BEAM POSITION MONITOR DEVELOPMENT FOR ITHEMBA LABS CYCLOTRON BEAM LINES*

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Abstract

At iThemba LABS intense proton beams, accelerated in a K=200 MeV separated-sector cyclotron with a K=8 MeV 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 measurement and alignment are done semi-destructively with profile grids at beam intensities of less than 1 µA. A prototype beam position monitor 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. iThemba LABS developed and manufactured the four section strip-line monitor chamber. The electronic equipment was developed at the Forschungszentrum Jülich-IKP, as part of the work done under a Scientific and Technological Agreement between Germany and South Africa. The equipment, consisting of an RF signal processing module (BPM-RF) and a data acquisition and control module (BPM-DAQ), sequentially measures and processes the monitor signals and delivers calculated horizontal and vertical beam position data via a serial network.

INTRODUCTION

At iThemba LABS [1, 2] a 30 µA beam of 66 MeV protons is used to bombard a Beryllium target for neutron therapy. Between treatments the beam is switched to the radioisotope production vault and the intensity is increased to 100 µA. The main RF-systems operate at 16.37 MHz and the rebuncher, in the transfer beam line between the injector and separated-sector cyclotron, at 32.74 MHz. For proton therapy a 200 MeV beam is used and the main RF-systems and rebuncher then operate at 26.1 MHz and 52.2 MHz, respectively. The beam current in the transfer beam line is 100 µA and in most of the high-energy beam lines 50 nA at 200 MeV. Beam alignment has to be done with preferably not more than 1 µA in order to prevent damage to sensitive components. The position and direction of the low intensity 200 MeV beam for proton therapy are continuously monitored and stabilized in the therapy vault using gas-filled profile monitors for beam position measurement. The position monitors will therefore not be used for the 200 MeV beam.

The beam pulse lengths vary from 1ns to 2.7 ns, and the charge per beam pulse from 385 pC to 611 pC per µA beam current, depending on the beam intensity and energy.

THE POSITION MONITOR

To limit the cost and down time of the accelerators the monitors should fit in the available space inside the existing diagnostic chambers and use existing flanges for feedthroughs, without remachining of the chambers. This limits the overall length of a monitor, which should measure the beam position in both the horizontal and vertical directions, inside the shortest diagnostic vacuum chamber to 60 mm, with allowance for existing diagnostic elements in the chamber. The inner diameter has to be larger than 100 mm to prevent interception of beam and the outer diameter smaller than 150 mm to allow installation through one of the round ports through which the beam enters or leaves the chamber. To prevent different designs and calibration factors a standard design suitable for all the beam lines and diagnostic chambers will be used.

The round port through which the monitors have to be installed suggests a cylindrical coaxial construction for the monitor electrodes and shield, instead of a square diagonally cut shoe-box monitors for which the inner diameter would be too small to allow for beam passage. It was therefore decided to use four electrodes, mounted co-axially inside a copper housing that can be inserted through a beam port. Contact fingers on the copper housing are pushed open by turning of a single nut on an internal clamp that presses contact fingers on the housing over the full circumference to the inside of the vacuum chamber port and thereby eliminating any inductance in the support structure of the housing.

Each electrode, which subtends an angle of 68°, is 40 mm long and has an inner radius of 65.5 mm. The electrodes have approximately the same length as the shortest beam pulse but are much shorter than the longest beam pulse with a length of 270 mm. Although the electrodes are short, and can be considered as buttons, they have nevertheless been dimensioned as 50 Ω strip lines and provision has been made for 50 Ω terminations at the downstream side of the beam to ensure addition of the inductively and capacitively coupled components of the signal. Semi-rigid cables, connected to the upstream side of the electrodes inside the vacuum chamber are routed to a flange with coaxial feedthroughs. Outside the chamber, for a distances of up to 2 meters, semi-rigid cables are used and from there coaxial cables with solid

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outer conductors connect the monitor to the electronic processing unit, at a distance of 20 m away outside the vault to prevent radiation damage to electronic components. Fig. 1 shows the housing and electrodes of the monitor.

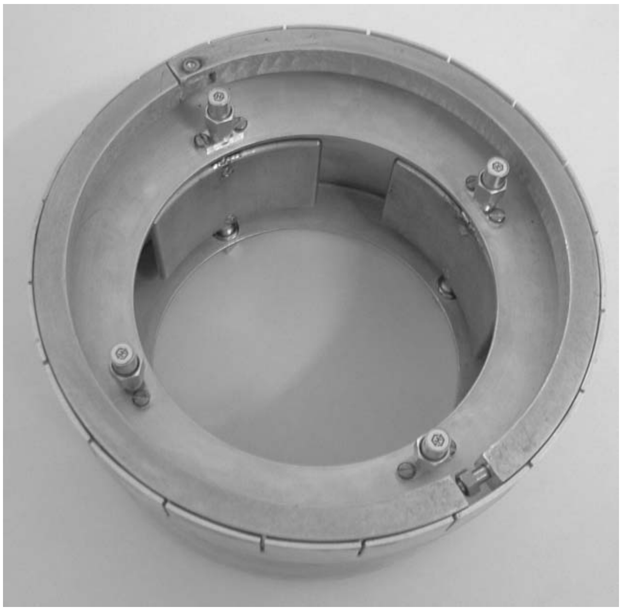

Figure 1: The beam position monitor.

To plan the electronic processing unit, and especially the small signal electronics, the monitor was installed close to the rebuncher in the transfer beam line to measure beam and unwanted signals with an oscilloscope and spectrum analyser. The amplitude of the bipolar beam pulses on the oscilloscope with 50 ohm input impedance, and 50 Ω terminations on the electrodes, were 7 mV for a 100 μA beam with the main RF systems running at 16.37 MHz. Fig. 2 shows the beam spectrum.

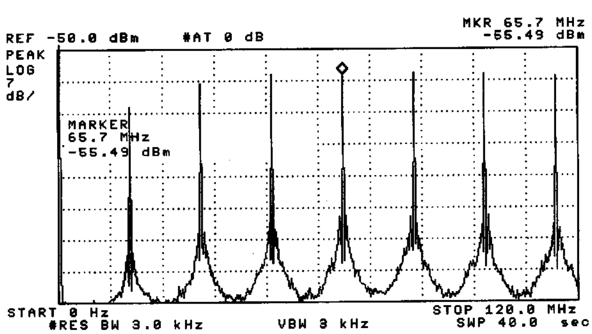

Figure 2: Beam spectrum measured with 50 Ω terminations on the monitor for a 100 μA proton beam in the transfer beam line.

With the main RF systems working at 26.1 MHz and the rebuncher at 52.2 MHz a signal of –82 dBm was measured at the rebuncher frequency without beam. That excludes beam measurement at this frequency. At the third harmonic, however, the signal strength without beam is –127 dBm. For 66 MeV operation the signal level, without beam, is –130 dBm at 65.48 MHz, the fourth harmonic of the main RF systems and the second harmonic of the rebuncher.

Since the first six harmonics in Fig. 2 have almost the same level and the second harmonic of the main RF systems cannot be used because of interference from the rebuncher, it was decided to use the third and fourth harmonics of the main RF systems for beam position For the 66 MeV and 200 MeV beams measurements will be performed at 65.48 MHz and 78.3 MHz, respectively.

CALIBRATION OF THE MONITOR

Since the voltages on the electrodes are not linearly related and accurately known as a function of the beam position with respect to the centre line, the monitor has been calibrated on an xy-table with the beam simulated with a conducting rod, tuned with an inductor to form an open-ended quarter-wave transmission-line resonator, driven by a sine wave generator at a frequency of 70 MHz. The voltages on the electrode were measured as a function of the x- and y-displacements from the centre line of the monitor. From the measured data, at intervals of 0.5 mm covering an area of 1600 square mm, a look-up table, that is used by the processing unit to calculate the beam position from the measured voltages on the four electrodes, has been compiled.

ELECTRONIC AND COMPUTER PROCESSING OF THE SIGNALS

The electronic equipment [3], consisting of an RF signal processing module (BPM-RF) and a data acquisition and control module (BPM-DAQ), sequentially processes and measures the monitor signals and delivers, via serial network, calculated horizontal and vertical beam position data. The GaAs RF multiplexer switches the monitor signals to the input of the common signal chain. In each acquisition cycle the four signals are subsequently measured before the position data are computed. Fig. 3 shows the RF Signal processing front-end unit. The RF part, consisting of narrowband super-heterodyne RF electronics, processes the monitor signal components at the selected higher harmonics. The center frequency is programmable between 50-80 MHz. The overall bandwidth can be set in 12 steps between 0.18Hz and 1kHz by means of analogue BPF and digital FIR filters. Automatic frequency and gain control tracks the signal changes. The data acquisition module consists of an 8bit micro-controller with an 8kbyte EPROM, 32kbyte RAM and built-in timer, half-duplex 1Mbit/s asynchronous serial interface with galvanic isolated twisted-pair transceiver for data communication, 12bit ADC for digitising of the demodulated electrode signals, a dual 12bit DAC for gain and filter control, several bits for timing and bandwidth control and a 3-wire serial interface for the control of the digital local oscillator. The firmware of the micro-controller controls the tuning, measuring and filtering functions according to the remotely set parameters. The strip-line pickup non-linearity will be corrected for each position readout, using a 3D stored array. Several BPM stations can be connected to the host computer via a common twisted pair serial bus cable. The stations are addressable. The host sets the parameter for the signal acquisition and processing and reads the measured data by means of uniform commands respectively. The prototype of the electronics has been manufactured and tested with simulated signals in the Forschungszentrum Jülich. For proper functioning of the equipment the difference in signal levels should not be more than 26 dB. It is planned that every monitor will have its own dedicated processing unit. This will allow independent frequency and bandwidth settings for every monitor, depending on beam intensity and RF interference levels at the different measuring points along the beamlines, and it will also speed up the rate at which beam position data can be acquired.

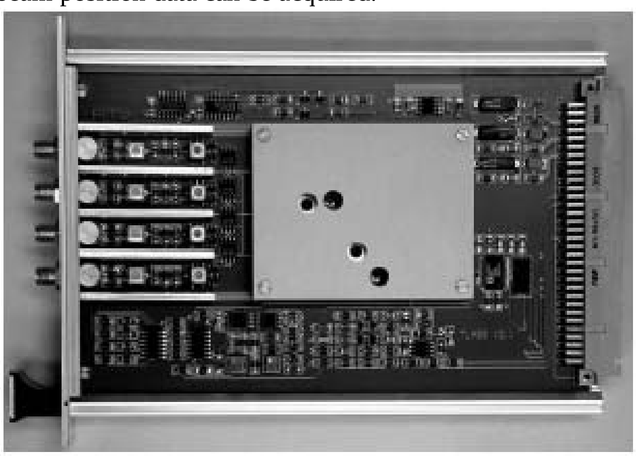

Figure 3: The RF signal processing front-end unit.

RESULTS OF MEASUREMENTS WITH BEAM

One monitor with its electronic processing unit has been installed in the transfer beam line between the two cyclotrons and has been found useful not only for monitoring the day to day beam position after energy changes but also for observing the drift in the beam position and the confirmation of short term beam stability. The monitor also gives a good indication of the order of magnitude of fast variations in the beam position by observing the spread in the display shown in Fig. 4. The beam position at the same point in the beamline has been measured at different intensities with and without the adjustment of bending and steering magnets. The change in the beam position could be followed to a beam intensity of less than 50 nA in the transfer beam line at 66 MeV operation. This is more than sufficient sensitivity for the purpose for which the monitors are intended. The monitor has also been installed for some time in the high-energy beam line, near but not directly next to a beam profile grid, and measurements were made on the 66 MeV beam. Again the currents through a bending and steering magnet were varied. The change in the beam position indication on the monitor could be followed and correlated with that on the profile grid with a beam current of less than 1 μA. These measurements, in the high-energy beam line, were made at a stage when the RF signal-processing unit has not been optimised for the design sensitivity.

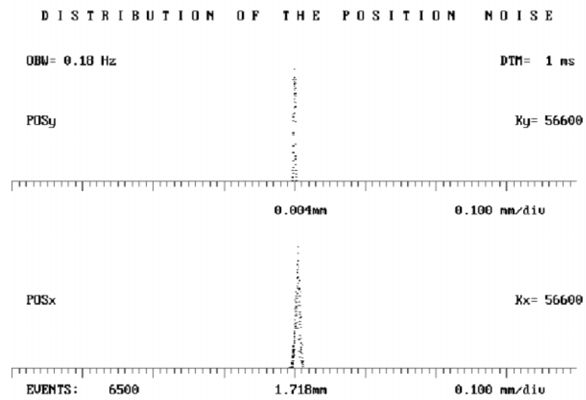

Figure 4: Vertical and horizontal graphic display of beam position distributions in the transfer beamline.

Since the four semi-rigid cables inside the vacuum chamber are arranged asymmetrically, because only one side flange is available for feedthroughs, it was necessary to ensure that the field around the beam and the flow of image charges are not distorted to such an extent that an offset would be measured for a centred beam. The symmetry of the beam position indication was therefore checked in the vacuum chamber in the frequency range 50 MHz to 80 MHz, by inserting a metal rod driven by a sine wave generator, in the center of the monitor. The offset in the horizontal and vertical positions is less than 0.1 mm over the whole frequency range. The monitor is insensitive to unsymmetrical grounding inside the vacuum chamber. Insertion of another diagnostic element, such as a phase probe, next to the monitor causes 0.15 mm shift in the displayed beam position.

CONCLUSION

The measurements with the position monitor and the operating experience with the equipment indicate that it will in future be a valuable addition to the existing diagnostic equipment and that it exceeds the required characteristics in terms of sensitivity and stability by far.

REFERENCES

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[3] J. Dietrich et al, IKP Annual Report 2003, Report Jül-4107 (2004).