A configurable electronics system for the ESS-Bilbao Beam Position Monitors

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Abstract

A versatile and configurable system has been developed in order to monitorize the beam position and to meet all the requirements of the future ESS-Bilbao Linac. At the same time the design has been conceived to be open and configurable so that it could eventually be used in different kind of accelerators, independently of the charged particle, with minimal change. The design of the Beam Position Monitors (BPMs) system includes a test bench both for button-type pick-ups (PU) and striplines (SL), the electronic units and the control system. The electronic units consist of two main parts. The first part is an Analog Front-End (AFE) unit where the RF signals are filtered, conditioned and converted to base-band. The second part is a Digital Front-End (DFE) unit which is based on an FPGA board where the base-band signals are sampled in order to calculate the beam position, the amplitude and the phase. To manage the system a Multipurpose Controller (MC) developed at ESSB has been used. It includes the FPGA management, the EPICS integration and Archiver Instances. A description of the system and a comparison between the performance of both PU and SL BPM designs measured with this electronics system is fully described and discussed.

Keywords:
Beam Position Monitor
Electronic Units
Control System
Sensitivity
Resolution

1. Introduction

Beam position monitors (BPMs) are the most frequently used non-interceptive diagnostic in particle accelerators, since they provide essential information both for precise monitoring and control of the beamline, and in general for the operation and optimization of the machine.

The term "beam position" refers to the center of gravity within the intensity distributions in the two coordinates transverse to the beamline [1], but also much more information such as tune, chromaticity, current, bunch shape or energy measured via time-of-flight can, in principle, be extracted from beam position measurements. For all these reasons, BPMs and, in particular, the corresponding driving electronics systems, remain a very active field of research in accelerator science and technology.

There are several ways of non-interceptively determining the position of the beam [2]. The most common method is based on capacitive coupling to the electromagnetic fields. To get the position of the beam, the signals from the electrodes of a beam monitor have to be compared. Determining the beam position from the ratio of the induced charges of the opposite electrodes could have different solutions depending on the type of particle accelerator. The various signal processing systems can be grouped into different families according to the employed techniques as can be found for instance in Shafer [2] and Vismara [3]. Key factors in this context are, among others, signal acquisition, normalization, and recombination. Some possible techniques available for the normalization process of the BPM sensor signals are the logarithmic conversion, the amplitude to time and the amplitude to phase normalization. For the signal recombination, individual signal treatment and the $\frac{\Delta}{\Sigma}$ algorithm are common techniques. Finally, the acquisition can be carried out in wide-band, narrow-band and using slow acquisition.

Analog electronics is required to conditioning the signal from the electrodes to the properties of the analog to digital converters (ADCs) and an appropriate trigger must be used for the digitalization. The acquisition system fulfills the requirements needed to supply a full set of data from the BPM to the digital processor. Some implementations of different types of commercial electronics acquisition systems can be found in the literature. In Suwada et al. [4], a data-acquisition system based on VME/OS-9 computers has been developed in order to control 90 stripline BPMs in real time for the KEKB injector linac. All analog signals are connected with monitor stations. In Cohen-Solal [5], the voltage signals coming from four capacitive coupling detectors for the proton IPHI linac were processed by a commercial log-ratio BPM electronics module from Bergoz [6]

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and an acquisition system based on National Instruments PXI. One of the solutions most commonly used for BPMs nowadays is the commercial solution offered by Libera [7], as can be seen for example, in Hartmann et al. [8].

Furthermore, different proprietary solutions have been also implemented. In this context, in Los Alamos National Laboratory, different log-ratio techniques have been developed for BPM systems, similar to the ESS-Bilbao (ESSB) solution. In Wells et al. [9] they developed a log-ratio circuit using a logarithmic response circuit for a pair of microstrip probe sensors to obtain the beam position. In Shurter et al. [10] a different logarithmic amplifier board has also been selected because its dynamic range and bandwidth makes an excellent beam signal detector as compared to other techniques. The signals were digitized by a 14-bit ADC. In the experiment described in Walston et al. [11] they tried to understand the limits of the BPM performance and evaluate their applicability to issues posed by the ILC. An estimation that an RF cavity BPM could provide a position measurement resolution of less than 1 nm was done. The resolution was measured using an in-house analog and digital electronics with fitting and digital down-conversion (DDC) algorithms with nine regression coefficients.

The systems mentioned above are not tailored to ESSB requirements, neither in terms of accuracy or stability specifications, nor in terms of getting an all-in-one serializable solution, ready to be connected to an EPICS control environment. Thus the main motivation of this work has been to develop an integrated solution fulfilling the requirements, being at the same time a versatile, open and configurable deployment, potentially adaptable to other accelerators.

Considering the ubiquitous nature of BPMs in any kind of charged particle accelerators, the aim of this work is to present a new electronics system for the BPMs of ESSB, but conceived to be open and configurable so that it could eventually be used in different kind of accelerators, independently of the charged particle, with minimal change. This work has been developed in collaboration between the ESSB [12] and the Department of Electricity and Electronics of the University of the Basque Country (UPV/EHU) to fulfill the requirements of the ESSB accelerator facilities (see Table 1).

The developed BPM electronics system is composed of the analog front-end electronic boards, the digital processing board and the corresponding control system. Two types of BPM detectors, capacitive buttons pick-ups (PU) and striplines (SL), have been designed and tested to verify the electronics system. The presented BPM system has been tested using an in-house test bench to simulate the beam displacement in typical proton or deuteron beamlines, with working frequencies 352 MHz and 175 MHz respectively, thus checking its versatility. The system works as expected, in a wide variety of situations, for proton or ions frequencies and button-type or stripline electrode configurations.

The contents of this article is divided in different parts. First of all, the ESSB BPM system is described. Next a section explains the electronics units and the control system. Then the calibration and the sensitivity of the proposed BPM system is presented. Finally, a last section explaining the different tests developed to validate the proposed design is also included.

Table 1: Main ESSB and BPM parameters

Parameter	**Value**	**Unit**
Beam Parameters		
Maximum beam energy	60	MeV
Maximum current	75	mA
Maximum pulse length	1.8	ms
Maximum repetition rate	50	Hz
Resolution and precision requirements		
Position resolution	10	μm
Position stability	100	μm
Phase resolution	0.3	°
Phase stability	2	°
Signal levels at the electronics input		
Input power range	50	dB
Maximum input power	-10	dBm
Minimum input power	-60	dBm

2. ESS-Bilbao BPM system

Table 1 summarises the parameters used in the design of the BPM electronics. It describes the main parameters of the beam, the signal levels at the entrance of the BPM electronics and the resolution and stability requirements.

The ESSB requirements for the BPMs are quite stringent for a proton linac, aiming at a position stability below 100 μm, a position resolution below 10 μm, a phase stability below 2° and a phase resolution below 0.3°.

The experimental setup consists of four different parts (Fig. 1) that will be described in the next sections [13]:

- The BPM Test Stand.
- The Analog Front-End (AFE) unit.
- The Digital Front-End (DFE) unit.
- The Control System.

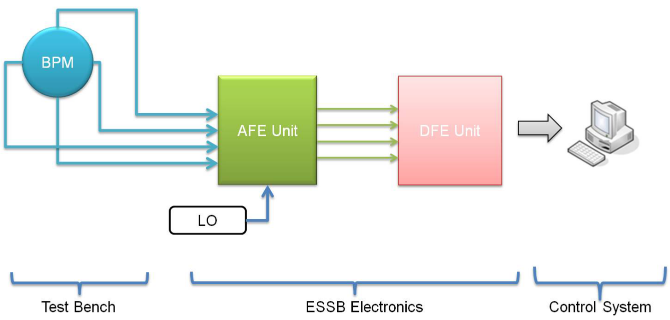

Figure 1: Simplified diagram of the BPM system.

2.1. BPM Test Stand

The test stand for simulating beam conditions was designed and fabricated at ESSB and UPV/EHU. The test bench is connected to the AFE unit as well as to the necessary RF equipment to simulate the beam. This implementation allows to test the developed electronics with the prototype BPM system.

The test bench is basically a transmission line composed of an internal static tube and a second movable outer tube [13]. The relative position of the internal one can be changed to simulate the beam displacement within a range of 20 mm for both axis with a position resolution of less than 10 μm using the corresponding micrometer knobs. A RF generator is connected to the transmission line to simulate the beam. In this study, the main frequencies of interest have been 175 MHz and 352 MHz.

Two types of beam position monitor detectors have been designed and implemented, SL and button-type PU. These detectors are commonly used as the front transducers for beam position monitoring in particle accelerators. They allow to detect the transverse position of the beam in the chamber with a $\frac{\Delta}{\Sigma}$ algorithm [2]. Using the same test bench and test mechanisms, both kind of electrode configurations have been tested. The assembling conditions of both kind of detectors have been kept as similar as possible to make an accurate comparison between them.

2.2. Pick-up configuration

This BPM design is based on four metalized ceramic feedthroughs as button PU welded to the beam pipe. These four ceramic feedthroughs are standard buttons from the industry [14], manufactured using metalized brazed ceramic and modelled for an impedance matching of 50 Ω, avoiding the resonance in the interest frequency range. This is reached varying the diameter and the thickness of the ceramic disc. The diameter of the center conductor is 1 mm, being the button diameter 12.2 mm. The feedthrough assembly angles have been fixed in 0, $\pi/2$, π and $3\pi/2$ configuration, as shown in Fig. 2.

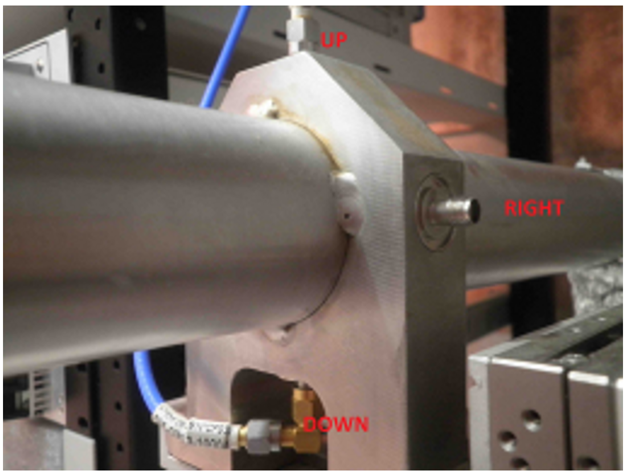

Figure 2: ESSB BPM test bench with PU, showing the position of the detectors.

2.3. Stripline configuration

The design of the SL detectors [15] is based on travelling wave sensors principles. In general, this type of detectors have well defined behaviour even for low beta and low intensity beams, as well as good functionality at low and high frequencies. SUPERFISH (2D) code has been used to simulate the physical properties and dimensions of the feedthrough and transition from strips to the outside N-type connector, as well as to find the optimum physical dimensions of the strips along the tube by analyzing the electromagnetic behaviour of the whole SL set.

The length of sensors is 200 mm and the tube chamber inner diameter of the SL set is 57 mm. The response of all detectors are identical ideally and they are located with a rotation of $\pi/4$ in the transverse plane of the tube (Fig. 3). The assembly angles of the strip sensors are $\pi/4$, $3\pi/4$, $5\pi/4$ and $7\pi/4$. Each electrode has a coverage angle of 0.952 rad. If this area were increased, coupling between adjacent sensors could happen, deterioring the signal integrity.

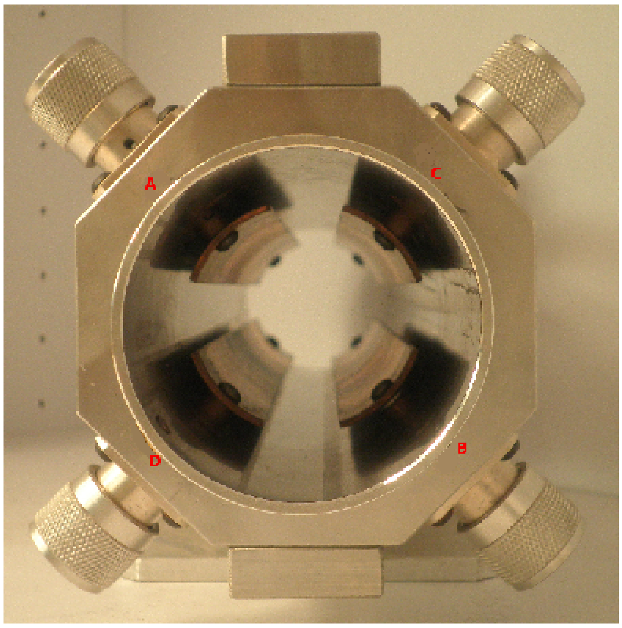

Figure 3: Internal view of the assembled SL in the laboratory, showing the position of the 4 detectors.

2.4. Comparison between both BPM configurations

As was explained above, the assembly of the test-bench is particular for each type of detector. In the PU case, the detectors are located over the X and Y axis, nevertheless, in the SL case, they are rotated at 45° from the axis. Moreover, the PUs are easy to install due to its small size in comparison with the SL.

Analyzing the measurement results, the PU detectors present a smoother power response in a broader frequency band, but their measured signal level is weaker, which can make this solution to be inappropriate for low beam currents and for low frequencies. On the other hand, SL detectors can provide more accurate positioning for low beam currents because they present higher output voltage. Furthermore, they could be used for very low frequencies but the detector size can be a problem for fabrication and installation.

Fig. 4 depicts the measured signal power with both detectors in the test-bench in a frequency range from low-frequency to 1.5 GHz and for an input signal power of 0 dBm. A smoother response of PU detectors can be observed while SL detectors exhibit a typical periodic behavior [2]. It can also noted the higher sensitivity of SL detectors and specially at low frequencies, below 100 MHz, where the signal level of the PU is very small.

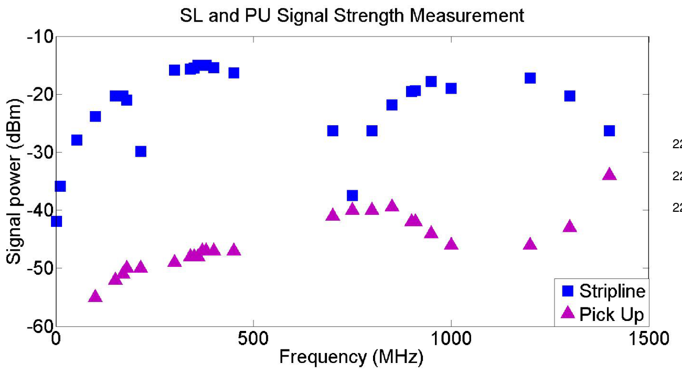

Figure 4: PU and SL power measurements up to 1.5 GHz.

In addition, the signal magnitude measured by the sensors was studied for a simulated beam of 352 MHz, and found to vary linearly with the input signal power in the range from -15 dBm to 20 dBm . In the SL case, the measured signal varies from -30 dBm to 0 dBm, whereas in the PU case, it varies from -60 dBm to -25 dBm. For an input signal of 0 dBm, the SL electrode detected -15 dBm and the PU electrode detected -44 dBm.

Regarding the detected voltage variation to displacement, the fitting equations for calculating the electrode voltage related to the applied displacement for each axis were calculated. PU sensors had more similar slope values than SL for both axis due to their accuracy in the fabrication procedure. Anyway the presented values are smaller because the sensitivity of the PUs is smaller.

The isolation between adjacent detectors was characterized using a vector network analyzer. Results in Fig. 5 show that isolation is much better for PU. It can be observed that, in this case, the coupling between detectors is so low that experimental results are close to the noise floor of the measurement system. Vector network analyzer measurements also confirm that the characteristic impedance of the SL detectors was around 50 Ω, as desired, and PU detectors presents a capacitive behaviour at aroung 352 MHz.

3. Electronic Units and BPM control system

The Electronic Units could be divided in two parts: the AFE and the DFE units.

- An AFE unit where the RF signals of any current sensor will be filtered, conditioned and converted to baseband.

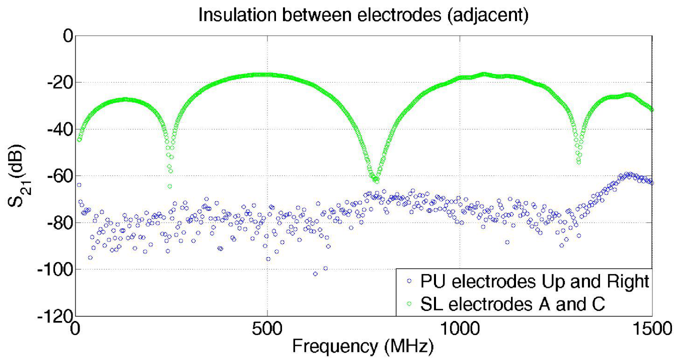

Figure 5: Detectors assembly for PU and SL.

- A DFE unit where the baseband signals are sampled to calculate the beam position, amplitude and phase, using a programmable hardware.

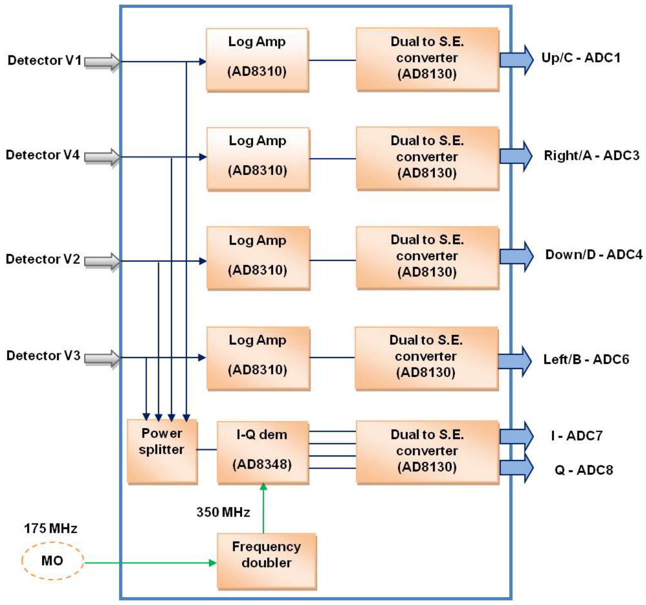

Figure 6: Schematic of the AFE unit of the BPM system.

3.1. Analog Front-End (AFE) unit

The AFE unit (Figs. 6 and 7) is responsible of filtering, conditioning and converting signals to base-band separating the information of the position, the amplitude and the phase of the beam [13], [16]. The AFE needs five input signals to operate correctly. Four are coming from the detectors of the test bench and the fifth one is the reference signal for the local oscillator (necessary for calculating the relative phase and the amplitude).

The method used to convert RF signals into baseband is based on the ESSB *Low Level RF* (LLRF) system [17], due to its easy and versatile implementation. This solution includes two in-house boards, a logarithmic amplifier (log amp) for measuring the position of the beam and an IQ demodulator for measuring the amplitude and the phase. To measure the X and Y beam positions, a 4-channel log amp board has been developed.

Each channel, based on the fast and high dynamic range AD8310 log amp (95 dB), is connected to one of the four BPM sensors. The AD8310 log amp has 50 Ω impedance input. This module has a bandwidth large enough (around 500 MHz) allowing to measure a large variety of particle beams.

Figure 8 shows the characteristics of the logarithmic amplifier board. The upper graphic represents the dynamic range of one log amp channel. The graphic located below depicts the crosstalk measured injecting an input signal in channel one and the corresponding induced level in the different neighbour channels.

The IQ demodulator is fed by the sum of the four BPM electrode signals. Each signal is converted from differential to single-ended using the AD8130 converter and sent to the DFE unit.

3.2. *Digital Front-End (DFE) unit*

The DFE unit consists of an FPGA (a high performance cPCI digital board based on a Xilinx [18] Virtex-4 with an additional 14 bit ADC) connected to the control system. It calculates the beam position, amplitude and phase. This amplitude shows an estimation of the beam current. The programmable hardware based on an FPGA with the ADC boards (VHS-ADC board from Lyrtech company [19]) samples the baseband analog signals, with a high sample frequency of 105 MHz, independently of the accelerated particle and its associated RF frequency.

Inside the FPGA, signals coming from the AFE are filtered to avoid noise and continuous components and the amplitude and phase of the beam are calculated using the CORDIC (COordinate Rotation DIgital Computer) algorithm [20]. As is explained in Section 4, detected signals are corrected to minimize the errors introduced by the AFE unit and the test bench. These will include the offset compensation and gain adjustment. As a result, using these corrected signals, the digital board provides the position, the amplitude and the phase of the beam with a high resolution.

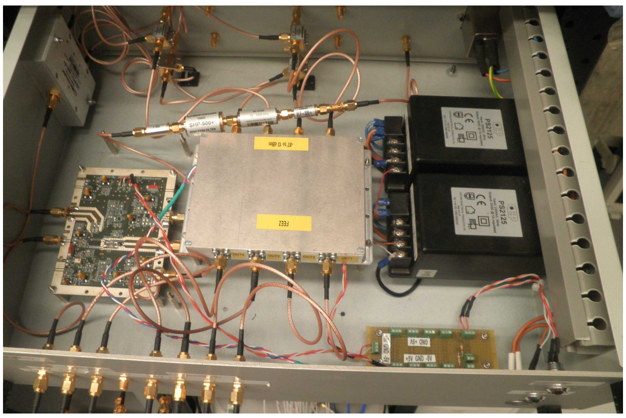

Figure 7: AFE unit including log amp and IQ demodulator boards, RF components and power supply distribution.

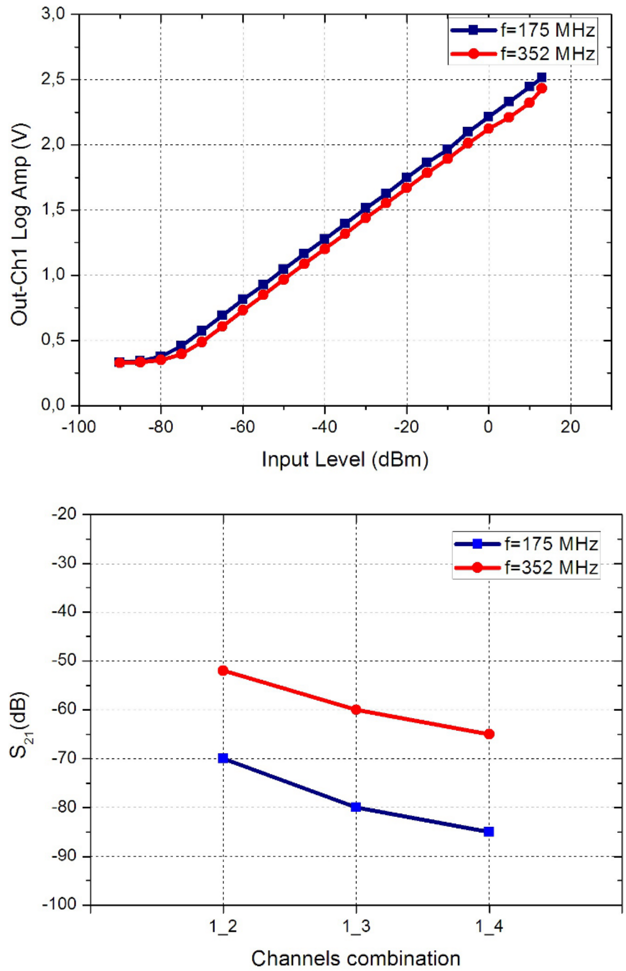

Figure 8: Measurements of the log amp board. Up: dynamic range of channel one. Down: crosstalk between the 4 channels of the same board.

3.3. *BPM Control System*

The fully integration of the BPM into an accelerator needs monitorization and archiving of the data. To handle these issues a Multipurpose Controller (MC) has been developed at ESS Bilbao [21], [22]. Concretely, it gathers some tools to easily adapt the controller to any application.

The main elements of the MC are the Control Hardware, specific for each application (it can be any instrument or card like an FPGA based board, an oscilloscope,...), and the Head System computer, which performs the data acquisition, monitoring and storage [23], as well as the system configuration and the setup of the EPICS interface .

As is schematized in Fig. 9, the process to be monitored/controlled is connected to the Control Hardware, which establishes a communication channel with the Head System. Considering a generic application, the Control Hardware is dedicated to the acquisition and processing of the data and the generation of as many control signals as required. Then, the processed data is read by the Head System which controls the communication with the board and performs any further data processing.

Nevertheless, the Head System is not only responsible of

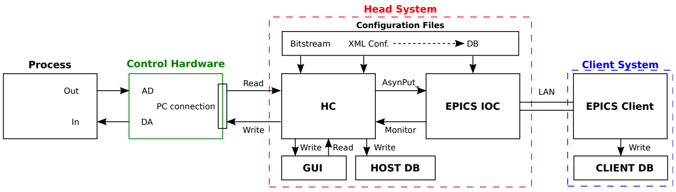

Figure 9: MC diagram.

the control hardware handling, but it also takes care of the EPICS server implementation and management, as well as the redundant local control. The Head System application structure can be split into two main blocks and an optional one: the Hardware Controller (HC) to manage the Control Hardware and the EPICS server to redirect the data to the Network.

One of the most important characteristics of the MC is its reconfigurability. It includes a single XML file, which contains all the information required of all the devices to be controlled. Once the user provides the file to the control software, it is parsed and used to successfully create any other configuration file which might be needed, like the EPICS database or any useful parameter.

Regarding the data logging capacity of the MC, two different ways of acting can be identified. On the one hand, there are the EPICS data logging clients which can be implemented fulfilling the users needs. On the other hand, the local data recording, directly from the HC into a MySQL database.

In the case of the BPM, the Control Hardware is implemented using a Lyrtech FPGA board and the Head System is implemented using a PC. Then, using the tools of the MC, the EPICS and Archiving integration is straightforward and reconfigurable by means of an XML file. In particular, this XML file includes the FPGA registers which acquire the data of the position monitors detectors, the set of signals to be included into the EPICS network and the calibration parameters. Hence, for example, this file is very useful when calibrating (next section) the BPM because the sensitivity parameters can be easily changed in the XML file by the operator. All the tools are easily accessed through the BPM control GUI, which is shown in Fig. 10.

4. Calibration and sensitivity of the BPM system

The calibration procedure is critical to calculate the correct position and to minimize errors. Two main calibrations can be performed in the system: the test bench calibration and the electronic calibration. Both of them are neccesary to be able to translate the steps measured by the ADCs from the FPGA to real position values in mm.

4.1. Electronics calibration

The four signals coming from the test bench go inside the AFE unit, and then, to the ADC modules of the FPGA. The output of the FPGA is communicated with the control system, which is running on it. The calibration of the electronics allows to calculate the conversion equations to transform the steps measured in the ADC channels of the DFE unit to the associated voltage values measured by the source detector. Knowing the detectors signal, it is possible to apply the $\frac{\Delta}{\Sigma}$ algorithm to interpret the signals from the four sensors accurately.

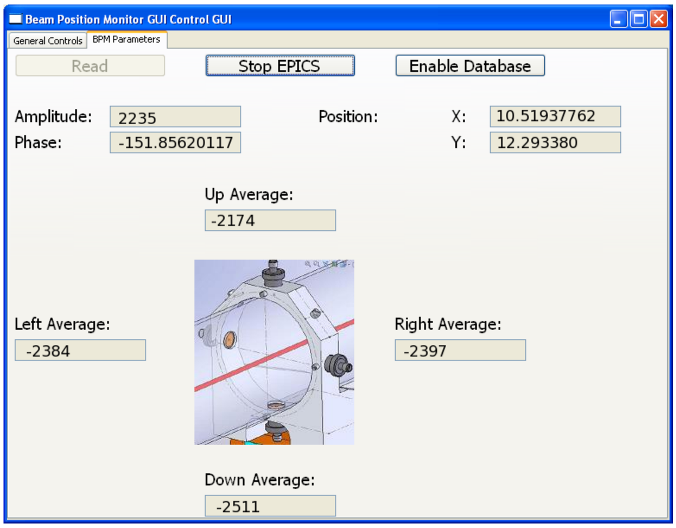

Figure 10: BPM Monitor GUI.

The $\frac{\Delta}{\Sigma}$ algorithm has been implemented in the HC, where the electrical center-of-mass beam position could be given by different expressions. Due to the assembly of both BPM detectors, two $\frac{\Delta}{\Sigma}$ algorithms have been used. The expressions selected for the PU BPM measurements have been the following:

$$X = \frac{\Delta_x}{\Sigma'} = \frac{U_{right} - U_{left}}{U_{right} + U_{left}} \tag{1}$$

$$Y = \frac{\Delta_y}{\Sigma''} = \frac{U_{up} - U_{down}}{U_{up} + U_{down}} \tag{2}$$

Other way to calculate the $\frac{\Delta}{\Sigma}$ algorithm is shown in the next equations used for stripline BPM calculations:

$$X = \frac{\Delta_x}{\Sigma} = \frac{(U_a + U_d) - (U_b + U_c)}{U_a + U_b + U_c + U_d} \tag{3}$$

$$Y = \frac{\Delta_y}{\Sigma} = \frac{(U_a + U_c) - (U_b + U_d)}{U_a + U_b + U_c + U_d} \tag{4}$$

where U_{right}, U_{left}, U_{up}, U_{down}, U_a, U_b, U_c and U_d are the voltages measured at each electrode of both BPM configurations. The electrical beam position is related to the real position through the inverse of the PU/SL sensitivities (see Equations (7), (8)).

4.2. Test bench calibration

After calculating the electrical beam position, the physical beam position is derived applying the test bench calibration parameters. To that end, the linearity of our test bench was characterized. Fig. 11 shows the differences between the real position and the obtained ones after the $\frac{\Delta}{\Sigma}$ algorithm. As it was expected, the BPM is more linear in the central area (the area where the points are inside the rectangle). It is shown the non-linear behaviour of the test bench, and also the relation of the nonlinearity with the distance to the center. Due to the non-perfect linearity of the system an additional block had to be added to the FPGA program for its linearization, the so-called test bench calibration block which is described next.

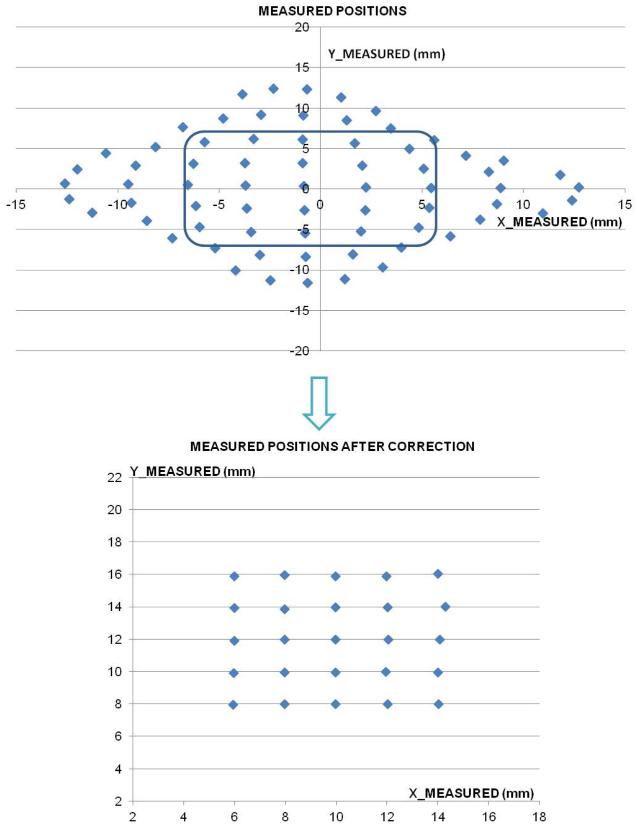

Figure 11: Linearizarion of the BPM test bench.

One possible solution for linearizing the system is presented in Equations (5), (6).

$$x_{real} = \sum_{i,j}^{4} a_{ij} \cdot X^{i}_{measured} \cdot Y^{j}_{measured} \quad (5)$$

$$y_{real} = \sum_{i,j}^{4} b_{ij} \cdot X^{i}_{measured} \cdot Y^{j}_{measured} \quad (6)$$

The coefficients a_{ij} and b_{ij} of the map functions that fit the measured position data were calculated. The order of the equation was increased up to four to obtain a good fitting (Table 2).

Table 2: Results of the linearization fitting, showing the sum of squares due to error (SSE) and R-square

	SSE	R-square
$X_{linearization}$	3.28e-028	1
$Y_{linearization}$	9.46e-024	1

After calculating the coefficients and adding the linearization block corresponding to the test bench calibration, a new test was done to prove that the output of the BPM was improved (Fig. 11).

Taking into account that the linearization is based on previous calibrations, it could be very sensitive to variations in the environment. Thus, a shielded electronics was used to maintain the fitting goodness. The linearization was applied to the central area after calculating the electrical center, being the linearization results fully satisfactory.

4.3. Sensitivity of both BPMs

Although the previously presented linearization method is accurate, a trade off between complexity and accuracy has been adopted in real FPGA implementation. So, a first order polynomial function has been used as follows:

$$x = F_x(X, Y) = k_x \cdot X + \delta_x \quad (7)$$

$$y = F_y(X, Y) = k_y \cdot Y + \delta_y \quad (8)$$

The constants k_x and k_y are characteristics of the test bench and they are related with the sensitivities $S_{x,y}$ of the used monitors. $\delta_{x,y}$ represent the deviation of the beam from the center position.

$$k_{x,y} = \frac{1}{S_{x,y}(0,0)} \quad (9)$$

Table 3 shows the different sensitivities among the used detectors and working frequencies. The obtained sensitivity values for PU are $S_{x,y} \approx 0.12$ mm^{-1} ($k_{x,y} \approx 8$ mm) and for SL $S_{x,y} \approx 0.07$ mm^{-1} ($k_{x,y} \approx 13$ mm).

Table 3: Test Bench Sensitivities for PU and SL at 352 and 175 MHz.

Pick-Up				
f (MHz)	**S_x[mm^{-1}]**	**S_y[mm^{-1}]**	δ_x	δ_y
352	0.1229	0.1182	10.37	11.96
175	0.1248	0.1252	10.32	12.06
Stripline				
f (MHz)	**S_x[mm^{-1}]**	**S_y[mm^{-1}]**	δ_x	δ_y
352	0.0717	0.0703	11.96	11.25
175	0.0791	0.075	12.36	11.81

5. Performance tests

In this section, the validation measurements for both BPM designs are described. The BPM system has been tested using the test bench, with both types of detectors, electronic units and the control system. Both detectors have been assembled and checked, PU first [13] and SL later [24], allowing the performance comparison between both BPMs.

5.1. Experimental setup

Two different beams have been reproduced using RF equipment at 175 and 352 MHz:

- Sinusoidal signal in continuous wave mode.
- Sinusoidal signal in pulsed wave mode.

Connection diagrams used for continuous and pulsed wave measurements are slightly different. The generators are used to simulate the beam (in continuous and pulsed mode) and to generate the local oscillator signal needed for the AFE unit.

5.2. Resolution and stability

The detectable change in the developed system (position resolution) was measured calculating the standard deviation of the position data acquired at the center position capturing 10000 position values sampled at 105 MHz. The position of the beam is calculated using the log amp board. Its dependence on the input signal power is shown in Fig. 12, which shows the relation between the input signal level in the electronics and the resultant position resolution values. For both deployments, PU and SL, the resolution obtained for an input power signal in the logarithmic boards over -60 dBm is better than 10 μm.

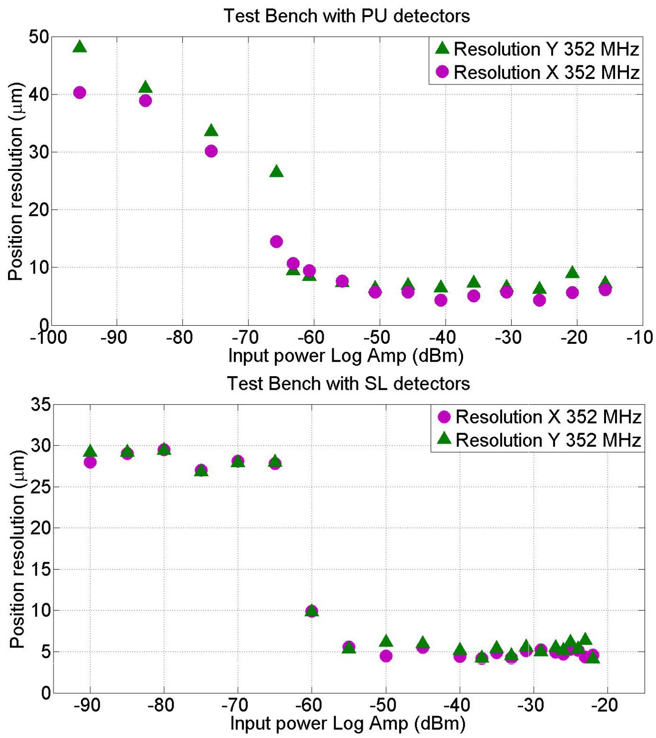

Figure 12: Position resolution at different input powers for PU (up) and SL (down) BPMs.

Tables 4-7 show the results for a given input beam power signal. The long term stability is affected by drifts in the electronics due to temperature variations. The temperature has been monitorized for several months and variations of less than 10 °C have been measured. Under these conditions, the system stability values have been maintained under the required specifications shown in Table 1. The long term stability has been calculated in the same way as the resolution but during a bigger time period. In addition, the resolution and the stability are also affected by vibrations, noise, cabling effects, etc.

The power levels used in continuous and pulsed wave mode are similar. The input levels of the generators have been configured to have always a similar signal level at the input of the electronics. In this way, the average input signal seen by the electronics should be similar in both cases. Tables 4-7 show the obtained results for a fixed input signal power (detectable by the AFE unit). The signal level, locating the simulated beam in the center of the tube, is -25 dBm detected by the log amp board and is -30 dBm measured by the IQ demodulator board.

Table 4: PU BPM results in continuous wave mode

Parameter	175 MHz	352 MHz	Unit
X axis Resolution (rms)	4	4.28	μm
Y axis Resolution (rms)	4.74	6.46	μm
Phase Resolution (rms)	0.11	0.116	°
X axis Stability (rms)	5.24	7.74	μm
Y axis Stability (rms)	21.36	26.7	μm
Phase Stability (rms)	0.204	0.386	°

Table 5: PU BPM results in pulsed wave mode

Parameter	175 MHz	352 MHz	Unit
X axis Resolution (rms)	5.8	3.8	μm
Y axis Resolution (rms)	6.03	5.5	μm
Phase Resolution (rms)	0.11	0.095	°
X axis Stability (rms)	8.32	7	μm
Y axis Stability (rms)	33.1	36.8	μm
Phase Stability (rms)	0.828	1.317	°

Table 6: SL BPM results in continuous wave mode

Parameter	175 MHz	352 MHz	Unit
X axis Resolution (rms)	5.71	5.37	μm
Y axis Resolution (rms)	5.83	5.19	μm
Phase Resolution (rms)	0.07	0.1	°
X axis Stability (rms)	12.06	9.59	μm
Y axis Stability (rms)	14.47	15.66	μm
Phase Stability (rms)	0.14	0.09	°

Table 7: SL BPM results in pulsed wave mode

Parameter	175 MHz	352 MHz	Unit
X axis Resolution (rms)	5.37	5	μm
Y axis Resolution (rms)	5.29	6.03	μm
Phase Resolution (rms)	0.01	0.05	°
X axis Stability (rms)	17.13	19.02	μm
Y axis Stability (rms)	22.71	15.2	μm
Phase Stability (rms)	2.54	2.52	°

All the results are fulfilling the requirements in Table 1.

With all the BPM system assembled, the obtained position and phase resolution values are very similar for the different configurations.

In general, the results for a continuous simulated beam are slightly more accurate with respect to the results for pulsed simulated beam. This minimal difference is affected by the implementation philosophy selected for pulsed mode (a single sample has been measured every pulse) and also because of the response time of the electronic units.

The presented slight differences, which do not compromise the ESSB Linac requirements, are due to the test bench assembling imperfections and environmental variations between measurements. From these results, it can be deduced that both PU and SL are within specifications, both for continuous and pulsed regimes.

The phase measurements shown before are relative to the RF main frequency. To prove that the phase is well calculated, phase variations have also been measured, introducing known delays in the cabling, always obtaining the expected value to less than 1° error.

6. Summary and Conclusions

A new versatile electronics system for the ESSB beam position monitors has been presented. The proposed design has been conceived to be fully configurable so that it could eventually be used in different kind of proton or ion accelerators with minimal change.

The system includes both button-type pickups or striplines as detectors and an analog front-end plus a digital unit, with a control system which integrates EPICS and Archiver. Both type of detectors, button-type pickups and striplines are complementary. Button-type detectors are the simplest monitors which present better mechanical properties and a smoother power response in a broader frequency band. Nevertheless, for low beam currents, button-type detectors signal level is weaker than striplines response, which have a significantly better response for low beam currents and could be used for very low frequencies. Several tests have been performed at simulated proton and deuteron beamlines at 352 MHz and 175 MHz RF frequencies, leading to resolution and accuracy values fulfilling ESSB requirements. As a whole, the presented BPM system, composed of the BPM electrode block, the analog and digital electronic units and the control system, constitutes an all-in-one integrated and serializable solution for accurate beam position and phase monitoring in ion accelerators.

Finally, next steps towards industrialization of the presented BPM system need to assure the robustness of the solution in a real particle accelerator environment. To this end, on the one hand, the BPM mechanical blocks will be manufactured using high-vacuum-compatible parts, ready to be integrated in the real beamline. On the oher hand, the electronics and proposed acquisition solution will be translated to the PCI eXtensions for Instrumentation (PXI) arquitecture, to benefit from a solid, dominant and extended open industry standard, ensuring upgradeability and easy maintenace of the Digital Front-End Unit as well as automation of the calibration process.

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