse response over time, which was measured to be about 48 ns (Figure 5).

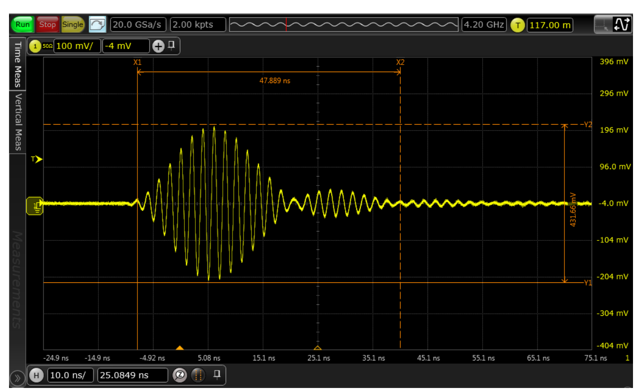

Figure 5: LC filter pulse response.

Considering that during single bunch and first turn operation, sampling the filter's impulse response is an effective way to calculate the position, we decided to extend the performances of the system with the possibility of switching the LC filter with a narrower SAW filter. In this case, with a typical bandwidth of about 1 MHz, the impulse response

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lasts longer (about 200 ns), and more samples can be collected, but losing the capability of the compensation (SAW filters frequency response is not suitable for pilot tone technique). This is a negligible drawback, since broadband noise dominates the improvements given by the compensation.

Industrialisation

The prototype front-end module was tested in machines with RF ranging from 352 MHz to 500 MHz. The module was controlled through the ethernet interface independent from the BPM electronics. The hardware design was then reviewed by the Instrumentation Technologies (I-Tech) company. The company has over 20 years experience in the accelerator field and established supply and production chains. The emphasis was put in the design for manufacturing which is essential for reproducible mass production.

The module's power supply has been changed from standard 12 V to Power-over-Ethernet (PoE) which reduces the number of cables and enables remote power cycle control. The prototype version was not optimized for special fill patterns, such as a "single bunch" fill pattern. The new module contains an additional RF path (selectable) with a SAW filter that stretches the short pulse to a usable filter ringing (200-250 ns) which is sufficient for a reliable position measurement. The original module was built from two PCBs connected over headers, while the new module is built from a single PCB which simplifies the mass production and eliminates failures associated with bad connection (Figure 6). From the installation point of view, the chassis and fittings were adapted to usually limited space in the tunnel and in order to facilitate the access for service. Nevertheless, thanks to MSP430 microcontroller bootloader, it is possible to reprogram its firmware through the Ethernet connection. A simple utility written in C (available through a GUI or CLI for batch updates) takes the binary file of the firmware, puts the microcontroller in bootloader mode and flashes it, checking the correctness of data.

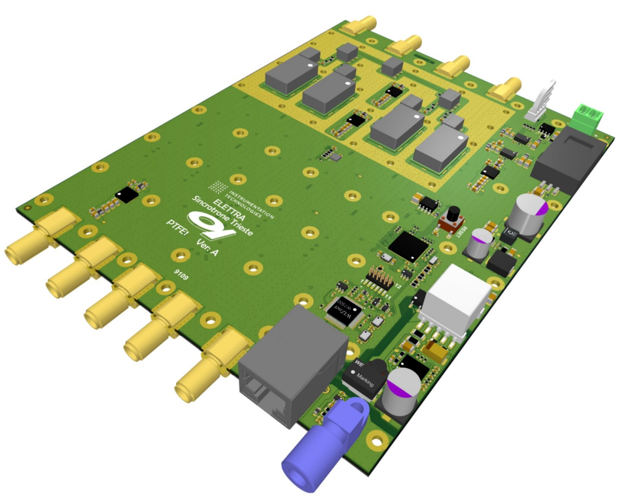

Figure 6: PCB rendering of the industrialized version.

DIGITAL ACQUISITION UNIT

After the first experience with a FPGA-based evaluation board [2], we decide to move on the in-house developed board based on Intel (formerly Altera) Arria 10 GX FPGA already presented [5]. The whole double digital receiver and demodulator, written in Verilog HDL, has been successfully ported on the new platform, adding several features. Now the system is capable to send data over 10-Gb Ethernet, thanks to SFP+ interfaces. This will allow continuous streaming of turn-by-turn data to the global orbit feedback. Also, the possibility to choose the output data rate with a variable filter (from turn-by-turn to 10 kHz) has been added.

However, we decided to go one step further: the final FPGA will be an Intel Arria 10 SX system-on-chip (SoC). The presence of an ARM hard processor assures more flexibility on higher level tasks, like system maintenance, configuration (remote firmware upgrade, diagnostic) and connection to the control system (Tango for Elettra).

Furthermore, the higher pin number of the future FPGA will allow to host two HPC FMC connectors, that means two beam position monitors per digital unit. In this case, a beam angle calculation can be performed between two consecutive BPMs, enabling an efficient beam position interlock to protect the vacuum chamber.

FMC Module

In order to use the new FPGA carrier board, we developed a 4-channel analog-to-digital conversion FMC card (Figure 7), based on Linear Technology LTC2107 ADCs, 16-bit, 210 MS/s. The input stage was carefully designed to handle 500 MHz signals, with a proper input impedance matching and an isolated balun for preventing ground loops. The clock tree relies on a Texas Instruments LMK04828 dual PLL, that generates and distributes to the four converters a clean sampling clock derived from machine revolution clock, with a fixed phase relationship.

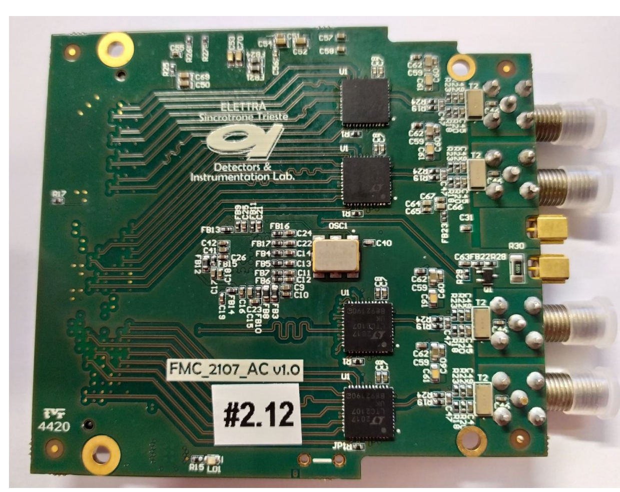

Figure 7: FMC card with 4 ADCs.

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Mechanics

The prototype of the digital acquisition unit was built from multiple boards connected with cables. After I-Tech's hardware review, the design was simplified and made ready for mass production. Due to more active and power-hungry components, the unit requires active cooling, provided by three fans. The cool air enters the chassis on the lower part of the front panel. The fans force the air through the PCBs to the upper part of the chassis. The warm air exits at the upper part of the back panel. The 19" width chassis was designed to allow easy access to the fans on one side and to the PCB on the other side. Such design provides easy and quick service or maintenance (Figure 8).

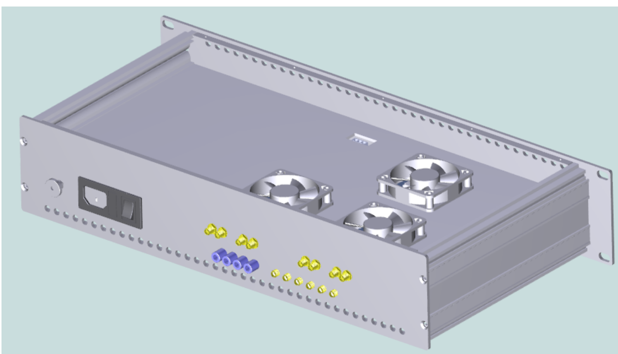

Figure 8: Rendering of digital platform.

CONCLUSION

The BPM system for Elettra 2.0 project was developed and updated over stages. The final prototype design was reviewed and further optimized for mass production. The collaboration between Elettra Sincrotrone Trieste and Instrumentation Technologies started in Spring 2021 with weekly review and development meetings. The meetings boosted the development pace which resulted in quick first articles production with expected deliveries still in year 2021 despite worldwide delay of components delivery. The mass production and final testing of the BPM system for Elettra 2.0 will be done by the Instrumentation Technologies with foreseen deliveries in year 2023.

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