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DIGITAL SIGNAL PROCESSING IMPROVEMENTS OF THE SPIRAL2 BEAM POSITION MONITORS AT LOW INTENSITY

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Abstract

The SPIRAL2 accelerator, designed for high intensity beams (up to 5 mA), needs to evolve for low intensities in order to reach the requirements of the S3 (Super Separator Spectrometer) experimental room. This means increasing the operating range of diagnostic monitors including the Beam Position Monitors (BPM). Twenty BPM are installed in the warm sections of the linac to measure positions, ellipticities and phases. The digital processing of the BPM acquisition has been modified to operate at low intensity. This was done by improving the signal-to-noise ratio with an increase of the averaging resolution, an improvement of the channel equalisation system and with a deduction of parasitic signals induced by the surrounding equipment. The process was also modified to operate with chopper frequencies above 1 kHz. A new BPM interface, with tables and graphical displays in order to control beam phases and energies in the linac, is now available. These new developments and measurement results in laboratory and with SPIRAL2 beams are presented, which show good results with a low intensity down to 1 μA.

INTRODUCTION

The Beam Position Monitors (BPM) are beam diagnostics installed in the quadrupoles of the warm sections of the SPIRAL2 LINAC. Twenty BPMs and their instrumentation chain measure the following characteristics: beam position, ellipticity (a characteristic of the transverse size) [1], beam phases and energy.

The four electrodes of a BPM pick up the electric field induced by the ion bunches from the beam. The generated signal is periodic and can be decomposed in harmonics, mainly at the accelerator frequency (h_1=88.0525 MHz) and at its double frequency (h_2=176.105 MHz). The level of the signal is mainly due to the beam intensity, its energy and the considered harmonic. Table 1 shows the expected signal level. The red values are below the detection threshold of the BPM device before modifications.

The BPM acquisition system was designed by the Bhabha Atomic Research Centre (BARC) to measure characteristics from high intensity beam. To meet the future demand of low intensity beam, an improvement of the instrumentation chain was previously done [1], making possible to measure beam characteristics with an intensity down to 50 μA, namely signal power down to -90 dBm. Below this intensity, the measurement precisions deteriorate quickly. Future beams of S3, including those of NEWGAIN [2], could have an intensity below this value. We should then increase the dynamic of measure for the low levels of signal. This improvement was achieved by modifying the digital signal processing.

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Table 1: Signal Level as a Function of the Beam Intensity

	h_1 (dBm)		h_2 (dBm)	
Beam intensity	min	max	min	max
5000 μA	-32.9	-22.4	-27.5	-22.6
500 μA	-52.9	-42.4	-47.5	-42.6
50 μA	-72.9	-62.4	-67.5	-62.6
5 μA	-92.9	-82.4	-87.5	-82.6
1 μA	-106.9	-96.4	-101.5	-96.6

DIGITAL SIGNAL PROCESSING IMPROVEMENTS

The signal coming from the four capacitive pickups are measured with an acquisition system developed by BARC. It consists of an analog section that filters and amplifies the signal which is digitized in the digital section. In this section, the data are processed by a Field-Programmable Gate Array (FPGA). A VME CPU board collects the data from several BPM for further digital processing and publication to the network. The signal processing modifications were made to the FPGA code in the digital section and to the C driver in the VME-CPU.

Architecture Modifications

In order to correct amplitude and phase differences between channels for all gains and ensure a stable measurements over time, the acquisition system is equipped with an equalization system [3]. A known sinusoidal signal, called "*Offset Tone*", is injected at the four inputs of the analog section. The frequency of this signal is close enough to the frequency of measured BPM signals so that the gain and phase shift of the acquisition channels are considered identical between the signal to be measured and the *Offset Tone*.

The measure of the *Offset Tone* allows the calculation of correction factors (in phase and gain) which are applied to the measurement of signals coming from the BPM. This correction was previously performed on the digital board. The gain and phase correction factors required to be calculated from IQ measurements by a CORDIC which introduced calculation errors.

To increase the precision of low amplitude signal measurement, the way to process the stabilization was changed. It is now achieved by the VME-CPU with a new driver. The *Offset Tone* generation is produced by a feed back loop in the FPGA. The new equalizations (in amplitude and phase)

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are optimized by using the feed back instead of the setpoint. This reduce the error when the setpoint is not fully reached. The resolution of the averaging has also been increase from 16 bits to 24 bits.

Parasitic Signal Removal

The BPM sensor and electronic are placed in an environment surrounded by equipment (accelerator cavities, amplifiers) working at the accelerator frequency. Parasitic signals are coupled to the real beam signal, producing an offset of measurement. For weak signal, this offset can be significant, leading to an impossibility to accurately measure the beam characteristics.

To solve this problem, the offset signal of each electrode is measured when the beam is absent (Fig. 1): The beam being pulsed, we use the OFF pulse time to get the offset signal characteristics (IQ). The offset signal is then deduced from the beam pulse IQ signals.

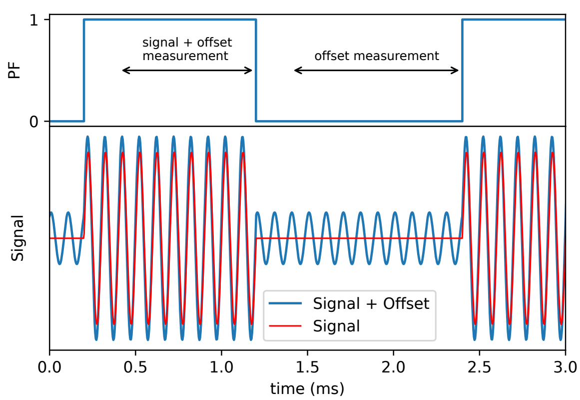

Figure 1: Principle of the parasitic signal removal.

Multipulse Mode

The beam is pulsed by a chopper frequency ranging from 1 Hz to 1 kHz. At the end of each beam pulse, the digital card send an interruption to the CPU for the data transfer. At high chopper frequency (> 50 Hz), the interruption are too close for the CPU to process the data, which lead to the crash of the driver.

To avoid crashes and to accommodate future requests of pulses rate above 1 kHz, the interruption rate is limited to 5 Hz. During the 200 ms interval, the FPGA process averages of the I and Q signals of the beam pulses.

TESTS AND VALIDATION

The modifications were tested and validated in laboratory. Measures were then carried out with the accelerator beam.

The modifications to the equalization system was tested using a RF generator. The FPGA was coded with the previous and the new algorithm for direct comparison.

Measurement errors in amplitude and phase are mitigated (Fig. 2) after modifications. One can see an improvement of

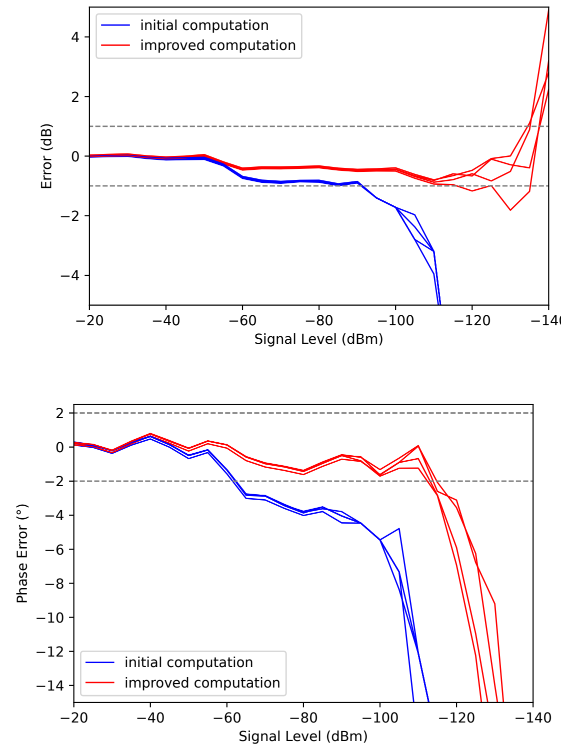

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Figure 2: Level and phase measurement error (receptively above and below) for the four channels as a function of the input level before and after the modifications of the algorithms (measurement of h_1).

the measurement dynamics from [−20 dBm; −90 dBm] to [−20 dBm; −120 dBm].

The offset deduction was tested in laboratory and validated on the LINAC. At low intensities, the measurements of the beam ellipicities along the LINAC with the parasitic signal deduction give very good results (Fig. 3). The ellipicities (h_1 and h_2) is calculated from their respective the signal amplitude and should have the same value. At low intensity, this measurement is very sensitive to perturbations. The initial computation shown an impossibility to measure ellipicity of 9 µA beam while the new computation was able to measure a 1 µA beam.

The multipulse mode was tested in laboratory and will be verified on the LINAC by the end of 2025. For the distribution of measurements at a 2 kHz pulses, a standard deviation decreases by a factor 10 by using the multipulse mode (Fig. 4). This results was expected as the multipulse mode, at this chopping rate, allows the average of the signals of 128 pulses. The expected reduction in measurement dispersion is $\sqrt{128} \approx 11.3$.

CALIBRATION

A new calibration of all BPM modules (Analog and digital cards) was done in July 2025 with the new CPU driver and a

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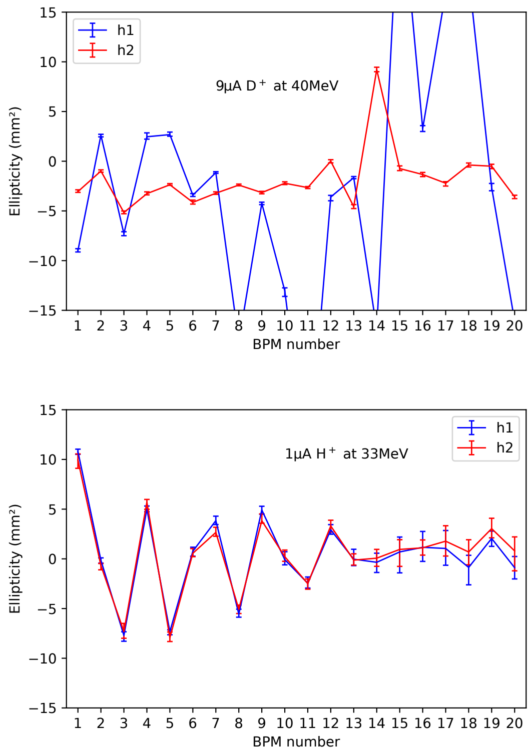

Figure 3: Ellipticity measurement from the harmonics h_1 and h_2 for a 9 µA 40 MeV Deuton beam with the initial computation (above) and a 1 µA 33 MeV Proton beam with the improved computation (below).

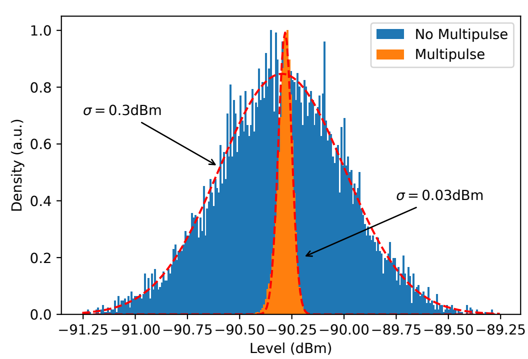

Figure 4: Measurement distribution at -90 dBm and a beam synchronisation of 2 kHz.

new GUI. BPM module calibration are done in 2 main steps. The first step is to perform amplitude and phase calibration for each module at h1 and h2. From an RF distributor and a calbox (calibration box) close to the module, 4 calibration signals at -20 dBm are applied on the 4 inputs of the analog card. A calibration process calculates gain and phase shift coefficients to correct amplitude and phase differences between the 4 channels in based on the *Offset Tone* on each channel. The second step is an absolute phase calibration. Calibration signals at h1 and h2 are generated at the place of BPM signals for each module. Phase shifts of each channel are measured and compensated to obtain the same reference phase for all inputs of BPM modules. From all calibration coefficients, correction parameters in amplitude and phase of each module and BPM are calculated and record in files named "Substitution file", one file by VME crate. When starting the VME crates, correction parameters are loaded into each CPU driver.

NEW BPM INTERFACE

In 2024, a new BPM Graphical Interface was defined and designed to control and display BPM measurements. This GUI is adapted for the tuning and the control of the beam. It provides in a main page an overview of the beam characteristics along the LINAC (positions X and Y, ellipticity, signal amplitude and phase).

The phase difference between two neighbouring BPM allows to deduce the averaged energy in the intermediate section (with 1 or 2 cavities). This value can be compared to the computed one (from Tracewin software [4]). The new GUI allows to follows in real time the energy shifts of each cavity. BPM amplitudes and phases and RF cavity amplitudes and phases can be archived and compared with the current values. From these comparisons, the beam shifts in the LINAC and the phase differences can be then controlled.

CONCLUSION

The presented modifications now allow to measure beam characteristics (positions, ellipticity, phases, energy) with low-intensity beams and meet the specifications required for physics experiments in S3. All these improvements were possible by the programming of a new C-driver in the VME-CPU and a new FPGA code in the digital cards. This new driver also allows us to calibrate analog cards more easily. A new graphic display has been developed to ensure better visualization and enable new measurement features.

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