OPERATIONAL EXPERIENCE WITH BEAM ALIGNMENT AND MONITORING USING NON-DESTRUCTIVE BEAM POSITION MONITORS IN THE CYCLOTRON BEAMLINES AT ITHEMBA LABS *

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Abstract

At iThemba LABS proton beams, accelerated in a K=200 separated-sector cyclotron with a K=8 solid-pole injector cyclotron, are utilized for the production of radioisotopes and particle radiotherapy. Low-intensity beams of light and heavy ions as well as polarized protons, pre-accelerated in a second injector cyclotron with a K-value of eleven, are available for nuclear physics research. Beam position monitors and associated computer-controlled electronic equipment have been developed for non-destructive alignment and continuous display of the beam position in the beam lines for the more intense beams used for therapy and the production of radioisotopes in cooperation* with Forschungszentrum Jülich. The monitors consist of four-section strip lines. Narrow-band super-heterodyne RF electronic equipment with automatic frequency and gain control measures the signals at the selected harmonic. A control module sequentially processes the signals and delivers calculated horizontal and vertical beam position data via a serial network to the computer control system. Eleven monitors have been installed in the beam lines. Operational experience with alignment and monitoring of the beam position is discussed.

BACKGROUND

The design and implementation of a prototype non-destructive beam position monitor and associated electronic module for signal processing in beam lines at iThemba LABS [1] have been reported before [2]. Since then eleven monitors and electronic modules have been manufactured. Four of these monitors, which have been planned for beam intensities of one μA and more, have been installed in the transfer beam line between the light-ion injector and the separated-sector cyclotron and the remaining ones in the high-energy beamlines leading to the neutron therapy and isotope production vaults. The main design considerations and limitation for the monitors, which should measure the beam position in both the horizontal and vertical directions, are that they have to be installed through the beam ports of the diagnostic vacuum chambers in the beam lines and fit into the available space together with the existing other diagnostic components. Since the cyclotrons are in operation for 24 hours per day and seven days a week the diagnostic chambers could not be removed for machining of additional flanges. The electronic modules were designed and built at the Forschungszentrum Jülich-IKP, as part of the work done under a scientific and technological agreement between Germany and South Africa.

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THE POSITION MONITOR

The four electrodes of the monitors are mounted co-axially inside a cylindrical copper housing as shown in Fig. 1. Although the prototype monitor, described before [2], could fit in the diagnostic vacuum chambers installation of the semi-rigid cables inside some of the chambers was difficult. In the final design the overall length of the monitors is therefore 15.5 mm shorter than before and have the dimensions shown in Fig. 1. The length of the electrodes, which are connected through 50 ohm resistors to ground inside the vacuum chambers, remained the same as before.

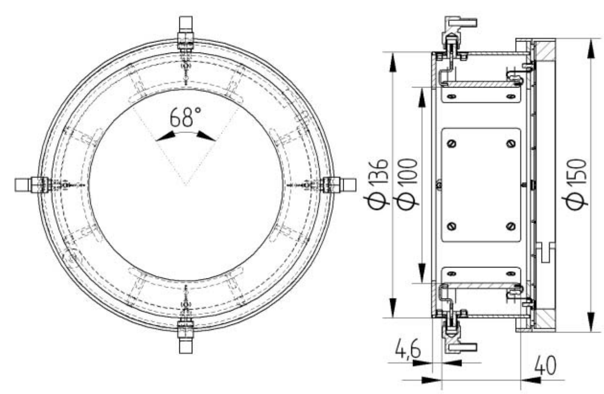

Figure 1: Front view and cross-section drawings of the beam position monitor with 50 ohm terminations on the electrodes.

ELECTRONIC SIGNAL PROCESSING

A block diagram of the electronic equipment used for signal processing of each of the eleven monitors is shown in Fig. 2. A GaAs RF multiplexer switches the monitor signals to the input of the common signal chain. In each acquisition cycle the four signals are sequentially measured before the position data are computed. The RF part, consisting of narrowband super-heterodyne RF electronics, processes the monitor signal components at the selected higher harmonic of the cyclotron RF frequency. The center frequency is programmable between 49 and 82 MHz. Automatic frequency and gain control tracks the signal changes. The overall bandwidth can be set in 12 steps between 0.18Hz and 1kHz by means of analogue BPF and digital FIR filters. A micro-controller controls the tuning, measuring and filtering functions according to the remotely set parameters. The non-linearity in the strip-line pickup is corrected for each position readout using a 2D stored array, determined by calibration of the monitor on an xy-table with the beam simulated by a conducting rod with an RF voltage applied to it.

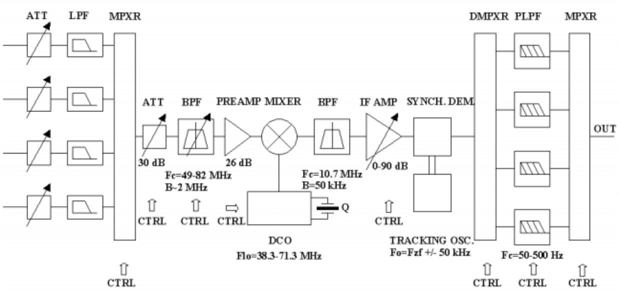

Figure 2: Block diagram of the electronic equipment for signal processing.

HARDWARE IMPLEMENTATION

To avoid radiation damage from the beam the electronic modules were placed outside the cyclotron and beam line vaults. Cable lengths were kept as short as possible by putting each module into the nearest electronic area. As a result, the BPM-stations were arranged in two groups: four units for the monitors in the transfer beam line in the low-energy electronics area and seven units for the monitors in the high-energy beam lines in another electronics area close by. The distance between the two groups is about 50 m.

The electronic modules are equipped with CAN-standard signal interface and use a dedicated serial protocol. They are connected to the serial port of the control computer with a CAN/RS232 converter. Due to the total length of the serial cable an additional bus driver was also installed. All these units with the control PC were placed in the low-energy electronics area.

ELIMINATION OF INTERFERENCE AND SENSITIVITY

Pickup on the electrodes of the beam position monitors at the fourth harmonic of the main RF systems and the second harmonic of the rebuncher, at which it was initially planned to use the monitors could be reduced to below –135 dBm, a level that can also not be detected by the electronic equipment, using cables with solid outer conductors and by proper tightening of the connectors with a wrench, even for monitors installed a few cm away from the rebuncher.

In the diagnostic chambers in which profile grid monitors (harps) are situated RF is introduced into the chambers through the large number of cables connected to the harp wires, leading to pickup on the beam position monitors. The pickup could be eliminated by connecting resistors in series with the harp wires directly outside the chambers to form RC filters with the 30 pF stray capacitance of each harp wire connection inside the chamber.

The slightly wider frequency range than originally planned, in which the electronic equipment can work, also allows the use of the fifth harmonic (81.85 MHz) for the 66 MeV beam. For the 200 MeV beam the third harmonic (78.3 MHz) is used. No pickup could be detected at these harmonics with a spectrum analyzer or the signal processing electronics.

The signal strengths at the input of the electronic equipment are –90 dBm for 1 μA in the transfer beam line and –107 dBm in the high-energy beam line. In the transfer beam line beam alignment worked well at proton beam currents as low as 40 nA, whereas in the high-energy lines beam currents of the order of 700 nA have to be used for alignment. For heavy beams, which move much slower, the charge density in Coulomb per meter in the beam packets is higher and the packets shorter resulting in greater sensitivity of the monitors. A 170 nA beam of 90 MeV carbon ions could be aligned with the monitors in the high-energy lines. By using a monitor without the 50 ohm resistors on the electrodes in the diagnostic vacuum chambers the sensitivity could be increased by a factor of almost two.

SOFTWARE FEATURES

Server-client architecture was chosen for the control programs to provide sufficient flexibility in development and operation. The server that runs on the control PC is the only program that can control the BPM-stations. A driver library was written for the server to perform the low-level communication with the control registers of the modules. The main tasks of the server program are:

1. Checking the status of the stations. It detects any newly connected or disconnected station on the bus. The updated list of the properly operating stations is sent to all clients.
2. Initialization of all available stations according to the actual value of the RF and the harmonics used for the position measurement.
3. Reading measured signal values regularly from those stations that are requested by any client and sending calculated position data to the appropriate client.
4. Forwarding control commands from any client to the requested BPM-station.

Two clients have been developed so far. The first one can be used for the control of a single BPM. It displays the position of the beam centre as measured by the selected monitor in the xy-plane, and displays the distribution of the measured horizontal and vertical position values as well. This client can connect to any BPM, even if the monitor is in an unused beam line or the beam is stopped at an upstream Faraday cup. This way it can also be used for noise and accuracy test measurements.

The second client works only with monitors installed in the actually used beam line. It gives an overall view about the transport of the particle beam along the line by depicting the measured positions at all monitors and connecting these points with a straight line both in horizontal and vertical planes. The resulting central-trajectory-like curves provide a very good visual measure of beam line settings, displaying the propagation of beam offsets along the transport system. A typical picture of this client is shown in Fig. 3.

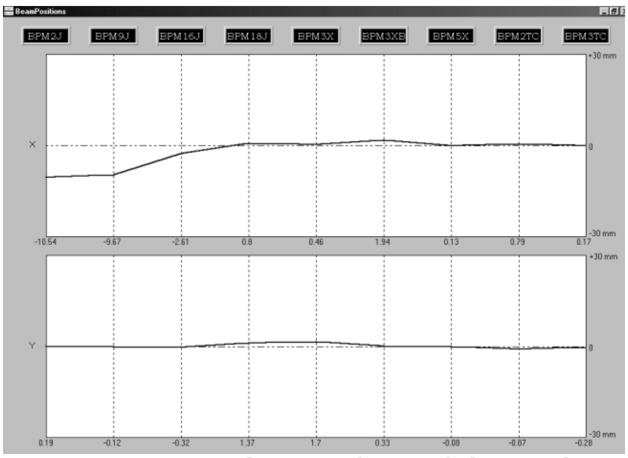

Figure 3: Horizontal (top) and vertical (bottom) beam positions measured along the beam lines from the injector cyclotron to the therapy vault in the high-energy beam line. The scale ranges are from minus to plus 30 mm. Directly downstream from the injector cyclotron the beam is about 10 mm off center in the horizontal direction.

BEAM ALIGNMENT

There are four sections in the beamlines where the arrangement of two BPMs and two steerer magnets can be used for automated beam alignment. This feature has been added to the second client. When using this option, the client program reads the positions measured by both monitors and the actual current of the steering magnets as well. From these data a transcendental equation can be written with just one unknown variable – it is the angular divergence of the central particle at the entrance point of the alignment section. After solving numerically this equation, the required changes in the steerer currents can be calculated to align the beam with the beam line axis downstream of the second steerer magnet. The client then writes the new current values into the appropriate variables of the control system.

A typical result of the automated beam alignment is shown in Fig. 4, where the beam has deliberately been steered off center with a bending magnet upstream of the steering magnets and beam position monitors. The distributions of the measured position values are displayed for both monitors. As can be seen, the beam position at the second monitor (at the bottom), after the second steering magnet, is well centred on the axis. The beam position indications of the monitors agree with those of the harps in the same diagnostic chambers.

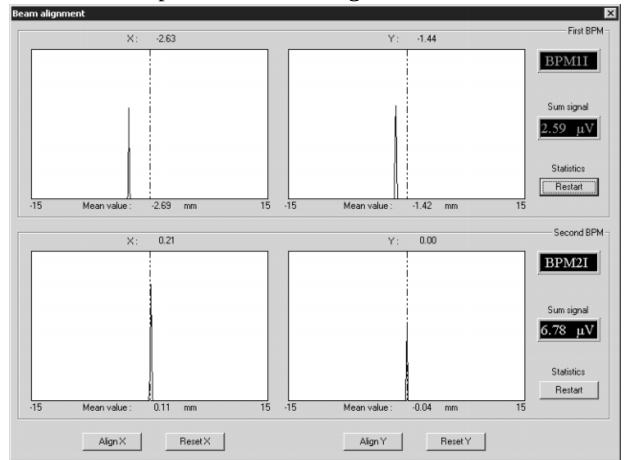

Figure 4: The user interface displayed for beam alignment. The aligned beam is centred at the second (bottom) BPM. The scale ranges are from minus to plus 15 mm.

CONCLUSIONS

Automatic alignment of the beam without mechanical insertion of beam intercepting diagnostic devices and continuous display of the beam position throughout the facility, as well as the fact that the effect of an adjustment to a cyclotron or beam line parameter on the beam position can be directly observed throughout the downstream part of the beam lines, proved to be very useful in the day-to-day operation of the beam lines. Beam alignment can now also be done at high intensities, thereby reducing beam losses and activation of components, since the beam center depends to some extent on the slit settings. Fast variations in the beam position, due to instabilities, could previously not be detected with the harps because of the slow electronic equipment used for current measurement. With the beam position monitors such variations can be instantaneously observed. For these reasons it is planned to install more monitors in the beam lines. The possibility of using the same electronic modules for different monitors by multiplexing between beamlines that are not simultaneously in use will be investigated.

REFERENCES

[1] J.L. Conradie et al, Cyclotrons at iThemba LABS, Proc. of the 17th Int. Conf. on Cyclotrons and their Applications (Cyclotrons'2004), Tokyo, October 2004, to be published.

[2] J. Dietrich et al, Beam Position Monitor Development for iThemba LABS Cyclotron Beam Lines, EPAC'2004, Lucerne, July 2004, p.2589.