DEVELOPMENT OF THE BEAM POSITION MONITORS SYSTEM FOR THE LINAC OF SPIRAL2*

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Abstract

The SPIRAL 2 facility will deliver stable heavy ion and deuteron beams at very high intensity, producing and accelerating light and heavy rare ion beams. The driver will accelerate between 0.15mA and 5 mA deuteron beam up to 20 MeV/u and q/A=1/3 heavy ions up to 14.5 MeV/u. It is being built on the site of the Grand Accelerator National d'Ions Lourds at CAEN (France). The accurate tuning of the Linac is essential for the operation of SPIRAL2 and requires from the Beam Position Monitor (BPM) system the measurements of the beam transverse position, the phase of the beam with respect to the radiofrequency voltage and the beam energy.

This paper addresses the advancement made during the last twelve months on the realization of the 22 BPM required for the SPIRAL 2 Linac. The BPM sensors are now completed and tested. The design of the acquisition card for the BPM of the SPIRAL2 Linac is given and will be described. The prototype card is realized and under test. The first results are given. The aim is to verify the main parameters: sensitivity, position and phase measurement, and the appropriate behavior of the BPM acquisition card in all cases (pulsed, electrode signal reconstruction, interlock, post mortem).

GENERAL DESCRIPTION OF THE DRIVER OF SPIRAL2

The SPIRAL2 facility being to be installed in Caen, France, is composed of a multi-beam driver accelerator (5mA/40Mev deuterons, 5mA/14,5meV/A heavy ions) and a dedicated building for the production of radioactive ion beams (RIBs). RIBs will be accelerated by the existing cyclotron CIME for the post acceleration and sent to GANIL's experimental areas. The injector constituted by an ion source a deuteron/proton source a L.E.B.T. and a M.E.B.T. lines and a room temperature R.F.Q. will produce, transports and accelerates beams up to an energy of 0,75MeV/u.

The accelerator is a superconducting LINAC equipped with two types of cryomodules. The lower energy section of the LINAC contains 12 modules of the first type "A" including one $\lambda/4$ resonator tuned for β= 0.04 particles velocity and 7 of the type "B" dedicated to the higher energy section contains two $\lambda/4$ resonators (β= 0.2). All the resonators operate at 88.0525MHz.

A doublet of magnetic quadrupoles takes place between the cryomodules for the horizontal and vertical transverse focusing of the beam. A diagnostic box is inserted between the quadrupoles and devoted to install beam diagnostics and flanges for coupling vacuum pumps. The total length of the LINAC is 30 m. In order to save room the Beam Position Monitors (BPM) have been inserted in the vacuum pipe inside the quadrupoles of the LINAC and buried at their turn in the quadrupole magnet. The Linac may accelerate deuterons, protons, heavy ions Q/A = 1/3 and Q/A = 1/6 either up to the maximum energy of 20 MeV/A. The table 1 exhibits the main characteristics in the particular case of deuterons.

Table 1: Main Beam Characteristics

Ions D^+ (I = 5mA)	Start of Linac	Frontier between families cavities	End of Linac
Energy	1.46	8.6	40
β	0.0395	0.095	0.204
Bunch phase extension (°;5σ)	33	14.5	9

THE BEAM POSITION MONITORS SYSTEM

BPM Sensors Design

Capacitive sensors have been selected. Twenty BPMs measure both transverse planes, two electrodes for the horizontal plane and two electrodes for the vertical plane (Electrodes aperture diameter: 48 mm, length in the direction of the beam: 39 mm, subtented lobe-angle: 62°). In order to save room the BPM sensors are designed to be inserted, after brazing with their flanges, in the vacuum pipe inside the quadrupoles of the LINAC (see Fig. 1) which are buried in their turn in the quadrupole magnet. The BPM are mechanically indexed to the quadrupole to insure that the location of the electrical center is known better than 0.2 mm. BPM are made of stainless steel.

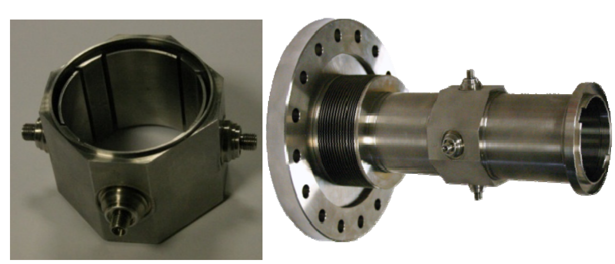

Figure 1: Left: view of the BPM sensor of the SPIRAL2 LINAC. Right: The sensor with its flanges.

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BPM Sensors Tests

Due to the location of the BPM sensors, special care has been taken for the quality insurance of the realization. All the components of the sensor were individually tested and measured. A test bench based on a coaxial transmission line has be designed and built to check their time response. Other measurements have been carried to provide data concerning the mechanical and electrical centres. The sensitivity of the BPM 1/Kx = 1/22.2 mm has been measured for $\beta = 1$ at f = 88 MHz [1] and is expected to be 1/15.6 mm (calculated value) for $\beta = 0.04$ at f = 88 MHz. This last value will be checked with two BPM mounted on the "Intermediate Test Bench" which will be used during the commissioning of the RFQ of SPIRAL2.

BPM Sensors Characteristics

Electromagnetic modelling of the BPM has been performed with "CST's" simulation software.

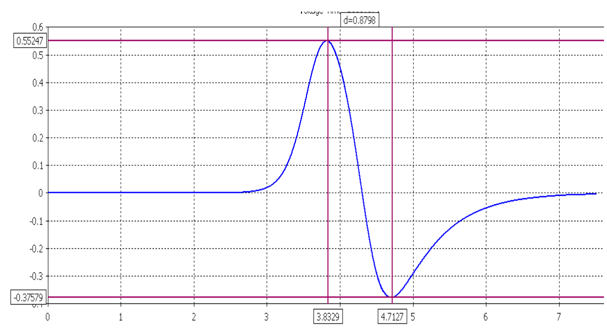

Figure 2 : CST simulated Response of a BPM electrode with CST to a square beam input of 1 ns duration.

Figure 2 shows the simulation of the response to a 5mA beam input current (rectangular square impulsion) centered in the beam pipe at $\beta = 0.2$.

The Fourier Transform processing of the signal delivered by the electrode exhibits mainly an 88.0525 MHz component for low β beams at the beginning of the LINAC and roughly six significant harmonics at the end of the LINAC at the maximum energy. ($\beta = 0.2$)

Measurement Requirements

The main BPM specifications are summarized in Table 2.

Table 2: BPM Specifications for the SPIRAL2 Linac

Position accuracy	150 µm
Position resolution	50 µm
Range of measurement	± 20 mm
Phase measurement error	± 0.5 °
Ellipticity measurement relative error	± 20 %
Input signal range	-63 dBm / -16 dBm

The horizontal and vertical transverse position measurements of the center of gravity of the particle beam are essential to achieve the beam transportation through the LINAC. The phase measurement of the bunches of the beam with respect to the radiofrequency reference voltage has also to be performed for a proper tuning of the acceleration of the beam through the LINAC structure. The velocity of a particular bunch to travel from a BPM to the next one will be calculated by the time of flight method and their energy will be drawn from these measurements. At last the beam shape based on the transverse beam ellipticity information contained in the second order moment of the transverse beam distribution will be calculated. This parameter will be used to tune the transverse matching of the beam in the LINAC. Experimental studies at $\beta = 1$ have been carried on our test bench [1].

LINAC Operation Modes

The accelerator normal daily operation mode is planned to be C.W. mode that means a succession of beam bunches at 88.0525 MHz.

Considerations on commissioning and tuning periods of the LINAC lead to consider also a pulsed mode operation in order to minimize the mean power of the beam. The shortest duration of a macro-pulse will be 100 µs. The repetition rate may be as low as 1Hz and as high as 1 kHz. The intermediate configurations have to be taken in account in order to reach the C.W. operation. The step to increase or decrease either the macro pulse duration or the repetition rate will be 1µs

THE BPM READ OUT ELECTRONICS

The BPM read out electronics is being realized at Electronics Division, of Bhabha Atomic Research Centre (BARC) in the framework of collaboration between SPIRAL2 with "Bhabha Atomic Research Center" and Tata Institute of Fundamental (India).

General Description

Each BPM sensor feeds a four inputs electronic module card; through an eighty meter long coaxial cable. The 20 BPM electronics modules will be located in VME 64x crate. Each module consists in an analog board sitting on the rear side of the VME backplane and a digital board on the front side. The block diagram of the BPM module is shown in Fig. 3.

Due to the gradual widening of the frequency spectrum of the successive expected BPM signals all along the LINAC, the electronic board is able to work at 88.0525 MHz or 176.1050 MHz to deliver the required information.

The design of the analog module is based on the scheme of auto-gain equalization using offset tone having frequency slightly offset from the RF reference. This tone is added at the input using a directional coupler to the four incoming sensor signals. The gain of the four channels is equalized with respect to the offset tone in the digital

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domain. The offset tone is generated by feeding the DAC with a corresponding discrete time sequence.

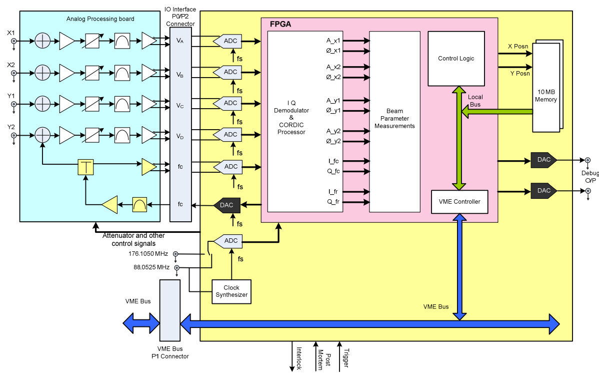

Figure 3: Hardware architecture of the BPM electronics.

This tone is stabilized in amplitude and phase in the digital domain using a feedback loop. The stabilized offset tone is divided in four parts and added at the input.

The four analog channels corresponding to the electrode signals, the selected RF frequency reference signal (88.0525 MHz or 176.1050 MHz) and the calibration tone signal are under-sampled and digitized by six respective 14 bits ADCs (ADS62P48) at the sampling frequency of 65.337 MHz: (256/345).88.0525 MHz. The digitized data are then sent to a high density FPGA (from Altera Corporation) for processing and calculations of the various parameters. The required results are stored in local memories. The discrete time sequence to generate the offset tone is programmed in the FPGA. The offset tone is selected by suitable filtering on the analog board the spectrum of the output signal of a DAC and sent back to the Digital board for amplitude and phase stabilization.

Software for the BPM System

The EPICS system has been chosen as the basic framework for command control. The software is being developed using SPIRAL2 topSP2 template for EPICS. The hardware architecture relies on a VME crate in which there is a Master CPU board MVME5500. The software architecture relies on VxWorks and EPICS. The BPM IOC, BPM Record EPICS DB, BPM record support, BPM Device Support and MVME BSP Driver correspond to the software components developed for BPM board data acquisition. The BPM Driver interfaces the VME BPM board with the rest of the BPM IOC on Master VME CPU board. For this purpose it uses the VME bus to exchange signals and data. The OPI is provided using CSS-BOY which access BPM custom record PV for BPM configuration and data acquisition.

Acquisition Modes

The BPMs data and measures are acquired in four modes: Normal, Interrupt, post mortem and electrode signal reconstruction. All the modes of acquisition are available for both pulsed and CW operating mode of the LINAC. In normal and interrupt modes 16 measures: Amplitude and phase of the four electrode signals and of the RF reference, the corresponding vector sum, phase shift between the vector sum and the RF reference, the X and Y beam positions and ellipticity are continuously acquired and stored in the internal memory of the FPGA at a rate of 10 µs. An average over N (N= 2^n) acquisitions may be predetermined by the operator and sent to the card via EPICS.

In normal mode the averaged data are made available when the EPICS driver reads the data in a scanning mode every 200 ms from the local VME memory.

In interrupt mode the data are transferred to the VME local memory after a signal named “Beam Available” (BA) which is distributed to each SP2 equipment to indicate that the beam is delivered by the accelerator while BA is “high” and cannot exist during its low duration (maximum frequency of 1 KHz). During C.W. mode a dummy signal “BA” is distributed to fix the measurement repetition rate. An acquisition signal is synthesized in the FPGA and its rising edge starts after the signal “BA” one with a predetermined delay Δ_D sent by the operator via EPICS. Measures will be acquired in the internal memory of the FPGA at a rate of 10 µs. The maximum value of N must allow an acquisition duration sequence over the maximum duration of the signal BA (1s). The data are stored in the memory of the FPGA until the arrival of the next acquisition pulse during the duration of which former data will be overwritten.

When an accelerator running dysfunction occurs (beam breakdown for instance), a stop acquisition signal is sent to the card by the “Machine Protection System” and the acquisition stops. The last acquired data memory address is saved in a register. An interrupt signal is sent by the BPM VME board to signify “Post mortem data”. The CPU decides to DMA transfer the data from the memory to the CPU local memory. The memory dedicated to post mortem data is a 10 Megabytes one and allows roughly a 2.5 s recording sequence.

A special operating mode called “Electrode signal Reconstruction Mode” is also foreseen. It allows the capture of one beam bunch over 345 RF pulses (3.9µs). This special mode of operation is not required for the daily LINAC operation (the filters of the analog section are needed to be then bypassed) but is expected to provide information on the behaviour of the running of the LINAC.

First Laboratory Tests Results of the Electronics

Due to the principle of the card, the equalization of the gain of the analog part has been checked over the dynamic range of the foreseen input beam current (β = 1).

For this purpose, a RF generator sends through a six channels splitter Minicircuit ZBSC-015, (power transmission discrepancy between the six channels: 0.04 dB, phase discrepancy: 0.1°) an 88 MHz or a 176 MHz signal. Four channels are connected to the four inputs of the card; one channel is used as a reference (the sixth is left free). The amplitudes of the input signal range from -15 dBm down to -60 dBm. The discrepancies between the

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signals of each output of the analog card and the reference channel were recorded and displayed on the Fig. 4, 5, 6, 7. All the measurements have been averaged over 64 samples sequence.

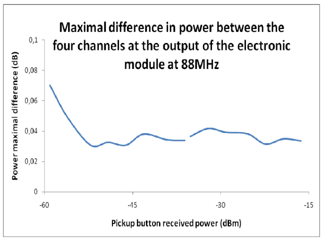

Figure 4: Maximum power difference between the four inputs at 88 MHz.

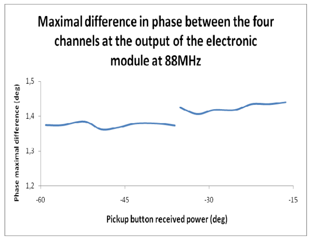

Figure 5: Maximum phase difference between the four channels at 88 MHz.

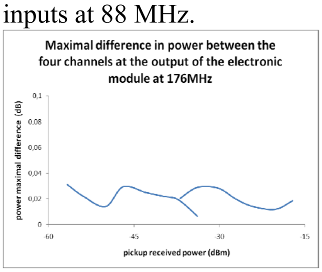

Figure 6: Maximum power difference between the four inputs at 176 MHz.

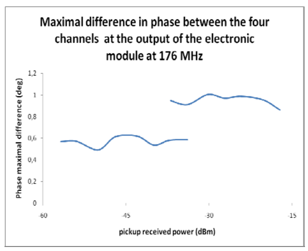

Figure 7: Maximum phase difference between the four channels at 88 MHz.

The variation of the powers ranges in a band of 0.04 dBm between -15 dBm and -55dBm at 88 MHz and less than 0.03 dBm at 176 MHz and remain in the same discrepancy band of the splitter.

As for the phase measurements, the variations stand below 1.4 ° and 1° respectively at 88 MHz and 176 MHz.

Concerning the position measurement, the generator signal was sent through the BPM sensor mounted on our test bench. A comparison has been established between the position calculated from both the power-meter and the electronic card measurements. Figure 8 exhibits a good agreement between the two kinds of measurements and shows in the vicinity of the center of the beam pipe (the most important zone to consider for the beam transverse tuning and stabilization), a position error below 10 µm for an input equivalent beam intensity of nearly 4 mA.

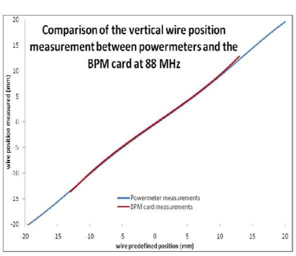

Figure 8: Results of a sweep over the X axis.

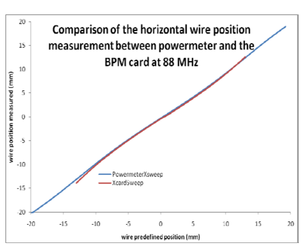

Figure 9: Results of a sweep over the Y axis.

Other Measurements

The other measurements deal with the reliability over 200 measurements carried in the "interrupt mode".

Two signal generators phase locked to each other were used. One of them supplies the RF Reference signal and the other supplies the inputs to the electronic module.

Table 2: Dispersion Measurements over 200 Samples for the Position and the Phase

88MHz	Input:-15 dBm		Input:-32 dBm		Input: -64 dBm	
N	4	64	4	64	4	64
Δ_x (µm)	8.2	2.5	9.9	2.5	112	29.7
Δ_y (µm)	9	3.3	10.7	2.5	123	25
Δ_{ph} (°)	0.09	0.03	0.1	0.03	1.1	0.3

The output of the second signal generator is split in four parts to serve as inputs to the BPM electronic module. RF output of this phase locked signal generator is pulsed modulated with the BA Linac signal. The data has been acquired in "normal mode" at every BA linac pulse using VME interrupt. N was fixed to 4 and 64 respectively during an 100 µs and 1 ms pulse duration and a repetition rate of 2 ms. The results fulfil the requirements. Similar results were obtained at 176 MHz.

Future Actions

The basic measurements concerning the position of the beam and the phase in normal and interrupt modes are now practically completed. The next step will be to test the electrode signal reconstruction mode which requires a special operation of the analog section (bypass of the input filters) and we finally carry the tests for the ellipticity measurements.

The accurate measurement of the phase of the beam will need to put on operation a dedicated circuit for the calibration of the phase lag through the four input cables to the card. This will be done by analyzing returned response to the offset tone signal sent towards the cable connecting the BPM sensor to the card. This part of the electronics will be determinant for the final accuracy of the measurements.

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[1] M. Ben Abdillah et al, Development of the beam position monitors for the SPIRAL2 Linac, IBIC2012, Oct. 1-4, 2012

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