NON-DESTRUCTIVE BEAM POSITION MEASUREMENT IN A PROTON THERAPY BEAM LINE*

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Abstract

Non-destructive beam position monitors (BPMs) have been in use at iThemba LABS for several years in the neutron therapy and radioisotope production beam lines, as well as in the transfer lines between the two K8 injector cyclotrons and the K200 separated-sector cyclotron. The sensitivity of these BPMs is limited by noise and pickup from the RF systems to about 300 nA in the high-energy beam lines. For proton therapy, using the scattering method, position measurements at beam currents as low as 20 nA have to be made. A new and more sensitive BPM as well as the electronic measuring equipment, using RF pickup cancellation and improved filtering, have been developed and installed in the proton therapy beam line. The BPM, the electronic equipment and the results of measurements at beam currents down to 10 nA for 200 MeV protons are described.

INTRODUCTION

Variable energy beams of light and heavy ions from ECR ion sources, as well as polarized protons, are used for nuclear physics research at iThemba LABS [1]. A high intensity 66 MeV proton beam can be switched between vaults for neutron therapy and radioisotope production for medical and industrial purposes. Proton therapy has been practised since 1993 with a 200 MeV beam at beam intensities of between 20 nA and 70 nA, using gas-filled multi-wire and segmented ionization chambers for beam position measurements. Non-destructive BPMs [2,3] that can fit in any of the standard beam diagnostic chambers together with other diagnostic elements were developed and installed in the high intensity beam lines. The sensitivity of these BPMs is not sufficient for use in the proton therapy line, owing to the dimensional restrictions on their length, noise in the solid state multiplexers and pickup from the main and the two flat-topping RF systems, that operate at the third and fifth harmonics, as well as from the rebunchers, that operate at the second and fourth harmonics.

The usefulness of the existing BPMs, not only for beam alignment and position monitoring, but also for detecting sources of beam instability, provided the incentive to investigate the possibility of building BPMs with greater sensitivity. Since beam phase measurements [4] in the separated-sector cyclotron could be made at beam currents in the nA range by cancellation of the relatively large pick-up signal, it seemed feasible that the same technique could be used for BPMs in the beam lines, where the level of the pick-up signals is much lower, to improve the sensitivity to such an extent that they can be used in the proton therapy beam line and perhaps also in the nuclear physics beam lines, where low intensity beams with variable energy are used. Tuned BPMs [5] were not considered because of the variable frequency operation of the accelerators. A new BPM, and a test set-up for signal processing electronics, similar to that which is used for beam phase measurements, was designed and built from available amplifiers, filters and measuring equipment. From past experience with the BPMs it is known that the level of the pick-up is the lowest at the third harmonic, i.e. at 78 MHz, for the 200 MeV proton beam. At 66 MeV the pick-up signal that is caused by the flat-topping system of the light-ion injector cyclotron is the lowest at the fifth harmonic, i.e. at 81.8 MHz. The third harmonic flat-topping system of the separated-sector cyclotron causes a much larger disturbance. The signal processing equipment was therefore built to operate in a 10 MHz band centred at 80 MHz.

THE BPM

The influence of the electrode dimensions on the signal level and harmonic content for different beams was calculated according to the method described by Timmer et al. [6]. The BPM electrodes are considered as capacitors that are charged by the beam and discharged through a resistor connected to ground. To verify the order of magnitude of the calculated value, a simpler and less accurate method, which assumes that charge appears only on the inside of the electrodes when the beam enters the BPM, and similarly disappears from the inside when the beam leaves it, was used to calculate the beam pulses with Laplace transforms. With the second method the pulse form differs, as can be expected, significantly from those of the first, but there is good agreement between pulse and harmonic amplitudes. The main BPM dimensions are shown in Fig. 1. To obtain larger harmonic

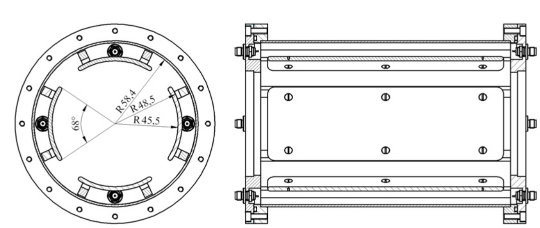

Figure 1: Cross-sectional views of the BPM.

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amplitudes than with the existing BPMs it was found necessary to deviate from the previous design by increasing the length of the electrodes to 170 mm, which is the physical length of the 200 MeV proton beam pulses. The BPM can therefore no longer fit into the standard diagnostic vacuum chambers and has to be installed separately from these chambers. A further increase in the length would result in an increase in the amplitudes of the first few harmonics of the beam pulses but was not implemented to take future space requirements into consideration. Each electrode extends over an angle of 68 degrees and has an inner radius of 45.5 mm to prevent interception of beam. The inner diameter of the beam pipe where the BPM is installed is 73 mm. SMA connectors on both sides of each electrode provide the facility to terminate the electrodes on both sides. Numerical field analyses, using finite element methods with the program TOSCA [7], showed that for a beam diameter of 10 mm the image charge on an electrode is 23.5% of the beam charge. The calculated rms signal levels, with only one termination on each electrode, for 1 nA proton beams are 10.7 nV for the fifth harmonic (81.86 MHz) at 66 MeV and 7.1 nV for the third harmonic (78 MHz) at 200 MeV, assuming homogeneous charge distributions in the beam pulses and pulse lengths of 13 and 9 degrees, based on previously determined beam pulse lengths as measured with capacitive phase probes, respectively. The calculated height of the beam pulses depends strongly on the assumed pulse length but the amplitudes of the harmonics do so to a much smaller degree. For heavy ion beams the signal levels are appreciably higher than that of the 66 MeV proton beam. The amplitudes of the lower harmonics are not sensitive to the inner probe radius and capacitance.

SIGNAL PROCESSING

Figure 2 shows a simplified block diagram of the electronic equipment for processing the beam signals. Because of the occasional high radiation dose in the area where the monitor is installed the multiplexer, comprising of electromechanical RF switches, and the first two amplifiers were installed in a separate electronics area and connected to the BPM through 20 m long cables, with solid outer conductors. The remaining equipment in Fig. 2 was installed in the control room, about 40 m away from the first two amplifiers. The overall attenuation in the cables is 1.57 dB. Included in the gain of the first amplifier, which has a noise figure of 1.2 dB, is the loss of the 1 dB attenuator at its input, which is essential for stability when connecting the input to a long cable. The overall amplification factor, including the cable loss and the 3.3 dB attenuation in the signal combiner, is 71.9 dB, which means that for 1 nA proton beams an amplitude of 42.4 μV for the fifth harmonic at 66 MeV and 28 μV for the third harmonic at 200 MeV can be expected at the input of the lock-in amplifier. Included in the final amplifier stage are an amplifier that limits the output signal level and an attenuator for protection of the final amplifier. To cancel the pick-up signal from the RF systems the beam signal is combined with the appropriate harmonic generated by a synthesizer with a signal of the main RF system as a reference. The phase and amplitude of the harmonic can be adjusted by computer control. This can be done by using previously measured calibration data of the synthesizer, or by measuring the phase and amplitude of the combined signals and those of the synthesizer signal separately. From these values the required phase and amplitude settings of the synthesizer can be calculated, provided that the amplitude and phase of the pick-up signal are stable. Noise in the output signal of the combiner is filtered in the lock-in amplifier, which provides filters with time constants ranging from 0.1 ms to 30 ks with 6, 12, 18 and 24 dB/octave roll-off. The effective time constant is approximately equal to the selected time constant, times the number of dB/octave roll-off as a multiple of 6 dB.

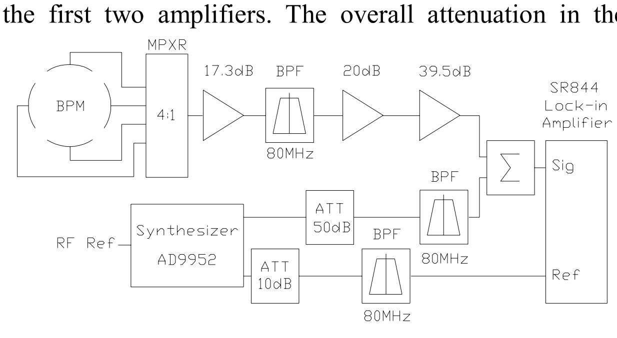

Figure 2: A simplified diagram of the signal processing equipment.

RESULTS OF MEASUREMENTS

Measurements were made mainly on the 66 MeV proton beam since it was the most often available. In terms of pickup it is the worst case since one of the RF systems, the flat-topping system of the injector cyclotron for light ions, operates at the measuring frequency. For 200 MeV only harmonics from the main RF systems contribute to pickup.

For the 66 MeV proton beam the measured amplitude of the fifth harmonic, after amplification, is 37 μV/nA. The calculated value is about 11% higher. For the 200 MeV proton beam the measured amplitude is 26.5 μV/nA. These measurements were made after pickup cancellation and at such high beam intensities and long time constants that the resultant pick-up signal and noise were insignificant.

The beam pulse amplitude of the 66 MeV proton beam has been measured at a beam current of 10 μA, with both ends of the electrodes terminated with 50 Ω resistors, one of these being the input resistance of a 40 dB wideband amplifier. The measured amplitude is 170 mV and the calculated value is 127 mV. The amplitude of the beam pulses is enhanced by the inductance in the leads that connect the electrodes to the feedthroughs. The effect of the inductances can also be seen in the presence of oscillations in the tail of the measured pulses. Since the electrodes are essentially transmission lines and not capacitors, it is to be expected that the measured amplitudes will be higher than the calculated ones. This, and the effect of the inductances have been verified by modelling the BPM electrodes with a circuit analysis program. The use of a different type of feedthrough, which will allow connections with much less inductance, is planned.

The amplitude of the pick-up signal varies from week to week since the amplifiers of the RF systems are retuned during beam energy changes. The pick-up signal level during operation with the 66 MeV proton beam is typically below 10 μV. For a nominal signal level of 7 μV the amplitude varied, partly due to noise, by plus and minus 1 μV over a 6-hour period. Variations in the amplitude and phase of the signal from the synthesizer are negligible compared to those of the pick-up signal. The combined pick-up and synthesizer signals can be reduced in a single step to below 1 μV by measuring the amplitude and phase of the synthesizer and the combined signals and adjusting the synthesizer signal to newly calculated settings. For the 200 MeV proton beam the amplitude of the pick-up signal, without cancellation with the synthesizer signal, is typically 2.4 μV.

The overall limitation to the lowest beam intensity at which the BPM can be used is determined by the time constants of the filters for noise reduction that are acceptable and measurement accuracy that is required. To keep the measured noise level below 2 μV, a time constant of 3 s and 24 dB/octave roll-off were selected. For a time constant of 1 s and the same roll-off, the noise level increases to above 3 μV.

Figure 3 shows measured BPM signals as well as estimated beam positions, based on measured and calculated beam signals as a function of the actual beam position. The difference between the estimates, based on measurement and calculation, is due to the different beam sizes and the dispersion in the beam directly downstream from the switcher magnet. From figure 3 it is clear that the BPM has to be calibrated, as was done with the BPMs that were built previously.

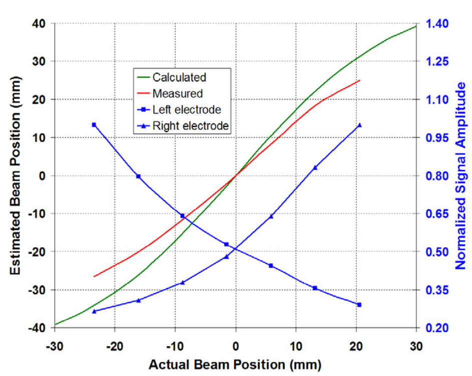

Figure 3: The calculated and measured beam position estimates as a function of the beam displacement. The measured beam position is the difference over the sum of the measured electrode signal s, multiplied with the inner radius of the BPM electrodes. For the calculated beam position, the signal levels on the electrodes were determined with the computer program TOSCA, for different positions of a 10 mm diameter beam. The actual beam positions in the BPM were calculated from the excitation current of the switcher magnet.

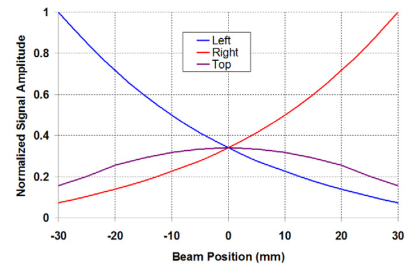

Figure 4: The calculated BPM signals as a function of horizontal displacement of a 10 mm diameter beam.

CONCLUSION

The lower beam current limit at which the BPM and the signal processing equipment described above can be used is a function of the acceptable measurement time and the required positional accuracy. At a beam current of 10 nA, the measurement time is estimated at fifteen seconds per electrode for a positional accuracy of 1 mm, provided there are no beam current variations during the measurement of the signals on the four electrodes. To eliminate the effect of such variations further averaging of the measured values is required.

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