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DEVELOPMENT OF BPM ELECTRONICS FOR TRIUMF'S BL4N*

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Abstract

The BL4N beamline at TRIUMF, currently under development within the scope of the ARIEL expansion, will transport a proton beam from the 500 MeV cyclotron to a new ISOL target station. The peak beam current will be varied from 1 to 100 microamps, and the beam position is expected to be accurately measured over a 10 mm range. The beam position is measured using inductive type pickups and new narrowband front-end electronics. The electronics consist of a crossbar-switched front-end, FPGA-based down-conversion and position calculation, and an SoC module for nonlinear corrections and device readout. This report presents the design and testing of the BPM electronics, including benchtop validation and beam test results. Measurements of position sensitivity, beam current dependence, and non-linearity are included.

INTRODUCTION

The TRIUMF BL4N [1] will deliver protons from the 500 MeV cyclotron to a new ARIEL ISOL target station. Routine operation is expected at peak currents below 10 µA for certain RIB production targets. The principal beam parameters are listed in Table 1.

Existing inductive BPMs [2] cannot operate reliably at such low currents due to the electronics' limited dynamic range and transfer impedance of the pickups. To address this, a new inductive BPM has been developed with a ferrite core for improved sensitivity, as well as electronics with extended dynamic range.

Table 1: Basic Beam Parameters of BL4N

Parameter	Value	Unit
Beam species	H+	
Beam energy	500	MeV
Peak current	1-100	µA
Pulse duty cycle	1-99	%
Pulse frequency	375-1126	Hz
Bunch frequency	23.06	MHz

MONITOR DESIGN

The BPM is based on the design presented in [2], with a ferrite core added to increase the magnetic flux through each loop pickup, thus increasing the transfer impedance of the monitor. The ferrite core is made from M2 material from National Magnetics Group and is supported by an aluminium support (Fig. 1).

Operation is at the second harmonic of the bunch frequency (46.1 MHz), chosen for its stronger coupling and reduced background noise. The coupling between the beam and pickups was simulated in HFSS, with and without the ferrite, as shown in Fig. 2. The ferrite increases the transfer impedance by 12 dB at 46 MHz. A drawback is a stronger crosstalk between the pickup electrodes, which reduces the transverse sensitivity of the monitor. HFSS simulations show the sensitivity to decrease from 0.42 dB/mm to 0.2 dB/mm, increasing the demand on the front-end electronics.

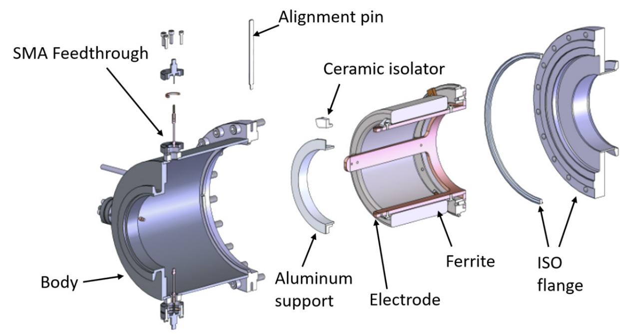

Figure 1: Exploded view of monitor.

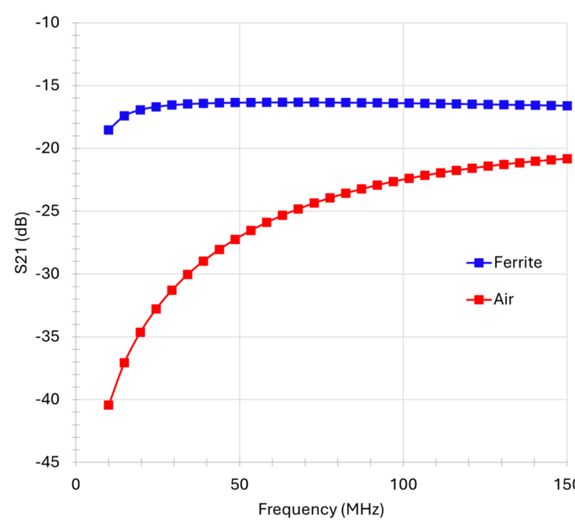

Figure 2: HFSS results for S21 coupling between beam and individual pickup, with and without ferrite core.

FRONT-END DESIGN

The BPM electronics consist of an RF front-end, an under-sampling analog-to-digital converter (ADC) and a FPGA-based digital down-conversion and position calculation (Fig. 3).

RF Front-End

The RF front-end (RFFE) was designed for 46.1 MHz operation. Each front-end (horizontal and vertical) consists of 2 wideband low-noise amplifiers (LNAs), matched to 46.1 MHz, separated by SAW bandpass filters centred at 46.1 MHz and variable 18 dB attenuators (Fig. 4). To reduce drift and gain mismatch, a crossbar switching scheme [3] was implemented using a DPDT switch placed after the

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first LNA. A SPST switch is used to inject a -40 dBm, 46 MHz self-test signal, for debugging purposes.

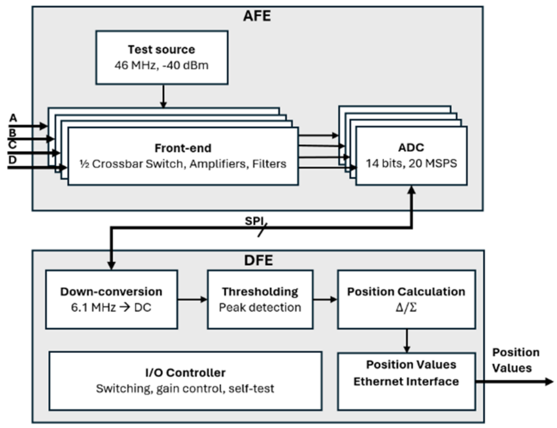

Figure 3: Block diagram of BPM electronics.

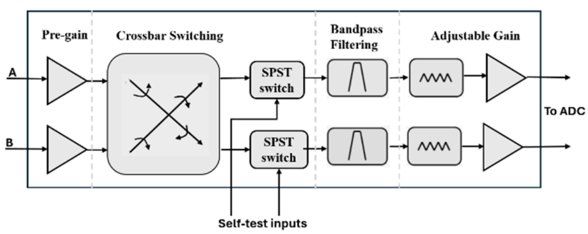

Figure 4: Block diagram of RF front end.

The crossbar switch is controlled by the FPGA and synchronized to the beam macro-pulses using a leading-edge detector. This allows the switching to occur between beam pulses, eliminating most of the switching transients which are present for ≤10 µs.

Digital Processing

An Altera DE10-nano module serves as the processing unit, with an ARM hard processor system (HPS) integrated with a Cyclone V FPGA. The FPGA performs all real-time processing and peripheral interfacing, while the HPS manages the Ethernet communication. An Avalon bus interface handles data transfer between the FPGA and the HPS. Key device parameters are stored in a 128-byte EEPROM and loaded into FPGA RAM on startup, with run-time modification possible via Ethernet commands.

A 20 MSPS ADC samples the 46.1 MHz input signal, producing an aliased 6.1 MHz digital signal. The sampling clock is generated by a PLL locked to the cyclotron RF frequency. A digital downconverter (DDC) on the FPGA mixes the input with 6.1 MHz quadrature sinusoids, producing in-phase (I) and quadrature (Q) components. The I/Q magnitude yields the beam envelope at the macropulse frequency.

A 3rd order CIC filter decimates the 20 MSPS data to 2.5 MSPS, reducing noise and processing load. Peak values are extracted from the down-converted data, by latching above an adaptive threshold. The threshold is continuously updated to be 25 % of the maximum value in the previous macro pulse, to avoid false latching at high signal levels. Position is calculated via the standard difference-over-sum method using the latched peaks, then filtered with a first-order IIR with adjustable bandwidth and another CIC stage for noise reduction. Data (positions, raw amplitudes, status registers) are streamed through a FIFO to the HPS for Ethernet transmission.

BENCHTOP RESULTS

The parameters of interest for a BPM are linearity, dynamic range, and input-referred position noise. To isolate the electronics' performance, a 46.1 MHz signal generator, a 1:4 splitter, and attenuators simulate a signal induced by beam current and displacement relative to the beam pipe axis. The input power for a given beam current is derived from previous beam measurements and is accurate to within 10 %. For all measurements, bandwidth was limited to 20 Hz using the on-board IIR filter.

Beam-current referred accuracy of position measurements was evaluated by sweeping the input power at various simulated displacements and comparing the measured position with the ideal reference (Fig. 5). The position error generally remained under 0.05 mm in the range 2 µA - 100 µA, increasing to 0.35 mm for beam currents below 2 µA. This increased error at low currents is a reproducible nonlinearity and can be compensated by the HPS in the future.

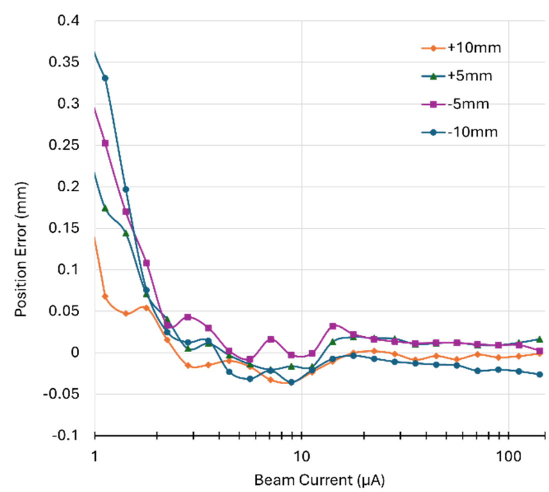

Figure 5: Non-linearity error at 50 % duty cycle.

The RMS position noise was measured by sweeping the input power for an on-axis beam and recording the standard deviation of 100 consecutive samples (Fig. 6). The measured noise was ≤60 µm for beam currents above 1 µA.

Expected position accuracy vs beam displacement was measured using the stretched wire method, in which a wire carrying an RF signal is displaced transversely through the monitor. Wire displacement was tracked to 20 µm accuracy and compared to BPM output at 100 µA simulated current and 50 % duty cycle. The combined nonlinearity of the monitor and electronics was within 0.3 mm for a ±10 mm range (Fig. 7).

BEAM RESULTS

A ferrite-core BPM was installed on TRIUMF's BL2A beam line, and a beam test was conducted with the new

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electronics. The monitor was connected to the electronics through 50 m long LMR400 cables. The machine operated at ~100 µA peak current with 2 % duty cycle. A vertical steering magnet was scanned, and the position was recorded with electronics as shown in Fig. 8. The position was swept over a 5 mm range, and the error was estimated from a linear fit to be ≤0.15 mm and is likely dominated by steering current errors. High beam spills prevented testing over a larger position range.

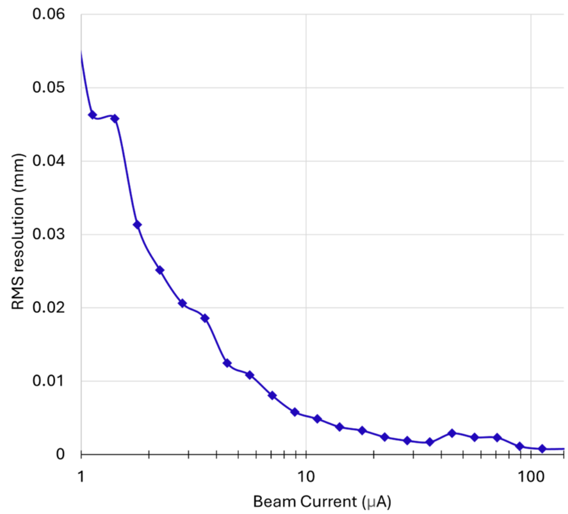

Figure 6: RMS position Noise at 50 % duty cycle.

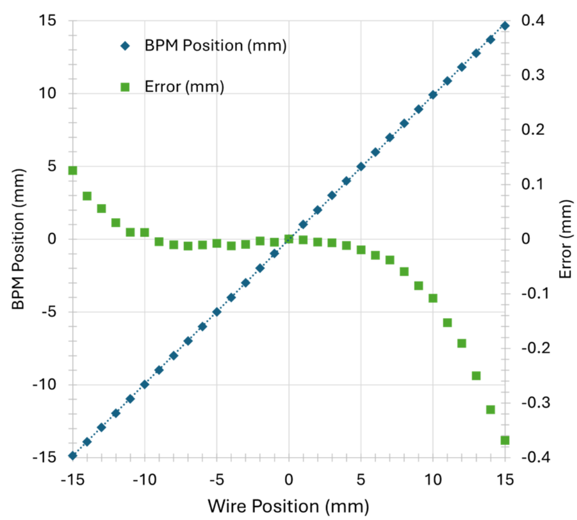

Figure 7: Benchtop error at 100 µA, 50 % duty cycle.

CONCLUSION

The addition of a ferrite core to the inductive BPM increases the coupling to the pickups, allowing the BPM to operate at low peak currents. New electronics were developed with wide dynamic range and improved channel matching to meet requirements of the BL4N beamline. Future work will focus on extending the operating range below 1 µA by adding front-end gain and implementing non-linear correction algorithms on the HPS module to further expand the usable position range.

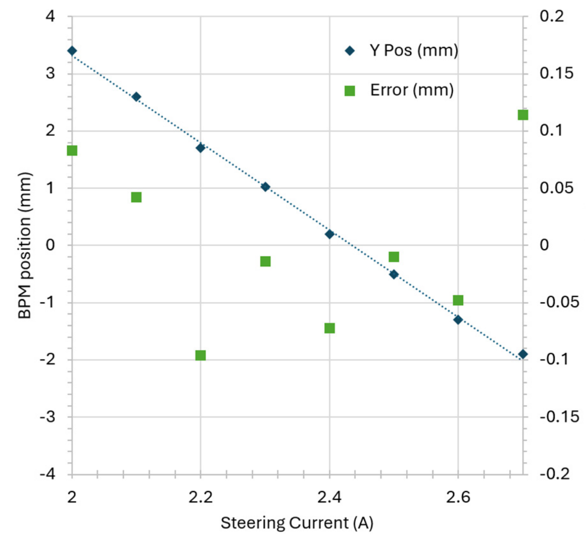

Figure 8: Beam position error at 100 µA, 2 % duty cycle.

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