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BEAM COMMISIONING OF BEAM POSITION AND PHASE MONITORS FOR LIPAc*

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Abstract

The LIPAc accelerator is 9-MeV, 125-mA CW deuteron accelerator that aims to validate the technology that will be used in the future IFMIF accelerator (40-MeV, 2 × 125-mA CW). LIPAc is presently under beam commissioning of the second acceleration stage (injector and Radio Frequency Quadrupole) at 5 MeV. In this stage two types of BPM's are used: four stripline-type to control the transverse position and phase at the Medium Energy Beam Transport line (MEBT), and three other stripline-type mainly for the precise measurements of the mean beam energy at the Diagnostics Plate. All the BPM's have been successfully tested and served to increase the duty cycle and the average power of the beam delivered down to the beam dump. Moreover, the BPM's were key devices for the transverse beam positioning and longitudinal beam tuning and validation of the RFQ and re-buncher cavities at the MEBT.

INTRODUCTION

Beam position and phase monitors have been used during the beam commissioning of the 5 MeV and 125 mA pulsed deuteron beam in LIPAc for beam transport and characterization. This is the first stage towards the goal of achieving an average power of 625 kW up to LIPAc's final energy of 9 MeV once the superconducting accelerator is installed later on. Now, the beam from the ion source is accelerated from the low energy ion source by a RadioFrequency Quadrupole and then transported by a Medium Energy Beam Transport Line down to a Low Power Beam Dump, able to sustain up to 0.1% of the nominal deuteron current. The BPM's have been used both to measure the transverse position of the bunch centroid and the longitudinal one, by measuring the phase of the bunches with respect to an absolute reference and is fulfilling the beam dynamics requirements.

INSTALLATION

Pickups

Firstly, the vacuum chambers of the Beam Position Monitors were positioned in their mechanical supports at the beamline (Fig. 1). Each pickup was aligned to the general coordinate frame of the accelerator with an accuracy lower than 150 µm [1]. To obtain this accuracy several reflector holders for laser tracker alignment were used in each pickup. The position of each holder was previously referenced to the mechanical center of each pickup in a CMM and the values obtained were used. Once the BPM's were perfectly aligned, they were tightened to the other components and vacuum leak tests were performed to ensure the goodness of the vacuum connection and the status of the vacuum chamber.

Cabling

The connection between the electrodes and the acquisition electronics was performed using several types of coaxial cables: 1) Flexible coaxial cables to connect the electrodes to a patch panel aside the beamline.2) Low losses cables for the long connections between the accelerator vault and the electronics cabinet. In this case, low losses RFS cable with double shielding has been used, with attenuation of less than 3 dB each 100 m.

To minimize the effect of the RF noises and misbalances between each channel, several mitigation measures where carried out: 1) Low losses cables were used for the big distance cables, 2) Cabinets with high EMC shielding (up to 60 dB below 1 GHz and 3) Long cables were phase matched down to 1° by adjusting the cable length for the bunch of four cables in each BPM using Time Domain Reflectometry to each cable.

In parallel, the status of the cabling and pickup was finally checked by analyzing the coupling measurement between the electrodes and the measurements at the test bench using a vector network analyzer.

ACQUISITION ELECTRONICS

As further explained in [2], the acquisition electronics is based in two main components: 1) an analog front-end (AFE) which conditions the RF signal coming from the BPM electrodes, and 2) a digital board which provides a fast digital treatment of the signal and communicates with the control system. The system uses an analog front-end to house the system calibration switches and an intermediate frequency stage, plus ancillary boards such as timing and clock distribution, on CompactPCI. As such, all parameters

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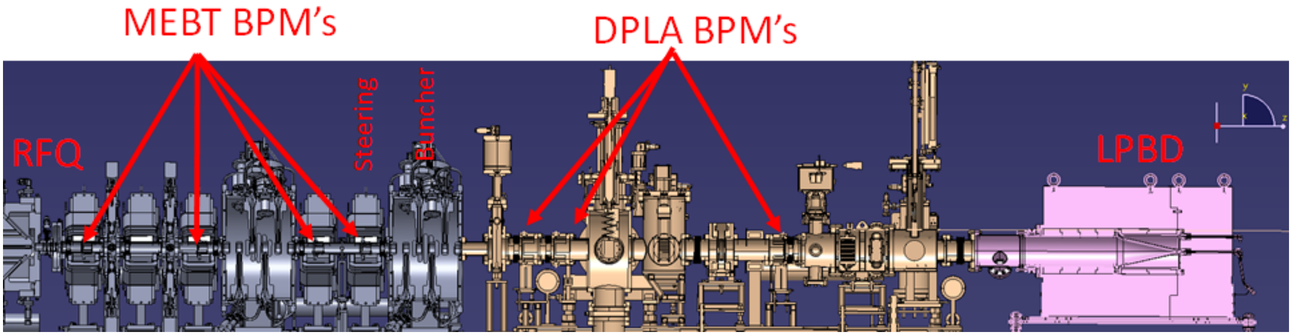

Figure 1: Layout of the LIPAc Phase B1/2 for RFQ and MEBT proton and deuteron pulsed commissioning.

for controlling the system are available for Linux OS via Ethernet, and given the low event rate output of the BPM system the integration in the Central Control System is via an ASYN driver. The timing boards are rather simple, consisting on a fan-out buffer for the gate signal from the general timing system. The RF signal for the calibration of each channel is generated by a dedicated RF generator. This generator can be accessed via Ethernet and the signal is distributed to each channel by an specific calibration board connected to each AFE board. The first digitizer was an 14-bit 100 MS/s VHS-ADC from Nutaq (formerly Lyrtech) for the first stages of Phase B. The gateware was a direct IQ demodulation developed in-house.
All the system was successfully verified and checked for the proton measurements and the low current deuteron beam runs, where seven BPM's were beam commissioned.

Upgrade

In preparation of the following accelerator stage, where the number of BPM's will be increased up to 20 devices along all the lines, the acquisition electronics was upgraded during the last phase of the deuteron high current campaign. As explained in detail in [2], the acquisition system has been designed and manufactured in CIEMAT for all the LIPAc BPM's, yet it was based on commercial digitizers.
The new acquisition electronics is based on the same architecture and analog boards than the previous one but, the digitizers and the clock boards have been replaced by new ones, designed and manufactured by Seven Solutions. The new system adds new features that have improved significantly the operation of the machine:

- A better synchronization with the rest of the machine (RF system and Timing System) by digital White Rabbit with subpicosecond precision.
- Higher ENOB than in the previous digitizers and thus resolution of the system.
- The acquisition and visualization of the intra-pulse parameters (position, phase, current), see e.g. Fig. 2.

CALIBRATION

The procedure for the calibration of the beam position monitors is based on two different steps:

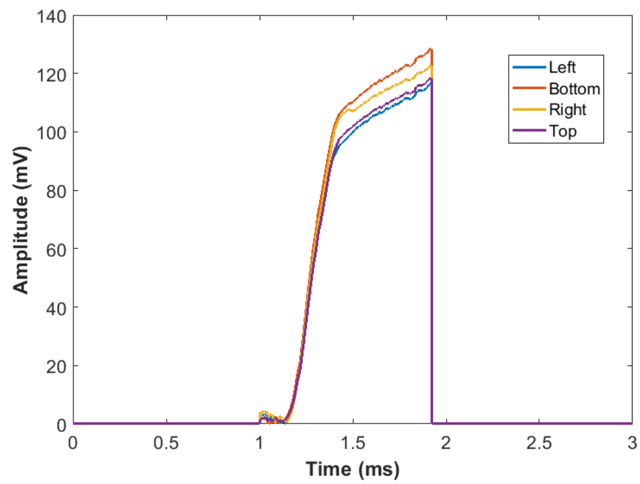

Figure 2: Example of evolution of the amplitude measurement of the four electrodes of a BPM during a single beam pulse.

- Calibration of the acquisition electronics (analog frontend plus digitizer). The signal from a calibrated signal generator is injected into one of the channels and the amplitude and phase signals acquired.
- Calibration of the cable path between the pickup and the electronics. This is the most tricky part due to the long distance between them. Almost 50 m exists between the MEBT pickups and the electronics, and more than 70 m in the case of the DPLA one. Several methods were tested, but due to limitations of the present AFE board, the method consisting in the evaluation of the calibration signal coupled to the near electrodes was chosen. This method has provided good results for the DPLA BPM's, but it is still not satisfactory for the MEBT ones due to the much lower coupling at those BPM's.

The amplitude and phase measurements are then corrected for the DPLA BPM's using the two constants calculated from both calibration steps. In the case of the MEBT BPM's further analysis is required in order to find a good method. For this reason, only measurements based in the DPLA BPM's are presented along this contribution.

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PICKUP SETTINGS

Each pickup is defined by a series of constants which identify their response to the beam stimulus. For simplicity, during the first run the constant of the pickups of the MEBT and the ones of the DPLA were grouped and set to the same value. As found during the test bench measurements [3], inversed sensitivities at 175 MHz for 5 MeV of 22.76 mm and 41.4 mm were set to the MEBT and DPLA BPM's respectively.

In case of the constant for the beam current extrapolation it is not so straightforward. The signal generated in the beam position monitor electrodes depends on the beam current but also on the bunch length, and to the beam energy and the transverse position to some extent. These properties have been used to get relative measurements of the bunch length as shown later.

POSITION MEASUREMENTS

The main goal of the electromagnetic stripline pickups is to monitor the transverse position of the beam centroid. In order to validate the measurements obtained with the pickups a bunch of tests were carried out both with proton and deuterons.

Resolution

The inherent resolution of the pickup can be determined by the use of the three last beam position monitors in the DPLA, where only beam expansion and no magnetic element exists. To discard the beam jitter and other errors coming from the beam itself, the method described in [4] is used. According to this method, the position in the middle beam position monitor is interpolated with the position of the first and last beam position monitor. The residual x, y_{res} of the difference between the measured x, y_{D2} and the interpolated $x, y_{\mathrm{calc,D2}}$ one is proportional to the resolution of the beam position monitor.

It is assumed than the three beam position monitors in the DPLA have the same inherent resolution σ_{D}, which is related to the residual measured resolution $\sigma_{\mathrm{D2,\,mes}}$ as:

$$\sigma_{\mathrm{D}} = \sigma_{\mathrm{D2,mes}} \sqrt{\frac{(L_1 + L_3)^2}{(L_1 + L_3)^2 + L_1^2 + L_3^2}} \qquad (1)$$

where L_1 is the distance between first -D1- and second -D2- DPLA BPM's, and L_3 the one between D2 and the third BPM -D3-, which in our case is 0.16 m and 1.11 respectively. In Fig. 3, it is shown the measurement of the D2 residuals and the gaussian fitting of the resolution.The result is a $\sigma_{\mathrm{D2,mes}}$ of 29 µm in horizontal axis and 15 µm in vertical for an averaging time of 400 µs. Thus, σ_{D} for a beam current of 100 mA and an averaging time of 400 µs is 22 µm in horizontal and 12 µm .

Steering

A steering magnet was used to create a dipole kick to the beam and analyze the sensitvity of the beam position monitors. Figure 4 summarizes the results for the vertical kick. The results, a slope between the expected and the measured values of 0.88 for D1 and D2 and 0.97 for DBP03, show the agreement is not bad from the kick expected from the dipole magnetic field to the measured one. However, there are several uncertainties to be considered for further analyses: 1) the real magnetic field created by the beam, 2) studies with a dedicated beam dynamics code. Moroeover, dedicated tests will be foreseen in the next runs using the slits in the DPLA.

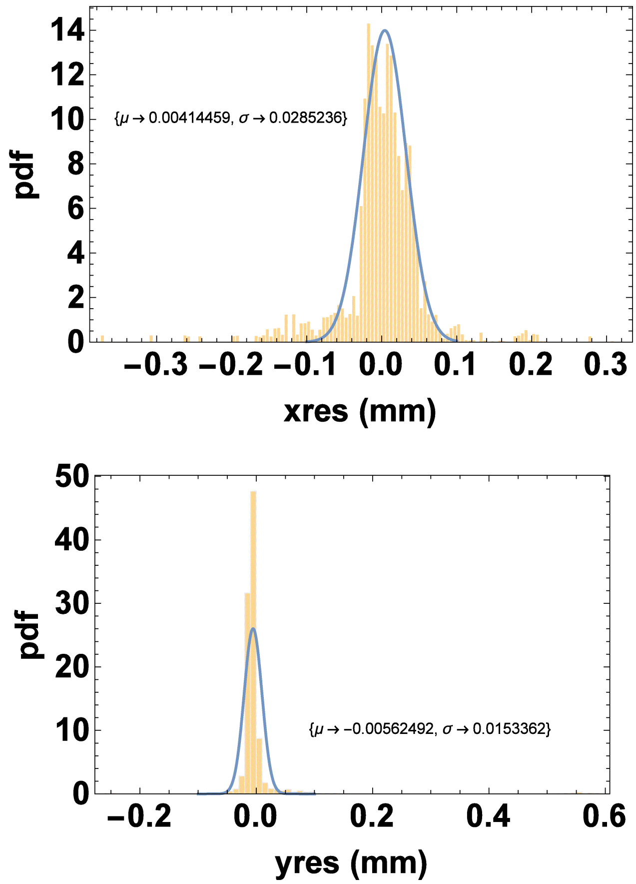

Figure 3: Resolution of the position measurement in DBP02 in horizontal (top) and vertical.

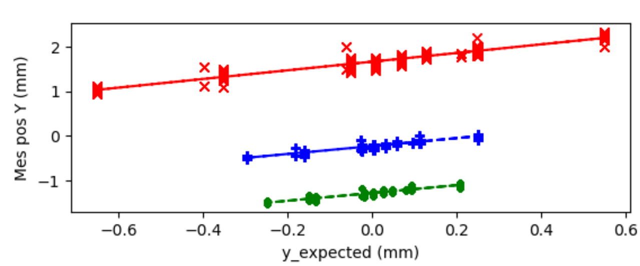

Figure 4: Horizontal steering tests of the DPLA BPM's: D1 (green), D2 (blue) and D3 (red).

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PHASE MEASUREMENTS

Apart from the beam position, the pickups are able to sense the longitudinal phase of the bunches. This provides essential information for the characterization of the accelerating and the buncher cavities, like the beam energy or the bunch synchronization.

Measurement Errors

The error of the measurements is made of several sources:1) The positioning error of each BPM. This error is calculated by using the standard deviation error given by the metrology survey of the accelerator. In the case of the MEBT and DPLA BPM's this error is kept under 150 µm. 2) The error in the phase measurement. This error is driven by the long path (50 and 80 m) between the BPM location and the acquisition electronics, and it is minimized by cable matching during the installation.

Proton Measurements

The phase measurements of the beam position monitors were used using the time of flight techniqueto determine the energy of the proton beam. The beam was 52 mA with a pulse width of 300 µs and a repetion rate of 1 Hz with old calibration method for the cables. The measurement was compared with the different electrodes of each BPM in the DPLA, as see in Fig. 5. The mean energy is established to 2.47 keV.

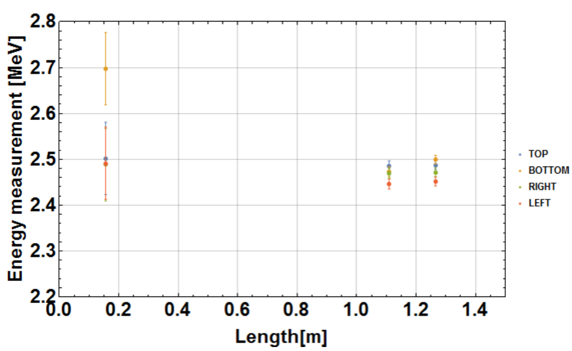

Figure 5: Energy measured at the DPLA for a 52 mA proton beam.

Deuteron Commissioning

Several measurements of the beam phase and energy were obtained for different machine configurations. As an example, the energy was obtained before and after the change of the acquisition electronics for low and high deuteron current, see Figs. 6 and 7, respectively.

CURRENT MEASUREMENTS

Another information that is provided by the pickups is the sum signal of the electrodes, which is related with the beam current as a first approach. In addition, as seen in Fig. 7, for a certain stable beam current and energy, the BPM sum voltage can provide important information about the longitudinal structure of the beam. For example, in

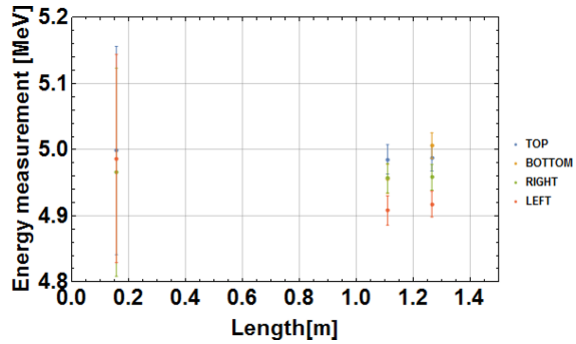

Figure 6: Energy measured at the DPLA for a 24 mA deuteron beam with the first digitizers.

case the field is increased in the buncher cavities from 40 to 280 keV, the BPM current is more than 30% bigger. From this data, further analysis will be carried out together with beam physics simulations in order to compare the measured BPM current with the expected bunch length.

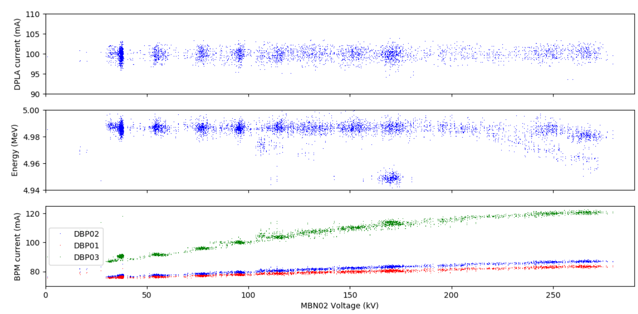

Figure 7: Evolution of the beam current, beam energy and BPM current during a voltage scan of the second buncher cavity for a 100 mA deuteron beam using the upgraded electronics.

CONCLUSIONS AND OUTLOOK

The beam position and phase monitors of LIPAc have been successfully commissioned during the pulsed deuteron beam commissioning both with protons and deuterons at the output of the LIPAc RFQ. Up to 125 mA have been transported up to the low power beam dump using the beam position monitors. A new electronics has been installed in preparation for the new commissioning stage, where twenty BPM's will be installed. The new electronics integrates digital synchronization with the RF system by the use of White Rabbit, and intra-pulse monitoring of the main parameters measured by the BPM's.The calibration method for the energy measurement has been validated, similar results have been obtained before and after the electronics upgrade. The pickups have been fully characterized and the measurement corrected accordingly. The postprocessing of the data continues and it is expected that beam position monitors yield precious information about the longitudinal shape of the beam and the beam transport optimization for the next phases, once the duty cycle is increased up to continuous mode and the superconducting linac is installed downstream later on.

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