BEAM POSITION AND PHASE MEASUREMENTS OF MICROAMPERE BEAMS AT THE MICHIGAN STATE UNIVERSITY REA3 FACILITY*

J. Crisp, D. Constan-Wahl, B. Durickovic, G. Kiupel, S. Krause, D. Leitner, S. Nash, J. A. Rodriguez#, T. Russo, R. Webber, W. Wittmer, NSCL/FRIB, MSU, East Lansing, MI 48824, USA
N. Eddy, C. Briegel, B. Fellenz, D. Slimmer, FNAL, Batavia, IL 60510, USA
M. Wendt, CERN, Geneva, Switzerland

Abstract

A high power CW, heavy ion linac will be the driver accelerator for the Facility for Rare Isotope Beams (FRIB) being designed at Michigan State University (MSU). The linac requires a Beam Position Monitoring (BPM) system with better than 100 micron resolution at 100 microamperes beam current. A low beam current test of the candidate technology, button pick-ups and direct digital down-conversion signal processing, was conducted in the ReA3 re-accelerated beam facility at Michigan State University. The test is described. Beam position and phase measurement results, demonstrating ~250 micron and ~1.5 degree resolution in a 45 kHz bandwidth for a 1.0 microampere beam current, are reported.

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) [1] will be a new accelerator-based user facility for research in nuclear physics. It will be located in the MSU campus and it is scheduled for completion in 2022. Its driver linac will accelerate ions as heavy as Uranium to energies higher than 200 MeV/u delivering up to 400 kW of beam power into a target. The desired Rare Isotope Beam (RIB) product of the reactions in the target will be transported to the different experimental areas after being selected in a fragment separator. Alternatively, the RIB can be thermalized, charge-bred and postaccelerated in the ReA re-accelerator [2] before being sent to an alternative experimental hall.

While the FRIB facility completion is scheduled for 2022, the first stage of the ReA re-accelerator was recently completed and connected to the Coupled Cyclotron facility (CCF) [2, 3]. During the measurements described in this paper, it has been used as a stand-alone accelerator to test the FRIB's prototype BPM system using a molecular Hydrogen beam produced by the off-line stable ion source.

DESCRIPTION OF REA3 AND THE BPMS

A Colutron-type ion source is used to produce several microamps of H_2^+ beam with an initial energy of 24 keV (defined by the 12 keV/u injection energy of the RFQ). The beam is then transported through an electrostatic transfer line and injected into a 4-rod 80.5 MHz RFQ after being bunched using a multiharmonic buncher. After the RFQ, the 600 keV/u beam is rebunched as it passes through a β = 0.041 SRF cavity operated at its zero-crossing phase (located in the first cryomodule (CM1) of the linac) and then accelerated to a few MeV/u when it passes through six more β = 0.041 SRF cavities located in the second cryomodule (CM2). Superconducting solenoids equipped with corrector coils inside the cryomodules are used to focus and steer the beam. During the tests, the two BPM sensors were installed in a drift space approximately 0.6 m down-stream of CM2 and separated by 2.08 m (Figure 1). Movable slits and Faraday cups in diagnostics stations before and after the BPMs were used to center and characterize the beam during the tests and beam attenuators and collimator slits were used to change the beam current.

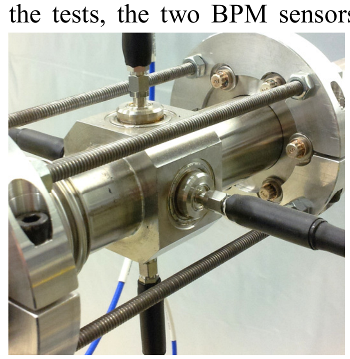

Figure 2: Prototype BPM as tested in ReA3.

The BPM system comprises two button-type BPM sensors (Figure 2, Table 1), signal amplifiers and digitizers that provide raw and processed data via EPICS channels to the control room. The button pickup has a design capacitance of 2 pF and impedance of 50 Ω. The

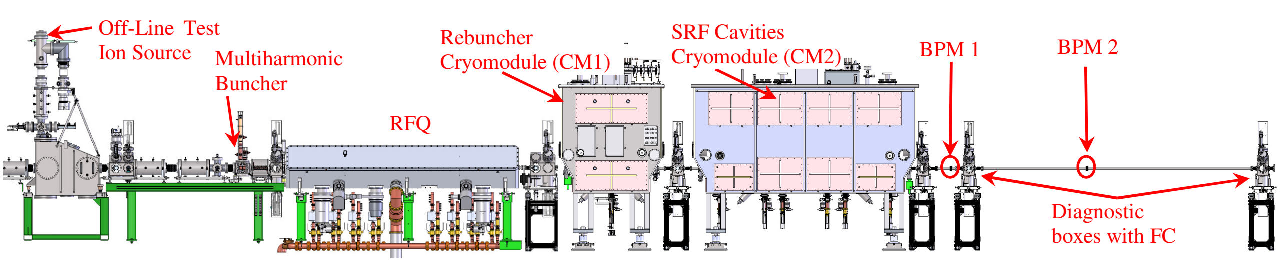

Figure 1: Layout of the ReA3 re-accelerator during the BPM tests.

* This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University, and the National Science Foundation, under Cooperative Agreement PHY-1102511.
#rodriguez@frib.msu.edu

ISBN 978-3-95450-138-0

signals from the buttons are small (~ -80 dBm), requiring amplification before digitization. Each front-end channel has a low-noise amplifier with 80 dB gain and 14 MHz band width centered near the 2nd beam harmonic at 161MHz. The entire analog front-end is enclosed in a shielded box and connected to the bpm using solid copper shielded coax to further reduce noise from surrounding systems.

The signals are digitized and processed by an 8-channel digital receiver board developed at Fermilab. This board was initially used for the ATF damping ring BPMs [4]. The board consists of 125 MS/s 14 bit ADCs connected to a Cyclone III FPGA.

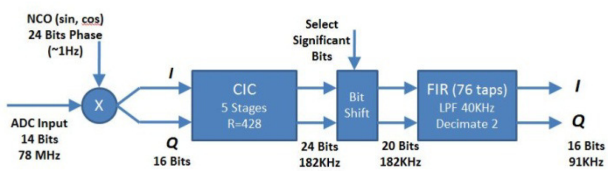

Figure 3: A block diagram of the DDC filter.

For the ReA3 system, an RF reference of 80.5 MHz is provided for the digitizer clock input. An internal PLL-based clock distribution chip sets the ADC clocks to operate at 32/33 of the RF clock. This undersamples the 161 MHz input signal producing an intermediate frequency (IF) of approximately 5 MHz. The IF signal is then processed by a Digital Down-Converter (DDC) circuit as shown in Figure 3. The output rate of the DDC is 91 kHz. The DDC yields the magnitude and relative phase of the input signal.

The 91 kHz output rate of the filter provides 2048 samples over a 22.5 ms window for each trigger. The beam pulse length was limited to approximately 25 ms for the tests. For each trigger, the front-end software reports the complete array of magnitude and phase data for the beam pulse as well as time-averaged values for positions, intensity and phase over the pulse.

Table 1: Characteristics of the BPMs

Parameter	Value
BPM aperture	1 3/8 in
Button diameter	20 mm
Signal frequency	161 MHz (2nd harmonic)
Trigger frequency	5 Hz

RESULTS OF THE TESTS

Several tests were conducted during 2012. The first tests confirmed the expected beam signal levels and uncovered an issue with electrical noise caused by the RFQ power amplifier. Electromagnetic shielding and filters were added to the BPM signal amplifiers in the following tests.

Beam Intensity Measurements

In an effort to understand the BPMs' performance at low currents and measure their response versus beam intensity changes, data were recorded while the beam current through the line was changed and measured in a Faraday cup located after the second BPM. The results of this measurement are shown in Figure 4 and demonstrate that the BPMs can be used with currents as low as 50 nA which is several orders of magnitude smaller than the anticipated 50 μA FRIB commissioning beam current. Their responses were linear over the range of available beam currents, which was limited by the ion source. The similarity in the results from the two BPMs indicates good reproducibility.

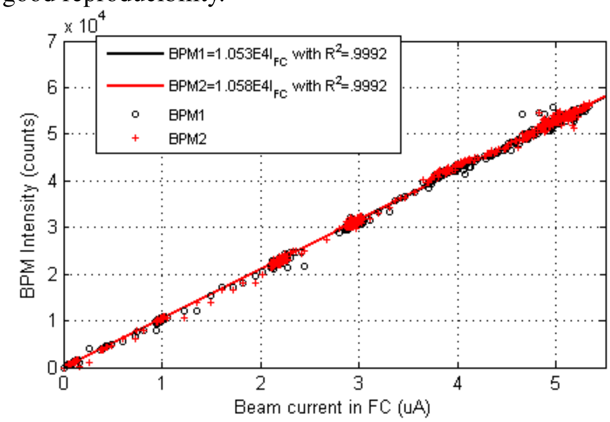

Figure 4: BPMs intensity signal vs. beam current. Currents as low as 50 nA could be measured.

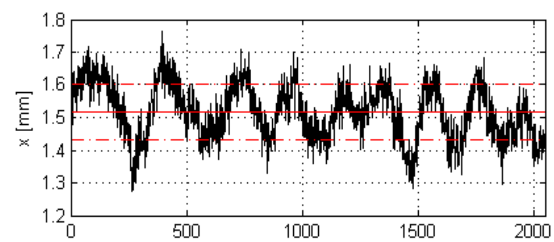

Figure 5: Typical measured beam position over 2048 consecutive samples (i.e. over 22.5 ms) for a 2 μA beam.

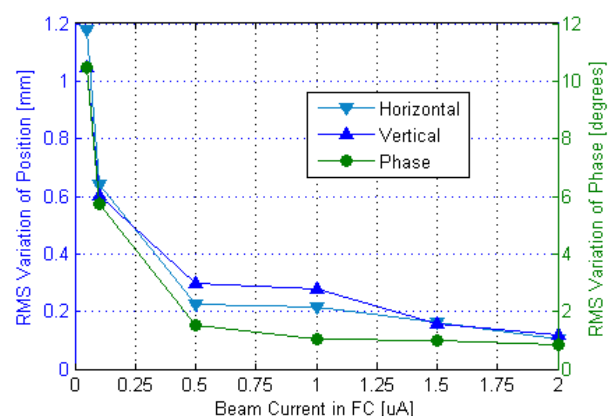

Figure 6: RMS variation of position and phase measurements as a function of beam current.

Variability of Position and Phase Measurements

Several experiments were conducted to characterize the resolution of the BPMs' position and phase measurements. Figure 5 shows the result of a typical

ISBN 978-3-95450-138-0

measurement; Figure 6 shows a summary of the RMS distribution of position results as a function of current. Without an independent measurement of actual beam motion, this data merely sets an upper limit for the achieved measurement resolution.

The variability for currents lower than 0.5 µA seems to be defined by the BPM system itself; however, this may not be the case for higher currents. Figure 5 suggests that coherent beam motion might be dominant at the 2 µA current level. The resolution of the BPM system at currents between 1 and 2 µA might be a fraction of the ~100 µm shown in Figure 6.

Beam Position Measurements

To observe the BPM system response to changes in beam position, data was recorded while the beam was steered several millimetres horizontally and vertically using the last correctors in CM2. Inside the cryomodules, the corrector coils are embedded in the solenoids which explains the horizontal and vertical coupling apparent in Figure 7.

Currently the position and intensity is scaled linearly. A 3rd order two-dimensional polynomial is being implemented to linearize and decouple the positions and to correct the intensity. The polynomial compensates for non-linearity effects with good results over two thirds of the pickup aperture.

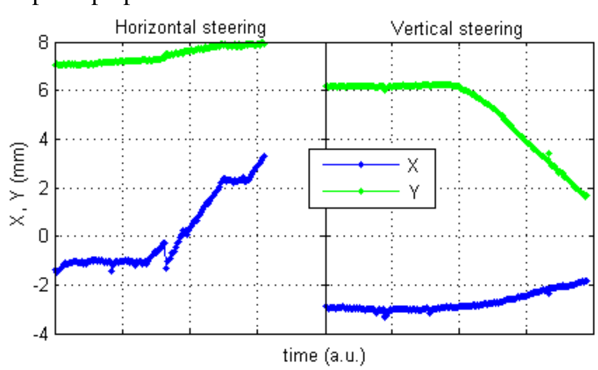

Figure 7: Beam position over time as it was steered horizontally (on the left) and vertically (on the right) during the test.

Phase Measurements

Simultaneous beam phase measurements enabled relative beam energy measurements by determining changes in time-of-flight. The beam phase at each of the two BPMs was observed as the beam energy was changed by scanning the RF phase of the last cavity in the second cryomodule.

Results show the expected sinusoidal-like phase variation between the two BPMs as a function of cavity phase setting (Figure 8). Measurement resolution was better than one degree of phase (17 picoseconds) in a 10 Hz bandwidth at 161 MHz for a 2 µA beam current.

The time-of-flight information provided by the BPMs has proven to be useful during the commissioning of the ReA3 linac. The time it takes to phase each cavity in the linac using the BPMs was reduced to a few minutes after automating the procedure, which is very important for FRIB given the number of cavities in the driver linac. More details on this procedure can be found in [5].

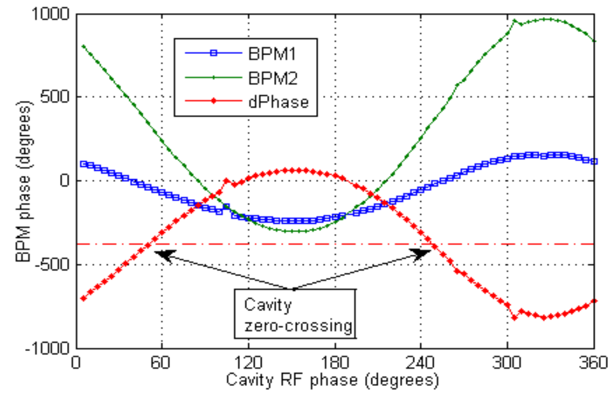

Figure 8: BPM phase measurements as the phase in the last cavity of CM2 is varied.

Signal to Noise Ratio Measurements

A spectrum analyser was used to measure noise with the amplifier located at the bpm and then at the digital receiver 18 m away. The noise power spectral density referenced to the amplifier input measured -167.4 dbm/Hz for both locations. No degradation in BPM signal quality was observed. This is relevant for FRIB because it is highly desirable that the amplifiers be located outside the tunnel to be shielded from ionizing radiation and accessible for maintenance.

CONCLUSION

The BPM experiments in the ReA3 facility have successfully demonstrated that high resolution for position and phase measurements with microampere beams can be achieved using button-type BPMs and 2nd harmonic signal processing. Scaling the ReA3 results to FRIB suggests a resolution 7 times better than the 100um at 100uAmp requirement. While work remains to assure this performance is achieved in the real FRIB accelerator environment, these tests provide a basis for proceeding with a FRIB BPM system design based on button-type pickups and a direct digital down conversion receiver.

REFERENCES

[1] J. Wei et al., "Progress towards the Facility for Rare Isotope Beams", FRYBA3, NA-PAC'13 Proc.
[2] D. Leitner et al., "Status of the ReAccelerator Facility ReA for Rare Isotopes", FRYBA4, NA-PAC'13 Proc.
[3] W. Wittmer et al., "Results from the Linac Commissioning of the Rare Isotope Reaccelerator - ReA", MOPSM07, NA-PAC'13 Proc.
[4] N. Eddy et al., "High Resolution Bpm Upgrade for the ATF Damping Ring at KEK", DIPAC'11.
[5] B. Durickovic et al., "RF Cavity Phase Calibration using Electromagnetic Pickups", THPHO14, NA-PAC'13 Proc.

ISBN 978-3-95450-138-0