A NEW BEAM POSITION MONITOR FOR THE TRIUMF CYCLOTRON BEAMLINES

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Abstract

The TRIUMF cyclotron provides a 500 MeV proton beam to the ISAC RIB facility. The development of targets capable of handling ever higher beam currents for RIB production imposes an increasing demand on proton beam control and stability. As a part of the effort, an upgrade of the beam position monitors in our transport lines is underway. The new design improves both the precision and accuracy of measurements. The BPM electronics developed in house are based on a GaAs multiplexer and a logarithmic amplifier with a 90 dB dynamic range which provides detection of the signals from the monitor electrodes. A mixed signal 160 MIPS DSP is used for data sampling and processing.

INTRODUCTION

Several proton beams with various intensities and energies can be simultaneously extracted from the TRIUMF H^- cyclotron and delivered to users. Beamline 2A transports a 500 MeV proton beam with currents ranging from a few nA to 100 µA to a solid target where radioactive ions are produced for the ISAC radioactive ion beam (RIB) facility. It is essential to control the beam current and beam position on the target to improve the ion production and the target lifetime. Harps, blade scanners and halo monitors are used for beam monitoring as needed. However, continuous beam measurement has become a necessity for new high power targets. A program of developing non-intercepting diagnostics is underway. In the framework of the program, a new beam position monitor (BPM) of the inductive type and associated wide dynamic range electronics have been designed and built.

THE BPM MONITOR

The BPM consists of four orthogonal inductive loop pickups which are sensitive to the azimuthal component of the time-varying magnetic field of the bunched beam. The proton beam current extracted from the cyclotron consists of a train of 0.5 to 5 ns wide bunches at 23 MHz. The train itself is 1 kHz pulse modulated with a variable duty cycle between 0.1 and 99.2%. In the frequency domain the beam induced signal in the pickups is represented by harmonics of 23 MHz up to about 1 GHz.

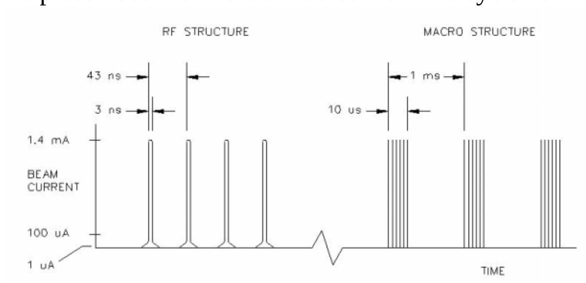

Figure 1: The time structure of the extracted TRIUMF proton beam.

The requirements of the monitor are driven by the accuracy of the beam position measurement and by beam spill considerations. To minimize spills caused by the interaction with the beam halo the inner diameter of the monitor is slightly larger than that of the beam pipe. Other parameters are summarized in Table 1.

Table 1: Parameters of the BPM

Current measurement accuracy	<3%
Absolute position accuracy	0.5mm
Relative position accuracy	0.2mm
Resolution	0.2mm
Range of linearity to 0.1mm	13mm
Low frequency cutoff	100 MHz
Transfer impedance at 46 MHz	3.3Ω@50Ω load
Loop inductance	82 nH
Electrode inner diameter	110 mm
Body length/diameter	143 mm/171 mm

For economy the body of the monitor (Fig. 2) is manufactured of 178 mm diameter stainless steel tube with welded flanges on each end. The copper block of four electrodes is inserted into the body from one side and secured to the flange with screws. The electrodes are supported from the other side by a ceramic ring. The copper block is machined as one piece to achieve the required mechanical precision. Once the electrodes are

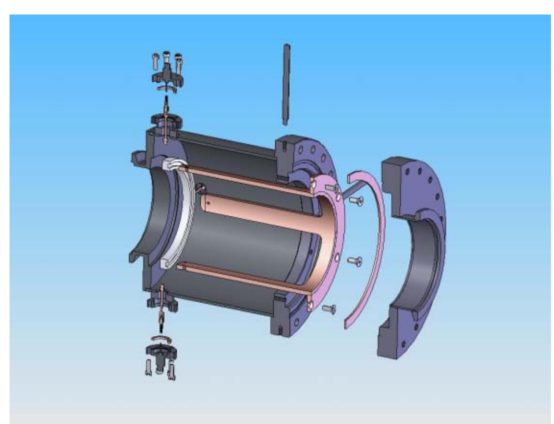

Figure 2: An exploded view of the sectional cut of the beam position monitor.

installed, the body is sealed with a conflat flange. The signals are taken from the electrodes by means of copper pins and flanged vacuum SMA feedthroughs. Four 75 mm long pins are attached to the flange for monitor alignment.

The transfer impedance of each pickup loop with an inductance Lp, external and internal radii a and b and length l loaded with a resistance R has a high pass filter characteristic:

$$Z_t = \frac{\mu_0 l}{2\pi} \log\frac{a}{b} \frac{\omega R}{\sqrt{\omega^2 L_p^2 + R^2}} \qquad (1)$$

with a corner frequency of $fc = R / 2\pi Lp$. For the 82 nH loop inductance the corner frequency is 97 MHz with a 50 Ω load. The relatively high corner frequency is not of concern since the difference in the output signal at the second (46 MHz) and higher harmonics does not exceed 3 dB taking into account losses in the signal cables. The transverse sensitivity of the monitor was calculated using formula from [1] to be 0.42 dB/mm and confirmed with the wire method. To ensure the required absolute accuracy the wire was moved through a set of 0.5 mm wide horizontal and vertical slits installed on both ends of the monitor. Using the slit masks, the wire could be aligned w.r.t. the mechanical center of the monitor with an accuracy of ~0.25-0.3 mm. The relative accuracy of the wire position was set by the stepper motor resolution of 0.015 mm. A typical linearity error of the monitor response to the displacement of the wire is shown is Fig. 3 The displacement characteristic is linear to 0.1 mm for excursions of up to ±13 mm.

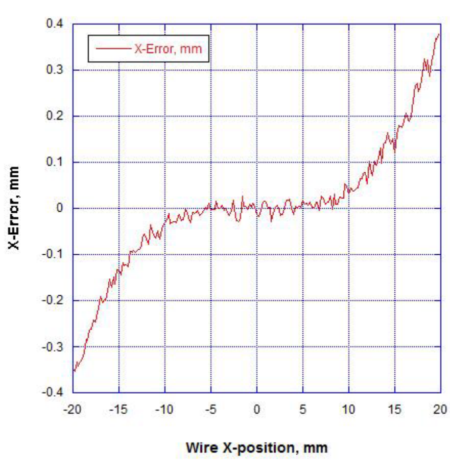

Figure 3: The deviation from linear of the monitor response to the transverse displacement measured with the wire method.

BPM ELECTRONICS

The electronics for the BPM is expected to provide position and intensity information, to have sensitivity and low noise down to 1 uA of beam current and a sufficient dynamic range.

No commercial electronics is easily available in the frequency range of 50-70 MHz to operate at the second or third harmonics of the bunch repetition frequency. This stimulated its in-house development. For the sake of simplicity the signal processing is based on a precision logarithmic amplifier (AD8306) with a usable dynamic range in excess of 90 dB [2]. The input signals from four loops of a BPM are sequentially multiplexed by a GaAs switch with a channel isolation of >50 dB. The insertion losses through the four branches of the switch were found to be within 0.01 dB of 0.80 dB. The selected signal passes through a 30 dB gain wideband amplifier and a 6% BW 46 MHz band pass filter to improve the signal-to-noise ratio at the input of the log detector. The detector circuit demodulates the incoming RF burst and gives a dc output proportional to the logarithm of the input signal amplitude. The log detector transfer function is approximately:

$$Vout = 20.2\ mV / dB\ (P_{rf} + 108\ dBm) \qquad (2)$$

The measured deviation from the logarithmic law conformance is plotted in Fig. 4 and results from the use of six 12 dB gain RF amplifying stages comprising the log detector circuit. The error is < ±0.5 dB over a range of 85 dB centered at -60 dBm.

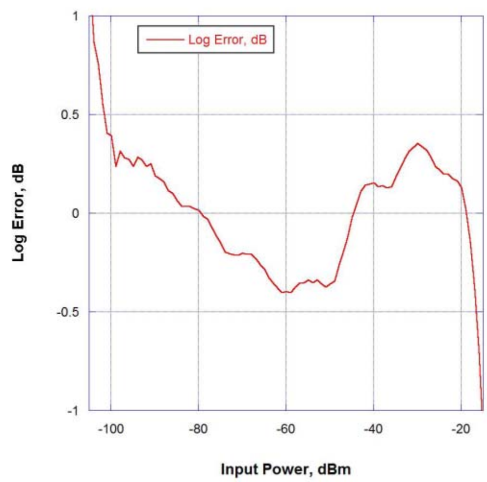

Figure 4: The error of the log detector linearity.

The output of the log detector is level shifted and digitized by a 14-bit 20 Msps ADC of a mixed signal DSP controller, ADSP-21992. The DSP controls the ADC conversion and multiplexer switching times, processes the acquired data with a log-ratio method [3] and outputs the results via three external to the chip 16-bit ±10 V DACs. The X and Y position output data are scaled such that:

$$X / Y[mm] = 0.42\, Vout\, [V] \qquad (3)$$

In addition, the signal level for each loop and their sum are available at outputs to represent the beam current. The acquisition cycle can be generated by means of either an external or internal trigger. In the latter case a Schmitt trigger circuit is implemented that fires when the RF input rises above approx -80 dBm at the leading edge of the beam pulse. This generates an interrupt to DSP.

The DSP can also perform other functions. Corrections for the log detector linearity error require a lookup table containing the deviation from an “ideal” logarithmic law response. Digital low pass filtering of acquired data and calculation of the mean value and standard deviation can be easily done by DSP. Many of these functions are being implemented.

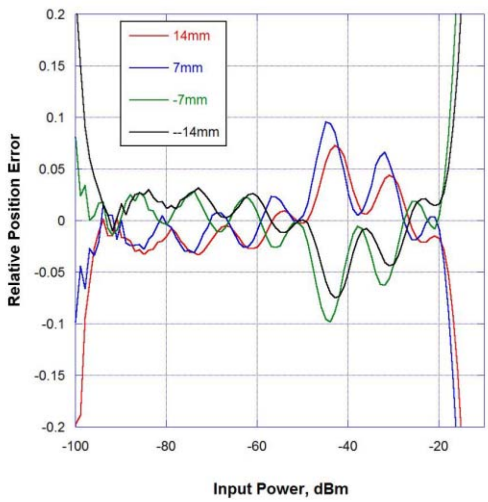

Figure 5: Relative position error. Beam displacements of ±7 mm and ±14 mm were simulated by attenuators.

Errors in the log detector linearity propagate to systematic position errors. The relative position error was measured using a signal generator and simulating the beam displacement with a set of attenuators (Fig. 5). The error oscillates with an amplitude of below 3% for a signal power ranging from -90 dBm to -50 dBm and increases to 5-10% for larger input powers.

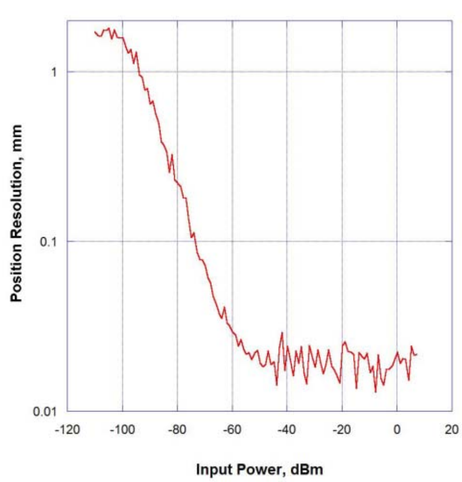

Figure 6: The rms position resolution due to the electronic noise measured over 100 samples.

The signal-to-noise ratio within the pass band of the log detector sets a limit to the position resolution. We measured it as the standard deviation of X and Y outputs over 100 consecutive samples. It is plotted in Fig.6 as function of the input power. For signal levels larger than –50 dBm the resolution is determined by the readout noise of the ADC. The resolution below -60 dBm can be improved by narrowing the bandpass filter at the expense of the response time. Currently it is set to 1 MHz to make possible measurements with a bunch train duration as low as 5 µs. The electronics fits in a double width NIM module.

BEAM MEASUREMENTS

One BPM unit was recently installed in our 2A beamline and beam tests were conducted. The signals from the loops were brought out via 50 m long double shielded coaxial cables to the processing electronics. Signal levels of -62 dBm were measured for the second harmonics and -59 dBm for the third and fourth harmonics with a 68 µA beam. It was verified that an additional gain of 13 dB can be obtained by building a resonant circuit with an external capacitor in parallel to the loop pickup and connecting it to a cable via an impedance matching transformer. This will allow the system to operate down to 1 µA.

The response of the monitor to a beam displacement was observed by varying the current of an upstream steering magnet, as shown in Fig. 7

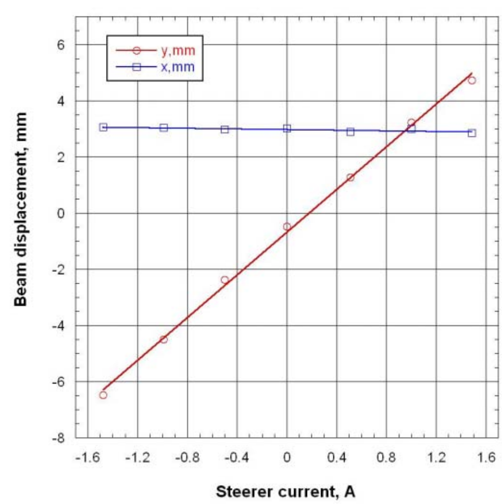

Figure 7: The response of the monitor to a beam displacement generated by an upstream steering magnet

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[3] R.E.Shafer, “Log-Ratio Signal Processing Technique for Beam Position Monitors”, AIP Conference Proc. 281, New-York, 1993, pp.120-128.